Biophysical, environmental, and economic implications of removing imported supplementary feed from a pasture-based dairy farm system

-An upper North Island case study

A thesis

submitted in partial fulfilment

of the requirements for the degree

of

Master of Management Studies in Agribusiness

at

The University of Waikato

by

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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2019

Abstract

The biological efficiency and profitability of pasture-based systems is optimised by matching pasture supply with the nutritional demands of the herd across the year. Despite the importance of grazed pasture to the profitability of pasture-based systems, the use of purchased (i.e., non-pasture) feeds (supplementary feeds) has increased considerably over the last two decades within the New Zealand (NZ) dairy industry.

Supplementary feeds may be offered to maintain or increase dry matter intake (DMI) and milk production during periods when pasture supply is insufficient to meet herd demands (i.e., a pasture deficit). However, published results indicate that, despite greater milk production and gross farm revenue (GFR), imported supplementary feed is not associated with an increase in profitability. In addition, the intensification of grazing systems through concurrent increases in stocking rate (SR) have been associated with poorer environmental outcomes, such as reduced water quality and increased greenhouse gas (GHG) emissions.

The primary objective of my Masters project was to investigate the biophysical, economic, and environmental effects of removing imported supplementary feed from a typical pasture-based system in the upper North Island of New Zealand. This was conducted over three years in Northland, New Zealand (35º56'39"S 173º50'34"E), using a quantitative case-study approach that compared three pasture-based dairy farming treatments differing in SR and the nature of feed supply. As a Control treatment, imported supplementary feed was offered as palm kernel expeller (PKE) during periods of pasture deficit (~ 550kg DM/cow/yr; ~ 10% of the cows' diet; PKE treatment). This was compared with two alternative systems to remove the need for PKE: 1) reduced SR (Pasture treatment); or, 2) growing potentially high yielding forage crops on the dairy platform and maintaining SR (Cropping treatment). I used the nutrient budgeting software OVERSEER to model treatment effects on nitrogen (N) leaching, phosphorous (P) loss, and GHG emissions. In addition, I conducted a Monte Carlo analysis to investigate economic performance of all three treatments and how it varied over a range of key input prices.

On average, despite no significant difference in milk production, operating profit tended to be lower in the Cropping treatment relative to the PKE treatment. In addition, after accounting for variability in market prices, the Cropping treatment returned a lower operating profit at every probability level relative to the PKE treatment and was, therefore, an inferior system for a profit-focused decision maker.

Milk production and associated GFR were lower in the Pasture treatment compared with the PKE treatment; however, there was no effect of treatment on operating profit at average market prices. When accounting for potential market price variability, the PKE treatment returned a greater operating profit in 70% of scenarios. As a result, the PKE treatment would likely provide a preferable system for a profit-focused decision maker, with low to moderate risk aversion. However, the relative profitability of treatments was highly dependent on the marginal milk production response (MMPR) to supplementary feed. Consistently large MMPRs to supplementary feed were achieved in the current study: 30 to 50% greater than published farm systems experiments. A reduction in the MMPR to supplementary feed by 10% eroded the profit advantage of the PKE treatment. In addition, despite no treatment effect on N leaching, GHG emissions tended to be lower in the Pasture treatment relative to the PKE treatment. As a result, a decision maker, paying or receiving incentives to reduce environmental externalities would likely be indifferent between the PKE and Pasture treatments, even with the large MMPR to supplementary feed achieved in the current study. Depending on the potential response to supplementary feed, profitability may be maintained with the removal of imported supplementary feeds from a pasture based system by decreasing SR.

Acknowledgements

Firstly, to my parents, Maree and Allister McCahon, they say we are a product of our decisions and not our environment, but the supportive environment you have always provided has given me the courage to take opportunities when they are presented and know that I am supported through all the ‘Upson Downs’. Thank you for your unwavering commitment toward my education and support in all my endeavours.

To my grandparents, Harold and Raewyn Robinson, and David and Lenna McCahon, thank you for your unconditional support and encouragement, you are the best role models, and friends, a boy could dream of.

To my supervisors John Roche, Mark Neal, Zack Dorner, and Graeme Doole. John, your passion and enthusiasm for research is infectious. Thank you for always making time for me, your positivity, endless encouragement, and witty comments, I am incredibly grateful for your support. Mark, thank you for leading me along the journey of ‘unconscious incompetence’ to ‘conscious competence’, whether the destination has been reached or not is up for debate, that is, “it depends”. Thank you for your patience, encouragement, and curiosity. Zack and Graeme, thank you for the time you have invested, your thorough comments, and insightful suggestions.

Thank you to DairyNZ for the financial support and to the many staff who have offered their knowledge, time, and encouragement. My sincere thanks go to Barbara Kuhn-Sherlock, for your statistical expertise and endless patience. To Jane Kay, Susan Stokes, and Jenny Burke, thank you for your academic and personal support.

Thank you to the Northland Dairy Development Trust and Northland Agricultural Research Farm staff and committees for your dedication and vision. In particular, thank you to Chris Boom and Kate Reed for your time and patience.

To my wider family, friends, and to my partner Memphis, thank you for your support throughout what has been a challenging, but rewarding journey.

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List of abbreviations

ABV	Australian breeding value
ANOVA	Analysis of variance
APC	Average pasture cover
BCS	Body condition score
BW	Breeding worth
CDF	Cumulative probability density function
CIDR	Controlled internal drug release
CP	Crude protein
CSR	Comparative stocking rate
DIM	Days in milk
DM	Dry matter
DMI	Dry matter intake
FTE	Full-time equivalent
FWE	Farm working expenses
GDP	Gross domestic product
GFR	Gross farm revenue
GHG	Greenhouse gas
HA	Herbage allowance
K	Potassium
LW	Liveweight
MC	Marginal cost
ME	Metabolisable energy
MMPR	Marginal milk production response
MR	Marginal revenue
MS	Milksolids
N	Nitrogen
NDF	Neutral detergent fibre
NIRS	Near-infrared spectroscopy
NZ	New Zealand
OAD	Once a day
P	Phosphorous
PA	Pasture allowance

PAS	Publically available specification
PKE	Palm kernel expeller
PSC	Planned start of calving
PSM	Planned start of mating
RFD	Relative feed deficit
ROA	Return on assets
SED	Standard error of the difference
SR	Stocking rate
SuR	Substitution rate
TFC	Total factor cost
TMR	Total mixed ration
TVP	Total value of product

Chapter 1: Introduction

The primary industries are an integral component of the NZ economy and are forecast to contribute ~ $45 billion in export earnings in the 2018-19 year (Ministry for Primary Industries, 2018); this is, primarily, comprised of dairy, meat, wool, forestry, and horticultural exports (Figure 1).

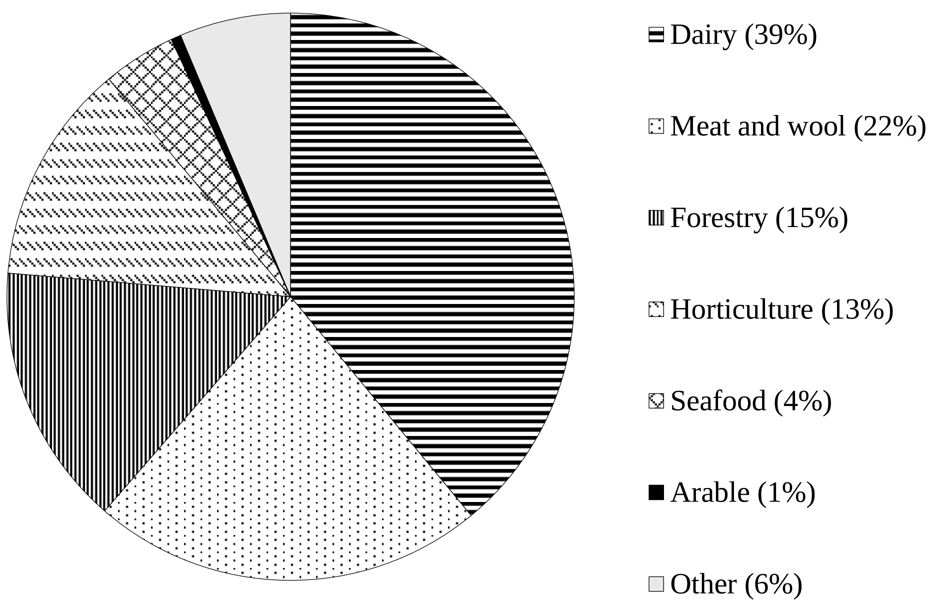

Figure 1: Contribution of individual sectors to total primary industries export revenue. Data sourced from Ministry for Primary industries (2018).

The contribution of the dairy industry to total export earnings is considerable (approximately, $17.5 billion in the 2018-19 year); dairy export growth has averaged 7.2% per annum over the past 26 years (Ballingall & Pambudi, 2017). Furthermore, the dairy industry contributes $7.8 billion (3.5%) to NZ's total gross domestic product (GDP), comprising of earnings from dairy farming ($5.96 billion) and dairy processing ($1.88 billion; Ballingall & Pambudi, 2017). The sector directly employs over 47,000 workers, with 33,500 employed on-farm and a further 13,500 within processing and wholesale (DairyNZ Limited, 2017d). Growth in dairy employment has averaged 3.7% per year since 2000, more than double the rate of growth in national employment (Ballingall & Pambudi, 2017). In addition, the dairy industry influences the NZ economy beyond its direct contributions to

GDP and employment, supporting numerous input and support service industries. For example, in 2016 farmers spent $711 million on fertilisers and agri-chemicals and $914 million on agricultural services (Ballingall & Pambudi, 2017). Therefore, the dairy sector, plays a crucial role in supporting rural NZ economies and their communities, accounting for 14.8% of Southland's economy, 11.5% of the West Coast economy, 10.9% of the Waikato economy, 8.0% of Taranaki's economy and 6.0% of Northland's economy (Ballingall & Pambudi, 2017).

The NZ dairy sector is unique relative to many other dairy producing nations due to both the nature of its production system, an export trade focus, and absence of direct government subsidies. The NZ dairy industry is predominantly pasture-based, enabled by a favourable temperate climate. This allows for high yields of pasture produced throughout the year, and year-round, *in situ* grazing of this forage, such that grazed pasture forms the primary component of the diet. This system offers cost advantages relative to housed systems, where cows are offered a total mixed ration (TMR). The relatively small population of NZ and high milk production per capita results in a relatively small domestic market for dairy products in NZ. As a result, the NZ dairy industry is export oriented, with over 90% of product exported (Destremau & Siddharth, 2018). This export focus exposes NZ dairy farmers to international milk markets and associated milk price volatility without government support in the form of subsidies.

With pasture forming the main component of a herd's diet, adverse climatic events, such as drought or periods of extended and heavy rainfall, can have a considerable effect on feed supply and utilisation, and, as a result, milk production (production risk). The prevalence of extreme weather events/episodes are expected to increase during this century, particularly in regions that are already prone: for example, drought in northern and eastern regions (A. Clark, Mullan, & Porteous, 2011).

Under more severe modelling estimates, the time spent in drought conditions in Northland may more than double by 2090 (Mullan, Porteous, Wratt, & Hollis, 2005). Offering imported supplementary feed is an effective strategy to reduce production risk, however, also increases a farmer's exposure to market risk in the form of imported feed prices and milk price. Increasingly, published results indicate that the increase in milk production and GFR from use of supplementary feed in grazing systems is not associated with an increase in profitability and may, in fact, be associated with a reduction in profit (Ramsbottom et al., 2015; Macdonald et al., 2017) or return on assets (ROA; Ma et al., 2018). Furthermore, intensification of agricultural systems has been associated with negative effects on the environment, such as through reduced water quality or an increase in GHG emissions (Parliamentary Commissioner for the Environment, 2004). Reductions in the negative externalities from the agricultural industry (N leaching and GHG emissions), and the dairy industry in particular, are increasingly important in ensuring farming is not unduly regulated in the future. Nevertheless, imported supplementary feeds have become a common component of NZ dairy farming systems.

The primary objective of my Masters was to investigate the biophysical, economic, and environmental effects of removing imported supplementary feed from a pasture-based grazing system.

Chapter 2: Literature review

2.1 Introduction

The majority of NZ dairy farms operate a pasture-based grazing system, with approximately 82% of the annual diet consisting of grazed pasture; the balance is comprised of forage crops (3.7%), supplementary feed harvested on-farm (6.3%), and supplementary feed purchased from outside the farm (8%; DairyNZ Economics Group, 2016). These pasture-based systems are enabled by the favourable temperate climate that exists within the main dairying regions of the country, allowing for extensive pasture growth and year-round, *in situ* grazing of this forage.

Pasture-based grazing systems reduce the required expenditure on capital infrastructure and machinery (Roche, Berry, et al., 2017), have less need for specialist management advice and decision support resources (Dillon, Roche, Shalloo, & Horan, 2005), and provide cost savings in labour and feed relative to housed systems (Dillon et al., 2005), ultimately resulting in low operating expenses/kg of milk (Roche, Berry, et al., 2017). Operating expenses have been reported to decrease at an increasing rate, as the proportion of pasture within the diet is increased (Figure 2; Dillon et al., 2005). The comparatively lower cost of production associated with pasture-based systems has, historically, underpinned NZ's competitive advantage within the international dairy market (Dillon et al., 2005).

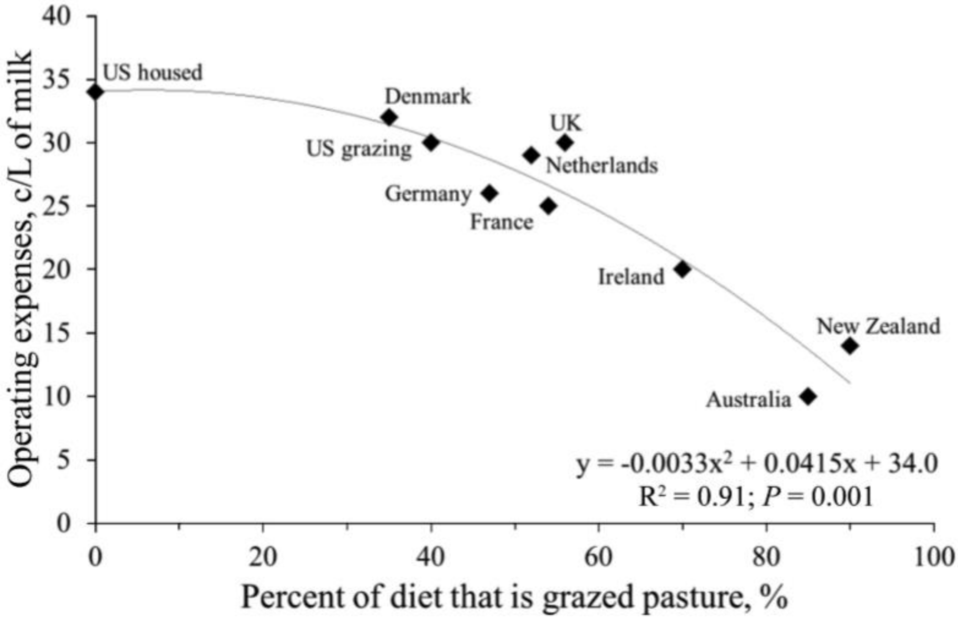

Figure 2: Reduction in operating expenses per unit of milk with increasing proportion of pasture in the diet (Dillon et al., 2005; Roche, Washburn, Berry, Donaghy, & Horan, 2017).

With pasture forming the main component of herd intake, pasture-based systems are heavily reliant on the quantity and seasonal distribution of pasture production, which are subject to both inter- and intra-year variability (Chapman, Rawnsley, Cullen, & Clark, 2013). Where pasture growth is insufficient to meet animal demand (a feed deficit), supplementary feed may be offered to increase DMI and milk production relative to what could be achieved without supplementation (Bargo, Muller, Kolver, & Delahoy, 2003).

The aim of this review is to overview the biophysical, economic, and environmental effects of offering supplementary feed within pasture-based grazing systems. This will, initially, involve an overview of factors that influence the balance between feed supply and demand and offer an understanding of the biophysical reasoning behind offering supplementary feed. I will then provide an overview of the factors that affect the milk production response to supplementary feed within these systems, given the importance of this factor in determining the farm-system level effects of offering supplementary feed. I will then assess the environmental and economic implications of offering supplementary feed within pasture-based systems.

2.2 Pasture supply

Feed supply within a pasture-based system is intrinsically linked to the regional pattern of pasture growth. This pasture growth pattern follows the seasonal variation in temperature, day length, radiation, and precipitation relative to evapotranspiration and drainage (i.e., soil moisture availability; Chapman et al., 2013). The pattern of pasture growth in NZ is consistent with other medium to high rainfall or irrigated temperate regions around the world. This growth pattern is further modified by the influence of latitude, topography, altitude, aspect, and coastal proximity, as these can affect maximum and minimum temperatures, day length, moisture availability, and dominant pasture species, as well as soil and management factors (McKenzie & Kemp, 2000). Variation in these factors result in significant regional variability in annual pasture production and its seasonal distribution as presented in Figure 3.

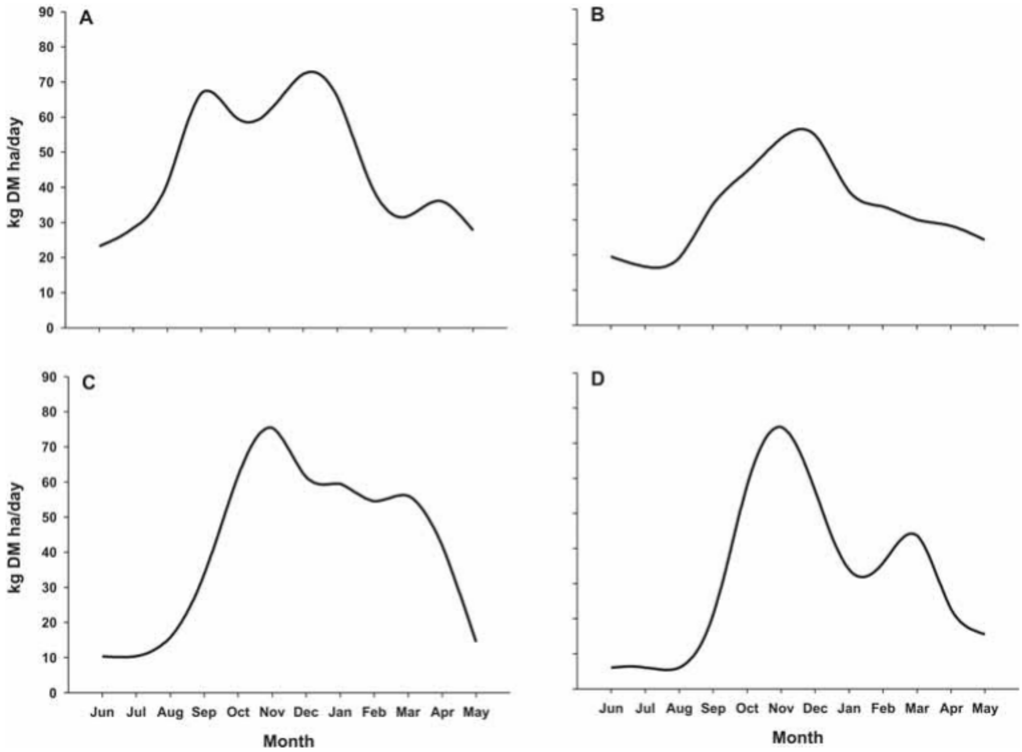

Figure 3: Seasonal profile of pasture production across 4 different sites in New Zealand: A) Waikato, B) Taranaki, C) Canterbury, D) Southland (Monaghan et al., 2004).

In addition to this seasonal variation in growth within a year, pasture production is also subject to inter-year variation, due to considerable climate variability characteristic in temperate regions (Taylor & Gentilli, 1971). Both the seasonality of pasture growth and the extent to which this inter-year variability fluctuates across the year are presented in Figure 4. This inter-year variability can result in system inefficiencies within pasture-based production systems as a result of the direct and indirect costs associated with the various management 'levers' employed to limit or control this variation (e.g., harvesting silage; Chapman et al., 2013).

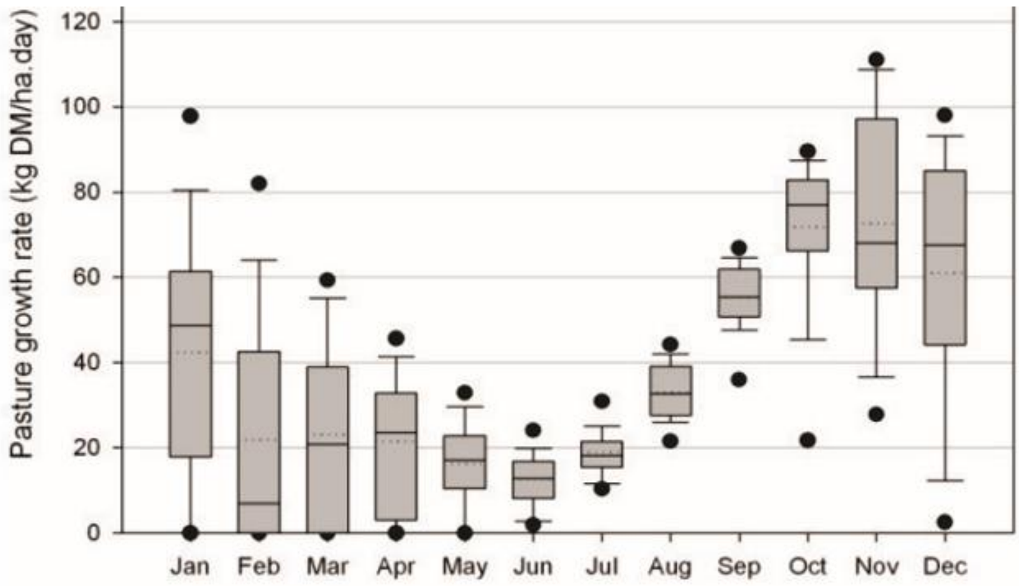

Figure 4: Inter-year and intra-year variability of pasture production; Hamilton, New Zealand (Chapman et al., 2013).

The biological efficiency of a pasture-based system is affected by the amount, quality, and seasonal distribution of feed grown, the proportion of this feed that is utilised by the animal, and the efficiency with which the animal partitions this utilised feed toward milk production at a system level (Holmes & MacMillan, 1982). This process forms the basis of efficient pasture-based dairy systems: the production of a high quantity of high quality pasture, converted to milk by efficient (genetically selected) cows at low cost (Kolver, 2003). The efficiency of this conversion of pasture into milk is influenced by the ability of pasture supply to match the nutritional demands of the herd across the year (Dillon, Crosse, Stakelum, & Flynn, 1995; Holmes et al., 2002; Leaver, 1985).

2.3 Animal demand

The nutritional demands of a herd at any point in time are determined by the number of cows and the nutrient demands of individual animals. The latter variable is, in turn, governed by the physiological state of the animals (i.e., whether they are pregnant, lactating, or non-lactating) and additional factors such as the liveweight (LW), breed, the genetic merit of animals, and their related growth rate and level of production (Leaver, 1985; Roche, Turner, et al., 2009d). The nutritional demands of the herd throughout the season and at key times of the year is, therefore, a function of the SR, the calving date, and lactation length of cows within the herd (Bryant, 1981; Holmes et al., 2002; Holmes & MacMillan, 1982).

2.3.1 Stocking rate

Stocking rate, fundamentally, determines the balance between feed supply and demand as it is a chief factor in determining 'herd demand'. It is a critical strategic decision within a pasture-based system because of its influence on pasture utilisation and milk production per hectare (Macdonald, Penno, Lancaster, & Roche, 2008; B. McCarthy, Delaby, Pierce, Journot, & Horan, 2011). Stocking rate on any farm is defined as the number of cows allocated to an area of land, generally at peak milk production (Macdonald et al., 2008).

Stocking rate strongly affects the balance of feed supply and demand through its effect on herd demand. A change in SR results in a proportional increase in the herd demand profile. Provided no further action is taken to change the supply of feed, an increase in SR will exacerbate feed deficits and diminish the size of any feed surpluses (Figure 5).

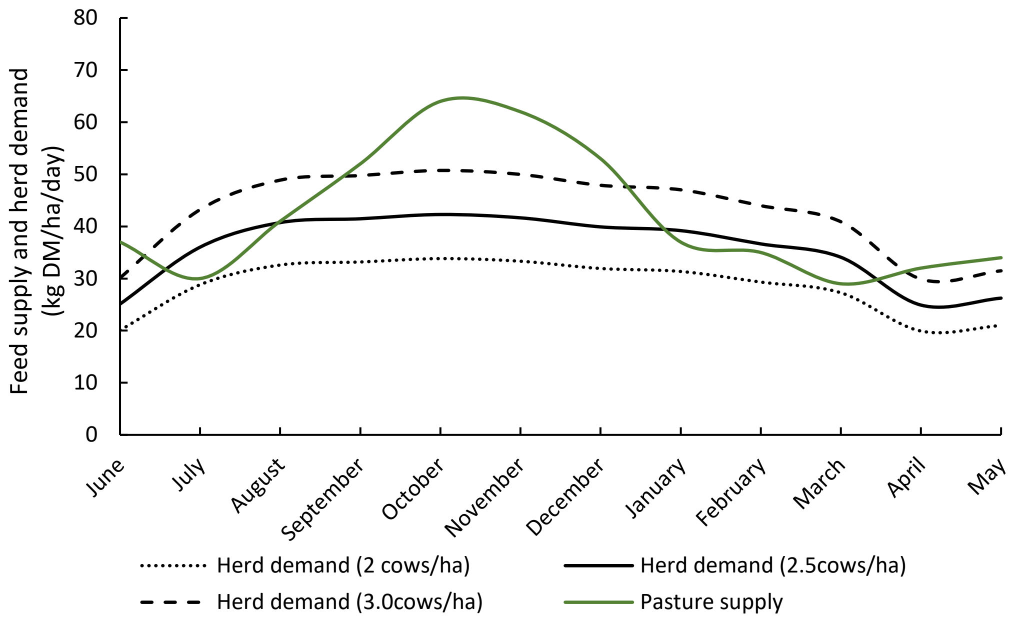

Figure 5: Stylised balance between feed supply and animal demand for a seasonal calving herd at differing stocking rates.

Macdonald et al. (2008) acknowledged that SR has significant limitations as a measure of the balance between feed supply and demand, when comparing different farms, farm systems, regions, or, even, cow breed choices on-farm. These inadequacies arise due to variation in pasture production potential between locations and differences in cow LW between and within breeds. These differences ultimately influence pasture supply and animal demand per hectare, and the quantity of feed needed to balance the system through either supplementary feed imported into the system or off-farm grazing. Macdonald et al. (2008) proposed a concept they called comparative stocking rate (CSR) as a more effective measure for assessment of the balance between feed supply and feed demand when comparing between farms, as it considers these farm-level differences, facilitating a comparison between regions and dairy farm systems. Comparative stocking rate is defined as the amount of LW relative to the amount of feed available, or, the kilograms of LW per tonne of feed dry matter (DM) available (Macdonald et al., 2008).

The profitability of pasture-based systems is strongly influenced by the efficiency of pasture utilisation, whilst concurrently achieving moderate per cow production (Dillon et al., 2005; Macdonald et al., 2008). However, a compromise exists within pasture-based systems between milk production per cow and per hectare (Stockdale

& Trigg, 1989). It is this compromise that led McMeekan (1960) to conclude that "in using SR as a weapon to increase per acre efficiency, we must accept a lower output per animal", a conclusion later reiterated by Macdonald et al. (2001; Figure 6). Within a NZ context, milk production is measured with respect to the quantity of protein and fat produced (colloquially termed, and referred to hereafter, as milksolids: MS). Macdonald et al. (2001) reported that as CSR increased, MS production per cow decreased due to a reduction in per cow feed availability and feed conversion efficiency. In contrast, MS production per hectare increased with CSR as a result of greater pasture utilisation.

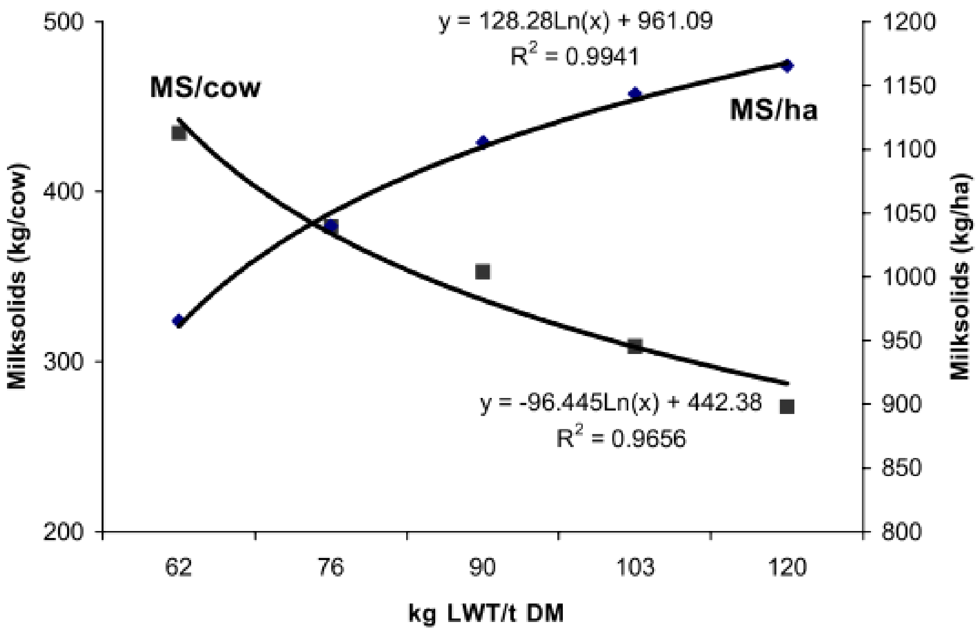

Figure 6: The effect of stocking rate on milksolids production per cow and per hectare (Macdonald et al., 2001).

Dry matter intake is a significant driver of milk production and vice versa (Kolver, 2003; Leaver, 1985; Peyraud, Comeron, Wade, & Lemaire, 1996). It is widely accepted that the relationship between herbage allowance (HA) and DMI is curvilinear (Peyraud et al., 1996). As SR increases, HA per cow declines, reducing DMI per cow (Macdonald et al., 2001). This reduction in HA causes animals to graze to a lower residual to achieve their nutrient intake requirements, increasing pasture utilisation. Macdonald et al. (2001) reported that pasture utilisation increased from 64 to 81% when SR increased from 2.2 to 4.2 cows/ha. However, this increase in pasture utilisation was partially offset by a simultaneous reduction in animal-level feed conversion efficiency (86 to 73 kg MS/t DM eaten). The reduced animal-level feed conversion efficiency resulted from an increase in the quantity of consumed energy being directed toward body maintenance as a result of the higher SR.

An optimal SR at a farm level not only considers the biophysical trade-off between pasture utilisation and feed conversion efficiency, but also the increased variable and fixed costs associated with a greater SR. At an economically ‘optimal’ SR, the greater returns from an increase in SR are exactly offset by the increased costs: that is to say, the marginal return equals the marginal cost. Economic modelling of previous SR experiments provided evidence that, from a profitability perspective, the optimal SR is between 80 to 90 kg LW/t DM, with an optimum at approximately 85 kg LW/t feed DM (Macdonald et al., 2017; Macdonald, Beca, Penno, Lancaster, & Roche, 2011). At this optimum SR, a cow would consume approximately 90% of an unrestricted intake (Macdonald et al., 2008; B. McCarthy et al., 2011), which quantifies the degree of compromise previously discussed. This optimum was hypothesised to shift toward 90 kg LW/t feed DM with the increased use of supplementary feeds in combination with a higher SR (Macdonald et al., 2017).

2.3.2 Calving date

Reliance on pasture as the main source of feed and the inherently seasonal nature of pasture supply, necessitates a seasonal calving pattern with a compact calving period to ensure alignment between pasture supply and herd energy demand (Garcia & Holmes, 1999). These calving strategies ensure that the increased feed demand of the herd in early-lactation coincides with peak pasture growth in spring, whilst also maximising lactation length (Roche, Washburn, et al., 2017). The term ‘compact calving period’ refers to a high proportion of the herd calving in a short period. Ideally, this constitutes approximately 50% of cows calving in a 2-week period following the ‘planned start of calving’ (PSC), with the entire herd having calved within a 10-week period (Roche, Washburn, et al., 2017). To maintain the appropriate seasonal calving pattern, a 365-day calving interval must be maintained, in theory, requiring each cow to be mated and conceive within an 80-day window following her calving date (Figure 7).

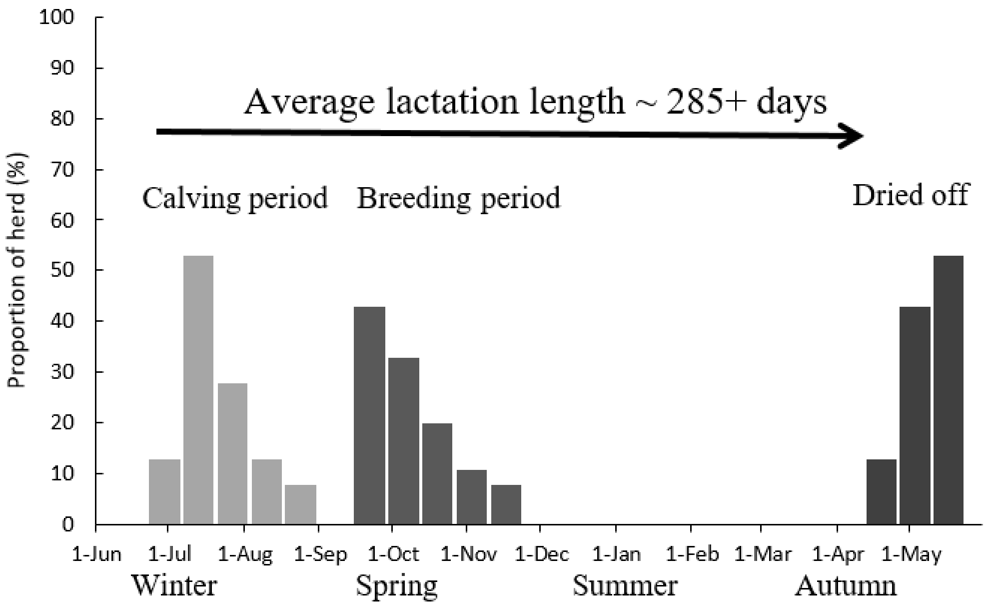

Figure 7: Proportion herd during calving, mating and dry off periods for a seasonal calving herd. Adapted from Roche et al. (2017).

The timing and distribution of cow calving dates can have a significant effect on the alignment between pasture supply and feed demand (Figure 8), as it sets the daily herd demand for each day of the year (Garcia & Holmes, 1999) and, more importantly, early in the growing season when pasture growth is less than animal demand. It is broadly recognised that, in an efficient, pasture-based system, the optimal PSC should be timed 50 to 60 days prior to the date at which the rate of pasture growth equals herd demand (known as balance date) to ensure that peak herd intake is best aligned with peak pasture intake (Dillon et al., 1995; Macdonald, Glassey, & Rawnsley, 2010; Roche, Washburn, et al., 2017).

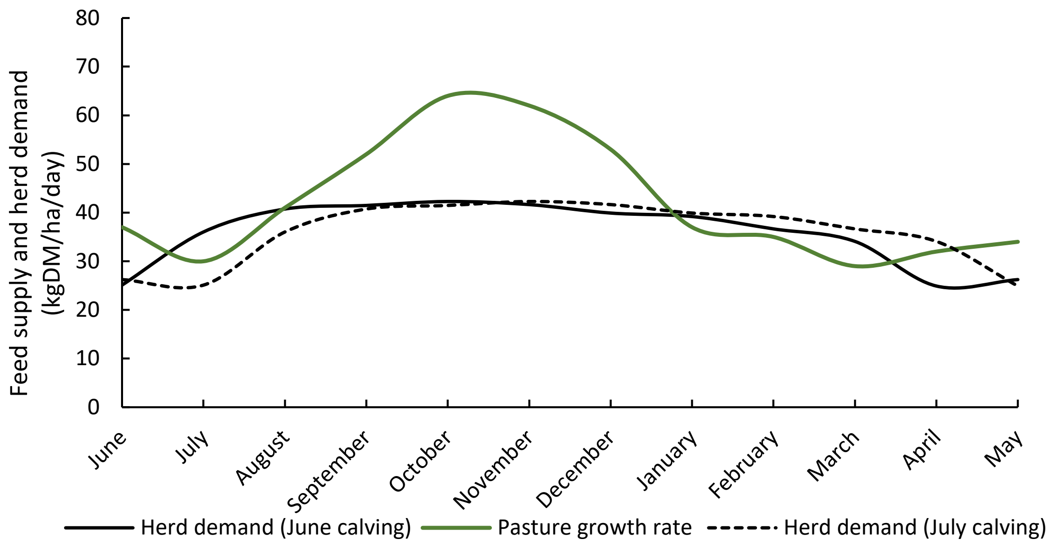

Figure 8: Stylised balance between pasture supply and animal feed demand for a seasonal calving herd at different calving dates.

2.4 Balancing supply and demand

As previously discussed, in seasonal calving, pasture-based systems, herd demand is aligned with pasture supply through strategic decisions around calving date (Dillon et al., 1995) and SR (Macdonald et al., 2008). However, even in systems with an optimally timed calving date and a suitable SR, there will be periods of the year where pasture supply is either insufficient or in excess of herd demand (Roche, Washburn, et al., 2017). Under temperate conditions, spring pasture growth increases at a greater rate than the increase in herd demand (Dillon et al., 2005). To ensure the herd's peak nutrient demands align with peak pasture production, pasture-based systems are strategically designed to face an early-spring deficit in growth. In addition, the inter-year variability in pasture production means that there will, invariably, be periods of the year where pasture demand exceeds pasture supply and vice versa. In an entirely pasture-based system, various management 'levers' can be employed to buffer the variability in pasture growth and optimise the alignment of pasture supply and animal demand (Chapman et al., 2013). These management strategies have been well documented (Holmes et al., 2002; Sheath & Clark, 1996) and can be broadly categorised into an effect on either:

- pasture supply, or
- animal demand.

The various supply-side and demand-side 'levers' employed to balance feed supply with animal demand in pasture-based systems will be discussed in succeeding sections.

2.4.1 Supply-side management levers

2.4.1.1 Rotation length

Two key targets have been identified as important factors affecting the balance between pasture supply and animal demand within a pasture-based system (Bryant, 1990; Macdonald et al., 2010; Macdonald & Penno, 1998):

(1) average herbage mass (kg DM/ha) at calving, and

(2) cow body condition (BCS) at calving.

Average herbage mass, which is also referred to as the average pasture cover (APC), is a measure of the quantity of pasture available at a given point in time divided by the area of the farm (i.e., kg DM/ha; Macdonald et al., 2010); body condition is an assessment of the degree of body reserves that an animal possesses, primarily adipose tissue (Roche, Friggens, et al., 2009). Achieving recommended targets at calving, rather than any other given time in the year, is particularly important, as the failure to meet these targets at calving will have detrimental carry-over effects on the production and reproduction of the herd for the remainder of the season (Bryant, 1990; Grainger, Wilhelms, & McGowan, 1982). For example, milk production has been reported to increase non-linearly with increasing BCS at calving up to a BCS of approximately 6.5, but with little increase in milk production beyond a BCS of 5 and a decline in production above 6.5 units (Roche, Lee, Macdonald, & Berry, 2007).

Cows must calve with sufficient BCS and pasture cover to ensure that adequate feed is available to meet the demands of the herd in early-lactation until the date at which the rate of pasture growth exceeds animal demand (balance date) without negative impacts on cow fertility. Ideally, cows should calve at BCS 5 with an APC of approximately 2200 - 2400 kg DM/ha (Bryant, 1990; Macdonald & Penno, 1998), depending the timing of calving relative to balance date (Macdonald et al., 2010). These targets are achieved through intentional manipulation of rotation lengths by controlling the daily area allocated to the herd. Well-established guidelines exist for the optimum rotation lengths during autumn (Autumn Rotation Planner) and spring (Spring Rotation Planner) to ensure an optimal balance between feed supply and demand in early-lactation (Macdonald et al., 2010). Rotation length is intentionally extended during the autumn by reducing the daily area allocated to the herd to build pasture cover whilst balancing pasture allowance (PA) per cow to ensure BCS targets are met. Subsequently, rotation length is slowly reduced in spring by increasing the daily area allocation per cow (Figure 9), increasing PA to ensure herd demand is met, whilst carefully managing available pasture covers to ensure the stored cover is not released too quickly before balance date. The storage and release of pasture cover, through managed variation in stocking intensity (area allocated per cow each day) and rotation length, is a key component to managing the intrinsic seasonality of growth within a pasture-based system. In addition, pasture cover acts as a buffer to daily or weekly variations in pasture growth, ensuring that pasture supply is sufficient to meet herd demand.

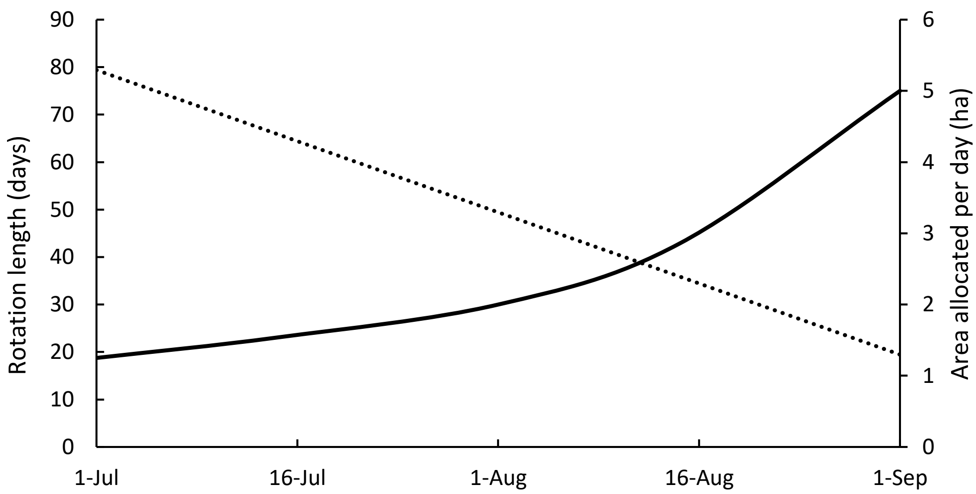

Figure 9: Visual example of a Spring Rotation Planner for a seasonal calving herd. Adapted from Roche et al. (2017).

2.4.1.2 Conservation of surplus

In optimally stocked systems, pasture growth exceeds demand during spring. This surplus feed can be conserved as silage and fed later when feed supply is insufficient to meet demand. This conservation process has a buffering effect on the pasture supply profile, allowing for greater synchrony between supply and demand (Figure 10). This conservation ensures utilisation of this surplus feed and prevents an excessive decline in quality. In contrast, deferred grazing may be used as a strategy to transfer this feed without direct harvesting costs, however, is associated with a decline in pasture utilisation (Devantier, Stevens, Rennie, & Tozer, 2017; McCallum, Thompson, & Judd, 1991).

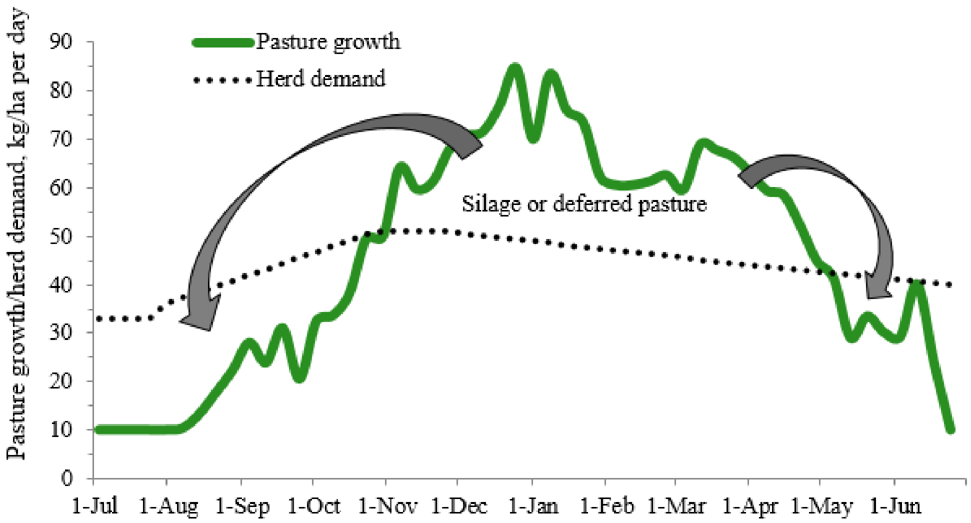

Figure 10: Buffering effect of silage conservation on feed supply profile (Roche, Washburn, et al., 2017).

2.4.1.3 *Reducing growth constraints*

At certain times of the year, pasture growth may be constrained by soil moisture and/or available N. Therefore, annual pasture production may be increased through irrigation or the strategic application of nitrogenous fertilisers or growth promotants, such as gibberellic acid. However, this is dependent on the presence of irrigation infrastructure, water, and a reliance on an adequate response to fertiliser or additive being achieved. Pasture growth responses to N are reduced in cold and/or dry conditions and the magnitude of these responses can be variable (Thomson & Roberts, 1982). These practices, therefore, present limited ability to manage unexpected pasture deficits resulting from unfavourable growth conditions.

2.4.1.4 *Forage crops*

High yielding forage crops or alternative pasture species can be used to increase annual feed production and transfer feed from the spring to periods of seasonal pasture deficit (e.g., summer, winter). However, crop yields are also affected by climatic conditions (e.g., drought), limiting their ability to buffer pasture growth in unfavourable environmental conditions (unless anatomically or physiologically tolerant). Additionally, planting crops reduces the area in pasture during late-spring/early-summer that is available for grazing, causing an increase in SR on the grazable pasture area while the crop grows (Holmes & Roche, 2007). This instantaneous increase in SR may be considered an advantage where a pasture surplus would be incurred during the crop growth period, thereby removing the need to conserve pasture silage. However, if a pasture deficit is incurred during the crop growth period, the increased SR will exacerbate the size of this feed deficit. Thompson et al. (1997) modelled the farm system effect of planting 8% of the grazing platform in turnips using the UDDER model. The MS response to this additional forage (50 - 60 g MS/kg DM eaten) did not compensate for the lower quantity of pasture silage conserved (180 kg DM/ha), reduced body condition (-0.2 BCS) and lower daily MS yield (-0.2 kg MS/ha), which occurred during the preceding crop growth period. Therefore, careful management is required to minimise any adverse effect on farm performance during the crop growth period.

2.4.2 Demand-side management levers

When supply side management levers are insufficient to bridge the gap between herd demand and pasture supply, greater synchrony may be achieved through reductions in animal demand. Management options include (Holmes et al., 2002; Sheath & Clark, 1996):

- a shift to 'once a day' (OAD) milking and acceptance of an associated reduction in production;
- the removal of culls from the herd earlier, thereby reducing SR at that time; or
- by drying cows off early and accepting shorter average herd lactation lengths.

Although effective at realigning supply and demand, all of these management decisions come with an associated reduction in milk production. In addition, culling and drying off decisions are permanent, at least within the current lactation, and may have implications for utilisation of any subsequent growth.

Importation of supplementary feed provides an opportunity to balance feed supply and demand without an associated negative impact on production. Where pasture supply is insufficient to meet herd demand, supplementary feeds may be offered to ensure that cows are not underfed and increase MS production beyond what could be achieved on pasture alone (Bargo et al., 2003).

2.4.3 Summary

The match between pasture supply and the nutritional demands of the herd throughout the year is a key factor affecting the biological efficiency of a pasture based system. The supply of feed relative to demand is intrinsically affected by the pattern of pasture growth. The nutritional demand of the herd is affected, at a system-level, by SR, calving date, and lactation length. The balance between pasture-supply and animal demand is further influenced by the implementation of numerous pasture and animal management levers. However, due to inter- and intra-year variability in pasture growth, there will be periods of the year when pasture growth is insufficient to meet herd demand. Supplementary feeds may be offered during such periods to ensure that the nutritional requirements of the herd are met to maintain milk production. In the following section, I will review the factors that affect the milk production response to supplementary feeds.

2.5 Supplementary feed

2.5.1 Suitability of pasture as a base feed

Well-managed temperate pastures are a nutritionally balanced feed for dairy cows producing up to 30 kg milk or 2.4 kg fat and protein (Holmes & Roche, 2007). The primary factor limiting production within such a system is the intake of sufficient quantities of metabolisable energy (ME); this is a direct result of a low DMI relative to what can be achieved when cows consume a TMR in a ‘confinement’ system (Kolver & Muller, 1998).

In support of the premise that the factor most limiting milk production in grazing cows is intake of ME, Kolver and Muller (1998) compared the milk production of Holstein Friesian cows grazing a TMR diet with a similar herd grazing pasture (44.1 vs 29.6 kg milk/day). In modelling the different scenarios, they deduced that 61% of the difference in milk yield could be attributed to the lower DMI of the grazing cows relative to those receiving a TMR diet (19.0 vs 23.4 kg DM/d). Less than 10% of the difference in production was attributable to the TMR herd having a more ‘balanced’ diet with respect to nutrient supply (Kolver & Muller, 1998). Further support was offered by Roche et al. (2010), who reported that varying the source of dietary ME, while keeping the total ME intake the same, had little effect on milk production. Substituting ME from high-quality perennial ryegrass with an equivalent quantity of ME from non-structural carbohydrate resulted in only a slight increase in milk yield (0.3 kg milk/kg DM starch) and protein yield (10 to 15 g/kg DM starch) and a decrease in milk fat yield (20 to 25 g/kg DM starch; Roche et al., 2010).

These results validate the nutritional suitability of well-managed temperate pastures as a complete diet for milking cows, dismissing any benefit of ingredient complementarity from a milk production standpoint by substituting alternative feeds for pasture to achieve a more nutritionally-balanced diet. Therefore, supplementary feed should only be provided where PA is insufficient to meet the daily DMI requirements of the herd (Roche, 2012).

The evidence that cows fed entirely on a pasture diet produce less than counterparts consuming a TMR diet (Kolver & Muller, 1998) has often been used as reasoning to offer non-pasture supplementary feeds to achieve higher DMI and increase production. This simplistic approach, however, fails to adequately recognise the fundamental trade-off between PA, DMI and pasture utilisation, and the underlying effect on per cow and per hectare production within a pasture-based system.

2.5.2 Immediate and deferred responses

The marginal milk production response to supplementary feed (MMPR) is defined as the increase in milk production/kg DM of supplementary feed offered (Leaver, Campling, & Holmes, 1968; Stockdale, 2000). Within the NZ context, this is often measured as the increase in MS/kg DM supplementary feed offered. The MMPR can be categorised into two general responses that relate to the timing of increase in milk production relative to the feeding event. An ‘immediate’ response is experienced during the period in which supplementary feed is offered, whilst an additional ‘deferred’ response can occur beyond the period of supplementation (Roche et al., 2013). The relative magnitude of these responses can be attributed to both animal-level and farm system-level effects of supplementation (Figure 11).

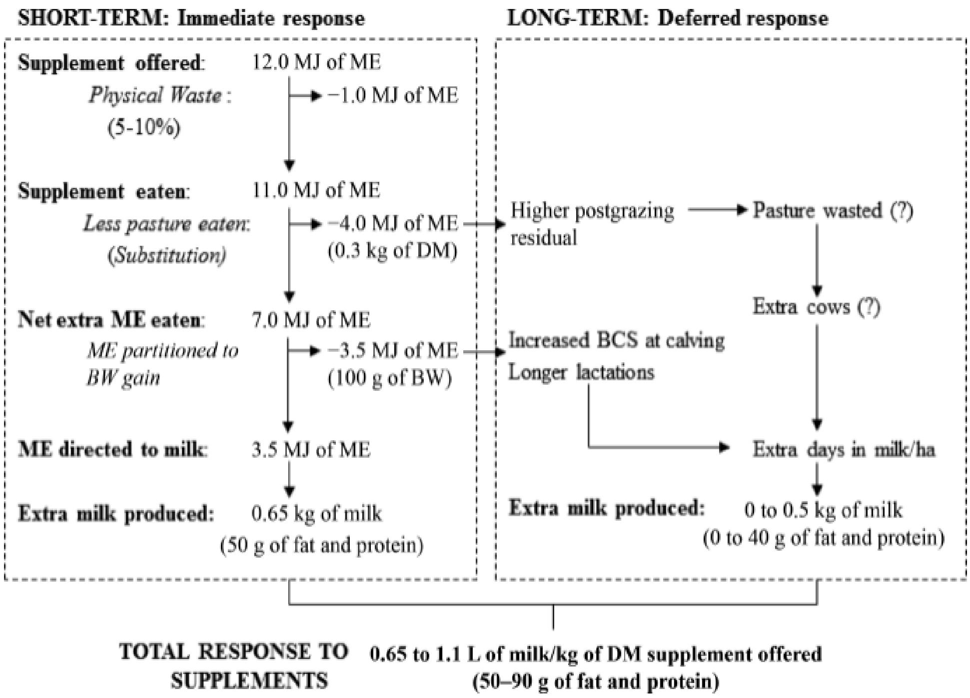

Figure 11: Schematic representation of short- and longer-term responses to 1 kg of supplementary feed DM offered/cow (Roche, Washburn, et al., 2017).

At an individual cow level, nutrition has been reported to have short term effects on the number of mammary cells and their secretory activity (Akers, 2002; Capuco, Wood, Baldwin, Mcleod, & Paape, 2001; Nørgaard, Sørensen, Sørensen, Andersen, & Sejrsen, 2005). An increase in mammary secretory cell activity has been postulated as a potential explanation for a proportion of the deferred response to supplementary feed (Roche et al., 2013). When supplementation ceases, the increased secretory activity remains (in the short-term); cows have greater hunger to fuel these demands. This would possibly increase DMI relative to cows that were not supplemented or, BCS spared through supplementation may be lost; this may lead to continued greater production in the short-term (Roche et al., 2013). In addition, offering supplementary feed results in spared pasture (substitution effect) and an associated increase in post-grazing residuals relative to what would have been achieved in an unsupplemented scenario (Roche et al., 2013). In a recent review of the literature, Poole (2018) reported that, on average, post-grazing height and mass increased by 1.4 mm and 42 kg DM/ha, respectively, for every additional kg DM of supplementary feed consumed. The utilisation of this spared pasture in later rotations and the increased days in milk resulting from greater cow condition (as a result of condition spared during supplementation) result in a deferred response to supplementary feed (Holmes & Roche, 2007). The extent of the deferred response to supplementary feed will be influenced by the degree to which this spared pasture is utilised, and its effect on sward characteristics and growth in future grazing rotations. Post-grazing residuals are known to influence pasture production and quality in future grazings, but the extent of this effect appears to be seasonally dependent (Lee, Donaghy, & Roche, 2008; Stakelum & Dillon, 1991). Therefore, the effect of pasture substitution on the deferred response to supplementary feed is also likely to be seasonally dependent (Poole, 2018; Stockdale, 2000).

Both the deferred and immediate response to a given level of supplementary feed decline with increasing DMI and it has been hypothesised that the deferred response is more sensitive to the level of feed allowance (Roche et al., 2013). In severe pasture deficits (post-grazing residual < 1200 kg DM/ha), the deferred and immediate responses are reportedly similar in magnitude (Bryant & Trigg, 1979; Roche, 2007). However, when pasture DMI is less restricted (e.g., post-grazing residual = 1600), the deferred response is approximately only 10 to 20% of the immediate response (Figure 12; Roche et al., 2013).

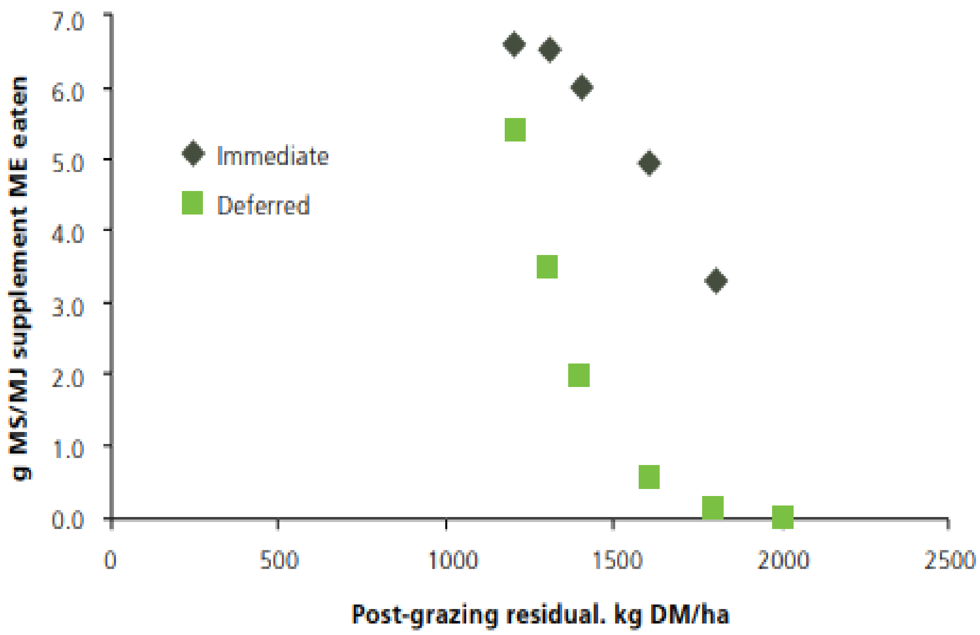

Figure 12: Effect of post grazing residual on the immediate and deferred responses to supplementary feed (Roche, 2015).

On an energetic basis, approximately 76 MJ ME are required for the production of 1 kg MS (Holmes & Roche, 2007). Therefore, if all the energy contained within a high quality supplementary feed (11 MJ ME/kg DM) was converted into milk, assuming no other nutrient was limiting, 1 kg DM would produce a theoretical MMPR to supplementary feed of approximately 140 g MS. This presents the theoretical upper threshold of potential MMPR to additional DM when assuming all the offered DM is consumed and all energy is converted into milk (Holmes and Roche 2007).

In a review of the literature, Bargo et al. (2003) concluded that the average MMPR to supplementary feed was 1 kg milk/kg DM. However, the majority of the studies reviewed were part lactation studies; as a result, the deferred response to supplementary feed was not captured, potentially underestimating the actual response (Roche et al., 2013). Macdonald et al. (2017) reported average MMPR to supplementary feed of 73 to 97 g MS/kg DM within a 3-year whole lactation experiment, for maize silage and maize grain, respectively; approximately 20% greater than the MMPR reported by Bargo et al. (2003). The difference in the MMPR to the different feeds was explained by feed ME content, with a similar MMPR of approximately 0.08 kg of milk/MJ ME.

Even when the immediate and deferred responses to supplementary feed are accounted for, the total response to supplementary feed is generally much less than the theoretical energetic calculation (Holmes & Matthews, 2001). This has been attributed to two effects:

(1) a reduction in pasture DMI when supplementary feeds are consumed (i.e., a substitution of the supplementary feed for pasture; Bargo et al., 2003; Stockdale, 2000); and

(2) the partitioning of energy toward the gain of BCS and inefficiencies in the conversion of consumed energy to milk through BCS gain and loss (Roche, Friggens, et al., 2009).

2.5.3 Substitution

The primary objective of offering supplementary feed to a grazing dairy cow is to increase the DMI and associated milk production of the herd relative to what would have been achieved under grazing pasture alone (Bargo et al., 2003; Leaver, 1985; Stockdale, 2000). However, when supplementary feed is offered to cows grazing pasture, incremental increases in supplementary feed consumption do not cause an equal additive increase in total DMI (Mayne, 1991). This is because cows refuse pasture after consuming the supplementary feed, a phenomenon referred to as substitution of supplementary feed for pasture (Kellaway & Harrington, 2004). That is, when cows grazing pasture are offered supplementary feed, pasture DMI declines. Furthermore, as the unsupplemented pasture intake increases, the magnitude of substitution resulting from supplementation also increases (Figure 13).

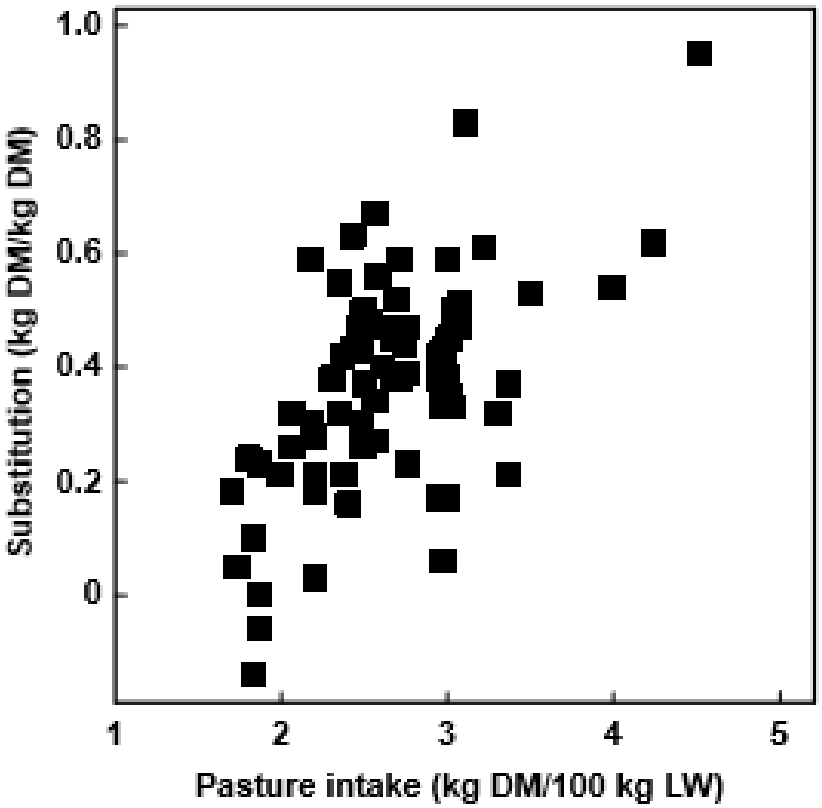

Figure 13: Relationship between unsupplemented level of pasture intake and substitution rate when supplementary feed is offered (Stockdale, 2000).

A negative relationship exists between substitution rate (SuR) and MMPR to supplementary feed (Figure 14; Stockdale, 2000). When SuR is large, the increase in total DMI from offering supplementary feed must be low and, consequently, the MMPR to supplementary feed is also low (Bargo et al., 2003).

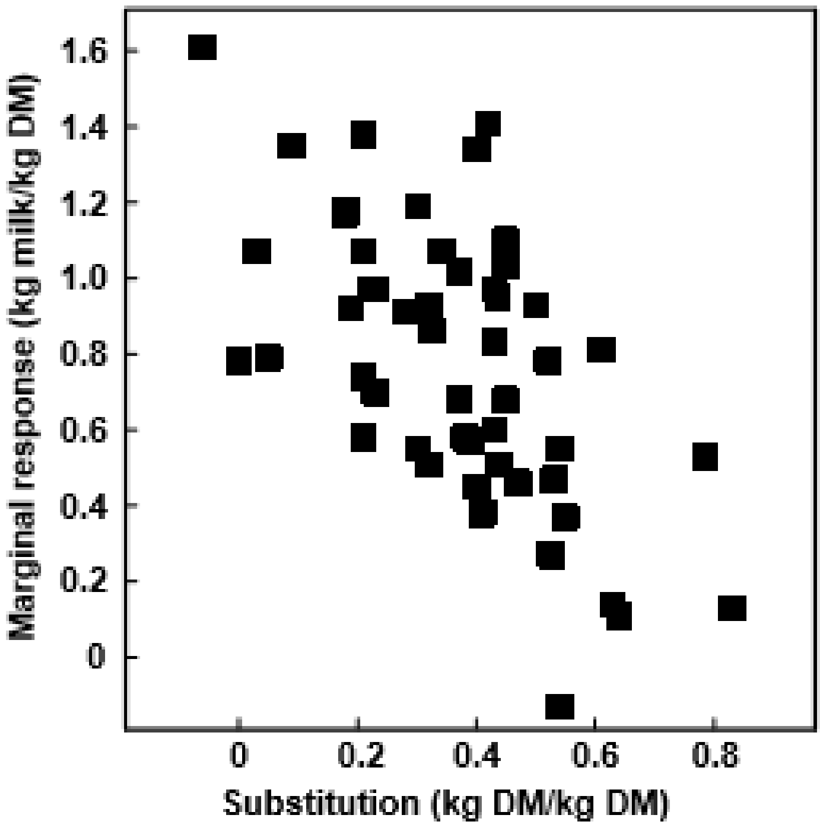

Figure 14: Relationship between substitution rate and the marginal response to supplementary feed (Stockdale, 2000).

There is general agreement that SuR is one of the main factors explaining the variability in measured MMPR to supplementary feed (Kellaway & Harrington, 2004; Kellaway & Porta, 1993; Stockdale, 2000). The SuR and related MMPR to supplementary feed are affected by several animal, pasture and supplementary feed factors (Bargo et al., 2003; Penno, 2002; Stockdale, 2000). These factors can largely be attributed to their effect on the relative feed deficit (RFD) of the herd (Holmes & Roche, 2007; Penno, 2002).

2.5.4 Relative feed deficit

To obtain a MMPR from supplementation, the cow must be able to increase total ME intake and utilise the additional feed for milk secretion or body tissue accretion pathways (Oldham & Emmans, 1989; Penno, 2002). Penno (2002) concluded that the single most significant factor determining the MMPR to supplementary feed was the RFD of the cow. The RFD presents a measure of the ability of the current diet to satisfy the nutrient requirements for a cow to meet her potential level of production. The RFD of a cow has an underlying influence on her SuR. Substitution rate increases when (Meijs & Hoekstra, 1984):

1) The DMI of a cow increases relative to her energy requirements; or,
2) The requirement for energy decreases.

Large immediate responses to supplementary feed are achieved when the RFD of a cow is large; in this situation, her DMI of pasture is low, leading to a correspondingly low SuR (Penno, 2002; Roche et al., 2013). Conversely, a negligible-to-small MMPR will be achieved when the RFD is small, due to a correspondingly high SuR. The RFD of a cow is determined by a number of factors (Bargo et al., 2003; Penno, 2002) such as:

1) Feed allowance
2) Feed quality
3) Cow genetics
4) Stage of lactation

The influence of these factors on the RFD will be discussed in succeeding sections.

2.5.4.1 Pasture and supplementary feed allowance and dry matter intake

When cows are consuming high quality feed, SuR increases as the energy intake of the cow is increased from either pasture or the supplementary feed (Bargo et al., 2003; Penno, 2002; Stockdale, 2000). For example, Grainger and Mathew (1989) reported an increase in SuR from 0 to 0.69 kg pasture DM/kg supplementary feed DM as PA increased from 8 to 33 kg DM/cow/day (measured to ground level). In further support of this, Meijs and Hoekstra (1984) demonstrated increasing SuR, when either PA increased (15 to 30 kg DM/cow/day) and when concentrate intake increased (0.8 to 5.6 kg DM/cow per day), to the extent that increasing the quantity of supplementary feed offered reduced the positive effect that increased PA has on pasture intake.

Dry matter intake has been identified as the main factor limiting milk production in grazing cows (Leaver, 1985; McGilloway & Mayne, 1996), specifically the intake of energy (Kolver & Muller, 1998). Pasture DMI is primarily affected by PA, which is defined as the amount of herbage above a specific sampling height allocated to livestock (kg DM/cow/day; Leaver, 1985). The relationship between PA and DMI is widely accepted as curvilinear: marginal increases in PA result in a decreasing marginal increase in DMI (Combellas & Hodgson, 1979; Peyraud et al., 1996; Poppi, Hughes, & L'Huillier, 1987). Similarly, a curvilinear relationship exists between supplementary feed allowance and DMI (Kellaway & Harrington, 2004; Kellaway & Porta, 1993). Therefore, as the level of feeding increases, through either increased pasture or supplementary feed allowance, the marginal increase in DMI is reduced. This relationship has a fundamental effect on SuR and the related MMPR to supplement. Several equations have been proposed to explain the relationship between DMI, PA and SuR:

Equation 1: SuR = 0.315 DMI - 0.445 (Grainger and Mathews 1989)

Equation 2: SuR = –0.34 + 0.16 DMI + 0.16 species + 0.11 season + 0.03 concentrate intake (Stockdale, 2000)

Equation 3: SuR = -0.55 + 0.05 PA - 0.0006 PA^2 (Bargo et al., 2003)

From these equations, as PA (Bargo et al., 2003) or DMI (Grainger & Mathews, 1989; Stockdale, 2000) increases, SuR increases. These equations agree with the concepts of RFD previously discussed; as PA increases, the ability of the diet to meet the herds diet is improved (reduced RFD), leading to an increased SuR and a correspondingly reduced MMPR to supplementary feed.

2.5.4.2 Pasture quality

The energy supplied by the base diet is determined by both the quantity and quality of feed eaten. In the absence of supplementary feeding, these two factors combine to determine the ability of the base diet to meet a cow's nutrient and energy demands. Pasture quality varies seasonally and is affected by the physiological state of the plant (vegetative or reproductive) and prevailing weather (Figure 15; Holmes et al., 2002; Roche, Turner, et al., 2009c). In addition, pasture quality and how it varies temporally, differ between pasture species.

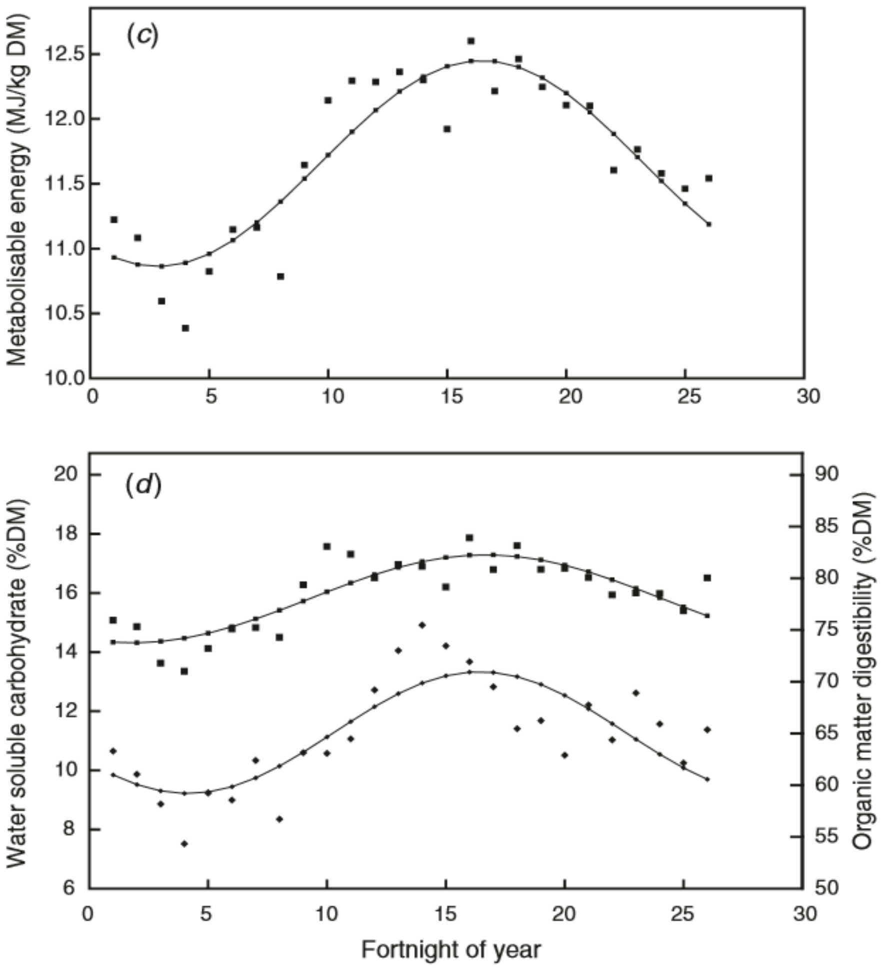

Figure 15: Seasonal variation in metabolisable energy and water soluble carbohydrate content of pasture (Roche, Turner, et al., 2009a).

Given two cows with the same DMI, a cow consuming high quality pasture (12 MJ ME) will consume a higher quantity of energy than a cow consuming lower quality pasture (9 MJ ME) and would, consequently, be expected to have a smaller RFD. In addition, if pasture is particularly low digestibility (< 65 - 70%), DMI may be restricted by rumen fill, reducing DMI for a given level of PA (Dixon & Stockdale, 1999; Van Soest, 1994).

Stockdale (1999) reported lower responses to concentrate in spring compared with summer, attributing this to the higher quality of pasture in spring (10.3 MJ ME/kg DM) relative to summer (8.7 MJ ME/ kg DM). However, this difference was confounded by the effect of stage of lactation, so could not be attributed solely to the effect of pasture quality. Both PA and pasture quality determine the ability of the base diet to satisfy the cows energy demands. The quantity and quality of supplementary feed offered interact with these factors to determine the RFD of a cow with a given energy demand.

2.5.4.3 Cow genetics

Cows of improved genetic merit generally eat more (Macdonald et al., 2008) and partition a greater proportion of nutrients toward milk synthesis pathways in preference to body accretion and condition gain (Horan, Dillon, Berry, O'Connor, & Rath, 2005; Roche, Berry, & Kolver, 2006). As such, the genotype of a cow affects its potential milk production (Linnane et al., 2004; S. McCarthy et al., 2007).

As the potential production of a cow increases, so does her demand for energy, resulting in a greater RFD under similar feeding conditions to a cow producing less milk and, consequently, a lower SuR (S. McCarthy et al., 2007; Penno, 2002). The MMPR to supplementary feed is, therefore, likely to be greater in cows with greater genetic potential for production. In support of this, several studies have reported lower SuR and higher MMPR to supplementary feed in cows with greater proportions of North American genetics (W. J. Fulkerson et al., 2008; Horan, Dillon, Faverdin, et al., 2005; J. Kennedy et al., 2003; Kolver, Roche, Burke, & Aspin, 2005), a strain of cow selected exclusively for milk production at the expense of functional traits like BCS.

2.5.4.4 Stage of lactation

Gradual involution of the mammary gland occurs as the stage of lactation progresses, resulting in a reduction in the number of secretory cells and secretory activity (Capuco et al., 2001). A greater proportion of energy is partitioned toward body accretion and less toward milk secretion as lactation progresses (Broster & Broster, 1984). Stage of lactation, therefore, has the potential to influence the relative magnitude of the immediate and deferred response to supplementary feed.

The effect of stage of lactation on the MMPR to supplementary feed is inconsistent. The interaction between stage of lactation and season may help explain this variability. Within pasture-based systems (seasonal calving), the effect of stage of lactation and seasonal changes in herbage quality are confounded (Stakelum, Maher, & Rath, 2007). In addition, grazing cows undergo seasonal restriction in pasture availability as management responds to pasture growth conditions. This seasonal variation in PA may cause variation in potential MMPR to supplementary feed across the season. It is, therefore, difficult to separate the effect of stage of lactation and season on the MMPR to supplementary feed (Penno, 2002). In a review of the literature, Penno (2002) reported that, despite an effect on milk production, stage of lactation had little effect on the MMPR to supplementary feed with early-, mid-, and late-lactation cows demonstrating average responses of 54, 38 and 56 g MS/kg DM, respectively. Stage of lactation explained little of the variation in the MMPR to supplementary feed, with the RFD being the most important factor explaining the variability of response. In contrast, in a more recent review of the literature, Poole (2018) reported MMPR to supplementary feed of 34.0, 48.1, and 54.0 g MS/kg supplementary feed DMI in early-, mid-, and late-lactation, respectively.

The variability of the MMPR to supplementary feed with stage of lactation is also likely to be influenced by the magnitude of the deferred response. High MMPR to supplementary feed can be achieved in mid- to late-lactation where small amounts of feed are imported into the system to overcome a seasonal restriction in pasture growth (Holmes & Roche, 2007), thereby allowing for increased lactation length. Pitman et al. (2005) reported the results of a 4-year demonstration study, where they compared a self-contained (Control) farmlet stocked at 3.3 Jersey cows/ha and a farmlet with the same SR importing supplementary feed (mean 811 kg DM/ha) to overcome seasonal feed deficits. On average, lactation length was increased by 30 days in the imported supplementary feed farmlet, resulting in average MMPR to supplementary feed of 140 g MS/kg imported supplementary feed.

2.5.5 Summary

Marginal milk production responses to supplementary feed include those that occur during the period of supplementation (i.e., immediate responses) and responses that occur subsequently (i.e., deferred responses) because of greater secretory cell numbers and activity, pasture saved for future consumption, improved BCS, and/or, associated, greater lactation lengths. The magnitude of MMPR to supplementary feed are, primarily, affected by the amount of pasture refused when cows are offered a supplementary feed (i.e., substitution rate; SuR); the SuR, in turn, is primarily controlled by the RFD (i.e., the adequacy of the consumed diet to meet the energy requirements of the cow). There are a number of feed and animal related factors that affect the RFD of the cow and, hence, the MMPR to supplementary feed, including feed quantity and quality, cow genetics, and stage of lactation. The profitability of offering supplementary feeds is strongly influenced by the MMPR to supplementary feed; I will review the effect of offering supplementary feed on the profitability of pasture-based systems in subsequent sections.

2.6 Economics of supplementary feed use

2.6.1 Principals of marginality and diminishing marginal returns

Although offering supplementary feed within a pasture-based system generally increases milk production and related GFR, costs associated with the provision of feed are a significant source of expenditure for pasture-based dairy farmers (DairyNZ Limited, 2017a). A growing body of literature indicates that although the use of imported supplementary feed is effective at increasing production and GFR, it is not necessarily associated with greater farm profitability (Ma, Renwick, & Bicknell, 2018; Ramsbottom, Horan, Berry, & Roche, 2015). This failure to achieve profit gains through increased milk production can be understood using the basic economic concepts of marginal revenue, marginal cost, and diminishing marginal returns. These concepts are, therefore, important, when making decisions that relate to the optimisation of feed supply and demand, to ensure the profitability and resilience of a dairy farming business.

Within agricultural production economics, it is often assumed that the objective of any farm manager is to maximise profit (Debertin, 2012). In reality, the goals of farm managers are varied and diverse, often encompassing social (work-life balance) and environmental outcomes (Pannell et al., 2006). If assigned an economic value, these additional goals can be encompassed within the definition of profit and maximised accordingly, sometimes termed the "triple-bottom-line" (social, environmental and financial performance; Elkington, 1997).

In the financial sense, profit (π) is defined in Equation 4 as the total value of product (TVP) minus the total factor cost (TFC; Debertin, 2012).

Equation 4: $\pi = TVP - TFC$

A business decision is said to increase profit if it contributes more to TVP then it adds to TFC. To effectively allocate resources that maximise profit, a farm manager requires an understanding of the fundamental principles of marginality. Decisions around profit maximisation are concerned with the incremental unit. Has employing the last unit of variable input been profitable? In order to assess this, the value of the marginal product (i.e., marginal revenue; MR) and the marginal factor cost (i.e., marginal cost; MC) must be compared. The MR is the value of the change in output (i.e., increase in MS production) resulting from an incremental change in the use of an input (i.e., allocation of supplementary feed; Debertin, 2012). Similarly, the MC is the increase in costs associated with an incremental increase in the level of input (i.e., cost of supplementary feed required to generate a specified increase in output; Debertin, 2012).

Many agricultural inputs display diminishing marginal returns. For example, Macdonald et al. (2017) postulated a non-linear MMPR with increased allowances of imported supplementary feed. The MMPR from reducing CSR from 95 to 86 kg LW/t DM (by importing supplementary feed) was 108 g MS/kg DM, further reducing CSR to 79 kg LW/t DM resulted in a MMPR of only 55 g MS/ kg DM, equivalent to a 2-fold reduction in response. The law of diminishing marginal returns states that, in general, each incremental unit of a variable input produces less and less additional output (Debertin, 2012).

As a result of diminishing marginal returns, each input unit yields increasingly lower marginal outputs and the value of marginal returns to that input declines. Profit is maximised at the point at which the MR is equal to the MC; that is, the point at which the cost of increasing inputs by one unit, is exactly matched by the return from that unit (Debertin, 2012). Many levels of input may return a profit; however, the concept of marginality is necessary to identify the level of input that maximises profit for the business.

These principles are often employed in partial budgeting exercises to assess the profitability of supplementary feed inputs.

Example situation:

Supplementary feed can be purchased for $350/t DM ($0.33/kg DM), and a MMPR to supplementary feed of 80 g MS/kg DM is expected (0.08 kg MS/kg DM).

Equation 5: $MC = \Delta C/\Delta q$

where ΔC = marginal change in supplementary feed price ($/kg DM), Δq = marginal change in MMPR (kg MS/kg DM)

$\therefore$ MC = 0.35/0.08

$\therefore$ MC = $4.38/kg MS

Provided that the milk price is greater than $4.38, the MR is greater than the MC of this feed and the use of imported feed appears to be profitable. However, this partial budgeting exercise fails to account for the full cost of the supplementary feed within temperate grazing systems.

2.6.2 Limitations of simplified marginal economics in pasture-based systems

By definition, the optimal combination of inputs and level of production for a given set of market conditions will vary in response to changes in the MC of inputs and the marginal value of product in the basic model of production economics. These simplified economic principles assume that a producer may employ easily-divisible, incremental units of an input and, therefore, may increase or decrease the use of an input until the point of profit maximisation is met (Debertin, 2012). However, input usage within a pasture-based dairy system possesses a degree of resistance to change (i.e., ‘stickiness’), in that resources such as land cannot be purchased in neatly divisible units (i.e., land is a 'lumpy input'; Fennell, 2012). In addition, the cost of variable input units (such as cows or supplementary feed) are affected by market conditions (i.e., price elasticity), such that input demand (and hence price) usually increases at greater milk prices, reducing the potential to generate additional profits from changing input levels. Also, whilst some inputs to production may be variable in nature (e.g., imported feed) many associated costs (e.g., depreciation of feeding-related infrastructure) are not; this can limit the ability of the producer to minimise input costs by reducing input usage. A further complication, peculiar to dairying in NZ, is the final milk price is often determined several months after incurring the cost of the additional inputs, making defining the point at which MR = MC difficult.

Even if market prices were known with certainty, there are limitations to a farmer’s ability to profitably respond to market signals. For example, Alvarez and Arias

(2003) reported that increasing farm size while holding managerial ability constant can result in diseconomies of scale; therefore, additional returns to increasing inputs may be limited if a farmer is unable to further increase managerial input. These factors can erode a farmer's ability to efficiently change the level of inputs employed in response to market fluctuations. Despite these limitations, when responding to short-term market fluctuations, marginal economic principles should be carefully considered in the face of longer-term decision making.

2.6.3 Farm system level implications

2.6.3.1 Fixed and indirect costs

For every unit increase in expenditure of imported feed, total costs must, by definition, increase by at least the cost of one unit. However, independent examination of international farm business datasets provides consistent evidence that as expenditure on supplementary feed increases, total expenses increase at a greater rate (DairyCo, 2012; Ma et al., 2018; Neal & Roche, 2018; Ramsbottom et al., 2015). Ramsbottom et al. (2015) identified that a €1/ha increase in purchased feed expenses were associated with a €1.53/ha increase in total expenses. This multiplication factor is similar in magnitude to that reported internationally and in NZ:

€1: €1.53 (Ireland)	(Ramsbottom et al., 2015)
1p: 1.62p (Britain)	(DairyCo, 2012)
\$1: \$1.66 (Waikato, NZ)	(Neal & Roche, 2018)
\$1: \$1.53 (Canterbury/Marlborough, NZ)	(Neal & Roche, 2018)

This disproportionate increase in total operating expenses, when the quantity of imported supplementary feed increases, has been attributed to an associated increase in labour, livestock husbandry, and machinery costs (DairyCo, 2012; Ma et al., 2018). Ramsbottom further identified an increase in both variable costs (e.g., fertiliser) and 'fixed' costs (e.g., land lease) associated with an increase in the use of supplementary feed. Variable costs and fixed costs increased 1.18 and 0.35 times the increase in expenditure on purchased feed, respectively (Figure 16). This is a reflection of the economic principle that, in the 'long-run all inputs are, at least in part, variable'(Debertin, 2012).

Although in the short term, a farmer may be constrained by land area and/ or herd size, in the long-run, as they intensify, they usually have the ability to increase many "fixed" inputs; for example, by leasing more land as the SR on the milking platform increases beyond the capacity to produce silage for the herd's feed deficit or by increasing electricity usage in the harvesting and cooling of more milk. These examples reflect that these costs are variable over the longer term. Counterintuitively, intensification, therefore, can lead to an increase in 'fixed-costs' over time.

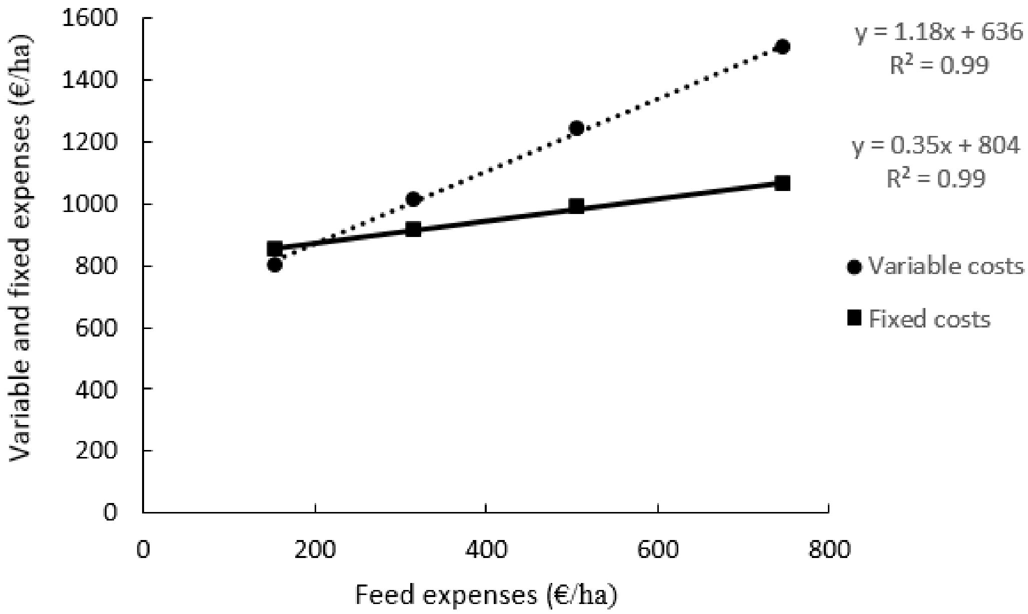

Figure 16: Increase in variable and fixed costs of production with increasing feed expenses. Data sourced from Ramsbottom et al. (2015).

In addition to the direct effect of purchased supplementary feed on total costs, Ramsbottom et al. (2015) identified potentially indirect effects of offering supplementary feed on the profitability of the farm systems as a result of substitution. Increased quantities of supplementary feed imported were associated with a significant reduction in pasture harvested (Figure 17).

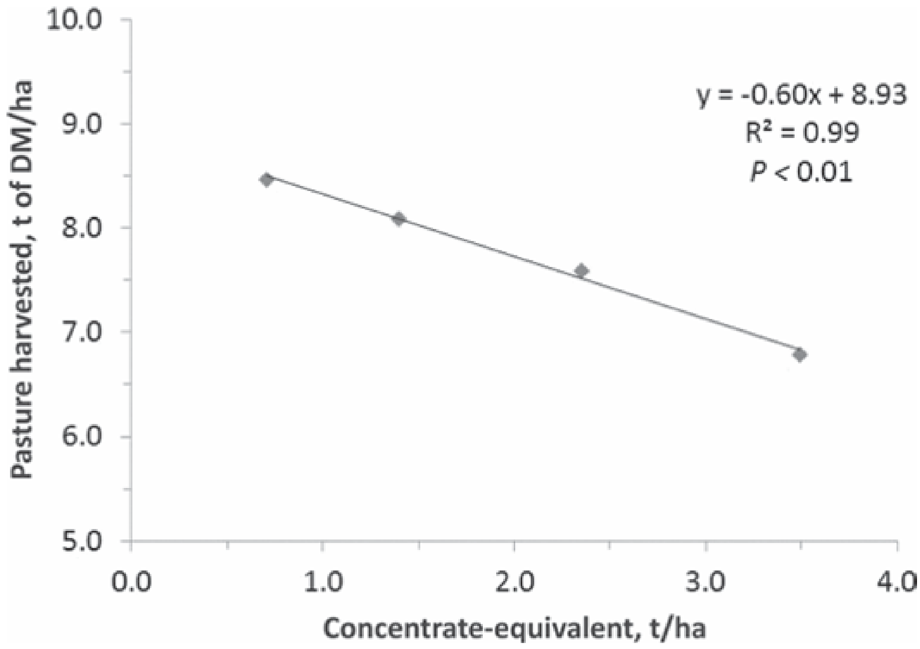

Figure 17: Relationship between the quantity of supplementary feed imported and annual pasture harvested (Ramsbottom et al., 2015).

Although the substitution of supplementary feeds for pasture results in the sparing of pasture when supplementary feeds are fed, if this feed cannot be utilised subsequently, it is wasted, leading to a reduction in pasture harvest. The cost of growing this pasture had already been incurred; but, if wasted it cannot contribute to revenue. As grown pasture is a less expensive form of feed than alternatives (Dillon et al., 2005), the substitution of pasture for imported supplementary feed (and potential wastage of grown pasture) results in an increase in the MC of production. A decrease in annual pasture harvest (t DM/ha) has been reported to be associated with a reduction in net profit per hectare of between €173 ($330)[1] /t DM (Hanrahan et al., 2018) and €268 ($510)[1]/t DM (Ramsbottom et al., 2015). Similarly, within the NZ context, a decrease in annual pasture and crop harvested (t DM/ha) has been reported to be associated with a reduction in net profit per hectare of $294 and $268 in the Waikato and Canterbury, respectively (Figure 18; Neal, Roche, & Shalloo, 2018). These results indicate that the financial effects of offering supplementary feed (variable, fixed, and indirect) are much greater than the direct increase in variable costs associated with offering supplementary feed. These costs

[1] 1€ is approximately 1.9NZD

are not accounted for in incomplete marginal analyses and partial budgeting, even though these are significant at a farm systems level. These effects are reflected in published results when examining the economic effect of increased supplementary feed use.

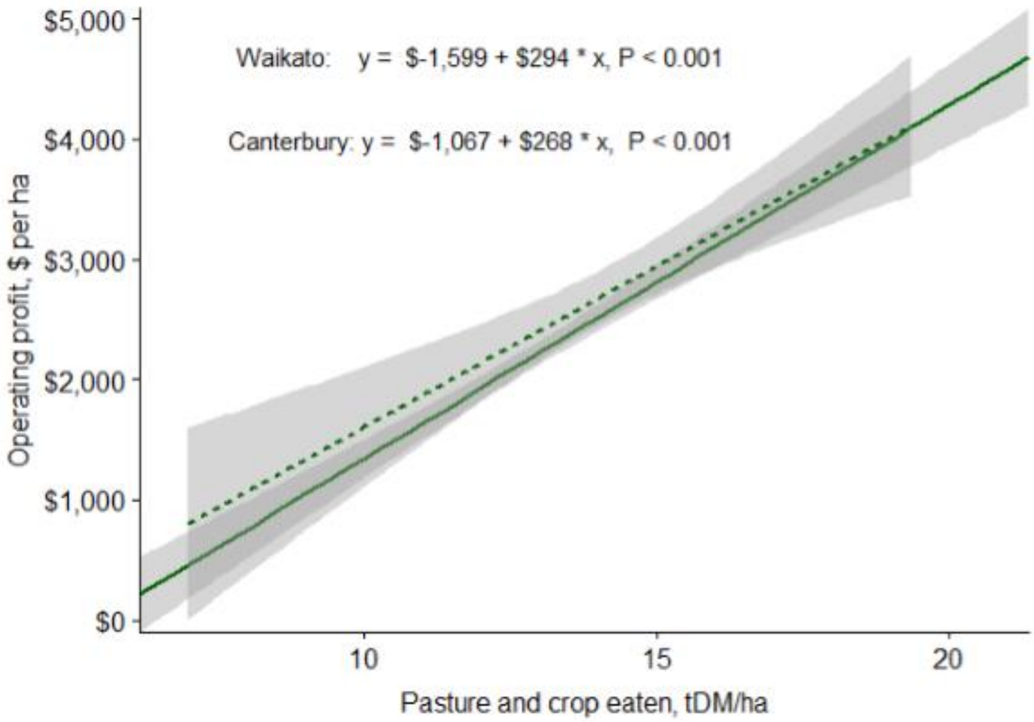

Figure 18: Association between annual pasture and crop eaten (t DM/ha) and operating profit ($/ha; Neal et al., 2018).

Numerous studies, including multi-year farm systems experiments (Macdonald et al., 2017), various modelling approaches (Beukes et al., 2005; Doole, 2014; Neal, Fulkerson, & Drynan, 2005; Romera & Doole, 2014), and analyses of farm financial databases (DairyCo, 2012; Hanrahan et al., 2018; Ma et al., 2018; Neal & Roche, 2018; Ramsbottom et al., 2015; Shadbolt, 2012; Shadbolt, Siddique, & Hammond, 2017; Silva-Villacorta et al., 2005), have examined the farm system effects of importing increasing quantities of supplementary feed. Unanimously, these studies conclude that offering supplementary feed in a pasture-based system increases production and GFR.

Silva-Villacorta et al. (2005) analysed four years of farm financial data and determined that MS production was positively associated with the quantity of additional feed used per cow and per hectare:

kg MS/cow = 284 + 0.05 (kg DM extra feed[2]/cow)

kg MS/ha = 701 + 0.096 (kg DM extra feed/ha)

In addition, they reported a positive association between the quantity of additional feed imported and the SR of the farm, a result verified by later studies (Ma et al., 2018; Shadbolt, 2012). In all four years of the analysis, systems importing increased quantities of supplementary feed had greater GFR per hectare. However, this increase in revenue was accompanied by an increase in farm working expenses (FWE[3])/ha, which were mainly associated with the higher SR, fertiliser, and overhead costs. As a result, despite the increase in revenue with increased supplementary feed use, the extra feed did not increase profitability.

In a three-year analysis Ma et al. (2018), undertaking a more complete analysis of more recent data, reiterated these earlier conclusions, reporting that the adoption of systems importing greater quantities of imported supplementary feed exerted a positive and significant effect on MS production and GFR. However, consistent with the conclusions of Silva-Villacorta et al. (2005), increased supplementary feed use increased dairy operating expenses and, ultimately, resulted in no significant effect on operating profit, but reductions in operating profit margin and ROA (Figure 19)[4].

[2] 'Extra feed', in this instance, refers to supplementary feed imported, pasture imported as winter grazing and maize grown on-farm (Silva-Villacorta et al., 2005)

[3] 'Farm working expenses' include cash expenses only (Silva-Villacorta et al., 2005) relative to 'farm operating expenses' which include depreciation, the value of any unpaid family labour and management, changes in feed inventory and non-cash adjustments where support land is utilised (Shadbolt, 2012).

[4] Note: Error in graph in publication- ROA from 'medium to high' should read as +6.9%

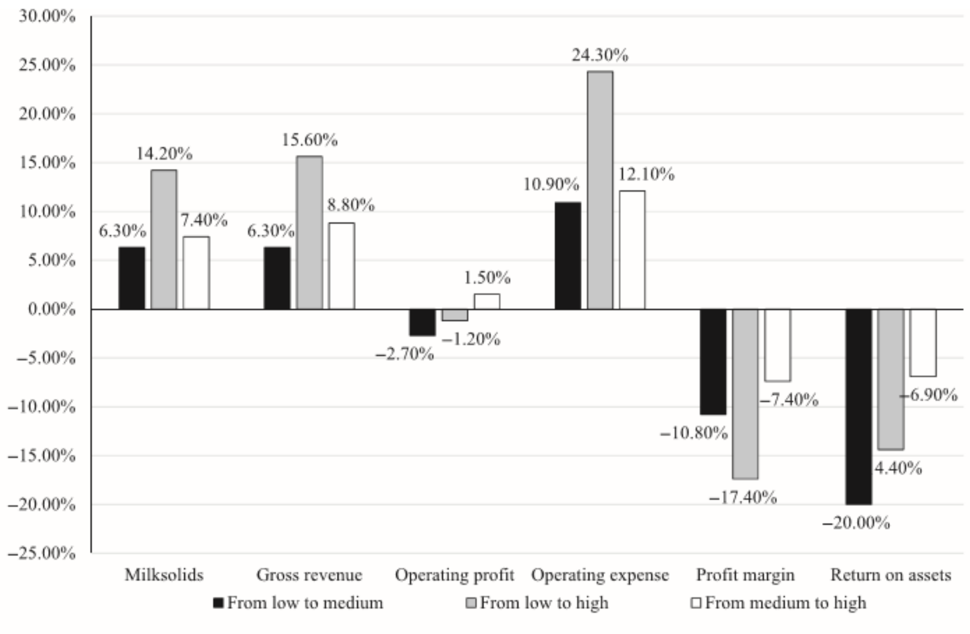

Figure 19: Percentage change in average treatment effects when shifting from 'low', 'medium', and 'high' supplementary feed use (intensity) systems (Ma et al., 2018).

Inherent differences exist within production systems between regions of NZ. For example, Jiang and Sharp (2015) identified heterogeneity in the technology employed between North and South Island dairy systems (e.g., the proportion of farms with rotary cow sheds). Further differences between regions extended to differences in the nature of the feed base and predominant feed management decisions; for example, the presence of irrigation infrastructure in Canterbury, in particular, and the prevalence of off-farm winter grazing in many regions of the South Island and lower North Island. These differences have the potential to affect the form and timing of when supplementary feeds are employed, how they are used to better match feed supply and demand, and the ultimate profitability of feed input decisions. Neal and Roche (2018) undertook an analysis of 12-years of farm financial data and reaffirmed the presence of these regional differences by stratifying samples by region. Farms in Canterbury, for example, were reported to import more feed (including off-farm grazing in winter for non-lactating cows), but had a greater ROA relative to their counterparts in the Waikato. Nevertheless, within region, operating expenses/kg MS increased by $0.42 to $0.44 for every additional tonne of imported supplementary feed or crop fed and the quantity of supplementary feed imported was not associated with greater profitability. In addition, they analysed the factors associated with differences in ROA between the top quartile (Q1) and the remainder of farmers (Q2 - Q4). Return on assets was associated with increased pasture harvest, greater SR, and increased production per cow; however, ROA was not associated with increased use of imported feed per ha.

Despite the agreement between the conclusions of Silva *et al*. (2005), Ma *et al.* (2018) and Neal and Roche (2018), some disagreement still exists on the overall effect of importing supplementary feed on farm profitability. Shadbolt (2012) and Shadbolt *et al.* (2017) conducted a 3-year and 9-year analysis, respectively, of farm financial statistics. In both studies, milk production and GFR were increased through supplementation. However, in contrast to the conclusions of other authors, operating expenses were reported to decrease per kg MS as supplementary feed use increased, resulting in no significant difference in ROA between systems importing increasing quantities of supplementary feed. However, these analyses do not account for region and are, therefore, affected by the confounding effect of region on supplementary feed use and ROA. This difference in methodology affects the practical applicability of these conclusions and may help to explain, at least in part, the inconsistency of these conclusions relative to other authors.

2.6.3.2 Risk and its implications

As identified earlier, profit is not the only driver of management. Other factors such as balancing risk and returns may be an objective for a decision maker depending on their degree of risk aversion. The use of imported supplementary feed reduces production risk by giving a farmer confidence that they can more easily buffer seasonal variations in pasture growth and feed supply. However, offering imported supplementary feed also increases the average cost of production (Neal & Roche, 2018), therefore, exposing a farmer to greater market risk (i.e., variation in milk price; Ma et al., 2018; Shadbolt, 2012) and greater managerial complexity (i.e., an increased number of feeding related decisions and greater potential for a less than optimal decision being made; Mounsey, 2015).

The effectiveness of importing supplementary feed as a risk management strategy depends on the relative exposure of the business to market and production risk and debt-equity ratios. Both production risk and market risk are important factors affecting the profitability of offering supplementary feed in pastoral grazing systems. However, it has been reported that variation in milk price (i.e., milk price volatility) is the most important risk in the NZ context (Neal et al., 2018) and suggested that, in NZ pasture-based systems, variation in MS price accounts for approximately twice the variation in profitability due to feed availability (M.Neal, personal communication, October 16^{th}, 2018). The importation of supplementary feed to reduce one risk (i.e., production risk) may, therefore, predispose the business to a greater degree of risk from another source (i.e., market risk); careful consideration of the use of supplementary feed as a risk mitigation strategy is necessary.

Patton et al. (2012) compared the biological and economic efficiencies of two farm systems differing in SR (2.45 cows/ha vs 2.92 cows/ha) and importing different quantities of supplementary feed (578 kg concentrate/cow vs 1,365 kg concentrate/cow). They concluded that the efficiency of increased importation of supplementary feed to overcome the seasonality of pasture production was highly dependent on the prevailing market conditions (milk and supplementary feed prices). The more intense system encountered increased losses when market conditions were unfavourable (high supplementary feed price and low milk price) but were more profitable where market conditions were favourable. In support of this, Romera and Doole (2014) employed optimisation techniques to a farm system and reported that the use of higher levels of imported feed (> 30% of the diet) was a profitable approach only where milk prices were high (> $7/kg MS).

The financial favourability of different supplementation strategies (high or low levels of imported supplementary feed per cow or per ha) is, therefore, highly dependent on prevailing market conditions. However; the long term favourability between systems will be influenced by the relative longer-term variability in milk and supplementary feed price (market risk), the price elasticity of supplementary feed relative to milk price, and pasture growth variability (production risk). The favourability of a system is also influenced by management capability, through the ability to achieve high MMPR to supplementary feed. In addition, overall preference between these strategies will also be affected by the risk aversion of the decision maker.

2.6.4 Summary

The use of supplementary feed can be an effective strategy to reduce milk production risk, although it simultaneously increases expenses and exposure to market risk (milk and supplementary feed prices). There is considerable and increasing evidence that, although effective at increasing milk production and associated revenue, increases in the quantity of imported supplementary feed within a pasture-based system are not associated with an increase in profit and may, in fact, result in a decline in ROA. This has been attributed to a non-proportional increase in total expenses with increased feed related expenditure due to greater variable, fixed and indirect costs (e.g., pasture wasted through substitution).

2.7 Feed intensification and the environment

2.7.1 Context

Agricultural systems have intensified internationally, driven by a desire to increase production and profitability (Ledgard, 2001). Agricultural system intensification can be defined as the process of increasing outputs per unit of land (Moller et al., 2008). The NZ dairy industry has undergone both significant expansion and intensification during the last two to three decades (Gray & Le Heron, 2010). Both the area of dairy land and the production per unit of this land have increased over the last 25 years (Table 1; Livestock Improvement Corporation & DairyNZ Limited, 2018). The area employed in dairy production has increased by over 70% and the number of dairy cows has more than doubled since 1992 (Livestock Improvement Corporation & DairyNZ Limited, 2018).

Metric	Historic (1992/1993)	Current (2017/2018)	% Change
Total cows	2,402,145	4,992,914	108%
Total hectares	1,023,545	1,755,148	71.5%
Average cows/ha	2.35	2.84	21%
Milksolids/cow	259	368	42%
Milksolids/ha	653	1,048	60%

Table 1: Comparison of historic and current performance metrics for the NZ dairy industry. Data sourced from Livestock Improvement Corporation and DairyNZ Limited (2018).

Intensification of this land has been driven by an increase in nitrogenous fertilisers, imported supplementary feed use (Doole, 2014; Ledgard et al., 2017), and, in some regions, irrigation (Ledgard et al., 2017). These intensification strategies have buffered the limitations imposed by the seasonality of pasture supply, facilitating greater SRs and longer lactation lengths (Doole, 2014; Ledgard et al., 2017). For example, the use of PKE as a supplementary feed has increased from 0.13 to 2.14 million tonnes per year within the last decade (Figure 20) and is responsible for a significant proportion of NZ's total annual milk production. At an average MMPR to supplementary feed of 80 g MS/kg DM, the volume of PKE imported within the 2017/18 season could, potentially, account for 8% of the national MS processed[5].

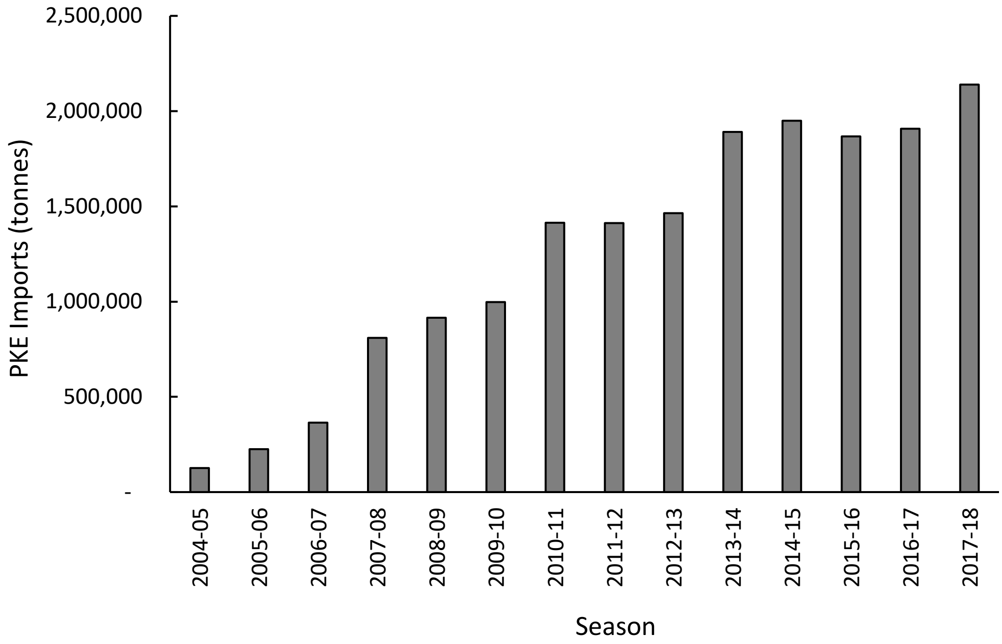

Figure 20: Import volume of palm kernel expeller in New Zealand over time. Data sourced from Statistics New Zealand (2019).

[5] Assumes:

- Annual PKE storage inventories are unchanged (the same volume of PKE is imported and fed)
- Dry matter percentage for PKE of 90% (DairyNZ Limited, 2017b)
- Total of 1840 million MS processed (Livestock Improvement Corporation & DairyNZ Limited, 2018)

2.7.2 Metrics of evaluation

Intensification is largely driven by the desire to increase production per cow and per hectare, with the expectation that this increased productivity will lead to greater financial returns. However, intensification can also result in increased environmental externalities; for example, greater N leaching and GHG emissions. There are two commonly used metrics to evaluate the environmental impact of intensification (Williams, Ledgard, Edmeades, & Densley, 2007); these involve:

1) assessing the total leaching or emissions changes, which may be further expressed per unit of scarce input (e.g., per cow or per hectare); or

2) by expressing the footprint per unit output (e.g., per kg MS).

2.7.3 Direct influence of stocking rate on nitrogen leaching

As discussed in previous sections of this review, SR is a key system level factor influencing pasture utilisation, milk production (per cow and per hectare), the perceived and real need for supplementary feed, and overall farm profitability (Macdonald et al., 2011, 2008; B. McCarthy et al., 2011). Pasture harvest is positively related to SR and, therefore, the quantity of N consumed per hectare also increases with SR. Stocking rate may, therefore, be assumed as a fundamental herd-level factor affecting the total quantity of N deposited, the geographical spread of the N in urine patches, and the associated magnitude of N leaching losses from dairy land. However, this assumption does not give consideration to the timing of excreta deposition, which has also been identified as a critical factor affecting N leaching (Shepherd, Snow, Phillips, & Glassey, 2010).

The direct connection between SR and N leaching has been questioned within the literature. Roche et al. (2016) compared the production, economic and environmental performance of 5 treatments differing in SR with the same annual N fertiliser use, importing almost no additional supplementary feed. Pasture utilisation increased at higher SRs, which contributed to an increase in milk production per hectare. Lactation length (days in milk (DIM) per cow) declined linearly as SR increased, reflecting the need to balance herd feed demand while managing pasture cover and cow BCS within a pasture-based grazing system. This reduced lactation length resulted in a decrease in estimated urine N excretion per cow during late-lactation and this coincided with the most climatically sensitive period for elevated N leaching (late-summer to winter; De Klein & Ledgard, 2001; Selbie et al., 2015). As a result, the quantity of N leached/ha per year declined linearly with an increase in SR. An increase in SR may, therefore, actually result in a reduction in N leaching at a farm systems level, provided that additional feed is not imported to support this higher SR and maintain or extend lactation length (Roche et al., 2016).

2.7.4 Effect of intensification on the environmental footprint of dairying

The 'Resource Efficient Dairying' trial was conducted to measure the physical productivity, economic performance and environmental effects of different feed input and management strategies within a pasture-based dairy system. Treatments differing in annual N application, SR, and the quantity of imported supplementary feeds were compared (Jensen, Clark, & Macdonald, 2005; Ledgard et al., 2006). Low supplementation with maize silage (5 t DM/ha), alongside a corresponding increase in SR (+0.8 cows/ha of pasture) resulted in a 5% increase in production per cow and a 16% increase in production per hectare. Despite this increase in MS production, the N leached per hectare of pasture remained similar to the Control treatment. This was attributed to an effect of reduced urinary N concentration due to the low crude protein (CP) content of the maize silage (Ledgard et al., 2006). However, there was an elevated level of leaching on the support land used to grow the maize (70 kg N/ha per year) and graze replacement heifers. When this was accounted for, N leaching/t MS was 7% greater in the low supplementary feed treatment (43 to 46 kg N/kg MS). Further increases in total N leached/kg MS were determined in the 'moderate' and 'high' supplementation treatments, in which greater quantities of imported feed were offered at progressively higher SRs (Figure 21). In contrast, the strategic use of a stand-off pad during the autumn and winter enabled increased environmental efficiency through a 25% reduction in N leached/kg of MS produced (Figure 21).

Within all three supplementary feeding strategies, the total on-farm footprint from intensification was reduced when offering a low protein supplementary feed. However, when accounting for the off-farm effect, both the total N leached and the N leached/kg MS increased with intensification.

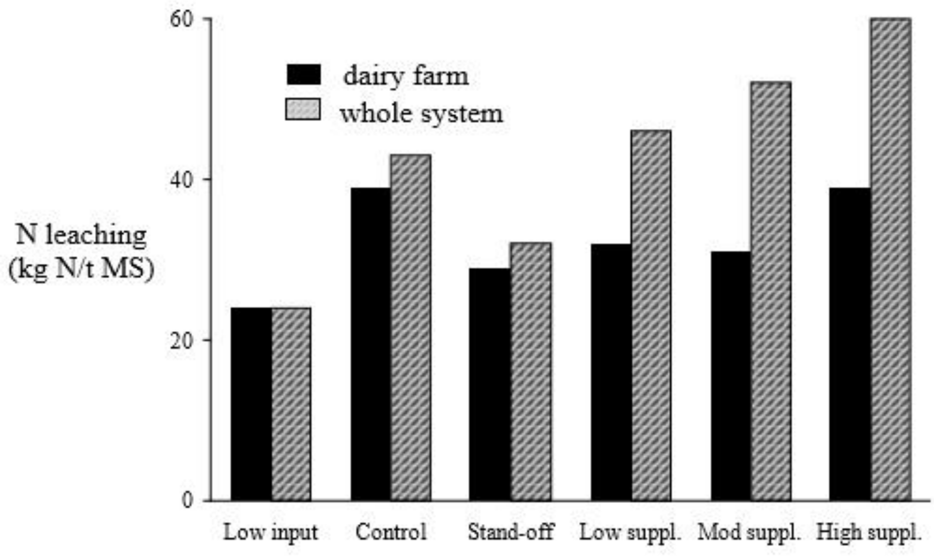

Figure 21: Effect of farm system change on N leached/ t MS at the farm and whole system level (Ledgard et al., 2006).

Similarities can be drawn between these experimental results and the commercial farm scenario. Ledgard et al. (2017) compared the production and environmental metrics of a survey sample of ‘low’ (< 500 kg DM/cow) ‘medium’ (500 - 1200 kg DM/cow) and ‘high’ (> 1200 kg DM/cow) input farms in the Waikato. When moving from the low to high input samples, average MS production was increased by 28% per cow (365 to 469 kg MS/cow) and 75% per on-farm hectare (1087 to 1900 kg MS/ha). In association with this increase in production, N leaching and GHG emissions per on-farm hectare increased 15% and 61%, respectively. Similar to the results of Ledgard et al. (2006), N leaching was elevated on the support land from the grazing of additional replacements and crop production. When this was accounted for, total N leaching/ha was approximately 70% greater in the high input system relative to the low input system. Despite this increase in the total environmental footprint, both N leaching and GHG emissions per tonne of MS were similar between low and high input systems (Figure 22). In this study, intensification was associated with an increase in the total environmental externality per ha, but with little change in the footprint per unit of product.

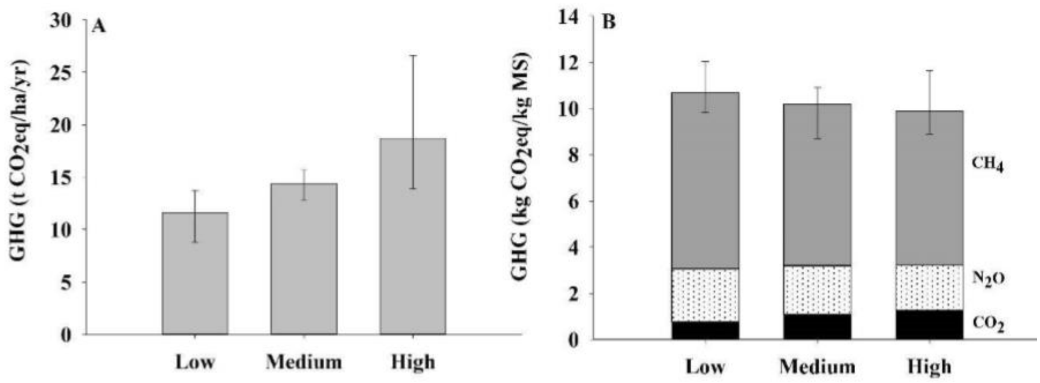

Figure 22: GHG emissions for 'low', 'medium' and 'high' input systems expressed as total emissions and emissions/kg MS (Ledgard et al., 2017).

2.7.5 Summary

The reviewed studies' results indicate a positive association between concurrent increases in SR and imported supplementary feed use and greater environmental externalities (i.e., N leaching and GHG emissions) per hectare. However, evidence also exists to suggest that increases in stock within a pasture-based system, *per se*, are not directly responsible for increases in N leaching; farm system intensification through increasing SR without an increase in imported feed could, in fact, reduce N leaching. In addition, there is evidence that some management practices (e.g., strategic use of stand-off pads) may be employed as successful strategies to reduce the negative effect of feed intensification on N leaching. The overall magnitude of the total environmental externality from intensification will depend on the net effect of any management changes on the farm system and how these changes influence the key factors determining nutrient loss or GHG production pathways (e.g., urinary N concentration, spread, and application timing). Both experimental and farm survey studies highlight the importance of accounting for the full system-level impact when attempting to appropriately quantify the environmental externalities associated with intensification and prevent the transition of pollution to 'off-farm' sources, particularly within the same catchment.

2.8 Conclusions

The biological efficiency of a pasture-based system is influenced by the match between pasture supply and the nutritional demands of the herd throughout the year. However, as a result of the inter- and intra-year variability of pasture growth, despite various management levers available to realign feed supply and demand, there are, invariably, periods of the year where pasture supply is insufficient to meet the demand of the herd (pasture deficit).

Supplementary feeds may be offered during periods of pasture deficit to ensure that the nutrient and energy requirements of the herd are met while maintaining or increasing milk production, with the expectation that this will increase profitability. However, there is evidence that, despite increasing milk production, increases in the quantity of imported supplementary feed offered within a pasture-based system are not associated with an increase in profitability. In addition, there is evidence to suggest that concurrent increases in SR and imported feed use can increase N leaching and GHG emissions per hectare.

My primary objective was to investigate the biophysical, economic, and environmental effects of removing imported supplementary feed from a pasture-based grazing system. This was conducted using a case-study approach comparing three pasture-based dairy farming treatments over three years in Northland. My hypotheses were:

1) Milk production would be reduced by removing imported supplementary feed and decreasing SR; there would not be a concurrent reduction in profitability, but N leaching and GHG emissions per hectare would be less.
2) Milk production and profitability would be maintained with similar N leached and GHG emitted per hectare by removing imported supplementary feed and growing forage crops on the dairy platform to maintain feed supply and SR.

Chapter 3: Biophysical implications of removing imported supplementary feed from a pasture-based system

3.1 Introduction

Within a pasture-based system, cows are typically grazed outdoors year-round with pastures harvested *in situ* by the grazing animal. Pastoral grazing systems have a number of advantages relative to housed systems, in which cows are fed a TMR, including their simplicity of establishment, low operating costs and perceived animal welfare benefits (Dillon et al., 2005; Macdonald et al., 2008; Ramsbottom et al., 2015; Roche, Berry, et al., 2017). However, pasture-based systems face challenges, imposed by the inter and intra-annual variation in pasture supply and seasonal changes in nutritive value (Chapman et al., 2013; Roche, Turner, et al., 2009c). When pasture supply is insufficient to meet herd demand (i.e., a pasture deficit), non-pasture feeds (i.e., supplementary feeds) may be offered to maintain DMI and milk production (Bargo et al., 2003; Holmes and Roche, 2007; Macdonald et al., 2017; Roche, 2017). Additional reasons for including supplementary feeds in the diet of grazing dairy cows could be a) to increase individual cow DMI and milk production/cow (Stockdale, 2000; Bargo et al., 2003), or b) increase the number of cows/ha (i.e., SR; Macdonald et al., 2008; Macdonald et al., 2017) and associated milk production/ha.

Within the last decade, the use of imported feedstuffs within the NZ dairy industry, particularly as PKE, has increased considerably (DairyNZ Economics Group, 2016) because of its low cost relative to other imported feedstuffs, its safety with regards to digestive disorders, and its ease of management (Baker, 2016; Mounsey, 2015). However, there is resistance toward the use of PKE, with increasing concerns about the adverse environmental footprint and biodiversity loss associated with palm oil production (Greenpeace, 2010; Virah-Sawmy, 2014). More recently, it has also been identified that PKE affects the concentration of certain milk fatty acids and has an adverse effect on some manufacturing processes (Fonterra Co-operative Group, 2015). Farmers, therefore, identified a need to examine alternatives to imported PKE within pasture-based production systems.

My objective was to examine the biophysical effects of removing PKE from a grazing system (Control; PKE treatment); the two strategies employed were: 1) remove PKE and reduce SR to accommodate the difference in feed supply (Pasture treatment), or, 2) remove PKE and maintain SR by growing potentially high yielding forage crops on a proportion of the farm to supply additional feeds coinciding with anticipated pasture deficits (Cropping treatment).

The experiment used a case-study approach to evaluate three distinct pasture-based dairy farm systems over three years. I hypothesised that milk production/ha would be similar in the PKE and Cropping treatments, but lower in the Pasture treatment, reflecting the lower SR and feed supply/ha.

3.2 Materials and methods

This experiment was undertaken at the Northland Agricultural Research Farm (NARF; 35º56’39”S 173º50’34”E, approximately 20m above sea level) over three lactations between June 2015 and May 2018. Pastures at the site consisted predominantly of perennial ryegrass (*Lolium perenne*), Italian ryegrass (*Lolium multiflorum*), kikuyu (*Cenchrus clandestinus*) and white clover (Trifolium repens). The experimental site comprised of two distinct soil types; specifically, a Kaipara clay loam and a Te Kopuru sand. All experimental procedures were approved by the Ruakura Animal Ethics Committee in accordance with the New Zealand Animal Welfare Act.

3.2.1 Climatic conditions

Monthly rainfall was recorded at a nearby climate station (approximately 2 km from the experimental site; 35°55'53.2"S 173°51'11.4"E) and is presented in Figure 23 for each lactation year (June - May) relative to the historic average for the 10 years preceding the experiment (2005 - 2014). Annual rainfall was below average (1,106 mm) in 2015/16 (929 mm), and above average in 2016/17 (1141 mm) and 2017/18 (1,268 mm). Annual rainfall over the three years of the experiment averaged 1,113 mm, comparable with the historic average (Figure 24).

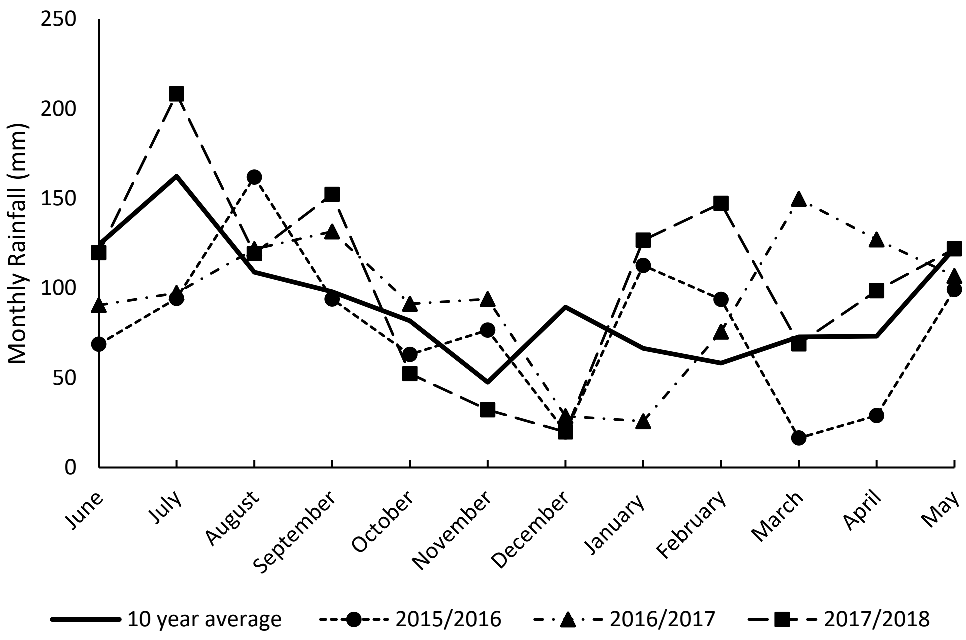

Figure 23: Distribution of total monthly rainfall (mm) for each experimental production season relative to the long term average (2005-2014). Data sourced from: National Institute of Weather and Atmosphere (2019).

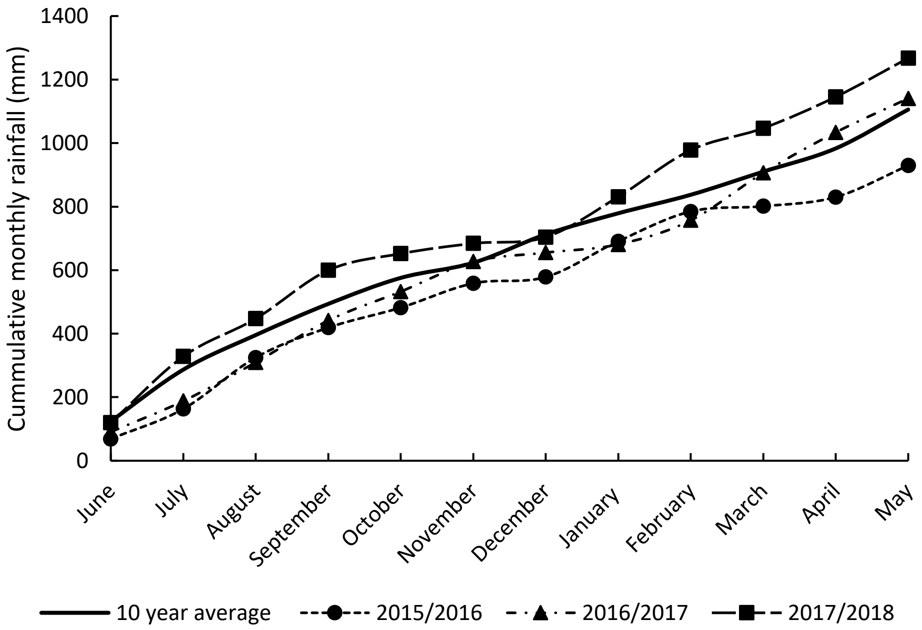

Figure 24: Cumulative monthly rainfall during the experimental period relative to the historic average (2005-2014). Data sourced from: National Institute of Weather and Atmosphere (2019).

3.2.2 Experimental design and treatments

Immediately prior to the initiation of the experiment, paddocks were blocked into groups of three, balanced for geographic location, soil type, pasture cover, pasture species, and proportion of the total farm effluent block. Paddocks within block were randomly assigned into 3 farmlets (28 ha). Each farmlet was then randomly allocated to one of three experimental treatments: “PKE”, “Pasture”, and “Cropping”. Once established, these farmlets remained unchanged for the duration of the experiment (Figure 25).

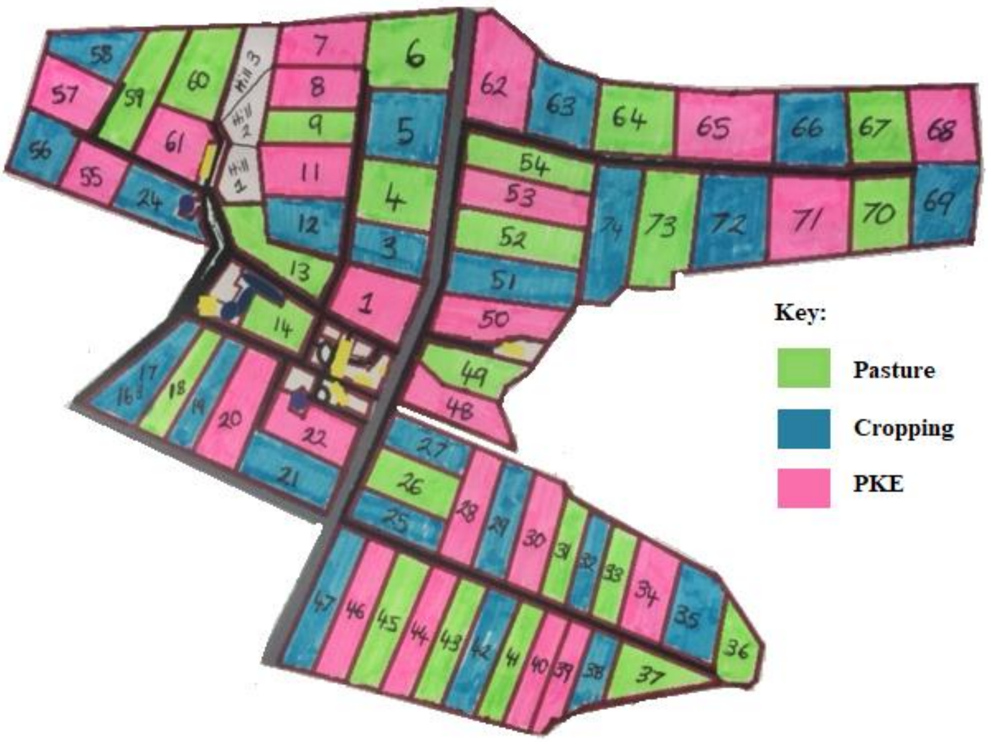

Figure 25: Northland Agricultural Research Farm map and the allocation of paddocks to each of the PKE, Pasture, and Cropping treatments.

Two-hundred and twenty-seven Jersey-Friesian cross cows were then randomly allocated to the PKE (n = 78), Pasture (n = 71), and Cropping treatments (n = 78), resulting in a SR at peak of 2.7, 2.5, and 2.7 cows/ha respectively. Treatment herds were balanced for productive traits (Breeding Worth (BW) and Production Worth (PW)), age, and BCS at the beginning of the experiment. The greater SR on the PKE and Cropping treatments reflected the greater anticipated feed supply. Peak SR varied slightly with production season; peak SR was 2.7, 2.8, and 2.9 cows/ha (76, 78 and 81 cows) in the PKE treatment 2.5, 2.5, and 2.6 cows/ha (70, 71, and 73 cows) in the Pasture treatment, and 2.7, 2.8, and 2.6 cows/ha (76, 78, and 74 cows) in the Cropping treatment, in the 15/16, 16/17, and 17/18 seasons, respectively.

Within the Pasture treatment, the herd's diet comprised entirely of pasture grown on-farm grazed *in situ* or conserved and fed as silage. In the Cropping and PKE treatments, additional feed was available in the form of forage crops grown on-farm and imported PKE, respectively. On average, 23% (22 - 25%) of the Cropping farmlet was planted annually in forage crops, including turnips, fodder beet, and maize. Within the PKE treatment, PKE was offered when the post-grazing residual was less than 40 mm (~1,600 kg DM/ha). The Cropping treatment began the experiment with approximately 2 t DM/ha of imported maize silage (55 t DM) and approximately 6.6 ha of newly resown ryegrass pastures to reflect expected conditions of a status quo cropping system.

3.2.3 Management of the experiment

3.2.3.1 Grazing and fertiliser management

Grazing management protocols were the same for all treatments, with all cows rotationally grazed in a manner similar to that described by Macdonald et al. (2008). Pasture cover was measured across the entire farm on a weekly or fortnightly basis; this was used to inform grazing management decisions. For all treatments, the intended post-grazing residual was 40 mm (1,600 kg DM/ha) across the entire year. All treatment herds were stood off pasture overnight when soil conditions were saturated or directly prior to forecasted heavy rainfall events to limit soil pugging.

3.2.3.1.1 Autumn/winter grazing management

As per the Autumn Rotation Planner, described by Macdonald et al. (2010), the daily grazing area was gradually reduced over the autumn/early-winter, thereby reducing the daily area allocation/cow, extending the grazing rotation, and increasing APC before the PSC (5th July). Due to the presence of kikuyu at the site, however, and the associated need to prevent excessive pasture covers to maintain pasture quality, target rotation lengths during this period differed from that of the Autumn Rotation Planner. Pastures were managed in accordance with best practice management for kikuyu (DairyNZ Limited, 2017c). Grazing area was reduced to approximately 1/100th of the total farmlet area prior to PSC. Rotation length was managed according to incident climatic conditions, with the intention of managing pasture quality while building sufficient pasture cover prior to calving (target of approximately 2,400 kg DM/ha APC at PSC).

Mechanical mulching of the existing pasture sward followed by undersowing of Italian ryegrass was practiced annually within kikuyu dominant paddocks during the autumn. The proportion of paddocks undersown with Italian ryegrass was balanced across treatments.

3.2.3.1.2 Spring/ summer grazing management

The Spring Rotation Planner, described in detail by Macdonald (2010), was practiced from PSC until balance date (date at which pasture growth is anticipated to be consistently greater than animal demand; approximately 10th September). Following balance date, where cows consistently grazed above target post-grazing residual (1,600 kg DM/ha), pasture conservation practices were employed to maintain target post-grazing residuals. Paddocks with a pre-grazing cover in excess of 3,200 kg DM/ha were removed from the rotation and the surplus pasture was conserved as baled silage. Silage bales from each farmlet were kept separate and were only made available for feeding on the farmlet from which they were made. A representative sample of silage was taken for DM analysis to determine the quantity of feed conserved as silage from each farmlet. Mechanical mowing (i.e., topping) of post-grazing residuals was practiced when considered necessary to maintain pasture quality in future rotations. However, this practice was avoided where possible through management of PA to meet animal demand.

3.2.3.1.3 Fertiliser management

The annual rate and distribution of nitrogenous fertiliser applications were managed to be approximately equal between farmlets. However, the timing and quantity of fertiliser applied varied between years to optimise pasture growth given incident climatic conditions. Nitrogen was applied as either Urea (Ballance®, Kapuni, New Zealand; N, P, K, S: 46.0, 0, 0, 0), Ammo36™ (Ballance®, Kapuni, New Zealand; N, P, K, S: 35.6, 0, 0, 9.2), or SustaiN® (Ballance®, Kapuni, New Zealand; N, P, K, S: 45.9, 0, 0, 0) at a rate of between 25 to 50 kg N/ha per application. Ammo36™ was preferentially applied during spring to ensure a strategic addition of sulphur, whilst SustaiN® was applied in late-spring and early-summer to limit volatilization losses of NH_3. Soils at the site had naturally high Olsen-P concentrations; as a result, no maintenance phosphorus fertiliser was applied over the course of the experiment.

3.2.3.2 Animal management

Milk production was seasonal, with cows calving mid-winter and breeding mid-spring. All treatment herds were managed according to the same decision rules (Macdonald and Penno, 1998; Roche et al., 2017).

Pre-mating heats were identified and recorded during the three weeks prior to the planned start of mating (PSM: 1st October). This was achieved through twice-daily observation of oestrous activity as indicated by tail paint applied directly to the tail head of each cow. Milking frequency was reduced to OAD for cows with a BCS of ≤ 3.5 or where individual cows had not displayed visual oestrus prior to the PSM. Non-cycling cows were not treated with intervaginal controlled internal drug release (CIDR).

Artificial insemination was performed during the first 6 weeks of the seasonal breeding period, followed by a 6-week period of natural mating with 2 Jersey bulls introduced per treatment. During the artificial insemination period, oestrus activity was observed at morning milking; cows with visual signs of oestrus within the preceding 24 hr period were nominated for artificial insemination that day.

Pregnancy diagnosis occurred at least 5 weeks following the conclusion of the mating period (17 weeks post-PSM). This was performed by manual palpation of the uterine contents. Cows that failed to conceive were identified for culling from the experimental herd. Approximately 20% of cows in each treatment herd were replaced annually based on pregnancy outcomes, health, genetic merit and age. These were replaced with primiparous cows prior to the following PSC. The timing of culling decisions was made in response to seasonal feed availability and assessed at an individual cow level with consideration of animal health. Lactation for individual cows was terminated based on calving date and BCS. Individual cows milked no later than 50 days prior to their expected calving date and were individually managed to ensure a BCS of 4.5 was reached by 31st May and a target BCS of 5 at calving.

All cows were grazed on-farm during winter. Young stock were grazed off-farm from approximately 4 months of age (i.e., November) and only returned as in-calf replacements prior to their first lactation (i.e., 22 - 23 months).

3.2.3.3 Animal health

The transition from late-pregnancy to early-lactation is a significant risk period for the incidence of metabolic disorders in dairy cows (Roche & Berry, 2006). In addition, the magnesium content of kikuyu dominant swards is low (B. Fulkerson, Griffiths, Sinclair, & Beale, 2010), further exacerbating the risk of metabolic disorders during this period. To reduce the risk of hypomagnesemia, magnesium oxide was top-dressed onto pastures pre-grazing (approximately 80 g/cow per day) to ensure a target intake of approximately 18 g/cow per day as per industry best management practice (DairyNZ Limited, 2009). This was implemented from approximately 2 weeks prior to the PSC until the PSM.

An anti-bloating surfactant was added to stock drinking water during periods of increased risk of bloat (e.g., high sward clover content). Zinc sulphate was added to stock drinking water (approximately 36 g $ZnSO_4.7H_2O$/cow per day), during periods of elevated risk of facial eczema as per best practice management (DairyNZ Limited, 2015). The timing of zinc introduction was determined through assessment of local fungal spore counts (*Pithomyces chartarum*).

Cows with high somatic cell counts or with a history of mastitis within the current lactation were treated with dry cow antibiotics (Cepravin®, MSD Animal Health, Wellington, New Zealand) and a teat sealant (Teatseal®, Zoetis, Auckland, New Zealand). All remaining cows were treated only with teat sealant.

3.2.3.4 Supplementary feeding

As described in the 'experimental design' section, PKE was offered to cows in the PKE treatment, when post-grazing residuals were consistently below 40 mm (~1,600 kg DM), reflecting a feed deficit. The quantity of PKE offered was measured using an auger bucket affixed with calibrated scales; PKE was offered in either feed bins on a concrete pad or in transportable bins within the paddock, depending on the quantities of PKE being fed and prevailing weather and soil conditions. Palm kernel was offered in transportable bins within the paddock where the daily allowance of PKE was low (≤ 1 kg DM/cow/day) and the soil moisture was such that little pugging damage would occur.

3.2.3.5 Cropping

3.2.3.5.1 Crop selection

Forage crops were grown on the 'milking platform' of the Cropping treatment with the intention of providing a greater quantity of feed across the farmlet than would be produced by pasture alone, particularly during summer, autumn and winter, when there is the greatest risk of feed deficit. No forage cropping was practiced on either of the Pasture and PKE treatments. The forage crops planted within the experiment were maize, turnips, and fodder beet. These were selected on several characteristics including the timing of feed availability, yield potential, and, in the case of turnips and fodder beet, the fact the cows harvest the feed themselves.

Both maize and turnips are widely used within the region of the experimental site and had been grown historically on the experimental farm prior to the experiment. As a C4 plant, maize is both anatomically and physiological adapted to levels of moisture stress that undermine the growth of C3 plants and shallow-rooted C4 plants (White & Hodgson, 2000) making it a suitable crop for Northland region, given the susceptibility of the experimental site to summer moisture deficit. Its purpose in the current experiment was for silage to be used in winter and early-spring. The maize cultivars used within the experiment were P0640 (2015/16) and P9911 (2016/17 and 2017/18; Pioneer®, Auckland, New Zealand).

Turnips have a relatively short maturity and are relatively low cost/kg feed consumed, making them suitable to transfer feed from spring to early-summer, when pasture growth and quality usually decline (de Ruiter et al., 2009). The turnip cultivars used within the experiment were 'Barkant' and 'Green Globe' (PGG Wrightson Seeds®, Christchurch, New Zealand).

Fodder beet was selected for its putative high yield potential (Gibbs & Saldias, 2014), which was necessary to enable re-grassing of the turnip and maize silage areas, enabling high stocking densities to be managed during the autumn. The fodder beet cultivar used within the experiment was SF Brigadere™ (Seed Force, Christchurch, New Zealand). Fodder beet was not sown in the 2017/2018 season as poor weather delayed potential planting date beyond what was deemed necessary to achieve an acceptable yield. The area in turnips and maize was increased in response to the removal of fodder beet in the 2017/2018 season (Table 2).

3.2.3.5.2 Paddock selection and rotation policy

Cropping paddocks were selected based on a number of factors including annual pasture production and associated requirement for renewal, excessively kikuyu-dominant, relative to other pastures, and previous cropping history. Cropped paddocks went through at least two cropping rotations before being restored to permanent ryegrass; this enabled greater control of kikuyu within renewed pastures. Cropping paddocks were soil tested when transitioned out of permanent pasture and any nutrient deficiencies were corrected accordingly.

3.2.3.5.3 Planting

All crops were planted in spring on the grazable farmlet area. Maize was harvested, stored as silage, and fed primarily during late-autumn and winter. Maize silage was offered using the same decision rules described for PKE. Turnips and fodder beet were grazed *in situ*. The timing of planting and the final harvest of these crops within any particular year (Table 2) was highly dependent on incident climatic conditions, which affected planting date, final yield, and pasture supply (and hence, timing of crop demand). Crops were sown as early as possible, provided that soil and climatic conditions were suitable and in order to maximise the available growing period and yield potential.

Best management practice for crop establishment was followed, including in seedbed preparation, sowing depth, and sowing rate. Selected paddocks were sprayed out with approximately 4 L/ha of glyphosate (540 g/L active ingredient). All crop paddocks were disc and power harrowed prior to planting and rolled after sowing.

Cropzeal boron boost (Ballance®, Tauranga, New Zealand; N, P, K, S: 16.0, 19.5, 0.0, 1.0) was applied to the turnips at planting at 250 kg/ha. Di-ammonium phosphate (Ballance®, Tauranga, New Zealand; N, P, K, S: 17.6, 20.0, 0.0, 1.0) was applied at planting to fodder beet. Urea was top dressed at a rate of 150 – 200 kg/ha in December to both the turnip and fodder beet crops. Di-ammonium phosphate was applied at planting to the maize at a rate of 250 kg/ha.

3.2.3.5.4 Harvest

The area, planting date and harvest dates for each forage crop in the 15/16, 16/17, and 17/18 seasons are presented in Table 2. Both the turnip and fodder beet crops were 'strip-grazed' using temporary electric wires. Once grazing of a forage crop began, cows were given a daily allowance until the crop finished. The allowance of turnips slowly increased from approximately 3 kg DM/cow per day toward 6 kg DM/cow per day over the grazing period. Fodder beet intakes were incrementally increased over a 10-day period from approximately 1 kg DM in day 1 to a maximum of 5 kg DM/cow per day; this facilitated a 'transition' of the rumen microorganisms onto a diet very high in oligosaccharide concentration to reduce the risk of ruminal acidosis, as per best management practice when grazing fodder beet (DairyNZ Limited, 2017e).

Table 2: Crop area, planting and harvest dates.

Year		2015/16	
Crop	Maize	Turnips	Fodder beet
Area (ha)	2.3	1.9	2.0
Planting date	19th October	19th October	12th October
Harvest date	31st March	6th January – 15th February	6th February – 3rd May
Yield (kg DM/ha)	22,174	9,014	15,784
Year		2016/17	
Crop	Maize	Turnips	Fodder beet
Area (ha)	1.9	2.6	1.5
Planting date	1st December	28th October – 4th November	1st November
Harvest date	21st April	6th January – 23rd March	6th March – 31st May
Yield (kg DM/ha)	14,211	9,108	16,027
Year		2017/18	
Crop	Maize	Turnips	Fodder beet
Area (ha)	2.6	4.4	-
Planting date	13th November	10th November	-
Harvest date	1st April	19th January – 14th April	-
Yield (kg DM/ha)	14,615	6,728	-

3.2.4 Measurements

3.2.4.1 Milk production and BCS

Treatment herds were milked into separate vats allowing for the measurement of daily herd milk production and composition. Milk volume and protein and fat percentages were reported at each milk collection. Annual accumulated milk yield and milk component yield was determined for each treatment herd. Adjustments were made for the volume of any recorded milk removed from the vat prior to collection (e.g., calf milk).

Body condition score was measured fortnightly as the mean BCS of a sample of 30 cows from each treatment herd following morning milking. Assessment of BCS was made on a 10-point scale, where 10 is obese and 1 is emaciated (Roche, Dillon, Stockdale, Baumgard, & VanBaale, 2004).

3.2.4.2 Pasture measurements

Pasture herbage mass (kg DM/ha) was reverse-calculated from compressed pasture heights, measured weekly or fortnightly across all treatment paddocks using a rising plate meter. The following regression equation was used to calculate pasture herbage mass from height measurements.

Equation 6: Pasture herbage mass (kg DM/ha) = 140 x pasture height + 500

Net herbage accumulation for each measurement period was then calculated for un-grazed paddocks as the increase in herbage mass during the accumulation period. Pasture growth rates were calculated by dividing the accumulated growth by the accumulation period. In the case of missing data or where growth could not be calculated due to a grazing event, treatment average growth rates were imputed for each paddock. Growth measurements greater than a threshold of -20 kg DM/ha/day were included in the analysis. This threshold was used due to the presence of negative growth rates unrelated to grazing events, which, if excluded, overestimated pasture accumulation. Average growth rates (kg DM/ha/day) for each season (i.e., winter, spring, summer, autumn) were estimated for each paddock and multiplied by the number of days in each season to calculate the seasonal pasture yield. Seasonal yields were accumulated to produce the annual pasture yield.

Treatment average pre-grazing and post-grazing mass was estimated as the average of the three paddocks of greatest and three paddocks of lowest pasture mass, respectively, at each farm walk. Although the use of this average possibly biases estimates to, slightly, underestimate pre-grazing pasture mass and overestimate post-grazing pasture mass, the effect was, likely, small and not material to the annual or seasonal average.

Monthly, pasture was sampled from paddocks pre-grazing and pooled across treatments. These samples were plucked by hand prior to grazing as a representative sample of what the cows would be consuming. Duplicate samples were dried at either 105°C (24hr) for DM analysis or 62°C (12hr) for analysis of nutrient content. Samples dried at 62°C were ground to pass through a 1.0 mm sieve and analysed for CP neutral detergent fibre (NDF), and ME (calculated from dry organic matter digestibility) by near-infrared spectroscopy (NIRS; Corson, Waghorn, Ulyatt, & Lee, 1999; Table 3). In addition, a botanical dissection of the pooled pasture sample was undertaken to determine the species composition of the pasture sward and its seasonal variation (Figure 26).

Table 3: Average seasonal[1] quality (% DM) and ME concentration (MJ ME/kg DM) of pasture.

	Winter	Spring	Summer	Autumn
ME	11.2 ± 0.7	11.6 ± 0.5	9.6 ± 0.6	10.1 ± 0.4
CP %	23.2 ± 1.9	18.1 ± 1.1	17.1 ± 3.6	23.3 ± 1.0
NDF %	44.4 ± 1.1	43.7 ± 2.9	51.0 ± 2.1	42.2 ± 4.5

[1]Winter (June to August, inclusive), spring (September to November, inclusive), summer (December to February, inclusive), autumn (March to May, inclusive).

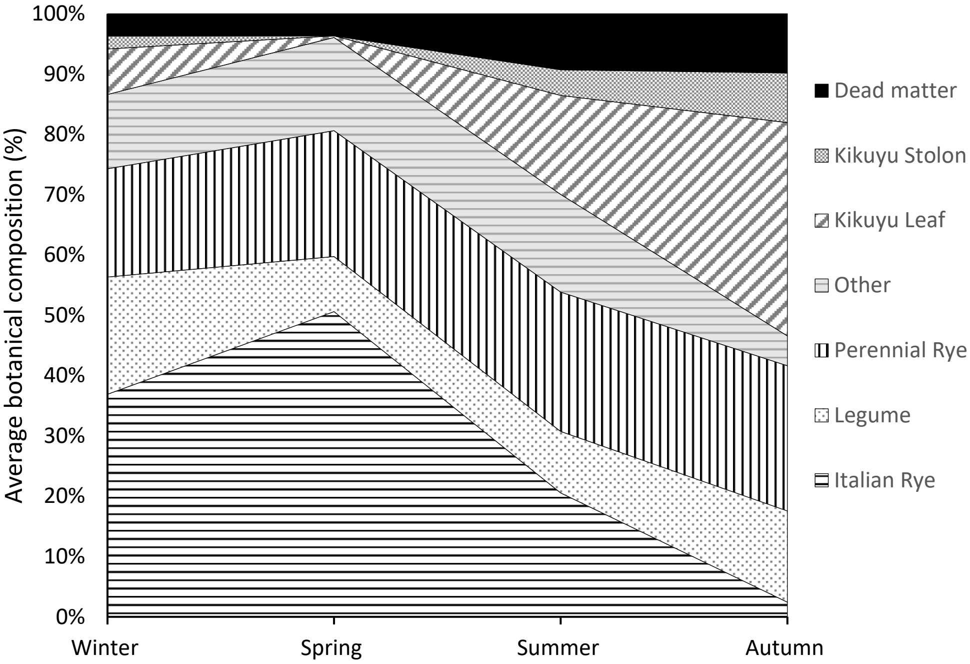

Figure 26: Average seasonal botanical composition of main sward constituents.

3.2.4.3 Feed quality and crop yields

The quantity of silage bales conserved from each treatment was recorded. Representative bales were weighed and a sample from each batch was analysed for DM percentage to estimate the total quantity (in kg DM) of silage conserved. In addition, silage was analysed for nutritional composition by NIRS.

Forage crop yields were estimated prior to harvest and a representative sample taken for DM analysis. Maize silage samples were also analysed using NIRS methods. Turnip yields were measured using a 1 m^2 ring thrown randomly in the crop paddock. The weight of turnips within 5 random sample rings were measured, the average weight was multiplied by the DM percentage to determine the DM yield.

Fodder beet yield was assessed by measuring the distance between drill row coulters to determine the length of a single row that would occupy a 1 m^2 area. The number of bulbs along this row length was counted within 20 random samples and averaged to provide a plant population/m^2. Twenty plants were randomly selected and weighed to provide an average plant weight. The average plant population/m^2 was multiplied by the average plants/m^2 and the DM percentage to determine the

DM yield (kg DM/ha). Daily crop allowance of both turnips and fodder beet were estimated by multiplying the daily area offered by the estimated crop yield.

Maize crop yields were estimated from stack size volume and industry standard bulk density values (DairyNZ Limited, 2017b). Daily maize silage allowance was measured in the same manner as PKE allowances using an auger bucket affixed with calibrated scales.

3.2.4.4 Kikuyu presence

A subjective visual assessment of the proportion of kikuyu within the sward was undertaken during summer in the 16/17 and 17/18 seasons. Visual assessment was conducted at 2 m intervals along a diagonal transect of each paddock. At each sampling site, a stick pointer was directed at the soil surface and a subjective visual assessment was undertaken around a 50 mm radius of the pointer. The proportion of kikuyu within a paddock was assessed as the proportion of sampling sites with kikuyu present. The procedure was undertaken by the same operator in each year.

3.2.5 Statistical analyses

Pasture yield (kg DM/ha) was analysed separately for each season using a weighted mixed model for repeated measures analysis of variance (ANOVA, Proc Mixed, SAS/STAT 14.3). The model included treatment, year, and their interaction as fixed effects, and paddock as a random effect. The number of measurements per paddock during each respective seasonal period was used for weighting.

All other reported variables were analysed using one-way ANOVA, with treatment included as fixed effect. Tukey adjustment was used for pairwise comparisons between treatments (within farming year). Data were $\log_{10}$ transformed, if required, to achieve homogeneity of variance. Results are presented as least-squares means and standard error of the difference (SED). Significance was declared if $P \leq 0.05$.

3.3 Results

3.3.1 Pasture production

The effects of experimental treatment and year on annual pasture production and its seasonal distribution are presented in Table 4. Year affected seasonal and annual pasture DM yield (P = 0.01), with annual pasture yield greatest in 2016/17 (June-July; 17,718 kg DM/ha), lowest in 2017/18 (15,678 kg DM/ha), and intermediate in 2015/16 (16,124 kg DM/ha). Average annual pasture production tended (P = 0.06) to be greater in the PKE treatment relative to the Pasture and Cropping treatments, which did not differ from each other. Treatment also affected the seasonal distribution of pasture production, with average autumn pasture production greater (P < 0.05) in the PKE treatment than the other treatments, which did not differ from each other. There was no interaction between treatment and year with respect to annual pasture production.

Table 4: Effect of treatment[1] and year on average seasonal[2] and annual pasture yield (kg DM/ha)[3].

	PKE	Pasture	Cropping	SED	*P*-Value
Winter					
15/16	3,446	3,472	3,720	207.9	0.35
16/17	3,706 [ab]	3,408 [a]	3,989 [b]	181.6	0.01
17/18	3,609	3,379	3,138	213.4	0.09
Mean	3,587	3,420	3,616	131.4	0.28
Spring					
15/16	6,182	6,185	5,706	189.0	0.02
16/17	6,474	6,545	6,181	193.1	0.15
17/18	4,961	4,975	5,190	263.1	0.63
Mean	5,872	5,902	5,692	129.3	0.23
Summer					
15/16	3,831	3,827	4,009	167.0	0.49
16/17	2,694	2,787	2,827	173.8	0.73
17/18	3,533	3,470	3,208	231.1	0.36
Mean	3,353	3,361	3,348	123.5	0.99
Autumn					
15/16	2,772	2,568	2,523	194.4	0.40
16/17	4,960	4,611	4,711	159.4	0.07
17/18	4,034	3,613	3,686	217.6	0.11
Mean	3,922 [b]	3,597 [a]	3,640 [ab]	121.6	0.02
Annual					
15/16	16,289	16,136	15,947	350.6	0.63
16/17	17,982	17,409	17,762	328.1	0.20
17/18	16,232	15,531	15,272	422.3	0.07
Mean	16,834	16,359	16,327	234.5	0.06

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha, respectively).
[2]Winter (June to August, inclusive), spring (September to November, inclusive), summer (December to February, inclusive), autumn (March to May, inclusive).
[3]Estimated from weekly or fortnightly assessment of compressed pasture height.

Table 5: Effects of treatment[1] on the average rotation length[2] during each season[3], average seasonal pasture mass[4] (pasture cover; kg DM/ha), the average pre- and post-grazing pasture mass[4] during each season and the quantity of silage conserved (kg DM/ha) and nitrogen applied (kg N/ha) annually.

Variable	PKE	Pasture	Cropping	SED	*P*-Value
Rotation length					
Winter	74	71	73	2.6	0.53
Spring	29	30	28	2.6	0.75
Summer	31	31	31	0.7	0.87
Autumn	37	40	39	2.9	0.54
Average pasture cover					
Winter	2,413	2,331	2,455	78.3	0.34
Spring	2,291	2,314	2,393	53.3	0.21
Summer	2,163	2,141	2,112	132.0	0.93
Autumn	2,099	2,130	2,075	79.0	0.79
Post-grazing residual					
Winter	1,468	1,410	1,527	55.1	0.19
Spring	1,581	1,592	1,614	44.9	0.76
Summer	1,558	1,552	1,556	56.3	0.99
Autumn	1,427	1,405	1,441	55.0	0.81
Pre-grazing residual					
Winter	3,527	3,471	3,597	64.5	0.23
Spring	3,125	3,184	3,286	125.2	0.47
Summer	2,843	2,848	2,727	219.0	0.83
Autumn	2,916	2,964	2,826	145.1	0.65
Silage conservation					
Pasture conserved as silage (kg DM/cow)	398 [b]	497 [b]	63 [a]	88.0	<0.01
Pasture conserved as silage (kg DM/ha)	1,112 [b]	1,272 [b]	166 [a]	238.8	<0.01
Nitrogen fertiliser					
Annual nitrogen application (kg N/ha/yr.)	167	177	162	31.4	0.89

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha, respectively).
[2]Reciprical of the proportion of the farmlet grazed on the day of the weekly or fortnightly pasture assessment.
[3]Winter (June to August, inclusive), spring (September to November, inclusive), summer (December to February, inclusive), autumn (March to May, inclusive).
[4]Estimated from weekly or fortnightly assessment of compressed pasture height.

The Cropping farmlet conserved less (*P* < 0.01) silage/cow and per ha than either the Pasture or PKE farmlet treatments, which did not differ from each other. Treatment had no effect on average seasonal rotation length, average pasture cover, pre- and post-grazing pasture mass, or the quantity of N applied annually (kg N/ha/yr; Table 5). The mean quantity of supplementary feeds offered per cow within each treatment are displayed in Table 6.

Table 6: Mean (standard deviation in parentheses) supplementary feed allowance per cow in the Pasture, Cropping and PKE treatments.

	PKE	Pasture	Cropping
Supplementary feed offered (kg DM/cow)			
Silage	291 (83)	368 (183)	63 (109)
Maize			529 (104)
Fodder beet			231 (161)
Turnips			303 (82)
PKE	515 (46)		
Total	805 (126)	368 (183)	1,126 (110)

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha, respectively).

3.3.2 Milk production

Treatment did not affect lactation length or any of the per cow milk production variables (Table 7). Yield of fat and 4% fat corrected milk (4% FCM) were greater (*P* < 0.05) in the PKE treatment when compared with the Pasture treatment and there was a tendency for the PKE treatment to produce more milk, energy corrected milk (ECMY), and protein (*P* = 0.09, 0.06 and 0.08 respectively) than the Pasture treatment. However, neither per cow nor per ha milk production variables were different between the PKE and Cropping treatments. There was no effect of treatment on milk protein concentration; however, milk fat concentration was greater (*P* < 0.001) in the PKE treatment than the other two treatments, which did not differ from each other.

Table 7: Effects of treatment[1] on average lactation length (days), annual milk production (kg/cow and kg/ha) and average milk composition (%).

	PKE	Pasture	Cropping	SED	*P*-Value
Lactation length	269	262	268	7.7	0.63
Production (kg/cow)					
Milk yield	4,191	3,976	4,048	178.6	0.51
ECMY	5,057	4,668	4,773	214.0	0.26
4% FCM	5,035	4,628	4,756	213.6	0.23
Fat	224	203	209	9.6	0.16
Protein	167	157	158	7.1	0.37
MS[2]	390	359	367	16.5	0.23
Production (kg/ha)					
Milk yield	11,726	10,124	10,998	580.1	0.09
ECM	14,148	11,888	12,969	709.9	0.06
4% FCM	14,089 [b]	11,787 [a]	12,923 [ab]	705.8	<0.05
Fat	627 [b]	516 [a]	568 [ab]	31.6	<0.05
Protein	466	400	429	23.5	0.08
MS	1,092 [b]	915 [a]	997 [ab]	55.0	<0.05
Milk composition (%)					
Fat	5.3 [b]	5.1 [a]	5.2 [a]	0.03	<0.001
Protein	4.0	3.9	3.9	0.04	0.21

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha, respectively).
[2]Yield of fat and protein (kg).

3.3.3 Body condition score

The effects of treatment on average seasonal BCS are presented in Table 8. There was no treatment effect on BCS prior to calving (June). However, there was a consistent trend ($P < 0.15$) for PKE cows to have a greater BCS during early-lactation when compared with cows in the other two treatments.

Table 8: Effect of treatment[1] on monthly average BCS.

Month	PKE	Pasture	Cropping	SED	*P*-Value
June	4.9	4.8	4.9	0.18	0.86
July	5.0	4.9	5.0	0.08	0.14
August	4.3	4.0	4.2	0.11	0.08
September	4.1	3.8	4.0	0.09	0.12
October	4.0	3.9	3.9	0.06	0.15
November	4.0[b]	4.0[ab]	3.9[a]	0.05	0.03
December	4.0	3.9	3.9	0.03	0.08
January	3.9	3.9	3.9	0.10	0.93
February	3.9	3.9	3.9	0.05	0.33
March	3.9	3.9	3.9	0.11	0.77
April	4.0	4.0	4.0	0.16	0.97
May	4.2	4.2	4.2	0.20	0.95

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha respectively)

3.3.4 Reproduction

Treatment did not affect any of the reproduction variables measured (Table 9).

Table 9: Effects of treatment[1] on submission rate[2], non-return rate[3], and non-in-calf rate[4].

Item	PKE	Pasture	Cropping	SED	*P*-Value
Submission rate	84	88	87	5.0	0.69
Non-return rate	76	78	74	6.0	0.78
Non- in-calf rate	7	8	11	3.2	0.58

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha, respectively).
[2]Percentage of cows submitted for AI within the first three weeks of the seasonal calving period.
[3] The percentage of inseminations where the cow did not return to heat within 24 days after the insemination.
[4]Proportion of cows that are not pregnant at the end of a 12-week seasonal breeding season.

3.3.5 Kikuyu presence

Treatment affected the mean proportion of kikuyu within the sward, with a lower proportion of kikuyu in the Cropping treatment relative to either the Pasture and PKE treatments, which did not differ from each other (Table 10).

Table 10: Effect of treatment[1] on the proportion of kikuyu within the sward.

	PKE	Pasture	Cropping	SED	P-Value
16/17	0.53 ^{b}	0.43 ^{ab}	0.22 ^{a}	0.089	<0.01
17/18	0.69 ^{b}	0.56 ^{b}	0.25 ^{a}	0.089	<0.001
Mean	0.61 ^{b}	0.49 ^{b}	0.23 ^{a}	0.083	<0.001

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha, respectively)

3.4 Discussion

3.4.1 Pasture

Importing supplementary feed as PKE increased estimated pasture DM production relative to reducing SR and/or growing crops to alleviate the anticipated feed deficit, with differences in pasture production being particularly evident during the autumn. These differences are consistent with treatment effects in estimated pasture intakes; metabolisable energy-based calculations of annual pasture DMI indicate that, on average, apparent pasture eaten in the PKE treatment was 762 kg DM/ha greater than in the Pasture treatment, while estimated pasture eaten was 3,110 kg DM/ha lower in the Cropping treatment than the PKE treatment. Although both techniques have limitations, data from weekly pasture walks as well as estimates of pasture DM production from back-calculation of ME requirements indicate that pasture DM production and harvest (i.e., pasture consumed/ha) were greater in the PKE treatment relative to either the Pasture or Cropping treatments.

This difference in DM production and consumption may be due to: 1) differences in grazing management; 2) a growth response to additional nutrients supplied by the supplementary feed; 3) a treatment effect on species composition within the sward; or 4) a combination of all three.

3.4.1.1 Grazing management and limitations to measurement

Farmlet treatment did not affect pre-grazing pasture DM mass, post-grazing pasture DM mass, average pasture DM mass, or rotation length, but differences in the annual sum of pasture disappearance were approaching significance; this provides confidence that the smaller numerical differences were, in fact, real and materially relevant when accumulated over a full season. The lack of significance may reflect a lack of ability to detect real differences between treatments, due to the size of measurement error relative to the mean difference between treatments. There is considerable error in the estimation of pasture mass using a rising plate meter (RPM), which is attributable to sampling error associated with measurement technique and human error (L'Huillier & Thomson, 1988; Lile et al., 2001; Piggot & Morgan, 1985; Prewer et al., 2002). For example, a standard error estimate for RPM measurements of approximately 350 - 450 kg DM/ha has been reported (L'Huillier & Thomson, 1988; Thomson, Mccallum, Howse, Holmes, & Matthews, 1997).

Average autumn rotation length was numerically shorter in the PKE treatment relative to the Pasture treatment in all three years of the experiment. As kikuyu is dominant within the pasture sward during the autumn period, a faster rotation may have had a positive effect on autumn pasture quality in the PKE treatment relative to the other treatments. As the back-calculation of pasture eaten uses a standard ME value for pasture, this may have over-estimated the pasture consumed in the PKE treatment during autumn. However, this is unlikely to explain more than 10% of the difference between treatments.

3.4.1.2 Additional nutrients

I postulate that at least some of the treatment effect on pasture production is a result of additional nutrients supplied by the imported supplementary feed. The conversion efficiency of consumed N into product is low in pasture-based grazing systems; a substantial quantity (> 70%) of consumed N is recycled through direct deposition in animal excreta (Ledgard, Luo, & Monaghan, 2011; Ledgard, Penno, & Sprosen, 1999). As a result, only a small proportion (> 30%) of N imported within supplementary feed would be exported in milk and meat, with the remainder returned in excreta; this could, potentially, contribute toward greater pasture growth in the PKE treatment relative to the Pasture and Cropping treatments.

On average, total N input, modelled through the nutrient budgeting model OVERSEER, as detailed in Chapter 4, was 42 kg N/ha/yr greater in the PKE treatment relative to the Pasture treatment; assuming that 70% of consumed N is excreted by the grazing animal (Ledgard et al., 1999) approximately an additional 29 kg N/ha would be returned through excreta in the PKE treatment relative to the Pasture treatment. Unfortunately, it is not possible to be as definitive with the Cropping treatment because differences between the PKE and Cropping treatments were confounded by additional N supplied by soil mineralisation in the Cropping treatment.

It has been estimated that, on average, a cow spends approximately 120 minutes per day within the farm dairy facilities (Ledgard & Brier, 2004; Rollo, Ledgard, & Longhurst, 2017). Further to this, within the PKE treatment, approximately 2 hrs/day were spent on the feed pad across the year. Therefore, assuming that the quantity of effluent deposited within these facilities is proportional to the time spent within them, approximately 17% of excreta from the PKE treatment would be captured as effluent. As stored effluent was spread across all treatments, the proportion of deposited excreta collected as effluent would not have contributed to a difference in growth between treatments. Further to this, an additional 5% of excreta is reportedly deposited to laneways (Ledgard et al., 1999) and would not contribute to a difference in growth between treatments. Therefore, approximately 77% of deposited excreta could be assumed to be returned directly to pasture; this would be equivalent to an additional 23 kg N/ha applied during grazing in the PKE treatment relative to the Pasture treatment. If I assume an average pasture DM response to applied N of 10 kg N/ha/yr (Harris, Clark, Waugh, & Clarkson, 1996), the additional N imported within the PKE treatment would be expected to increase pasture DM production by 230 kg DM//ha/yr in the PKE treatment relative to the Pasture treatment. Such an effect would account for approximately half of the numeric difference in average annual pasture accumulation between the PKE, Pasture and Cropping treatments.

The timing of PKE supplementation relative to the timing of pasture DM production is also consistent with the premise that additional N in the supplementary feed is a contributory factor to the greater pasture DM production in the PKE treatment relative to the other treatments. The growth response to applied N is generally proportional to soil temperature (Harris et al., 1996; Thomson & Roberts, 1982); hence, growth rate differences might be expected to be greater during the spring. However, there were no differences in pasture production evident during spring. This may reflect the timing of when supplementary feeds were used within the system and, hence, the timing of application of additional N. The average seasonal distribution of PKE allowances (kg DM/ha) is presented in Figure 27.

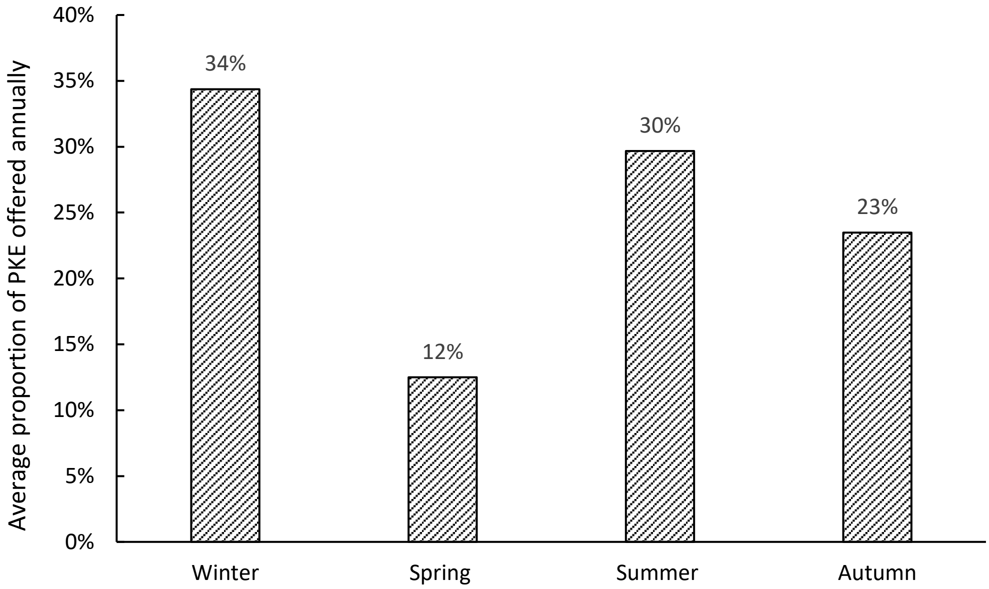

Figure 27: Average seasonal proportion of annual PKE allowance (kg DM/ha).

A low proportion of supplementary feed was fed during spring; hence, little pasture growth in response to nutrient imported in supplementary feed could be expected during this period. Whilst a greater proportion of supplementary feed was offered during summer, any potential growth response to deposited N may have been limited by soil moisture deficit, but potentially resulted in an accumulation of N inputs within the soil. This accumulation of N, in addition to further N input from supplementary feed offered in autumn, potentially contributed to the greater pasture production in the PKE treatment during autumn relative to the other treatments.

Although PKE supplies additional nutrients other than N, average soil P (Olsen-P = 52 mg/kg) and potassium (K; QTK = 20 mg/kg) of the soil were greater than that considered optimum for plant growth (20 - 30 and 5 - 8, respectively; Edmeades et al., 2010; Roberts, Morton, O'Connor, & Edmeades, 1996). Therefore, the effect of additional P and K on plant growth was, likely, very small in this instance. Further potential differences in pasture growth between treatments may be explained by an effect of treatment on the botanical composition of the pasture sward.

3.4.1.3 Species composition

In the Cropping treatment, 23% of the farmlet was planted in forage crops, on average, annually. As a direct result, the Cropping treatment had a greater proportion of paddocks resown with permanent ryegrass annually. This contributed to differences in the average species composition of pasture swards between treatments, with more perennial ryegrass-dominant pastures in the Cropping treatment relative to the Pasture and PKE treatments. There are marked differences in the annual production and seasonal distribution of ryegrass and kikuyu growth (Botha, Meeske, & Snyman, 2008; B. Fulkerson et al., 2010; García, Islam, Clark, & Martin, 2014). It is plausible, therefore, that the difference in species composition has contributed to differences in pasture production between treatments.

Although pasture species dissections were undertaken, these samples were pooled across treatments and, so, were not sufficient to confirm such an effect. However, a subjective visual assessment of the proportion of kikuyu within paddocks was conducted in the autumn of 2016/17 and 2017/18. This confirmed that, on average, Cropping paddocks had a lower proportion of kikuyu present within the sward. Kikuyu growth would be expected to be greater than that of ryegrass during autumn in the environment studied (Botha et al., 2008; B. Fulkerson et al., 2010; García et al., 2014). Therefore, the lower proportion of kikuyu in the Cropping treatment may explain, at least in part, the reduction in pasture growth during this period relative to the PKE treatment.

3.4.1.4 Summary

Pasture production was greater in the PKE treatment relative to the Pasture and Cropping treatment with differences in growth particularly pronounced during the autumn period. I cannot determine, with certainty, the cause of the differences in growth between treatments; however, based on my results, I postulate that differences in pasture production between treatments were due to the combined effects of grazing management, nutrient input from imported supplementary feed, and differences in the sward species composition between treatments.

3.4.2 Milk production

On average, MS production per hectare was 16% less in the Pasture treatment, relative to the PKE treatment, but not significantly less in the Cropping treatment. Treatment effects are most likely a result of differences in: 1) Production per cow per day; 2) Lactation length (DIM); and 3) Stocking rate, although only SR was significantly affected by treatment. Nevertheless, the cumulative effect of these factors is likely the reason for the significant difference between treatments.

The lactation profiles for the PKE, Pasture, and Cropping treatments are displayed in Figure 28, Figure 29, and Figure 30 for the production seasons 15/16, 16/17, and 17/18, respectively. On average, MS production per cow per day was greater in the PKE treatment (1.46, 1.50, 1.39 kg MS/cow/day) relative to both the Pasture (1.40, 1.47, 1.24 kg MS/cow/day) and Cropping treatments (1.45, 1.43, 1.23 kg MS/cow/day) in the 15/16, 16/17 and 17/18 production seasons, respectively. On average, DIM/cow were 7 days longer in the PKE treatment (269 days) relative to the Pasture treatment (262 days), but not different to the Cropping treatment (268 days). Stocking rate was intentionally greater in the PKE treatment (2.8 cows/ha) relative to the Pasture treatment (2.5 cows/ha) to reflect the greater availability of feed from off-farm. Although the Cropping treatment was predicted to supply sufficient feed to maintain the same SR as the PKE treatment, and was successful in this in the 15/16 and 16/17 seasons, the SR in the Cropping treatment needed to be reduced in the 17/18 season because of lower than predicted pasture and crop production. As a result, on average, the SR was numerically greater in the PKE treatment relative to the Cropping treatment.

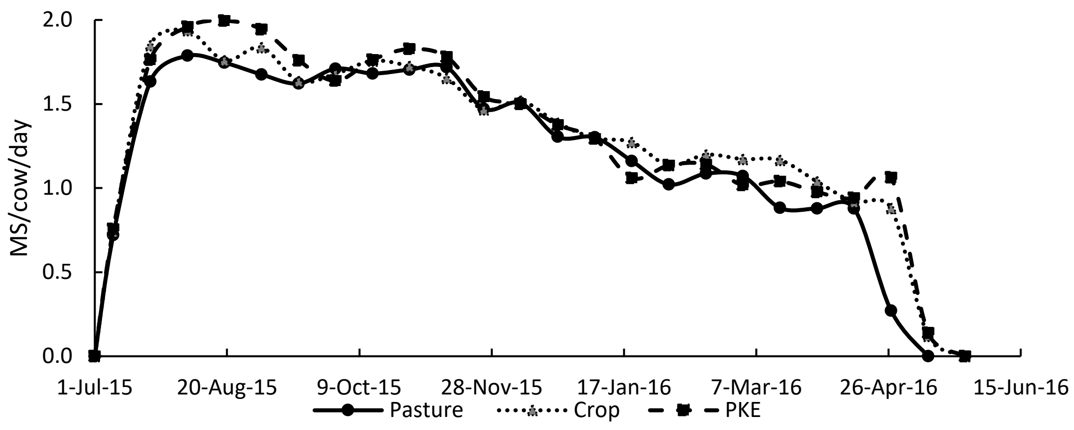

Figure 28: Milksolids production per cow per day for the PKE, Pasture, and Cropping treatments for the 2015/16 season.

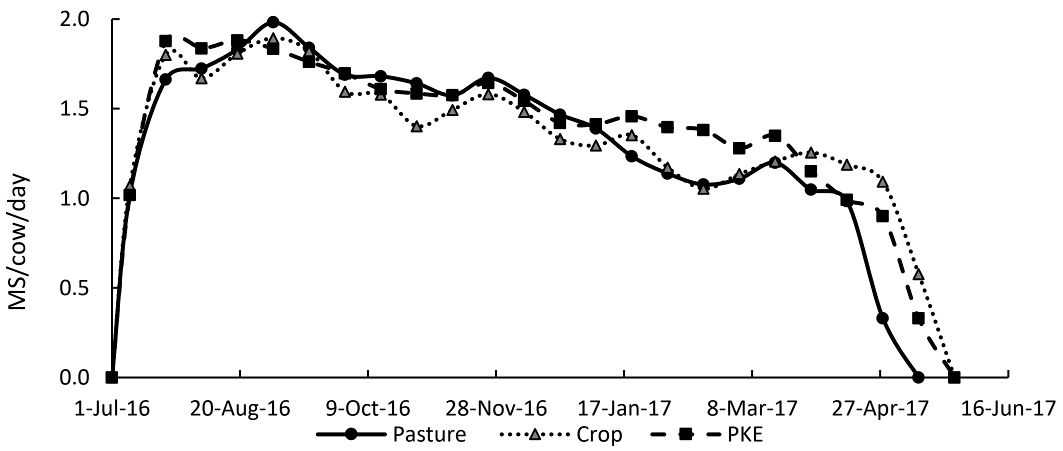

Figure 29: Milksolids production per cow per day for the PKE, Pasture, and Cropping treatments for the 2016/17 season.

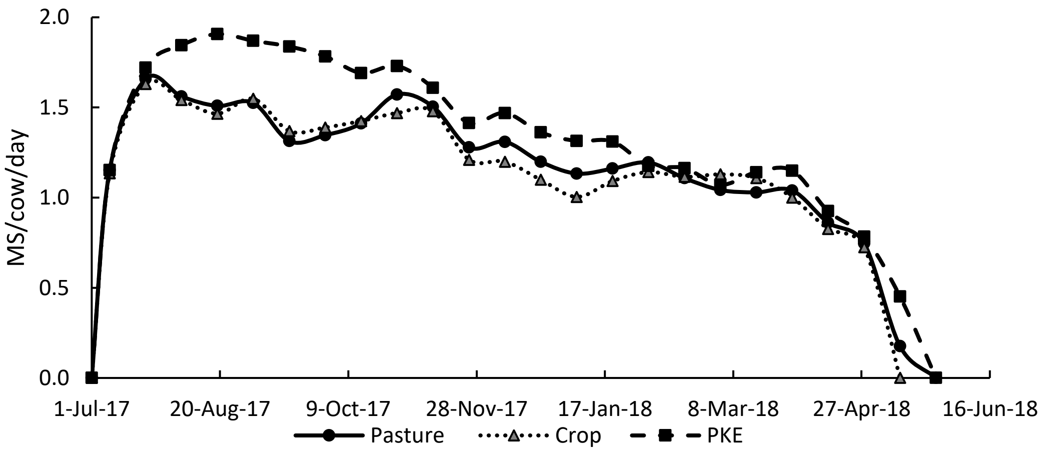

Figure 30: Milksolids production per cow per day for the PKE, Pasture, and Cropping treatments for the 2017/18 season.

The magnitude of these effects, as a component of the total difference in production between the PKE and Pasture, and PKE and Cropping treatments are presented in Figure 31 and Figure 32, respectively.

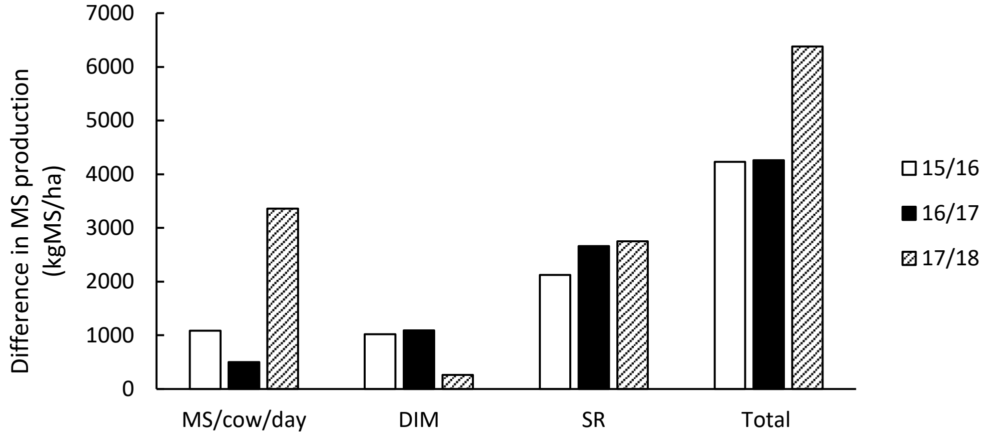

Figure 31: Difference in total milksolids production between PKE and Pasture treatments attributable to SR, DIM, and MS/cow per day for the 15/16, 16/17, and 17/18 seasons.

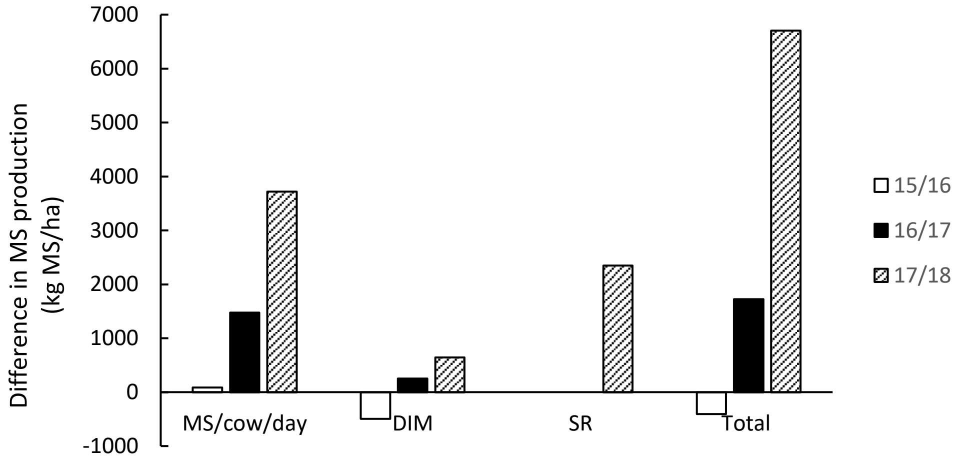

Figure 32: Difference in milksolids production between PKE and Cropping treatments attributable to SR, DIM, and MS/cow per day for the 15/16, 16/17, and 17/18 seasons.

Treatment differences in milk production between the PKE and Pasture treatment were the result of a relatively consistent SR effect (on average, 52% of the total response), although the proportion of the effect attributable to production/cow per day was greater in the 17/18 season. In contrast, reasons for treatment effects on milk production between the PKE and Cropping treatments were variable, with DIM being the primary factor in the first year, production/cow per day the primary driver in the 16/17 season, and both production/cow per day and SR primary factors in the 17/18 season. The contribution of these factors to the wider response to supplementary feed and the factors affecting this response will be discussed in the following sections.

3.4.2.1 PKE vs Pasture

A fundamental factor affecting differences in milk production between the PKE and Pasture treatments was the system-level response to supplementary feed. Milksolids production per hectare was 151 kg, 152 kg, and 228 kg greater in the PKE treatment relative to the Pasture treatment in 15/16, 16/17, and 17/18 production seasons, respectively. The additional milk came from the supply of 1,273 kg DM/ha/yr, 1,429 kg DM/ha/yr, and 1,625 kg DM/ha/yr PKE in the 15/16, 16/17, and 17/18 production seasons, respectively. Therefore, the MMPR to supplementary feed offered were 119 g MS/kg DM, 106 g MS/kg DM, and 140 g MS/kg DM in the respective years. The factors contributing to the magnitude of this response and the between year variability are important to understand.

3.4.2.1.1 Magnitude of response

Milk production responses to supplementary feed within the current trial averaged 122 g MS/kg DM across the 3 years of the experiment. In a review of the literature Bargo et al. (2003) reported an average response to supplementary feed of 1 kg milk/kg DM, or, at MS percentage of 7.5%, approximately 75 g MS/kg DM. Therefore, MS responses to supplementary feed in the current experiment were, on average, approximately 60% greater than that reported from their review. The design of the current experiment does not allow for me to conclusively explain the relatively large response to supplementary feed in the current experiment. However, a number of potential factors may explain, at least in part, this elevated response:

1) The 'systems-level' nature of the response to supplementary feed in the current experiment (i.e., a response to SR, pasture utilisation, and any additional milk produced after the period of supplementary feeding; i.e., deferred milk);
2) A deleterious effect of reduced milking frequency in the Pasture treatment in the 2017/18 season;

3) Strict policies governing the timing and quantities of supplementary feed allowance;

4) An effect of pasture species on the RFD; and

5) Cow genetics.

3.4.2.1.1.1 Systems-level response

The elevated response to supplementary feed is explained, at least in part, by the whole lactation ‘systems-level’ nature of the experiment. The studies reviewed by Bargo et al. (2003) analysed the immediate effect of supplementary feeds on milk production (i.e., a direct response to energy provided by supplementary feed at the time of feeding). However, in the current experiment, both the quantity of feed offered and the SR varied between the PKE and Pasture treatments. The SR was intentionally lower in the Pasture treatment, relative to the PKE treatment because of the ability to increase feed supply in the PKE treatment (i.e., through purchased feed). Therefore, within the current experiment, the effects of increasing feed supply and increasing SR on milk production are inextricably linked. Furthermore, there were treatment effects on pasture production, which, provided this additional feed was utilised, would have contributed to the some of the increase in MS production being attributed to the supplementary feed. In other words, the increase in pasture production resulting from the supplementary feeding reduced the amount of PKE needed, thereby increasing the actual response to the supplementary feed through additional pasture utilised.

In addition, pasture utilisation is reportedly affected by SR, with an increase in pasture utilisation at a greater SR (Castle, Drysdale, & Watson, 1968; E. Kennedy, O’Donovan, Murphy, Delaby, & O’Mara, 2007; Macdonald et al., 2008). In the current study, supplementary feed was offered tactically during periods of pasture deficit to support a greater SR in the PKE treatment than the Pasture treatment. As a result of this greater SR, pasture utilisation could be expected to be greater in the PKE treatment during periods where supplementary feed was not being fed; for example, during spring, when pasture nutritional value is greatest. The systems-level response to supplementary feed would include any potential increase in milk from additional pasture grown and utilised, which, while not directly supplied by the supplementary feed, was facilitated by systems change as a result of offering supplementary feed.

The effect of increasing SR on the systems-level response to supplementary feed is, however, not consistent with the published responses. Patton et al. (2012) reported large responses to supplementary feed of 113 g MS/kg DM when increasing SR (2.92 vs 2.45 cows/ha) and concentrate allowance (1365 kg DM/cow vs 578 kg DM/cow), with an effect on pasture utilisation postulated as a contributory factor. In contrast, Penno et al. (1996) reported lower responses to supplementary feed (82 vs 88 g MS/kg DM), when the SR was greater (4.46 vs 3.24 cows/ha) and more supplementary feed was offered per cow (1,736 vs 767 kg DM/cow), despite reporting an increase in annual herbage accumulation (1,000 kg DM/ha) at the greater SR. The lack of agreement between these studies may reflect the multifactorial nature of the MMPR to supplementary feed. Despite a lack of consistency between studies, the results reported by Patton et al. (2012) suggest that large MMPR to supplementary feed, comparable to that achieved in the current study, can be achieved when supplementary feeds are used to increase SR.

Whilst, the systems-level nature of this response may explain why the achieved response to supplementary feed in the current experiment was greater than component analyses reviewed by Bargo at al. (2003), the achieved responses in the current study are still greater than the majority of reported responses to supplementary feed from other systems-level studies conducted within pasture-based systems (Delaby, Peyraud, & Delagarde, 2001; Horan, Dillon, Faverdin, et al., 2005; E. Kennedy, O'Donovan, O'Mara, Murphy, & Delaby, 2007; J. Kennedy et al., 2003; Macdonald et al., 2017; Stockdale, 2000). Therefore, the elevated response to supplementary feed in the current study is, likely, due to a combination of additional factors.

3.4.2.1.1.2 Reduced milking frequency

The response to supplementary feed in the third year of the study was elevated relative to the achieved responses in the first and second year of the experiment and this affected the average response to supplementary feed. In the third year of the experiment (2017/18), spring pasture production and utilisation were severely limited due to high rainfall and saturated soil conditions. As a result of declining feed availability and BCS, and to remain compliant with animal ethics conditions, milking frequency was reduced for a period of 6-weeks in early-lactation to once daily milking (OAD) for the Pasture and Cropping herds to reduce the physiological stress on the cows.

Reducing milking frequency has been reported to have a negative carry-over effect on whole season milk production due to effects on mammary cell activity and reduced secretory cell number (i.e., decreased cell proliferation and increased cell death) reducing production both in the period of reduced milking frequency (immediate effect) and subsequent to the cows returning to twice-daily milking (carry-over effect; Grala et al., 2011; Hale, Capuco, & Erdman, 2003; Nørgaard et al., 2005; Wall, Crawford, Ellis, Dahl, & McFadden, 2006). As a result, the difference in milk production between treatments in the 17/18 season can be separated into an effect due to 1) restricted feeding in the Pasture treatment (i.e., a response to additional ME provided by the supplementary feed in the PKE treatment); and 2) a reduction in whole season milk production, due to OAD milking in early-lactation in the Pasture treatment. This OAD effect may help to explain the large 'systems-level' response to supplementary feed that was achieved in the third year of the experiment.

Kay et al. (2013) investigated the effects of restricted feeding and reduced milking frequency in early-lactation on whole season milk production. They reported an 8% and 9% reduction in milk production when herds were milked OAD or offered a restricted intake (40% of control DMI), respectively, for a 3-week period in early-lactation. Production was reduced further to 13% when cows under a restricted feeding regime were milked OAD for the same 3-week period. These results suggest a partially-additive effect of milking frequency and feeding level (Kay et al., 2013); that is, the negative effect of OAD milking on whole season production is proportionally lower when cows are feed-restricted (i.e., 4% reduction in milk production when milked OAD in a restricted feeding environment relative to an 8% reduction without feed restriction). The results of this study suggest that where cows are underfed in early-lactation, such as what occurred in the Pasture and Cropping herd in the current experiment, at least a 4% reduction in production could be attributable to the deleterious effect of short term OAD milking on whole season production.

Both the stage of lactation and duration over which OAD milking is practiced influence the ‘lactation long’ effect of OAD milking on milk production (Remond & Pomies, 2005; Stelwagen et al., 2013). Reduced milking frequency was practiced over a 6-week period in the current experiment relative to the 3-week period conducted by Kay et al. (2013). Therefore, the effect of OAD milking may be even greater in the current experiment relative to that reported by Kay et al. (2013). Reducing milking frequency to OAD for a 6-week period in early-lactation has been reported to reduce whole lactation milk production by 12% (Phyn et al., 2011). However, the experiment reported by Phyn et al. (2011) was not conducted in a restricted feeding environment, and, as deleterious effects of underfeeding and OAD milking are only partially additive, the 12% effect reported by Phyn et al. (2011) would likely overstate the effect of reduced milking frequency in the current experiment. It is not possible to determine, with surety, the true size of the OAD effect in the current experiment. However, OAD milking could be expected to reduce milk production by between the 4% and 12% effects reported by Kay et al. (2013) and Phyn et al. (2011), respectively. This OAD effect would have contributed to a greater ‘systems level’ response to supplementary feed in the 2017/2018 year and, therefore, in the overall average.

The potential size of this OAD effect may be approximated by comparing the differences in MS/cow between treatments in the 17/18 season, relative to the preceding two years of the experiment. On average, production per cow was 7% greater in the PKE treatment relative to the Pasture treatment in the 15/16 and 16/17 years. However, in the 17/18 season, production per cow was 13% greater in the PKE treatment relative to the Pasture treatment. This would suggest that a potential 6% of the difference in MS/cow between treatments could be attributable to the underfeeding and OAD effect in the 17/18 season, which is consistent with the effect of duration of OAD discussed previously. Although it is not possible to determine the relative magnitude of the underfeeding and OAD effects, it appears that the deleterious effect of OAD milking on whole lactation production was at least comparable to that reported by Kay et al. (2013) for a 3-week period in early-lactation.

Attributing some of the system-level response to supplementary feeds to the period of OAD milking in the Pasture treatment would explain at least some of the large response to supplementary feed in the third year of the experiment. Accounting for a 4% effect of OAD milking on whole season milk production, the 'amended' response to supplementary feed in the third year of the experiment was approximately 118 g MS/kg DM, bringing this in line with the achieved responses in the first and second year of the experiment. Nevertheless, even with this adjustment, the average response to supplementary feed within the current experiment (114 g MS/kg DM) would be greater than other systems-level responses reported within the literature.

3.4.2.1.1.3 Strict decision rules

Responses to supplementary feed are affected by pasture substitution: that is, the substitution of supplementary feed for pasture when supplementary feed is offered (Kellaway & Harrington, 2004; Stockdale, 2000), with the level of substitution related to the RFD of the cow (Stockdale, 2000; Penno, 2002). Therefore, management decisions that minimise the substitution effect when feeding supplementary feeds are likely to result in a greater response to supplementary feed. In the current study, supplementary feed allowance was determined by strict decision rules around post-grazing residuals, with supplementary feed only offered when post-grazing residuals were less than 3.5 cm (~ 1,600 kg DM). Poole (2018) reported that the post grazing residual mass could, potentially, be used as a measure of the RFD and, hence, be used to predict potential response to supplementary feed. Therefore, I postulated that the strict decision rules that governed supplementary feeding allowances within the current study contributed to the large response to supplementary feed achieved.

In disagreement with this premise, however, similar decision rules were employed by Penno et al. (1996), when they achieved responses of 89 and 81 g of MS/kg DM of maize grain and maize silage, respectively. Therefore, these decision rules, alone, do not explain the large responses achieved within the current trial relative to other experimental studies. Nevertheless, these decision rules may contribute to greater responses to supplementary feed relative to that achieved within commercial operations if input decisions are driven by factors other than the RFD (i.e., post-grazing residual mass). Lower responses to supplementary feed may be achieved in practice, where a fixed daily allowance is offered, irrespective of PA, as may occur, for example, during the breeding period, with the expectation that this may improve fertility. Further research is required around the potential difference in MMPR to supplementary feed attributable to management and the practical implications for pasture-based systems.

3.4.2.1.1.4 Pasture species

Kikuyu pastures are generally of lower digestibility and, therefore, ME (MJ ME/kg DM) when compared with ryegrass pastures (Botha et al., 2008; B. Fulkerson et al., 2010; García et al., 2014). Because of this, all other factors being equal, a cow grazing kikuyu dominant pastures will consume a lower quantity of energy than a cow grazing ryegrass pastures for the same DMI. A greater response to supplementary feed could, therefore, be expected from cows grazing kikuyu-based pastures than ryegrass pastures.

On the basis of this premise, I postulate that the effect of kikuyu on forage quality and, therefore, RFD contributed to the elevated response to supplementary feed in the current experiment. Although the study design does not allow me to test this premise, it is supported by Fulkerson et al. (2008) who reported a 5-year average response to supplementary feed of 115 g MS/kg DM when increasing the quantity of concentrates offered to high genetic merit cows grazing a kikuyu-dominant sward (average ME: 8.9 MJ ME/kg DM). The magnitude of this response is comparable with the 3-year average response to supplementary feed achieved within the current experiment of 114 g MS/kg DM (when accounting for the OAD effect in the 17/18 season). Average pasture quality (10.6 MJ ME/kg DM) within the current study was not as low as that reported by Fulkerson et al. (2008); therefore, the effect of pasture quality on RFD and response to supplementary feed might be less profound in the current study. However, a high proportion of supplementary feed was offered during the summer and autumn period (53%), during which average pasture quality was 9.9 MJ ME/kg DM and, therefore, more representative of the conditions reported by Fulkerson et al. (2008).

I cannot determine, with certainty, the effect of pasture species on the size of the response to supplementary feeds in the current study relative to other reports; however, the results of Fulkerson et al. (2008) suggest that the responses achieved within the current experiment are likely, at least in part, a result of lower pasture energy concentration than often used in published experiments.

3.4.2.1.1.5 Genetic merit

Responses to supplementary feed are affected by the genetic potential for milk production of the herd (Ferris, Gordon, Patterson, Mayne, & Kilpatrick, 1999; W. J. Fulkerson et al., 2008; Horan, Dillon, Faverdin, et al., 2005; Kellaway & Harrington, 2004; Penno, 2002). All other factors being equal, a cow with a greater genetic potential for milk production will have a greater RFD and, hence, would be expected to have a greater response to supplementary feed than a cow with lower genetic potential for milk production (Penno, 2002). In support of this, Fulkerson et al. (2008) compared the productivity of high Australian Breeding Value (ABV) and low ABV cows at different concentrate allowances. Increasing concentrate allowance from 'Low' (0.34 t DM/cow) to 'Medium' (0.84 t DM/cow) resulted in a greater response to supplementary feed (126g MS/kg DM) in high ABV cows compared with low ABV cows (100 g MS/kg DM).

In the current study, the average BW (a measure of genetic merit accounting for the economic value of different traits) of the treatment herds at the initiation of the experiment was 151. This compares to an average of 54 ± 35.4 reported by Macdonald et al. (2017); this could also explain a proportion of the elevated response in the current study (114 g MS/kg DM average after accounting for potential OAD effect) relative to that reported by Macdonald et al. (2017; 73 - 97 g MS/kg DM). Whilst it is not possible to determine the effect of genetic merit on the response to supplementary feed within the current experiment, there is sufficient evidence to suggest that a MMPR to supplementary feed could be expected had the experiment been repeated with cows with lower genetic potential for milk production.

3.4.2.1.2 Between year variability

Understanding the between year difference in the achieved response to supplementary feed could also provide insight into the factors affecting the response to supplementary feed. The achieved milk production responses to supplementary feed varied by up to 32% between years. Penno (2002) reported that milk production responses to supplementary feed are primarily affected by the RFD of the cow. The RFD is a measure of the ability of the diet to meet the energy or nutrient demands of the cow at a particular point in time (Penno, 2002). Similarly, CSR reflects the quantity of LW per t DM feed available, reflecting energy demand in the system (i.e., maintenance and production requirements are directly related to the number of cows, which is related to the LW) relative to the quantity of feed available per hectare to meet that demand (Macdonald et al., 2008). As both CSR and RFD are a reflection of the balance between feed supply and demand, the realised CSR of a system may provide an indication of the RFD incurred within a system and, hence, the potential response to supplementary feed on an annual timescale. Based on this premise, I anticipated that a greater response to supplementary feed would be achieved from a greater CSR, which would reflect a greater RFD; as such, CSR would explain, at least in part, the variation in achieved MMPR to supplementary feed between seasons. The relationship between the CSR of the PKE systems without supplementary feed offered (i.e., the RFD if supplementary feed was not offered) and the response to supplementary feed, both 1) without; and, 2) with accounting for the OAD effect in the 2017/18 season are presented in Figure 33.

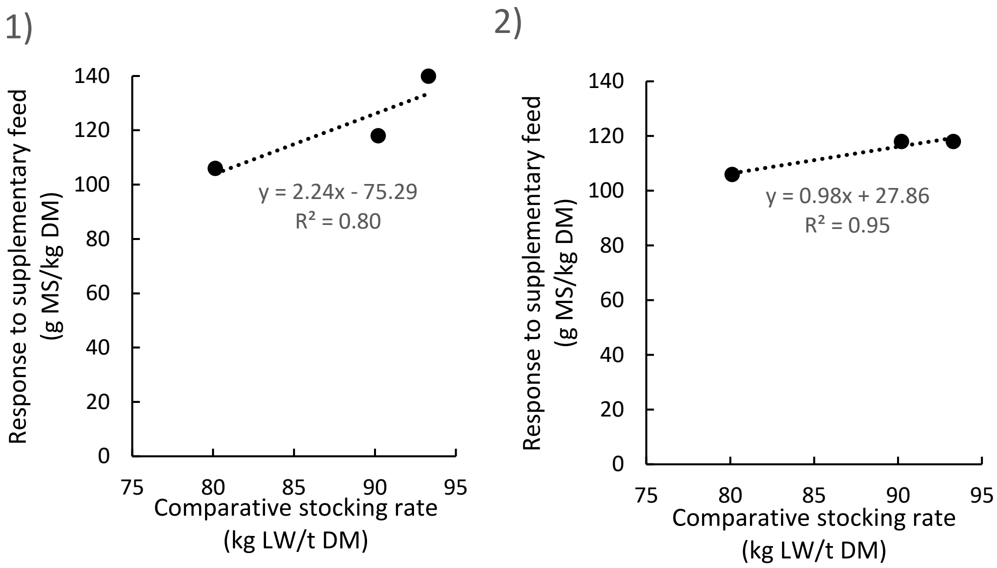

Figure 33: Relationship between CSR (kg LW/t DM; without PKE offered) and the response to supplementary feed (g MS/kg DM) achieved within each year of the experiment both 1) with, and, 2) without, account of the OAD effect in the 2017/18 season.

When accounting for the OAD effect in the Pasture treatment in the 17/18 season, there was little variation in the response to supplementary feed between seasons; a large amount of the resulting variation was explained by the influence of CSR. This suggests, therefore, that:

- at least in the current system; and

- within the range of CSR reported; and
- where supplementary feed allowance is governed by strict decision rules based on the RFD (i.e., post-grazing residual mass) such that the quantity of supplementary feed offered is reflective of the RFD;

Comparative stocking rate provides a potential estimate of the annual RFD and the potential MMPR to supplementary feed within a system. However, despite the between year variability in MMPR to supplementary feed being largely explained by CSR, the magnitude of the between year variability was small relative to the average response to supplementary feed. Therefore, at least over the range of CSR reported, the large MMPR to supplementary feed achieved in the current study were largely explained by factors not captured within the estimation of CSR.

3.4.2.2 Cropping treatment vs PKE treatment

Although not significant, the numeric differences in milk production between the Cropping and PKE treatment have a biophysical basis and were, most likely, explained by feed supply. I believe the differences are real and it would be inappropriate to not discuss these because of the risk of type II statistical error (i.e., accepting a 'false' null hypothesis). A similar SR was maintained in the Cropping treatment relative to the PKE treatment by growing potentially high yielding forage crops on the dairy platform to increase total feed grown per hectare. Production within this system was, therefore, affected by the quantity of additional feed generated through the cropping process. The quantity of additional DM produced through the cropping process was dependent on; 1) the achieved crop yields; and 2) the potential pasture production lost during the cropping process and, subsequently, because of the cropping process. The additional feed offered as crop (kg DM/ha), the estimated loss in pasture production (kg DM/ha), and the overall yield advantage for each experimental year (kg DM/ha), are displayed in Figure 34.

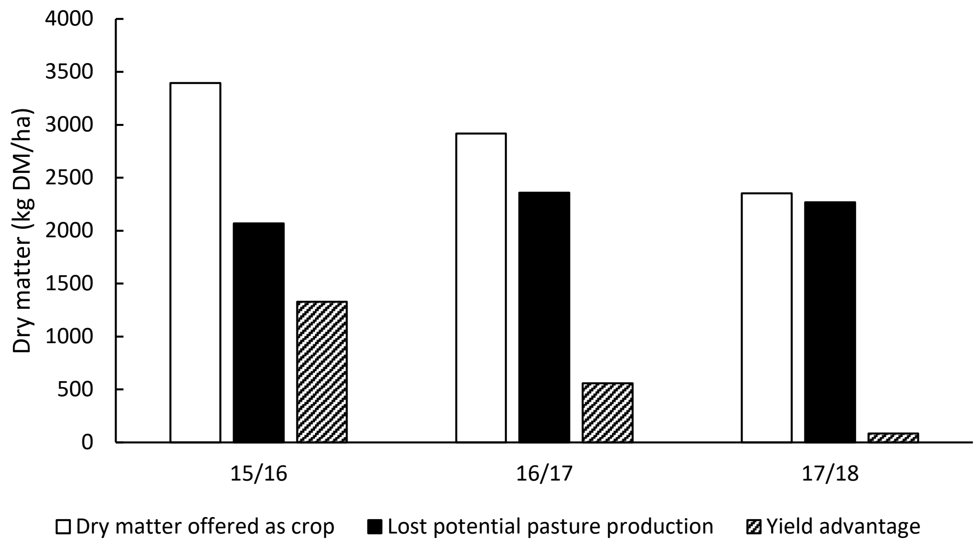

Figure 34: The additional feed offered as crop (kg DM/ha), estimated loss in pasture production (kg DM/ha), and the yield advantage (kg DM/ha) from the cropping process in each experimental year.

The difference in MS production between the Cropping and Pasture treatments was dependent on the net yield advantage from cropping (additional forage allowance – potential loss in pasture production) and, hence, the ability to provide sufficient DM to support the greater SR in the Cropping treatment. There was a linear relationship between the net cropping yield and the difference in production between the Cropping and Pasture treatments (Figure 35).

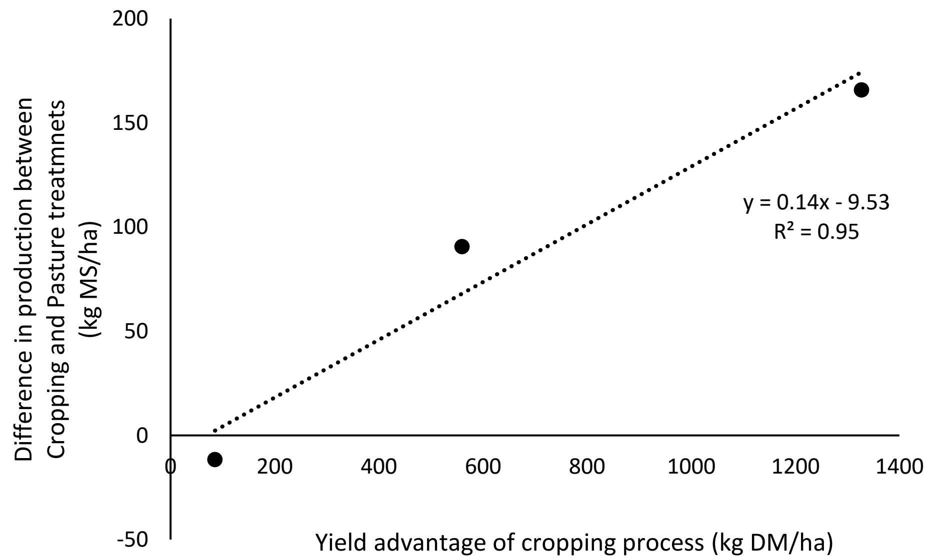

Figure 35: Relationship between the yield advantage of the cropping process against the difference in milk production between the Cropping and PKE treatments.

In addition, there was a linear relationship between pasture yield during the spring and summer period (t DM/ha) and average crop yield (t DM/ha; Figure 36). In other words, in years when weather conditions were favourable for crop growth, and a high crop yield was achieved, these same weather conditions were favourable for pasture growth and the opportunity cost of lost pasture production was large, reducing the advantage a summer crop might offer. In contrast, in years when climatic conditions were unfavourable for pasture growth and there was greatest need for the crop, the conditions also limited the yield potential of the crop. This linear relationship reflects that both pasture and crop growth are affected by the same environmental conditions, suggesting limitations to the use of crops to mitigate variation in feed supply, and hence, production risk.

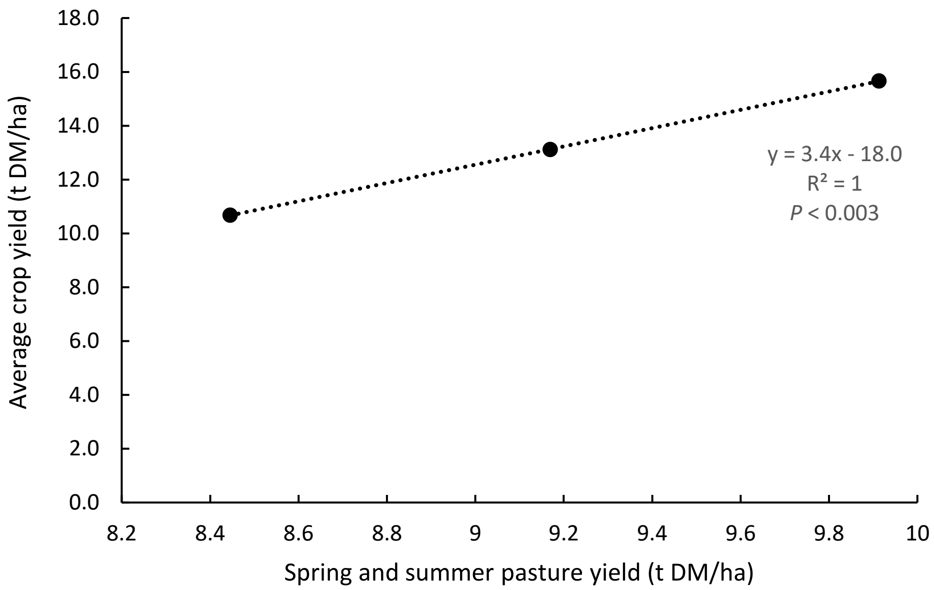

Figure 36: Relationship between spring and summer pasture yield and average crop yield.

In the 17/18 season, similar to the situation in the Pasture treatment, due to wet spring conditions and resultant low pasture growth, OAD milking was practiced for a 6-week period in early-lactation in the Cropping treatment to reduce the physiological stress of the cows in the Cropping herd. However, the SR was initially greater in the Cropping treatment than the Pasture treatment and, in addition, the inventory of maize silage was low due to poor maize yields in the previous season. As a result, the RFD in the Cropping treatment was more pronounced than in the Pasture treatment and further action (force majeure) was undertaken to ensure the welfare of the treatment herd. The SR was reduced in response to this feed deficit, with culls (n = 4; 5%) removed early from the treatment herd. In addition, a further 14 cows (17%) were grazed off the property, returning after a period of 5 weeks.

As a result, milk production in the Cropping treatment in the 17/18 season was affected by 1) a carry-over effect from previous years, with respect to low feed inventory; 2) a resultant effect on underfeeding in early-lactation; 3) an effect of OAD in early-lactation on whole season milk production; and 4) a substantial SR effect for a 5-week period in early-lactation. Due to the multifactorial nature of these effects on MS production in the Cropping treatment in 2017/18, it was not possible to draw any meaningful conclusions from responses to additional feed in the Cropping treatment relative to the Pasture treatment.

When excluding the 2017/18 season, the average response to additional DM allowance as forage crop was 40 g MS/ kg DM in the Cropping treatment. This response was similar in magnitude to short term responses to turnips in mid-lactation reported by Penno, Bryant, Napper, and Copeman (1996) and Clark et al. (1996) of 66 g MS/kg DM and 36 g MS/kg DM, respectively. The achieved response in the Cropping treatment was 67% lower than the response to imported supplementary feed achieved in the PKE treatment. The lower response to additional feed allowance in the Cropping treatment relative to the PKE treatment probably reflects the loss of potential pasture production through the cropping process. The average MS response to the net yield advantage of the cropping process (i.e., additional forage allowance – potential loss in pasture production) averaged 143 g MS/kg DM, which was comparatively greater than the response/kg DM achieved in the PKE treatment (122 g MS/kg DM). Differences in the response to additional feed within the PKE and Cropping treatments were, possibly, explained by feed quality. On average, the response to additional energy was 11.2 and 11.1 g MS/MJ ME in the Cropping and PKE treatments, respectively. Therefore, the response to additional energy were the same in the Cropping and PKE treatments, suggesting that these elevated MMPR relative to published results, were driven by similar factors in both the Cropping and PKE treatments.

3.4.2.3 Summary

Large milk production responses to imported supplementary feed were achieved in the current study. The experimental design does not allow me to, conclusively, determine the cause of these response to supplementary feed; however, I postulate that these large responses were due to: 1) The ‘systems-level’ nature of the response to supplementary feed; 2) a OAD effect in the 17/18 season; 3) the strict decision rules governing the supplementary feed allowance; 4) An effect of pasture species, and hence, pasture quality; and, 5) Cow genetics.

Lower systems-level MMPR to forage crops were achieved in the Cropping treatment relative to the MMPR to imported feed in the PKE treatment due to lower pasture production associated with cropping. When accounting for the difference in pasture production, similar milk production responses to additional ME offered were achieved in both the PKE and Cropping treatments.

3.4.3 Body condition score and reproduction

Body condition score is an assessment of the proportion of body fat that a dairy cow possesses and is widely recognised as a gross, but reasonably accurate measure of a cow’s energy reserves (Roche, Friggens, et al., 2009). In addition to the influence of genetics and other cow-level factors, herd-level management factors such as SR (Macdonald et al., 2008; S. McCarthy et al., 2007; Roche, Berry, Lee, Macdonald, & Boston, 2007), feed allowance (McNamara, 1991; Roche, 2007; Roche et al., 2006), and diet type have been reported to affect cow BCS (Roche, Friggens, et al., 2009). Therefore, it could be expected that farm system treatment would affect BCS in the current experiment.

The effect of treatment on the seasonal profile of BCS in the 15/16, 16/17 and 17/18 seasons are presented in Figure 37, Figure 38, and Figure 39, respectively. All treatments followed a similar inter-calving BCS profile, comparable to the “W-shaped” BCS profile reported by Roche et al. (2007) for cows grazing pasture in the upper North Island of NZ. In the current study, there were only small differences in BCS between treatments during early-lactation. The lack of effect of farm systems treatment on BCS is supported by the results of Roche et al. (2006), Roche (2007), and Roche et al. (2007) who reported that nutrition during the first 4 to 5 weeks of lactation has little, if any, effect on the rate of BCS loss in early-lactation (Roche et al., 2009); rather, nutrition tended to reduce the duration of BCS loss. The results of the current study are in agreement with the general principal that lipolysis, and hence BCS loss in early-lactation, is primarily regulated by genetic factors (Roche, Friggens, et al., 2009; Smith & McNamara, 1990).

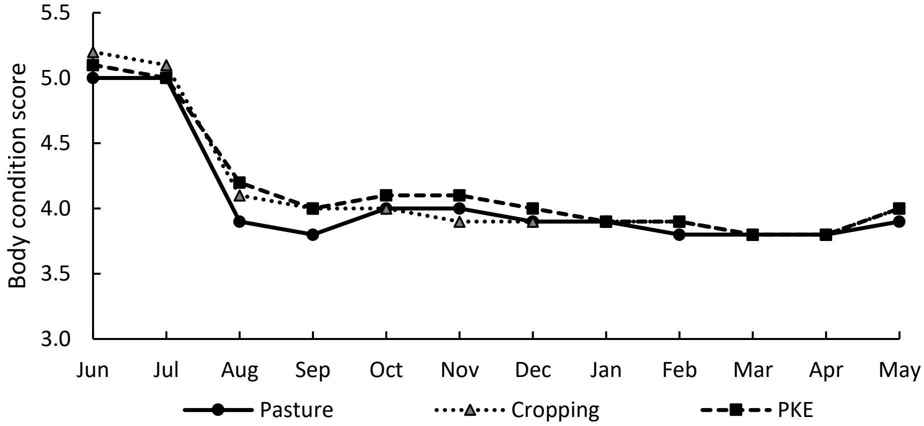

Figure 37: Effect of treatment on visually assessed BCS in the 15/16 season.

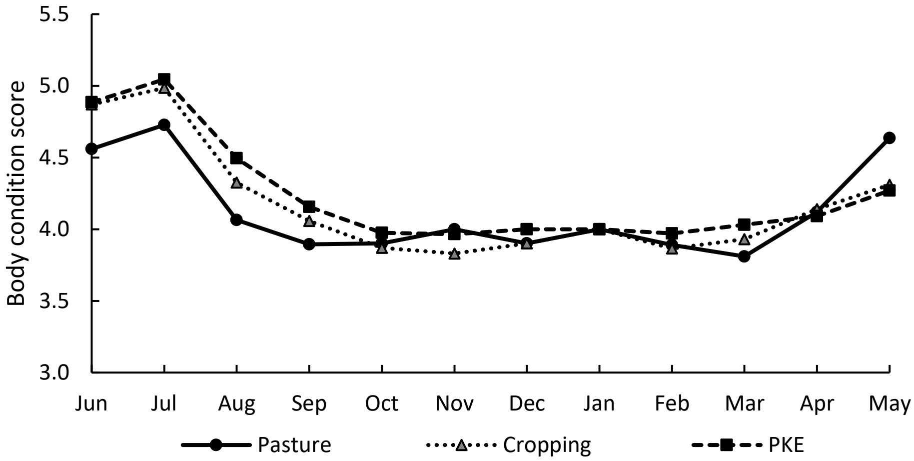

Figure 38: Effect of treatment on visually assessed BCS in the 16/17 season.

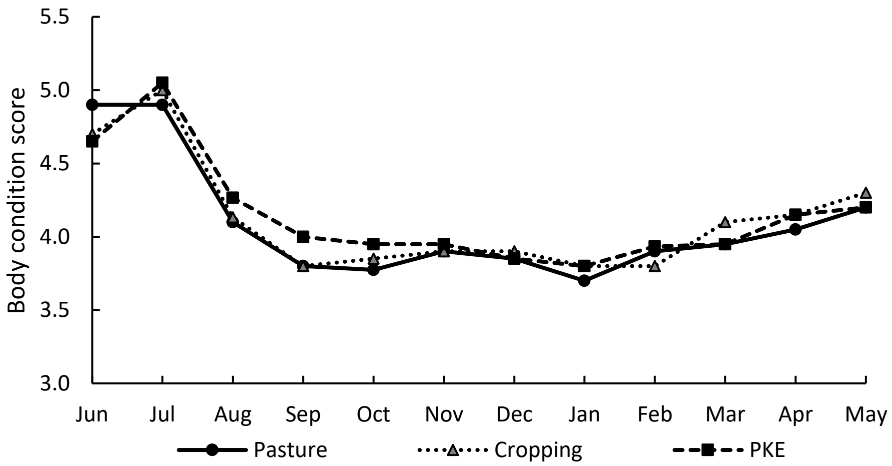

Figure 39: Effect of treatment on visually assessed BCS in the 15/16 season.

Nutrition has been reported to affect reproductive outcomes, particularly through its effect on the energy balance in early-lactation and during the mating period. For example, Burke et al. (2010) subjected cows to a severe feed restriction (45%) during the first two weeks of the mating period and reported an 8% reduction in 6-week in-calf rate. Further to this, Roche et al. (2007) reported a 3 to 4% reduction in 6-week and 12-week in-calf rates for each unit BCS lost postpartum, when measured on a 10-point scale. However, both these studies reflect the effect of a substantial gross under-nutrition of dairy cows and would indicate, at least if the effect is linear, that a 'normal' feed restriction experienced in early-lactation would have small, if any, effects on reproduction. In the current study, treatment had no effect on any of the measured reproductive variables. The lack of effect of treatment on reproduction is unsurprising given the small differences in BCS, and hence, potential energy balance that existed between treatments.

3.4.3.1 Summary

Only small differences in BCS existed between treatments, reflecting that BCS loss in early-lactation is primarily driven by genetic factors. In addition, there were no differences in reproductive measures between treatments, which, when published nutritional effects on reproduction in grazing cows are considered, is unsurprising, given the lack of difference in BCS and, hence, energy balance between treatments.

3.5 Conclusions

The removal of imported supplementary feed from a grazing system reduced milk production when SR was reduced to accommodate lower feed supply (Pasture treatment). The lower milk production in the Pasture treatment was due, primarily, to a SR effect, which was consistent across years. Although, milk production was not significantly reduced in the Cropping treatment, this, probably, reflects a lack of statistical power to detect a difference in Year 2 and 3. Future work needs to consider this limitation in my approach. Despite similar responses to net additional feed (MJME), after accounting for differences in pasture production, the systems-level response to Cropping was approximately 70% lower than the response to imported supplementary feed achieved in the PKE treatment. This was due to the lower pasture production associated with the cropping process.

Large responses to supplementary feed were achieved in the current experiment. Although the experimental design of the current experiment does not allow me to explain, conclusively, the reasons for the large responses, I believe that they were due to the combined effects of: 1) The ‘systems-level’ nature of the response to supplementary feed; 2) a OAD effect in the 17/18 season; 3) the strict decision rules governing the supplementary feed allowance; 4) an effect of pasture species, and hence, pasture quality; and, 5) cow genetics.

Chapter 4: Environmental implications of removing imported supplementary feed from a pasture-based system

4.1 Introduction

The global population is predicted to exceed 9 billion people by 2050, reportedly requiring a 70% increase in overall food production to meet the demand (Food and Agriculture Organisation of the United Nations, 2009). However, concern exists, globally, around the adverse effects that further intensification of agricultural production systems might have on water and air quality (Huebsch et al., 2013; Place & Mitloehner, 2013). For example, the global livestock sector is estimated to contribute approximately 18% (7.1 billion tonnes of CO_2) of total GHG emissions when accounting for emissions associated with production of inputs (including land use change), processing, and transportation (Food and Agriculture Organisation of the United Nations, 2006). This raises concerns around the potential future effects on environmental outcomes, if food production systems are to meet the demands of this growing global population.

Within pastoral grazing systems, the quantity of N leached, P lost to water, and GHG emissions (mainly as methane, nitrous oxide and carbon dioxide) are primary environmental concerns (Ledgard, Schils, Eriksen, & Lou, 2009; Watson & Foy, 2001). Nitrogen use efficiency within pastoral grazing systems is inherently low (Ledgard, Luo, et al., 2011; Ledgard et al., 2009) because the N concentration of intensively managed pastures is, generally, in excess of animal requirements (Kolver & Muller, 1998; Ledgard et al., 2009; Roche, Turner, et al., 2009b). This surplus N is excreted by the grazing animal in high concentrations within the urine patch and can contribute to increased nitrate concentrations in soil solution, leading to an increase in N leached to ground water or nitrous oxide emissions (Di & Cameron, 2007; Oenema, Velthof, Yamulki, & Jarvis, 1997). The magnitude of N inputs is a key factor affecting the quantity of N cycling within a pastoral grazing system, the surplus of N, and potential losses of N through leaching (Ledgard et al., 2009) or nitrous oxide emissions (Luo, de Klein, Ledgard, & Saggar, 2010). Methane emissions within pastoral systems are produced primarily through enteric fermentation, with the yield of methane being affected by quantity and quality of feed consumed (Pinares-Patiño, Waghorn, Hegarty, & Hoskin, 2009; Waghorn &

Woodward, 2006), although the use of supplementary feeds, particularly those with a large transport footprint, adds to this GHG footprint.

The use of imported supplementary feeds within pastoral grazing systems has been a common strategy to support increased SR and DMI/cow in order to increase milk production (Bargo et al., 2003). Offering imported supplementary feed increases the quantity of feed supplied per hectare, can influence the quality of the diet, and introduces additional N inputs in the form of protein contained within the supplementary feed. Offering imported supplementary feed is, therefore, likely to influence the quantity of N leached, P lost to water, and GHG emitted from a pastoral grazing system.

My objective was to determine the effects of removing PKE from a grazing system on N leaching, P loss, and GHG emissions; strategies to facilitate removing PKE included 1) reducing SR, or, 2) growing forage crops on the milking platform to increase total feed supply, so as to maintain a similar SR to the Control (PKE) treatment. I hypothesised that N leaching, P loss, and GHG emissions would be lower in the Pasture treatment, relative to the PKE treatment, in reflection of the lower SR and milk production. In contrast, I hypothesised that N leaching, P loss, and GHG emissions would be the same in the Cropping and PKE treatments as a result of a similar SR, and milk production.

4.2 Materials and methods

The experiment was conducted as previously outlined in Chapter 3.2 over three lactations between June 2015 and May 2018 at the Northland Agricultural Research Farm (NARF; 35º56’39”S 173º50’34”E, approximately 20 m above sea level). All procedures were approved by the Ruakura Animal Ethics Committee in accordance with the New Zealand Animal Welfare Act.

4.2.1 Experimental design and treatment

Refer to Chapter 3.2 for experimental design and treatment methods.

4.2.2 Environmental modelling

Regulation and industry responses to improving environmental outcomes are directed toward limiting negative externalities (N leaching and GHG emissions), as opposed to controlling inputs through regulation, allowing farmers to find innovative solutions to achieve these targets (Pinxterhuis & Edwards, 2018). As a result, decision support resources for quantifying environmental externalities at an individual farm level and across a range of land uses are required to measure and place limits on sources of pollution. The nutrient budgeting model OVERSEER® (referred to hereafter as Overseer; Ministry for Primary Industries, Fertiliser Association of New Zealand and AgResearch, Palmerston North, New Zealand; Watkins & Selbie, 2015) is the most commonly used decision support resource for calculating nutrient loss at a farm scale in NZ (Parliamentary Commissioner for the Environment, 2018).

The Overseer model allows for environmental outputs to be estimated on an annual timescale when populated with farm specific inputs, such as soil type and production-related data (Watkins & Selbie, 2015). A recent report by the Parliamentary Commissioner for the Environment (2018) identified concerns about Overseer that undermine its suitability for use by regional councils as a regulatory resource to set nutrient limits. Despite these limitations, Overseer is widely considered the 'best available option' for estimating the environmental footprint at a farm scale (Dunbier et al., 2013; Maseyk, Brown, & Taylor, 2018).

4.2.3 Modelling methodology

Environmental modelling was undertaken using Overseer Version 6.3.1 to evaluate differences in N leaching, P loss, and GHG emissions between treatments. Each biophysical year was modelled separately to assess the consistency in environmental effects across years. Although annual rainfall and distribution data were available for each treatment year, long term average climate data were used to inform the model, as is recommended practice when using annualised management and production data (Roberts et al., 2018).

Monthly (e.g., stock numbers, fertiliser application) and annual (e.g., milk production and supplementary feed use) biophysical data from the experiment were used as detailed inputs to inform the model where appropriate and available. Each treatment was separated into three distinct management units (‘blocks’), reflecting underlying differences in soil type and effluent management (Table 11).

Table 11: Specified management block details

	Area	Soil type	Liquid effluent applied (yes/no)
Block 1	7.5	Kaipara clay loam	Yes
Block 2	17.5	Kaipara clay loam	No
Block 3	3.0	Te Kopuru Sand	Yes

Liquid effluent was managed similarly in all three treatments, with a holding pond system sprayed infrequently (during spring and autumn) at a low application rate (< 12mm). Pond solids were emptied annually and applied to non-effluent blocks in late-autumn. Urea fertiliser applications were specified on a monthly basis at the recorded rate of application (kg N/ha). The quantity of pasture conserved as silage within each treatment was split between blocks relative to its proportion of the total treatment area.

The default for nitrous oxide emission factors was changed from ‘farm specific emissions factors’ to ‘annual emissions factors’, as is recommended practice, due to overestimation of nitrous oxide emissions when using farm specific estimates (de Klein, van der Weerden, Kelliher, Wheeler, & Rollo, 2017). Emissions within the Overseer analysis include all ‘direct’ and ‘embodied’ GHG emissions associated with production, based on an LCA approach and following Publically Available Specification (PAS) 2050 guidelines (Wheeler, Ledgard, & Boyes, 2011). Modelled emissions, however, do not include those associated with product processing or transport (Wheeler et al., 2011).

4.2.4 Statistical analyses

Overseer output data were analysed using one-way ANOVA with treatment included as fixed effect. Tukey adjustment was used for pairwise comparisons between treatments (within farming year). Results are presented as least-squares means and standard error of the difference (SED). Significance was declared if $P \leq 0.05$.

4.3 Results

4.3.1 Total environmental footprint

The effects of experimental treatment on key environmental loss metrics (per hectare) are presented in Table 12. Farm N surplus was lower in the Cropping treatment ($P < 0.05$) relative to PKE treatment, but differences between the Pasture treatment and either the Cropping or PKE treatments were not statistically significant. In contrast, treatment had no effect on N-use efficiency. Nitrogen leaching tended ($P < 0.1$) to be greater in the Cropping treatment than both the Pasture and PKE treatments, which did not differ from each other. There was insufficient variation in P loss to undertake a statistical comparison; nevertheless, I present the treatment mean P loss in Table 12.

Methane emissions were less in the Pasture treatment ($P < 0.05$) relative to the PKE treatment, with the Cropping treatment intermediate. Treatment did not significantly affect nitrous oxide emissions, but there was a tendency for carbon dioxide ($P = 0.11$) and total emissions ($P = 0.07$) to be greater in the PKE treatment than the Pasture treatment, with the Cropping treatment intermediate.

Table 12: Effect of treatment[1] on N, P and GHG metrics[2] expressed per hectare

	PKE	Pasture	Cropping	SED	*P*-Value
Nitrogen (kg N/ha)					
N leaching	16.3	15.7	21.7	2.3	0.08
Farm N surplus	215.3 [a]	184.0 [ab]	163.3 [b]	16.1	<0.05
N-use efficiency (%)	30.7	31.0	35.0	2.3	0.18
Phosphorous (kg P/ha)					
P loss	1.4	1.3	1.3		
GHG emissions (CO_2 equivalents/ha)					
Methane	8,615 [a]	7,242 [b]	8,076 [ab]	393	<0.05
Nitrous oxide	2,730	2,616	2,364	235	0.34
Carbon dioxide	1,632	1,191	1,350	175	0.11
Total emissions	12,977	11,049	11,790	688	0.07

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha respectively).
[2]Estimated using Overseer modelling with 3 years of experimental data.

4.3.2 Environmental footprint intensity

The effects of experimental treatment on key environmental loss metrics at an intensity level (i.e., measured per kg MS) are presented in Table 13. In contrast to the results when presented on a per hectare basis, treatment had no effect on farm N surplus/kg MS. Nitrogen leaching/kg MS tended ($P < 0.15$) to be greater in the Cropping treatment relative to the PKE treatment. However, there were no differences in N leaching/kg MS between the Pasture treatment and either the Cropping or PKE treatments. Treatment had no effect on average P loss, methane, nitrous oxide, carbon dioxide or total emissions per kg MS.

Table 13: Effect of treatment[1] on N, P, and GHG metrics[2] expressed per unit of production (kg MS).

	PKE	Pasture	Cropping	SED	*P*-Value
Nitrogen (kg N/kg MS)					
N leaching	0.015	0.017	0.022	0.003	0.15
Farm N surplus	0.20	0.20	0.17	0.02	0.19
Phosphorous (kg P/kg MS)					
P loss	0.001	0.001	0.001	0.0001	0.23
GHG emissions (CO_2 equivalents/kg MS)					
Methane	7.88	7.92	8.12	0.24	0.58
Nitrous oxide	2.49	2.86	2.40	0.29	0.30
Carbon dioxide	1.49	1.30	1.37	0.19	0.61
Total emissions	11.87	12.08	11.89	0.69	0.94

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha respectively).
[2]Estimated using Overseer modelling with 3 years of experimental data.

4.4 Discussion

Few studies have analysed the effect of systems level changes in SR and imported feed allowance on both N leaching and GHG emissions. In addition, where N leaching and GHG emissions have been compared, this comparison has often been between a system with no imported feed against systems considered "medium' or 'high' intensity. I had the unique opportunity to analyse the effect of removing a relatively low quantity (~ 550 kg DM/cow/yr; ~ 10% of cow's annual diet) of supplementary feed from a pasture-based dairy system in Northland.

4.4.1 Effect of farm system on nitrogen leaching

4.4.1.1 PKE vs Pasture

Removing a low-to-moderate CP supplementary feed from the farm system and decreasing SR to balance feed supply and demand did not significantly reduce N leaching on the milking platform. These result are consistent with those of both Ledgard et al. (2006), under experimental conditions, and Ledgard et al. (2017), when examining associations across a sample of commercial dairy farms. Ledgard et al. (2006) compared N leaching modelled through Overseer in six dairy systems that differed in feed input and SR. Increasing the SR (3.8 vs 3.0) and importing a 'small' quantity (i.e., 'Low' treatment) of maize silage (5.5 t DM/ha; 1.5 t DM/cow) resulted in no significant increase in the quantity of N leached on the dairy platform (not accounting for any N leached through the process of growing imported supplementary feed). In addition, Ledgard et al. (2017) examined the associative environmental effects between low input (< 500 kg DM/cow) and medium input (500 - 1200 kg DM/cow) systems in the Waikato. Despite an increase in the quantity of imported feed (1.0 vs. 2.9 t DM/ha), SR (2.9 vs. 3.3 cows/ha), and N fertiliser inputs (110 vs. 158 kg N/ha), there was only a slight increase in N leaching (26 vs 28 kg N/ha) when modelled through Overseer (not accounting for any N leached through the process of growing imported supplementary feed). Although commonly assumed to be a principal factor in the effect of dairy systems on water quality, changes to SR, in my results, and in much of the published literature, fails to affect modelled and measured loss of N from the root zone of dairy pastures.

Although milk production can be limited if the supply of CP is insufficient relative to animal requirements, this is rarely the case in temperate grazing systems

(Pacheco & Waghorn, 2008; Roche, 2017). Where dietary CP exceeds animal demand, the excess CP is excreted, predominantly, as urinary N within localised patches (Ledgard, 2001). Urinary N is deposited in a concentrated form at a rate of between 200 and 2000 kg N/ha (Selbie, Buckthought, & Shepherd, 2015) and is widely considered to exceed the potential capacity for pasture uptake (Buckthought, Clough, Cameron, Di, & Shepherd, 2016; Haynes & Williams, 1993; Jarvis, Scholefield, & Pain, 1995). Excess N is liable to leach from the soil profile following nitrification and when rainfall exceeds evapotranspiration and available soil moisture storage capacity (Haynes & Williams, 1993; Ledgard et al., 2009; Whitehead & Raistrick, 1993). Under these conditions, the nitrate ion is liable to leach from the soil profile due to its high solubility and negative charge, causing it to be repelled from soil surfaces (McLaren & Cameron, 1996).

For a given soil type and climate, the 1) quantity, 2) concentration, and 3) timing of urinary N deposited onto pastures are the main determinants of N losses from a pastoral dairy system (Ledgard, Luo, et al., 2011; Roche et al., 2016; Romera, Levy, Beukes, Clark, & Glassey, 2012; Selbie et al., 2015). The influence of these contributing factors will be discussed in greater detail.

4.4.1.1.1 Quantity

The N surplus is a measure of the excess N within a farm system that is, potentially, liable to loss via leaching, ammonia volatilisation and gaseous loss (Beukes et al., 2012; Pinxterhuis & Edwards, 2018). Nitrogen surplus is calculated as the difference between N inputs and N removed in saleable products as milk, meat, and supplementary feed removed off-farm (Ledgard et al., 1999). There was no significant difference in N surplus between the PKE and Pasture treatments. The lack of significant effect possibly reflects a lack of statistical power to detect differences in this measurement, with only three replicates and relatively small differences in N surplus between treatments compared with the inter-year variability in modelled metrics between farm years. The PKE treatment imported, on average, 1,443 kg DM/ha of PKE, with an average CP content of 15.5% DM; this is equivalent to importing 224 kg more protein/ha or 35.8 kg more N/ha in the PKE treatment when compared with the lower SR, Pasture treatment (assuming protein in feed = 6.25 x N ; Freer, 2007). Furthermore, N fertiliser application was, on average, 10 kg/ha less, and modelled clover N fixation was 17 kg/ha greater, in the PKE treatment compared with the Pasture treatment. On the output side, on average, the PKE treatment produced 66 kg/ha more milk protein than the Pasture treatment; this is equivalent to an additional 10.3 kg N/ha removed in product (assuming protein in milk = 6.38 x N ; Freer, 2007). Therefore, notwithstanding the lack of statistical significance, the calculation of N surplus (input minus output) indicates a biologically relevant difference in N surplus of 32 kg N/ha (15%) between the PKE and Pasture treatments. It was, therefore, surprising that the Overseer simulations predicted that farm system change did not affect N leaching. Beukes et al. (2012), for example, reported a linear relationship between N surplus and N leaching when N surplus was less than 250 kg N/ha. The results of the current study do not support such a linear relationship, probably suggesting that farm system-level variables other than N surplus had an effect on N leaching. The proportion of the N surplus lost through leaching was 12% greater in the Pasture treatment relative to the PKE treatment, suggesting that, despite a lower N surplus in the Pasture treatment, the surplus N was at greater risk of leaching relative to the PKE treatment. This effect may be explained by potential differences in the concentration and timing of urinary N return.

4.4.1.1.2 Concentration

4.4.1.1.2.1 Due to dietary protein

As the N concentration of urine deposited increases beyond a pasture's capacity for uptake, an increased quantity of N will be liable to leach from the soil during drainage (Selbie et al., 2015). Urinary N concentration is affected by the quantity of dietary N supplied relative to animal demands (Kebreab, Castillo, Beever, Humphries, & France, 2000; Spek, Bannink, Gort, Hendriks, & Dijkstra, 2013). For lactating animals grazing temperate pastures, dietary CP concentrations exceeding 20% are in excess of animal requirements (Pacheco & Waghorn, 2008). Offering a supplementary feed with a lower CP content than pasture may decrease dietary CP intake/cow (depending on the effect on total DMI and, hence, N intake), potentially reducing urinary N concentration (Jarvis, Wilkins, & Pain, 1996; Tomlinson, Powers, Horn, Nordstedt, & Wilcox, 1996). For two systems with a similar N surplus, a reduction in urinary N concentration would decrease the amount of N in urine patches that exceeds the capacity for pasture uptake, reducing the potential for N leaching losses from each urine patch (Ledgard, Luo, et al., 2011). The CP content of PKE is generally lower than that of grazed pasture, except in very dry summer conditions (DairyNZ Limited, 2017b). Feeding PKE, therefore, would be expected to reduce diet CP percent, and hence, lower urinary N concentration relative to the Pasture treatment. Although the N surplus/ha (inputs – outputs) was numerically lower in the Pasture treatment, the smaller surplus was, likely, returned in a more concentrated urine, thereby exceeding the capacity of pasture to recover the deposited N by a greater amount and increasing the leaching potential of this surplus N from the urine patch.

Despite a small difference in N surplus between the PKE and Pasture treatments, there was little predicted difference in N leaching between treatments due to a greater proportion of the surplus N being leached in the Pasture treatment. This may have been due, at least in part, to greater urinary N concentration from cows in the Pasture treatment, which could lead to greater leaching of this surplus N.

4.4.1.1.2.1.1 Sensitivity to crude protein content of supplementary feed

The quantity of urinary N excreted is affected by the quantity of N consumed (Broderick, 2003; Burgos, Fadel, & Depeters, 2007; Hendriks, 2016; Kebreab et al., 2000). As a result, the effect of offering and, hence, removing a supplementary feed from a farm system on N leaching is, very likely, sensitive to the CP content of the supplementary feed relative to that of pasture. If a supplementary feed with a greater CP content than pasture is offered (in a non-protein limiting diet), the surplus dietary CP will be greater, leading to a greater amount of N to be excreted in urine and, assuming no change in urine volume, urinary N concentration, thereby, increasing the risk of N leaching. This effect can be modelled in Overseer by substituting the same quantity of energy provided by PKE with alternative supplementary feeds containing different amounts of CP. Assuming no limiting amino acids in the PKE treatment and no increase in ME intake with the different supplementary feeds offered, it is reasonable to assume that that there would be a negligible increase in production by offering a supplementary feed with greater CP (Pacheco & Waghorn, 2008). The additional CP consumed will, therefore, increase the quantity of urinary N deposited and, assuming no change in urine volume, the amount of N leached/ha (Pacheco & Waghorn, 2008). The effect of the CP content of a supplementary feed on N leaching modelled in Overseer is presented in Figure 40.

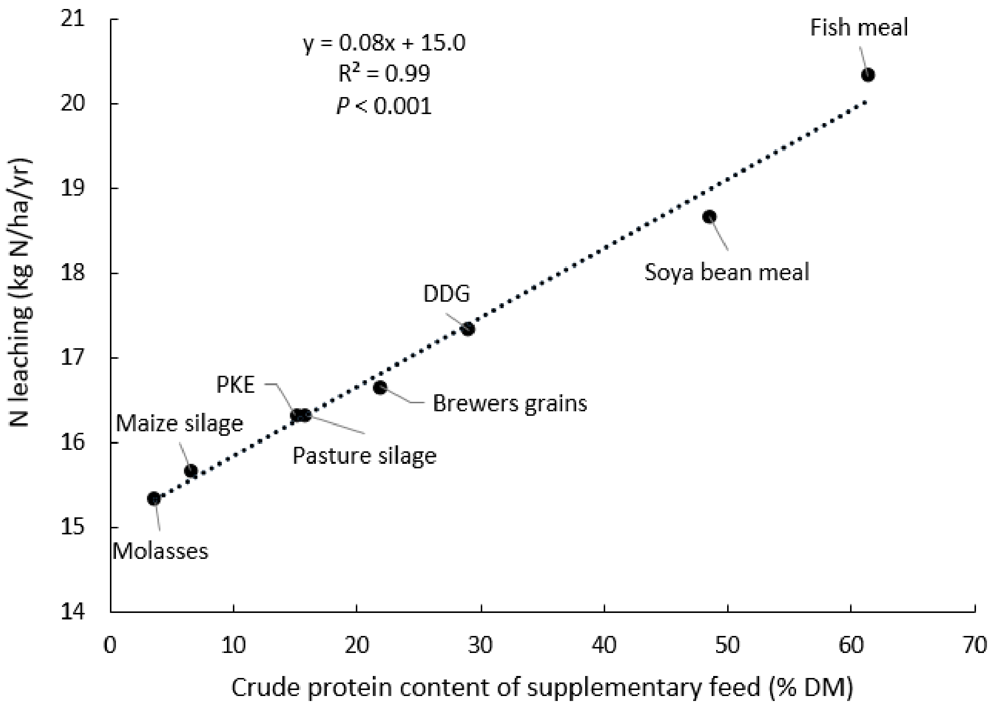

Figure 40: The relationship between the crude protein content of a supplementary feed and the quantity of N leached (kg N/ha/yr).

The positive relationship presented here is supported by the results of Hendriks (2016), Castillo et al. (2000) and Kebreab et al. (2000) who reported a positive relationship between dietary N intake and urinary N output. The effect of removing a supplementary feed on N leaching, therefore, is likely sensitive to its CP content. If a supplementary feed has a lower CP content than pasture (as for PKE), its removal from the system will likely decrease N surplus; however, this may increase urinary N concentration and, hence, the risk of this surplus N leaching. In contrast, removing a supplementary feed with a higher CP content than pasture will decrease both N surplus and urinary N concentration, reducing the quantity of N liable to leach and its risk of leaching.

4.4.1.1.2.2 Concentration due to stocking rate

The quantity of N consumed and, therefore, excreted per cow, and the associated concentration of urinary N, may also be influenced by SR (Roche et al., 2016; Romera et al., 2012). At a greater SR, all other factors being equal, feed allowance per cow, and the related dietary N intake per cow would be less (Roche et al., 2016), potentially lowering surplus dietary CP for individual animals and, as a result, the quantity of N excreted in urine. Furthermore, the number of urine patches deposited per hectare increases with SR (Dennis et al., 2011). Assuming that urinary N volume per cow is unaffected by SR, the excreted N would potentially be spread over a greater quantity of urine patches, resulting in a reduction in urinary N concentration per urination patch (Roche et al., 2016). By reducing the amount of N deposited in the urine patch, the percentage of urinary N recovered by pasture may be increased, thereby reducing the risk of N leaching (Ledgard, Luo, et al., 2011). In support of this, Roche et al. (2016) reported a reduction in N intake per cow, N excreted per cow and N leached per hectare with increases in SR; the reduction in urinary N concentration during 'sensitive' months for N leaching risk was postulated as a contributory factor.

The effect of changes in SR and/or the quantity of supplementary feed offered on N intake and N excretion per cow is dependent on the overall effect on CSR (kg LW/t DM). An increase in CSR would lead to a lower feed allowance per cow (Macdonald et al., 2011) and a reduction in dietary N surplus (g/cow/day) and urinary N concentration, whilst a reduction in CSR will have the opposite effect, all other factors remaining equal. The experiment was designed such that CSR was similar across treatments; therefore, the effect of SR on urinary N concentration was, likely, counteracted by the importation of feeds to maintain feed allowance/cow.

Differences in SR will, however, also affect the number of urine patches deposited hectare (Dennis et al., 2011), irrespective of CSR, and the related potential for overlap of urine patches. Overlapping urine patches have been reported to have a considerable influence on N leaching loss (Pleasants, Shorten, & Wake, 2007; Romera et al., 2012). Pakro and Dillon (1995) reported that N leached under dual urination patches was 2.9 to 3.6 times greater than that of a single application. Therefore, all other factors being equal, increases in SR could potentially lead to an increase in leaching because of an increased proportion of overlapping urine patches.

The net effect of changes in SR and supplementary feed use on N leaching, when holding other factors constant such as DIM, is affected by:

- changes to dietary N intake/cow and, hence, urinary N output and concentration;

- whether the supplementary feed is employed or removed to alter CSR; and
- any change in the number of urine patches deposited per hectare.

Further differences in leaching may result from effects of treatment on the timing of the surplus dietary CP and the associated urinary N output.

4.4.1.1.3 Timing of urinary nitrogen deposition

During periods where pasture growth and its related capacity for N uptake are reduced and/or where there is increased risk of drainage (high rainfall relative to evapotranspiration), the risk of surplus N leaching from the soil is increased (Ledgard, Luo, et al., 2011; Selbie et al., 2015). The period between late-summer and early-winter is widely accepted to be a period of increased risk of N leaching (De Klein & Ledgard, 2001; Selbie et al., 2015). During this period pasture growth is generally reduced due to lower soil temperatures and solar radiation. In addition, the risk of drainage is elevated during this period due to increased rainfall and lower rates of evapotranspiration. Therefore, situations that result in a greater N surplus per cow and, potentially, per ha during this period increase the likelihood of N leaching (De Klein & Ledgard, 2001; Ledgard, Luo, et al., 2011; Selbie et al., 2015). Roche et al. (2016) reported that a longer lactation increased the risk of N leaching in grazing systems because lactating cows tend to have a greater dietary N surplus than non-lactating cows and, therefore, a greater urinary N concentration. They also reported a linear decline in lactation length with increasing SR and CSR. In the current experiment, there was no treatment effect on CSR or on DIM/cow. As a result, there was no increase in the number of lactating cows during the critical drainage period, beyond the effect of a small difference in SR.

Because of the lack of a difference in DIM between the treatments there would be little effect of lactation state on the timing of urinary N return during the critical period. As a result, the influence of the timing of excreta return on the risk of N leaching between treatments would be expected to be small. However, to further complicate the assessment of system-level factors that affect N leaching in this study, there were differences in the feeding and related effluent management systems between treatments, specifically through the use of a feed pad, which has the potential to influence the timing of N return and, therefore, N leaching.

4.4.1.1.4 Effects of feed pad use on risk of nitrogen leaching

Within the current experiment, during the period of greatest risk for drainage and, therefore, N leaching, supplementary feed was predominantly offered on a concrete feed pad with the daily time spent on the pad averaging approximately 2 hours/day across the year. The use of a feed-pad in a grazing system allows for the collection and even re-application of excreted urine and faeces. This has the potential to reduce N leaching through two main pathways (Christensen, 2013):

1) Effluent can be stored and applied when environmental conditions are less risky for N leaching (i.e., lower risk of drainage or increased pasture growth), and
2) Effluent can be applied evenly across the paddock at a rate substantially lower than that applied under the urine patch.

Despite the reported potential for reduced N leaching with the use of stand-off facilities (Christensen, 2013; de Klein, Monaghan, Ledgard, & Shepherd, 2010; de Klein, Smith, & Monaghan, 2006; Ledgard et al., 2006), according to the Overseer simulations, the use of a feed pad in my study did not reduce N leaching losses. There was no difference in N leaching (16.3 kg N/ha/yr) in the PKE treatment when modelled either with supplementary feed offered on a feed pad (current practice) or with supplementary feed offered in the paddock. This is in contrast to the results of Ledgard et al. (2006), who reported a 25% reduction in N leaching when cows were stood off for 18 hours/day from mid-May to early-July. It's possible that the outcome differences between these studies reflects differences in stand-off times and, possibly, differences in soil type.

Increasing the modelled time that cows were stood-off to 12 hours per day in the current experiment, also, did not affect N leaching (16.7 kg N/ha/day). The absence of a reduction in N leaching when standing cows off pasture is probably a reflection of the high rates of modelled denitrification losses from the soil type on the study farm (26 kg N/ha/yr in the PKE treatment) and the associated low level of N leaching from urine patches (3 kg N/ha/yr in PKE treatment). The primary mechanism by which standing cows off pasture reduces N leaching is through a reduction in N leached from urine patches (Christensen, 2013; De Klein & Ledgard, 2001). As N leaching from urine patches was low, because of high rates of denitrification, there was little opportunity to reduce N leaching on the current soil type through stand-off practices.

4.4.1.1.5 Sensitivity of results to soil type

I expected that the lack of difference in N leaching between treatments in my study may be due to a high proportion of surplus N being denitrified on the present soil type, which may not occur in lighter textured soils. There is considerable variability in the potential of soils for denitrification and N leaching; for example, poor draining clay soils generally have high denitrification potential and, associated, nitrous oxide emissions, but lower N leaching losses (De Klein, Barton, Sherlock, Li, & Littlejohn, 2003). The sensitivity of N leaching outcomes to changes in soil type were tested by modelling the soil as a 'light' textured Red Hill sandy loam (a light textured soil in close proximity to the experimental site).

The simulation indicated a numerical increase in the N surplus of both the Pasture (190 kg N/ha/yr) and PKE (221 kg N/ha/yr) treatments in the 'light' textured soil relative to the clay soil, driven by a modelled increase in N fixation from clover. However, despite the increase in N surplus with soil type in both treatments, N surplus remained approximately 14% lower in the Pasture treatment relative to the PKE treatment. Therefore, despite changes in the modelled rate of clover fixation, the difference in N surplus between treatments was unaffected by soil type. Similar to the conclusions for the clay soil type, despite the numeric difference in N surplus between treatments, a greater proportion of this surplus N leached in the Pasture treatment, which resulted in no difference in N leaching between treatments on the light textured soil (50 kg N/ha/yr). Therefore, the difference, or lack thereof, in N leaching between treatments was not sensitive to soil type.

4.4.1.1.6 Effect of feed pad

Whilst the effect of treatment on N leaching was not sensitive to soil type, the influence of standoff practices on N leaching was highly sensitive to soil type. On a light textured soil, the modelled N leaching was 20% lower (50 kg N/ha to 40 kg N/ha) when cows were stood off for 12 hours/day year round, relative to the 2 hr average achieved in the current experiment. This was similar in magnitude to the 25% reduction in N leaching through stand-off reported by Ledgard et al. (2006).

The difference in effect between soil types was a reflection of the greater N leaching from urine patches in the light textured soil, and associated greater potential to reduce N leaching through stand-off practices.

4.4.1.1.7 Summary

In summary, at least within the variables considered in the current experiment, the influence of the timing of the N surplus on N leaching was low, likely because of a lack of effect of treatment on lactation length and the high denitrification potential of the soil type (so, no effect of stand-off practices). The effect of removing an imported supplementary feed of low-to-moderate CP on N leaching from a pasture-based system was not sensitive to changes in soil type, but modelled N leached from both the Pasture and PKE treatments increased on a sandy- or clay-textured soil. In addition, whilst the ability to reduce N leaching through stand-off practices on the current soil type was low, this potential was improved greatly on a sandy textured soil.

4.4.1.2 PKE vs Cropping treatment

Removing imported supplementary feed from the farm system and using forage crops to increase the quantity of feed grown on the dairy platform and maintain the SR resulted in an increase in N leaching. Despite a 20% reduction in N surplus between the PKE and Cropping treatments, N leaching was increased by 30% from 16.3 to 21.7 kg N/ha/yr. This is supported by the results of Schröder & Neeteson (2008), who reported that a greater proportion of N surplus is leached from arable land uses relative to pastoral land use across a range of soil types. For example, under a clay soil type, they reported that 31% and 11% of N surplus was leached under arable and pastoral land uses, respectively. In the current experiment, on average, 13% and 8% of N surplus was leached from the Cropping and Pasture treatments, respectively. Differences in the proportion of N surplus leached from the Cropping treatment in the current study, and the arable system reported by Schröder and Neeteson, may potentially be explained by differences in the intensity of the cropping rotation.

Within the current experiment, the opposing trends of N surplus and N leaching in the Cropping treatment are a reflection of the way in which N surplus is calculated. The calculation of N surplus does not include inputs of N from soil mineralisation, a factor expected to increase under tillage. Cultivation of soil results in large quantities of organic N being mineralised and made available for plant uptake or leaching (McLaren & Cameron, 1996; Mosier et al., 1998; Powlson, 1980). In my study, modelled N mineralisation increased approximately 2.3 times following cultivation (Figure 41). This acted as a large input of N, which was not accounted for in the calculation of N surplus and was in addition to N applied as fertiliser. In addition, this increased mineralisation coincided with a period of reduced plant uptake (Figure 41) due to the removal of vegetation which potentially reduced the opportunity for uptake of this mineralised N and increased the risk of leaching loss. This process was repeated in early-autumn following grazing of the crop, resulting in a reduction in plant uptake and a subsequent increase in mineralisation through pasture renovation practices (Figure 41). These events coincide with the sensitive period for N leaching, further increasing the leaching risk of this mineralised N.

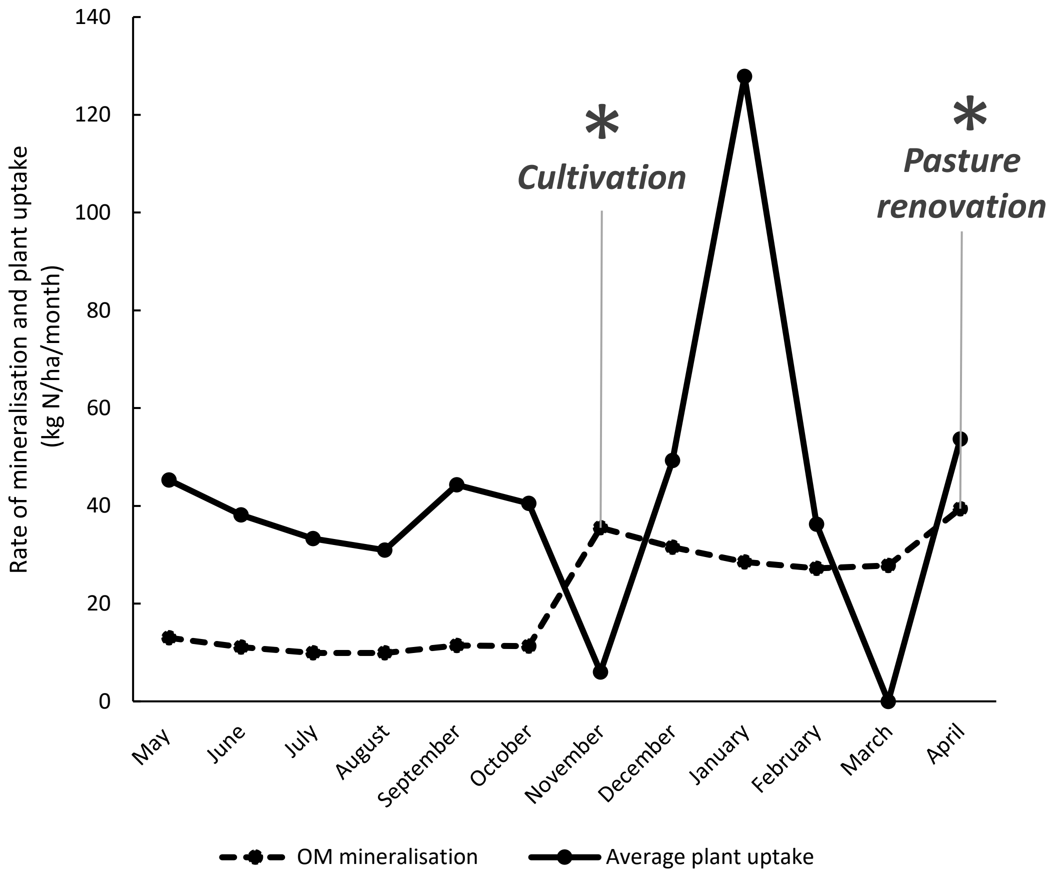

Figure 41: Average modelled rate of mineralization and plant uptake in the area cropped in turnips.

4.4.1.3 Relationship between nitrogen surplus and nitrogen leaching

Across all treatments and experimental years, there was no relationship between N surplus and N leaching in the current study (Figure 42). This was surprising given the strong relationship between farm-gate N surplus and N leaching losses reported in the literature (Beukes et al., 2012).

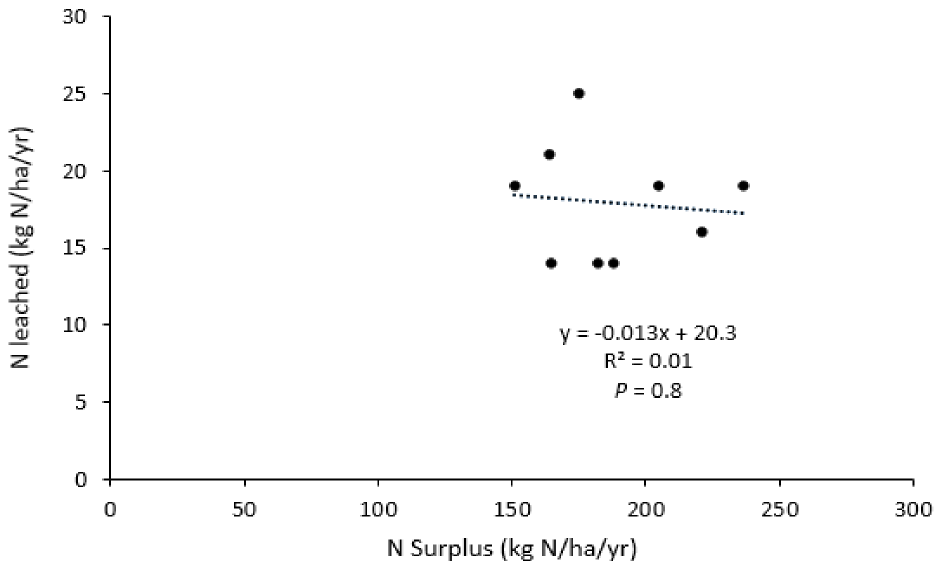

Figure 42: Relationship between N surplus (kg N/ha/yr) and N leached (kg N/ha/yr) across treatments.

Outcome differences between these studies may reflect the small number of samples and relatively small range of N surplus within farm year in the current experiment. Nevertheless, the results of the current study suggest limitations to the use of N surplus as a predictor of N leaching across different farm systems, suggesting that management practices have the potential to affect the proportion of N surplus leached from a system.

4.4.1.4 Whole systems effect on nitrogen leaching

When analysing the effect of farm systems changes on environmental outcomes, it is necessary to consider both the full effect within the farm system as well as the wider potential effect outside the farm gate (Chobtang, Ledgard, Mclaren, & Donaghy, 2016). Failure to account for the full footprint of a system change may result in the unconscious shifting of pollution to sources outside the farm gate or pollution swapping from one form to another (e.g., reduced N leaching but increased nitrous oxide emissions), with no net benefit in terms of environmental outcomes (Luo et al., 2010).

Within the current experiment, the environmental effects associated with increasing feed supply within the Cropping treatment are accounted for in modelling estimates, as the forage crops have been grown on the dairy platform. There is, therefore, no 'hidden' off-farm environmental external effects associated with growing this additional feed, as any effect is internalised within the farm boundaries.

In contrast, within the modelling estimates of the PKE treatment, no account has been made for the off-farm N leaching associated with the production of PKE. In fact, due to its nature as a by-product, it is difficult to determine the appropriate share of the environmental cost of PKE production. Several methodological approaches have been developed to allocate environmental externalities between processes that contribute to more than one output (multi-function processes; Frischknecht, 2000). For example, Dynes et al. (2018) employed an economic allocation methodology to apportion GHG emissions to the production of PKE, based on the contribution of PKE to total revenue from palm products. They reported that PKE should receive attribution, on average, for a contribution of 1.55% of the total GHG footprint of palm products, which is in agreement with Virah-Sawmy (2014), who reported a 1% contribution of PKE to total export earnings from palm products in 2011. Due to the low economic contribution of PKE to total palm product revenue, the magnitude of apportioned off-farm N leaching associated with PKE production is also likely to be small.

The total environmental effect of offering a supplementary feed can be separated into the effect of producing the additional feed and the on-farm effect associated with offering this additional feed. The N leaching loss associated with the production of additional feed is lower in the PKE treatment than the Cropping treatment. This difference is due to the high rates of N mineralisation associated with the cropping process and the low N leaching attributable to the use of the PKE external to the farm (based on the small revenue share of a by-product). This suggests, solely from a N leaching perspective, that there are advantages to the use of supplementary feeds that are both low CP and by-products (with low N loss attributable to their production).

4.4.2 Effect of farm system on phosphorous loss

There was insufficient variance in P loss measurements to conduct an ANOVA analysis and, therefore, no treatment effect on P loss. This lack of treatment effect on P loss was, however, also reflected in only small numeric differences in P inputs (9 kg P/ha/yr) and outputs (3 kg P/ha/yr) between treatments. Within the current experiment, there was no difference in P loss between treatments reflecting a lack of significant effect of treatment on P inputs or outputs.

4.4.3 Effect of farm system on greenhouse gas emissions

4.4.3.1 Total greenhouse gas emissions

Total greenhouse gas emissions in the PKE treatment averaged 13 t CO_2-equivalents/ha; the contributions of methane, nitrous oxide and carbon dioxide to these emissions are presented in Figure 43. The emissions profile is similar to that reported by Ledgard and Falconer (2015), who reported an average of 68%, 23%, and 9% of emissions as methane, nitrous oxide, and carbon dioxide respectively for a sample of low input dairy farms in the Waikato.

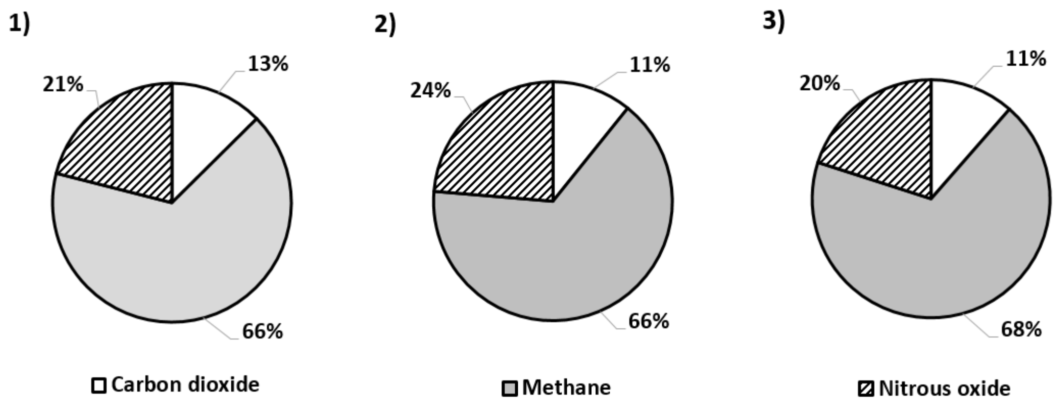

Figure 43: Average methane, nitrous oxide, and carbon dioxide emissions as a proportion of total emissions (CO_2 equivalents/ha/yr) for: 1) PKE; 2) Pasture; and 3) Cropping treatments.

There was a trend (P = 0.07) for total modelled GHG emissions (CO_2-equivalents/ha/yr) to be lower in the Pasture and Cropping treatments (15% and 9%, respectively), when compared with the PKE treatment (Figure 44); further, emissions of each of the three gases were lower in the Pasture and Cropping treatments. Therefore, there was little or no ‘pollution swapping’ with respect to GHG emissions: there was no trade-off from reducing emissions from one gas source, by simultaneously increasing emissions from another gas source (Ledgard, Lieffering, Zonderland - Thomassen, & Boyes, 2011).

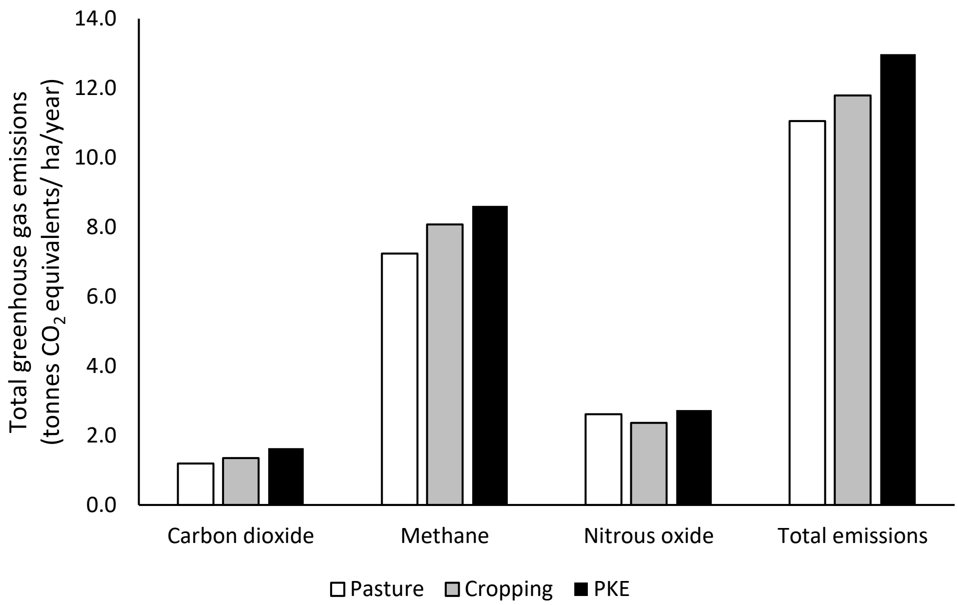

Figure 44: Effect of treatment on modelled carbon dioxide, methane, nitrous oxide, and total emissions.

4.4.3.2 Carbon dioxide

Modelled carbon dioxide emissions/ha tended ($P = 0.11$) towards being 27% and 17% lower in the Pasture and Cropping treatments, respectively, relative to the PKE treatment. This was the largest proportional difference in emissions of any of the individual gases. These differences occurred, primarily, from a modelled reduction in emissions associated with 'supplementary feeds'. Palm kernel expeller has a high carbon footprint (kg CO_2-equivalent/kg DM) relative to other feeds due to emissions associated with the land use change component of its production (Dynes et al., 2018; Ledgard & Falconer, 2015). For example, Ledgard and Falconer (2015) reported a carbon footprint for PKE of 0.506 kg CO_2-equivalents/kg DM, which was approximately 1.5 times the carbon footprint of baled pasture silage. The removal of PKE from the farm system in the current experiment resulted in a tendency towards lower carbon dioxide emissions ($P < 0.11$) due to the comparatively high carbon footprint associated with PKE production (kg CO_2-equivalents/kg DM).

4.4.3.3 *Methane*

Modelled methane emissions were 16% lower in the Pasture treatments than the PKE treatment but not significantly less in the Cropping treatment. Although this reduction in methane was less than the proportional reduction in carbon dioxide emissions, the change in methane emissions accounted for the largest reduction in total GHG emissions, as methane was the largest gas source (Figure 43).

The reduction in methane accounted for 71% and 45% of the total reduction in GHG emissions in the Pasture and Cropping treatments, respectively. The modelled reductions in methane emissions relative to the PKE treatment were caused, primarily, by differences in 'enteric methane emissions'. Enteric methane emissions are affected by the quantity and quality of feed digested (Pinares-Patiño et al., 2009; Waghorn & Woodward, 2006). Therefore, differences in methane emissions between treatments are likely to reflect differences in feed supply, and hence, milk production, between treatments. Total MS production per hectare was 16% and 9% lower in the Pasture and Cropping treatments relative to the PKE treatments which is in line with the numerical reduction in methane emissions. Differences in modelled methane emissions between treatments appear to be well explained by differences in milk production between treatments (Figure 45). For every increase in milk production (kg MS/ha), methane emissions increased (P < 0.001), on average, by 7.13 kg CO_2-equivalents/ha.

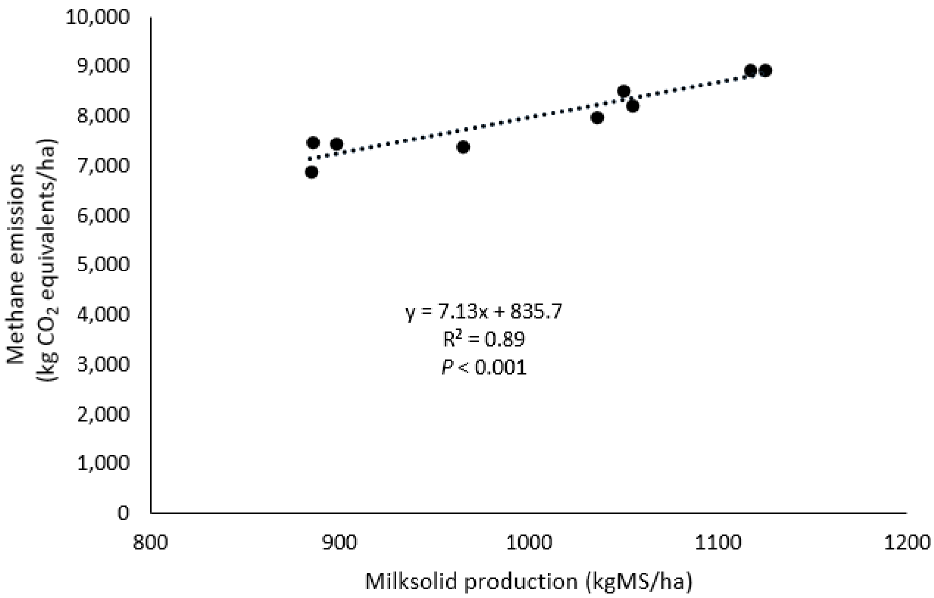

Figure 45: Association between milksolids production (kg MS/ha) and methane emissions (kg CO_2-equivalents/ha).

4.4.3.4 Nitrous oxide

Despite a lack of significant differences between treatments, modelled nitrous oxide emissions were numerically 4% and 13% lower in the Pasture and Cropping treatments, respectively, relative to the PKE treatment. These differences were, primarily, associated with differences in emissions related to excreta (paddock and effluent). The effect of treatment on nitrous oxide emissions follows a similar trend to the effect of treatment on N surplus. The association between N surplus and nitrous oxide emissions are presented in Figure 46. The linear relationship presented here is supported by the results of Schils et al. (2008) who also reported a linear relationship between N surplus and nitrous oxide emissions (kg N/ha/yr).

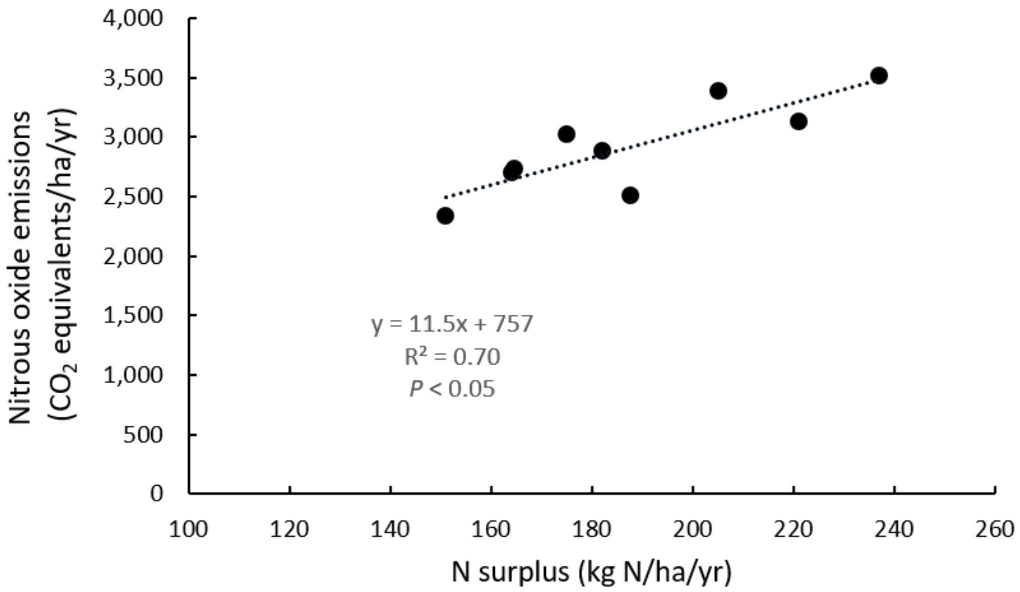

Figure 46: Association between N surplus and nitrous oxide emissions.

4.4.3.5 Emissions intensity

Despite higher total emissions (CO_2-equivalents/ha) in the PKE treatment relative to the Pasture and Cropping treatments, emissions intensity (CO_2-equivalents/ kg MS) was similar across all treatments (Figure 47). Although GHG emissions per hectare were lower in the Pasture and Cropping treatment relative to the PKE treatment, milk production per hectare was also lower, resulting in no net effect on emissions intensity between treatments. These results are supported by those of Ledgard et al. (2017) who reported little difference in emissions intensity between systems with low, medium and high feed inputs, despite an increase in emissions per hectare with an increase in imported feed use.

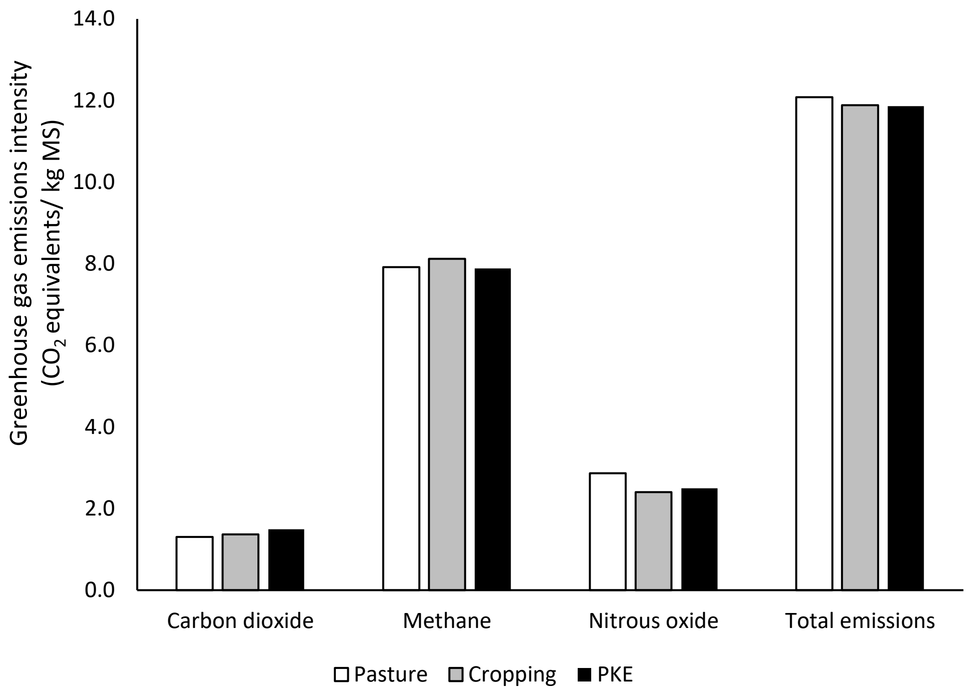

Figure 47: Treatment differences in greenhouse gas emissions intensity.

4.5 Conclusions

The removal of a relatively small quantity (~ 550 kg DM/cow/yr or approximately 10% of the cow's diet) of a low-to-moderate CP supplementary feed, from a pasture-based dairy farm system, either through 1) a reduction in SR (Pasture treatment); or 2) by growing potentially high yielding forage crops on the dairy platform (Cropping treatment), were not effective strategies to reduce N leaching. Despite a small reduction in N surplus, a higher proportion of N surplus was leached in the Pasture treatment, potentially due to an increase in the CP percentage of the diet and an associated increase in urinary N concentration. In addition, despite a reduction in N surplus, N leaching was increased by maintaining SR and replacing imported supplementary feed with forage crops grown on the dairy platform. This was due to large modelled rates of mineralisation during the cultivation and pasture renewal processes, which accounted for a considerable input of N into the system that was not accounted for in the calculation of N surplus. There was no significant difference in P loss to water between treatments, the small numeric differences in P loss between treatments could largely be explained by the difference in P inputs and outputs between treatments.

In contrast to the results for N leaching, the removal of PKE from a pasture-based system was an effective strategy to reduce total GHG emissions, largely due a reduction in methane emissions. Modelled methane emissions were linearly related to DMI and, therefore, milk production. Intake/ha was lower in the Pasture and Cropping treatments relative to the PKE treatment; as a result, methane emissions/ha, and hence, total emissions/ha, were reduced with the removal of PKE from a pasture-based system. In addition, there were no differences in emission intensity (CO_2-equivalents/ kg MS) between treatments, further confirming that the difference in total emissions between treatments was driven by differences in production as opposed to differences in environmental efficiency between treatments.

Chapter 5: Economic implications of removing imported supplementary feed from a pasture-based system

5.1 Introduction

Pasture-based dairy production systems have lower operating expenses relative to housed systems, in which cows are offered a TMR; this is because of lower labour and machinery requirements from cows harvesting pasture *in situ* (Dillon et al., 2005). The unit cost of milk production has been reported to decline at an increasing rate with increasing proportions of grazed pasture in the annual diet of the cow (Roche, Washburn, et al., 2017). Similarly, it has been reported that every additional tonne of pasture harvested within a pasture-based system is associated with an increase in operating profit; this is equivalent to NZ$300 to $500/ha (Hanrahan et al., 2018; Neal et al., 2018; Ramsbottom et al., 2015).

Despite the importance of grazed pasture to the profitability of pasture-based systems, imported supplementary feeds may be offered when pasture supply is insufficient to meet herd demands to maintain DMI and milk production (Bargo et al., 2003; Holmes & Roche, 2007; Macdonald et al., 2017; Roche, 2017). Additionally, imported supplementary feeds may be offered within a pasture-based system to either:

- increase individual cow DMI (Bargo et al., 2003; Stockdale, 2000), or
- the number of cows per hectare (i.e., SR; Macdonald et al., 2017; Macdonald et al., 2008).

Either of these options can increase milk production per hectare, in the expectation that this increased production will lead to greater profitability.

Recently, however, a number of studies have concluded that increasing the level of supplementary feeds offered in grazing systems to either increase milk production/cow or to increase SR reduces operating profit (Macdonald et al., 2017; Ramsbottom et al., 2015) and ROA (Ma et al., 2018), as well as increasing unit cost (Dillon et al., 2005). Both Ramsbottom et al. (2015) and Macdonald et al. (2017)

highlighted a 50 to 60% increase in total costs/ha above the cost of feed as the primary reason for the poor financial return relative to biophysical responses.

My objective was to examine the financial effects of removing PKE from a grazing system (Control; PKE treatment) by either 1) reducing SR (Pasture treatment); or, 2) by growing high yield-potential forage crops on the dairy platform to potentially provide a home-grown, low-cost alternative to imported supplementary feed to maintain SR (Cropping treatment). I hypothesised that, profitability could be maintained with the removal of imported supplementary feed from a pasture-based grazing system.

5.2 Methods

5.2.1 Experimental design and treatment

Refer to Chapter 3.2 for experimental design and treatment methods.

5.2.2 Econometric analysis methodology

Financial data from the current experiment were used to determine the relative financial performance of the treatments within each experimental year. The proportion of costs allocated between treatments was determined in a similar manner to that described by Macdonald et al. (2011) and Macdonald et al. (2017). Specifically, wherever itemised revenue and expense data for individual treatments could be separated and directly attributed to that treatment (e.g., milk revenue and feed expenses), these data were directly apportioned to the respective treatments. Wherever data could not be directly attributed to an individual farmlet (e.g., electricity, administration etc.), due to the research farm operating as a single commercial operation (and the resulting structure of the farm accounting system), total itemised financial data were apportioned between treatments based on established per cow and per hectare ratios (Macdonald et al., 2017; Macdonald et al., 2011). These ratios were extracted from commercial databases used to measure and benchmark the economic performance of dairy farm businesses in NZ (DairyBase, DairyNZ, Hamilton, New Zealand) and Australia (Red Sky, Red Sky Agricultural Pty Ltd., Bacchus March, Australia; Macdonald et al., 2017; Macdonald et al., 2011). In addition, the time spent on each treatment, over and above farm operations common on all farms (e.g., feeding out PKE and break feeding forage crops) was recorded and used to calculate labour and machinery ratios for each treatment. These ratios were used to allocate relevant costs between treatments.

Labour ratios were used to allocate labour expenses between treatments: 1.6 full time equivalents (FTE's) were employed on the research farm, removing FTE associated with undertaking the experiment. Assuming an annual total of 2,500 hours per FTE, gives a total annual time budget of 4,000 hours for the farm. It has been reported that 85% of labour costs are attributable to per cow costs (Macdonald et al., 2011). Therefore, 85% of the total time budget (3,400 hours) was apportioned between treatments based on the respective SR in that year. The recorded hours for each treatment (i.e., hours over and above the requirements common for all treatments) were then allocated to each treatment and the remaining proportion of the total time budget was apportioned evenly between treatments. The total hours allocated to each treatment were then used to calculate a labour ratio which was applied to allocate the total labour cost between treatments for each respective year.

Machinery ratios were used to allocate vehicle expenses, vehicle and equipment depreciation, and repairs and maintenance costs between treatments. The total hours of annual tractor operation were calculated from the change in engine hours between years. The total operating hours were apportioned between treatments based on the recorded hours of operation (i.e., hours over and above the requirements common for all treatments) with the remaining proportion of total hours allocated evenly between treatments.

The financial data were then used to the calculate the following financial outputs for each treatment:

- Gross farm revenue
- Total operating expenses
- Farm operating profit

Non-cash adjustments were made for additional capital requirements and the value of any changes in BCS and pasture silage feed inventory between years. The value of additional capital infrastructure required for each treatment (e.g., effluent storage, feed pad and stand-off facilities) was assessed for an average size dairy farm in the Northland region (300 cows; DairyNZ Limited, 2017a) operating at a SR comparable to the Pasture treatment (2.5 cows/ha; 120ha). The marginal value of capital between treatments was assessed on a per hectare basis and apportioned to the respective treatments. An assumed interest rate of 6.5% was used within this analysis, with consideration of current interest rates (JDJL Limited, 2019) and longer term average interest rates (Neal & Cooper, 2016).

The energy lost or gained due to any change in BCS inventory between financial years was estimated assuming 30 kg LW/BCS unit, an energetic requirement of 50 MJ ME/kg LW gained and the sparing of 37 MJ ME/kg LW mobilised (DairyNZ Limited, 2017b). The value of any change in condition at a herd level was costed on an energetic basis relative to the cost of PKE in $/MJ ME. The value of any change in pasture silage inventory was valued at market cost. These non-cash adjustments were included in the calculation of operating profit which was averaged over the three experimental years to provide a single estimate of the relative profitability of each treatment.

Stochastic modelling techniques were used to assess and compare farm operating profit (non-cash adjusted) and its variability for each of the three treatments when accounting for the likely variability of key input variables. @Risk is a tool for performing Monte Carlo analysis that allows key input variables to be modelled as a distribution to determine the likely variation in output variables (Palisade, 2017). Distributions were incorporated for key input variables, specifically milk price ($/kg MS), PKE price ($/tonne), urea fertiliser price ($/tonne) and grass silage price ($/t DM) to determine potential variation in operating profit (non-cash adjusted) for each treatment. The potential variability of milk price was approximated with a 15-year dataset of mean annual (inflation adjusted) milk price, fitted with an 'extended value distribution' with mean $6.16 ± 1.54/kg fat and protein. A 'Weibull distribution' with mean $287 ± 47/tonne was attached to the price of PKE and an 'extended value distribution' with mean $711 ± 91/tonne attached to the price of urea as approximated by Neal and Cooper (2016) over 76 data points. The distribution of grass silage price was assumed to be the same as that of PKE for an equivalent quantity of ME. The PKE distribution parameters were adjusted based on the DM content of PKE (90%), and the average ME of grass silage (10.1 MJ ME/kg DM) and PKE (11 MJ ME/kg DM), resulting in a "Weibull distribution' with a mean of $292 ± 48/t DM. Correlations between these input variables were also included in the analysis, as specified by Neal and Cooper (2016). These correlations are presented as a correlation matrix in Table 14.

Table 14: Input price correlation matrix.

Correlation matrix	Milksolids price ($/kg MS)	Urea price ($/tonne)	PKE price ($/tonne)
Milksolids price ($/kg MS)	1		
Urea price ($/tonne)	0.1	1	
PKE price ($/tonne)	0.5	0.1	1

A Monte Carlo analysis consisting of 10,000 iterations was then performed using @Risk software (Palisade, 2017) to generate cumulative probability distribution functions (CDF) for each treatment; these detail the likely distribution of operating profit given the estimated variability of key input prices.

The sensitivity of conclusions to the response to supplementary feed was assessed by manually varying milk production within the stochastic model to achieve desired responses to supplementary feed. The sensitivity of conclusions were also assessed relative to the inclusion of a non-cash adjustment for differences in the negative environmental externalities between treatments, herein referred to as the ‘externality adjusted operating profit’. Within each year, differences in the quantity of N leached (kg N/ha/yr) and total GHG emitted (t CO_2-equivalents/ha/yr) between treatments, as estimated through Overseer in Chapter 4, were valued relative to the PKE treatment and this adjustment applied to each treatment. The quantity of N leached per ha was valued at $20 per kg N leached as indicated by Neal (2015) as the implied shadow price to achieve moderate reductions in N loss. The quantity of CO_2-equivalents emitted was valued at $25 per kg CO_2 in line with medium-term forecasts for CO_2 prices (Luckow et al., 2015).

5.3 Results and discussion

Despite numerous studies analysing the biophysical effects of using imported supplementary feed within pasture-based systems, the majority of studies have failed to analyse these effects on whole farm system profitability. This is important, as recent studies of international farm databases have reported no association between the quantity of supplementary feed offered within a pasture-based system and operating profit and have suggested that farm profitability may, in fact, decline, with this strategy.

I have taken a dual approach to the econometric analysis consisting of; 1) a deterministic analysis and, 2) a stochastic analysis. In the deterministic analysis I have used a single point estimate of the mean price for key input variables (milk, urea, PKE and grass silage prices) to compare the relative profitability of treatments in average market conditions. Within the stochastic analysis, I have fitted a distribution to these variables to analyse how the relative profitability of treatments varies when accounting for the likely distribution of market prices.

5.3.1 Deterministic analysis

The effects of treatment on 3-year average GFR ($/ha), total expenses ($/ha), operating profit ($/ha), and externality adjusted operating profit ($/ha) are presented in Table 15. Gross farm revenue per hectare and total expenses per hectare were greater in the PKE treatment relative to the Pasture treatment. However, neither GFR nor total expenses per hectare were different between the PKE and Cropping treatments. There were no differences in operating profit or externality adjusted operating profit per hectare between the PKE and Pasture treatments. However, operating profit and externality adjusted operating profit per hectare tended to be greater ($P < 0.15$) in the PKE treatment relative to the Cropping treatment.

Table 15: Effect of treatment[1] on 3-year average gross farm revenue ($/ha), total expenses ($/ha), operating profit ($/ha), and externality adjusted operating profit ($/ha).

Measure	PKE	Pasture	Cropping	SED	*P*-Value
Gross farm revenue ($/ha)	7,197[a]	6,068[b]	6,596[ab]	316.0	0.03
Total expenses ($/ha)	4,870[a]	4,040[b]	4,902[a]	189.7	0.01
Operating profit ($/ha)	2,264	2,113	1,562	314.9	0.14
Externality adjusted operating profit ($/ha)	2,202	2,113	1,424	308.4	0.09

[1]Pasture treatment herd fed only pasture grown or conserved on-farm (2.5 cows/ha). Cropping and PKE treatment herds offered forage crops grown on-farm or PKE, respectively, in addition to pasture grown or conserved on-farm (2.7 cows/ha and 2.8 cows/ha, respectively).

5.3.1.1 Gross farm revenue

On average, GFR per hectare was 16% less ($1,129) in the Pasture treatment, relative to the PKE treatment, but not significantly different in the Cropping treatment. Treatment effects on GFR per hectare were primarily a result of differences in milk production and, hence, revenue from milk sales, with an additional small effect due to revenue from stock sales between the PKE and Pasture treatments. This is in agreement with the conclusions reported by others that investigated the use of supplementary feed within a pasture-based system (DairyCo, 2012; Hanrahan et al., 2018; Ma et al., 2018; Macdonald et al., 2017; Neal & Roche, 2018; Ramsbottom et al., 2015; Shadbolt et al., 2017; Silva-Villacorta et al., 2005).

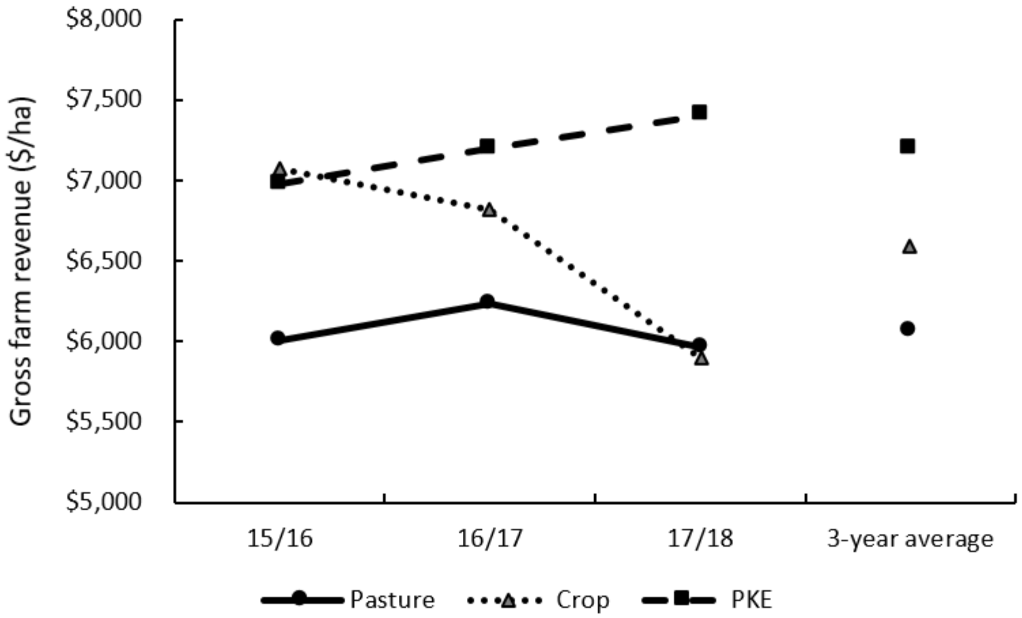

Figure 48: Effect of treatment on gross farm revenue per hectare by year and 3-year average.

5.3.1.2 Operating expenses

Average operating expenses per ha were 17% ($831) lower in the Pasture treatment relative to the PKE treatment, but not significantly different in the Cropping treatment (Figure 49). The effect of treatment on operating expenses between the PKE and Pasture treatments is in agreement with the general conclusions that offering imported supplementary feed within pasture-based systems increases operating expenses per hectare (Hanrahan et al., 2018; Ma et al., 2018; Macdonald et al., 2017; Neal & Roche, 2018; Ramsbottom et al., 2015; Silva-Villacorta et al., 2005). For example, in a three year analysis of farm financial data, Ma et al. (2018) reported that operating expenses were 10.9% lower per hectare in ‘low’ relative to ‘medium’ input pasture-based systems.

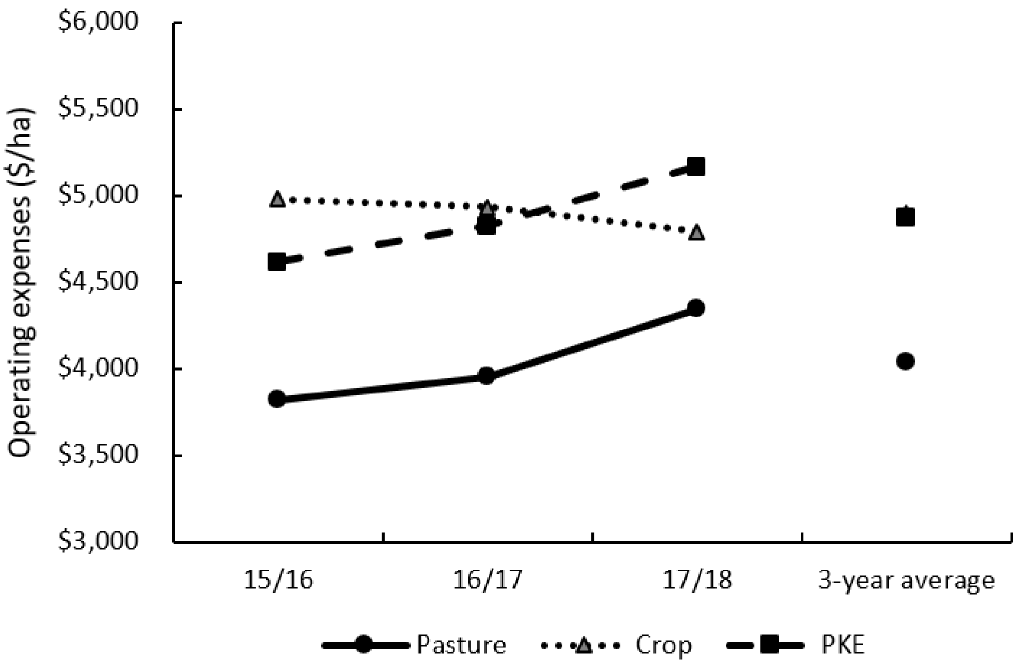

Figure 49: Effect of treatment on total operating expenses per hectare by year and 3-year average.

Average operating expenses per hectare were similar in the PKE and Cropping treatments, but milk production/ha was numerically less in the Cropping treatment in Yr 2 and 3; therefore, operating expenses/kg MS were consistently greater in the Cropping treatment in all three experimental years (Figure 50). In comparison, average operating expenses were similar in the Pasture ($4.41/kg MS) treatment relative to the PKE treatment ($4.45/kg MS; Figure 50). The effect of treatment on operating expenses/kg MS, when the PKE and Pasture treatments were compared, was linearly related to the response to supplementary feed (Figure 51).

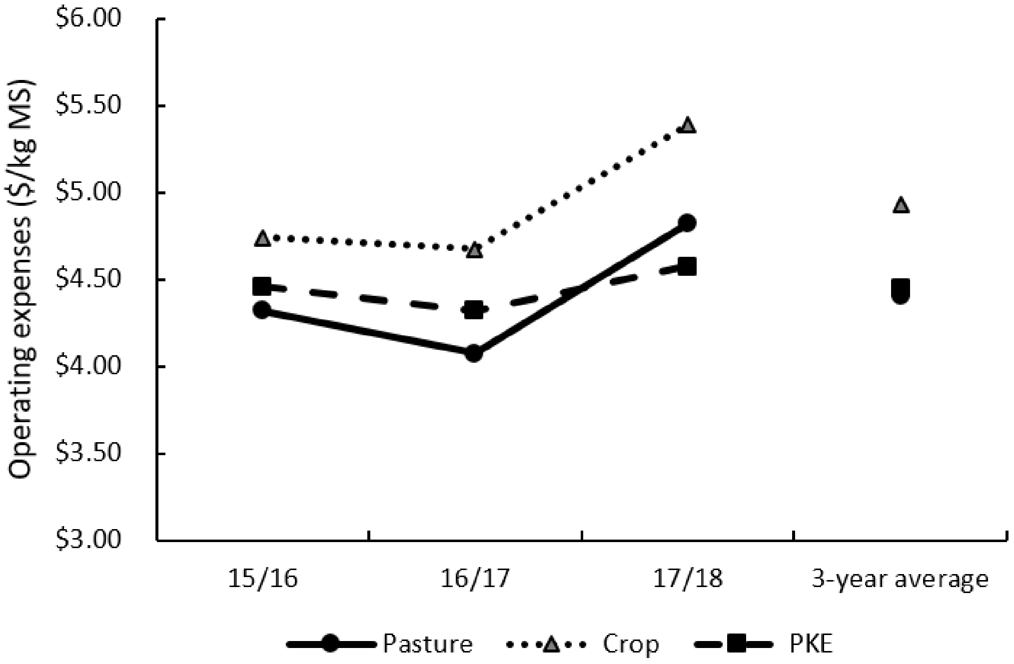

Figure 50: Effect of treatment on operating expenses per kg MS by year and 3-year average.

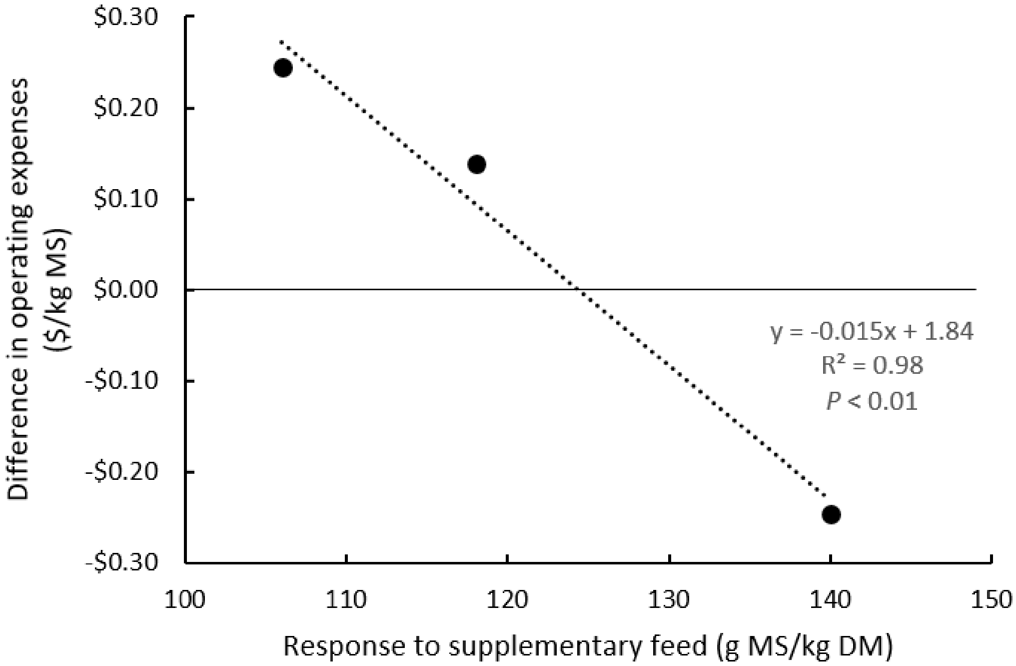

Figure 51: Effect of response to supplementary feed on the difference in average operating expenses per kg MS between the PKE and Pasture treatments.

On average, across all treatments, total expenses increased by between $1.55 and $2.13 (average $1.89) for every $1 increase in feed related expenses (grass silage, imported supplementary feed, and cropping expenses; Figure 52). This non-proportional increase in total operating costs with increased expenditure on imported supplementary feed is consistent with international studies of farm databases (DairyCo, 2012; Neal & Roche, 2018; Ramsbottom et al., 2015). For example, Ramsbottom et al. (2015) reported an associated increase in total expenses of €1.53/ha for every €1/ha increase in purchased feed expenses. In addition, Neal and Roche (2018) reported an associated increase in total operating expenses of $1.66 for every additional $1 spent on imported feed and crops in pasture-based systems in Waikato NZ.

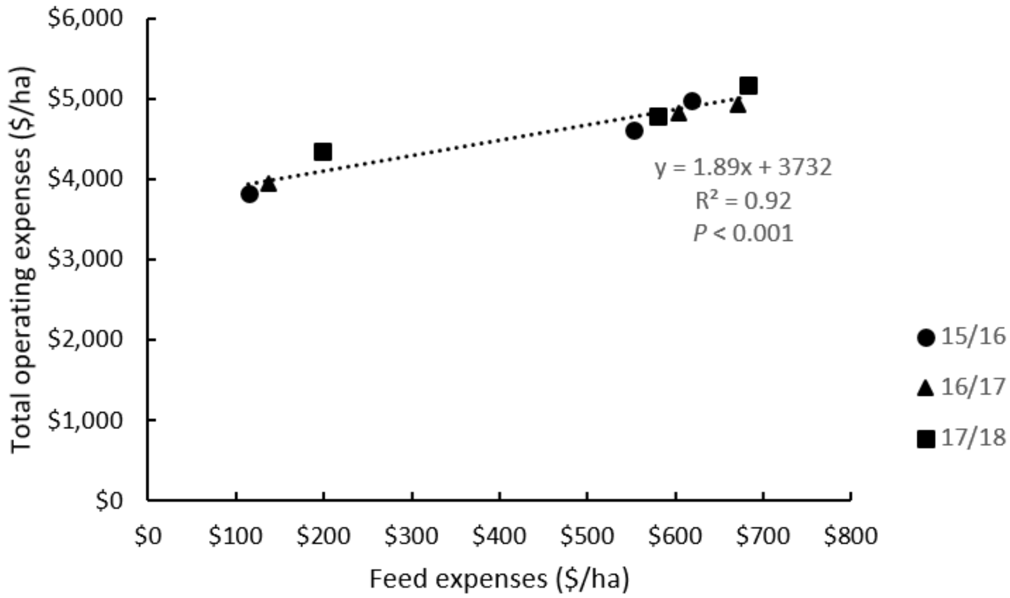

Figure 52: Effect of feed related expenditure per hectare on total expenditure per hectare across treatment and within year.

5.3.1.3 Operating profit

The net difference, or lack thereof, in operating profit between treatments was a result of treatment effects on GFR and operating expenses per hectare. Despite no significant differences in GFR and operating expenses per hectare between the PKE and Cropping treatments, on average, operating profit per hectare tended ($P < 0.15$) to be lower in the Cropping treatment relative to the PKE treatment. On average, operating profit per hectare was $701 lower in the Cropping treatment relative to the PKE treatment (Figure 53). In contrast, there was no significant difference in operating profit per hectare between the Pasture and PKE treatments; numeric differences in operating profit between these Pasture and PKE treatments between years were linearly related to the response to the supplementary feed (Figure 54). On average, operating profit per ha was $151 lower in the Pasture treatment relative to the PKE treatment, equivalent to less than 10% of total operating profit (Figure 53). On average, despite the large MMPR to supplementary feed achieved in the current study, there was no significant difference in operating profit per hectare between the PKE treatment and Pasture treatments.

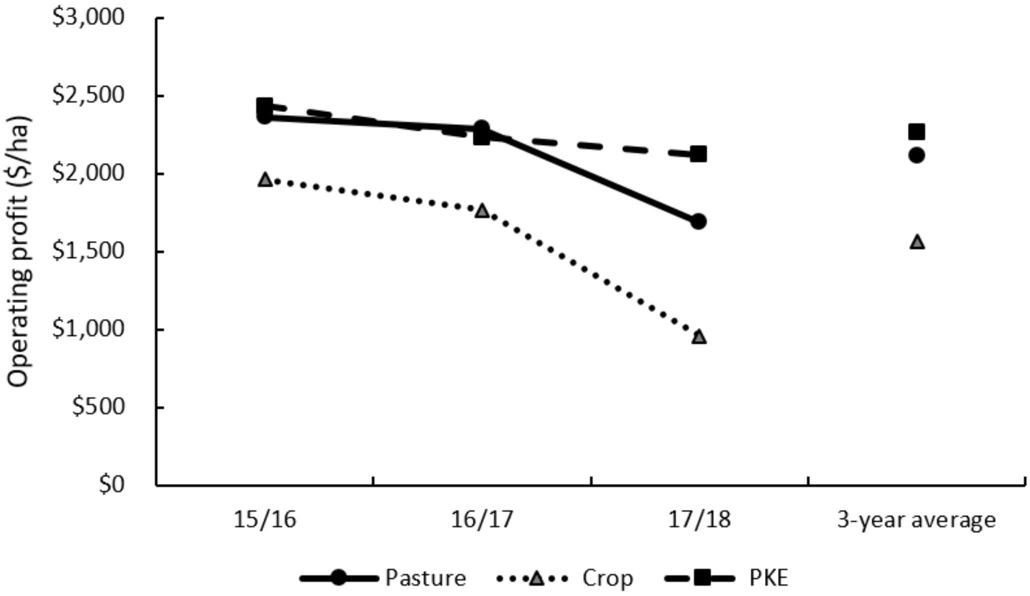

Figure 53: Effect of treatment on operating profit per hectare by year and 3-year average.

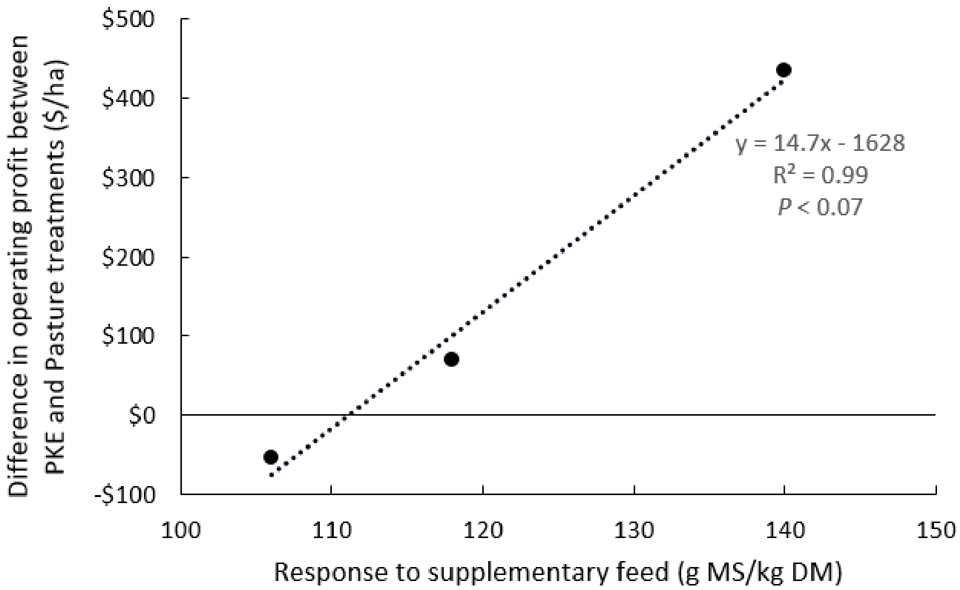

Figure 54: Effect of response to supplementary feed within the PKE treatment on the difference in operating profit between the PKE and Pasture treatment.

The effect of offering imported supplementary feed within a pasture-based system on operating profit in the current study is not consistent with the general conclusions reported in the literature. Increasing the level of imported supplementary feed offered in a pasture-based system has been reported to lower operating profit (Macdonald et al., 2017; Neal & Roche, 2018; Ramsbottom et al., 2015) and ROA (Ma et al., 2018). Therefore, in the current study, the removal of PKE from a pasture-based system could have been expected to have had a positive effect on operating profit per hectare. For example, Macdonald et al. (2017) reported 25% and 18% lower operating profit per hectare when offering 1.3 t DM/cow as cracked corn grain ($1390) or 1.1 t DM/cow as corn silage ($1812) relative to a system with no imported supplementary feed ($1845). Outcome differences between the current study and that reported by Macdonald et al. (2017) reflect differences in both the MMPR to supplementary feed and the milk price used within the analyses. Macdonald et al. (2017) reported responses to imported feed of between 73 and 97 g MS/kg DM relative to an average MMPR to supplementary feed of 118 g MS/kg DM achieved in the current study. These differences in the MMPR to supplementary feed were reflected in differences in the cost of the marginal milk between these studies. Macdonald et al. (2017) reported a cost of marginal milk of $0.76/ kg milk ($6.27/ kg MS) and $0.72/ kg milk ($5.43/ kg MS) when corn grain or corn silage were offered, respectively. In comparison, in the current study, the average marginal cost of milk between the PKE and Pasture treatments was less at $4.87/kg MS (range $3.61 to $5.73/kg MS). This difference in the marginal cost of milk between these studies, in addition to a comparatively greater milk price used within my analyses ($6.16/kg MS vs $5.50/kg MS), explain the outcome differences between these studies.

At average market prices, despite consistently large MMPRs to supplementary feed, there was no significant difference in operating profit per hectare between the PKE treatment and Pasture treatments, with any numerical difference being less than 10% of total operating profit.

5.4 Stochastic analyses

A stochastic model was used to analyse the effect of variation in key input prices to treatment effects on operating profit. @Risk software (Palisade, 2017) was used to perform a Monte Carlo analysis, with distributions attached to key input variables to determine the likely variation in operating profit, given the inherent variability of the input variables. The result of this stochastic analysis are displayed in Figure 55 as CDF for each treatment; these detail the likely distribution of operating profit. A CDF is a useful tool to guide medium to long-term decision making, as it allows for the stochastically dominant set (i.e., the preferable scenario) to be determined (Hardaker, Gudbrand, Anderson, & Huirne, 2015). If a CDF lies entirely below and to the right of another, the treatment yields a preferable outcome at every probability level and is said to be stochastically dominant in the first degree (Hardaker et al., 2015).

If the CDF's cross, neither treatment is preferable across every probability level. For a treatment to be preferable to another, the potential advantage from selecting the treatment over the other must outweigh the potential disadvantage. This is apparent when the area framed by the curves, above and to the right of the point of intersection, is less than that below and to the left of the intersection (Hardaker et al., 2015). Second order stochastic dominance is established when this condition holds provided that the dominating treatment also has a minimum value for x which is greater than the dominated treatment (Hardaker et al., 2015).

In the current study, the Cropping treatment was first order stochastically dominated by the PKE treatment as defined by the lack of intersection between the CDF functions and the greater operating profit of the PKE treatment. Despite the intersection of the CDF's for the Cropping and Pasture treatments at the upper end of the distributions, the Pasture treatment outperformed the Cropping treatment in the majority of scenarios (> 90%) and returned a greater minimum operating profit. As a result, the Cropping treatment was second order stochastically dominated by the Pasture treatment. Therefore, when accounting for the likely variability of key input prices, the Cropping treatment was the least favourable treatment, irrespective of the risk aversion of the decision maker.

The CDF functions for the PKE and Pasture treatments intersect, therefore, neither treatment was preferable at every probability level. The PKE treatment returned a greater operating profit in approximately 70% of scenarios and returned, on average, a greater operating profit. However, the Pasture treatment outperformed the PKE treatment when operating profit was low or negative and returned a greater minimum operating profit. As a result, neither the conditions of first order nor second order stochastic dominance held between the Pasture and PKE treatments; a profit maximising decision maker's preference between the treatments is dependent on their degree of risk aversion when facing market volatility. For example, a particularly risk averse decision maker may prefer the Pasture treatment, as it minimises economic losses when market conditions are unfavourable (e.g., low milk prices and high supplementary feed costs).

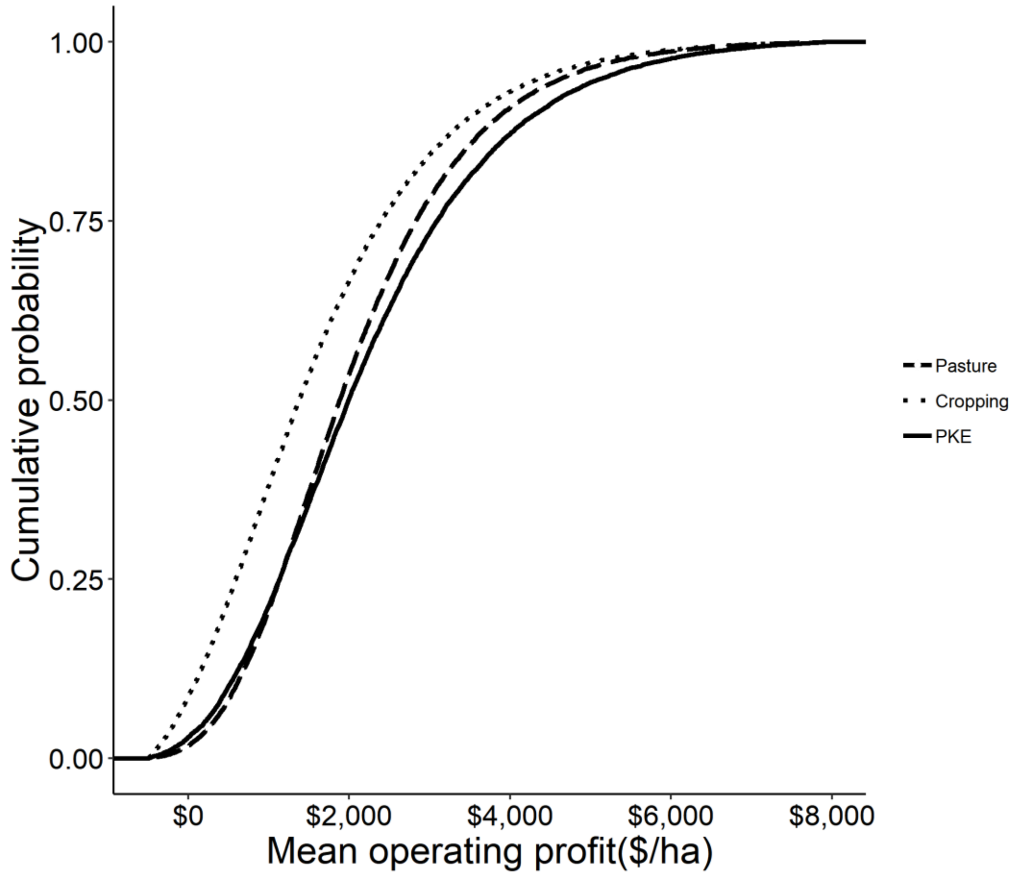

Figure 55: Cumulative probability density functions for the PKE, Pasture and Cropping treatments.

Total risk (i.e., standard deviation of operating profit), including potential upside and downside risk, was 14% and 7% lower in the Pasture and Cropping treatments relative to the PKE treatment which was comparable to the proportional differences in production between these treatments. However, the proportion of scenarios in which a negative operating profit was observed was similar in the Pasture (2%) and PKE (4%) treatments but greater in the Cropping treatment (12%). In all treatments, milk price was the single largest factor causing variation in operating profit (Figure 56, Figure 57, and Figure 58) accounting for 38% of the total variation in operating profit per hectare in all three treatments and assuming no change in farmer behaviour associated with a high or low milk price. Within the PKE treatment, risk due to milk price alone accounted for more than twice the risk due to variation in PKE price (Figure 56).

A decision maker's preference between the PKE and Pasture treatments is dependent on their risk aversion. The proportion of scenarios in which a negative operating profit was observed were similar in the PKE and Pasture treatments. In addition, the PKE treatment returned a greater operating profit relative to the Pasture treatment in 70% of scenarios. The net potential economic advantage of the PKE treatment relative to the Pasture treatment in favourable market conditions outweighed the net disadvantage in unfavourable market conditions. Therefore, the PKE treatment would likely provide a preferable system for a decision maker with low-to-moderate risk aversion when accounting for the likely variability of market prices.

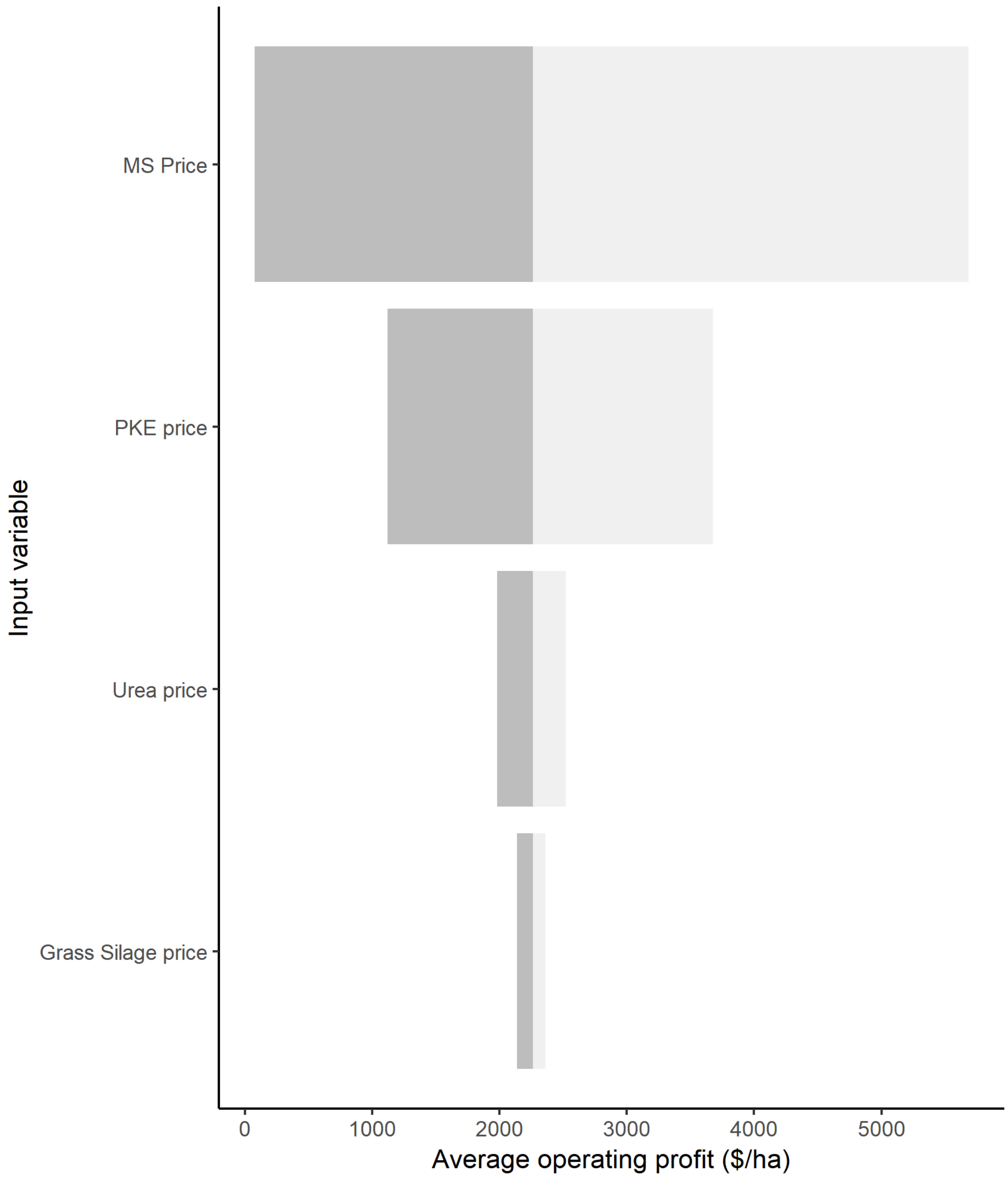

Figure 56: Tornado graph of the relative effect of risky inputs on operating profit per hectare in the PKE treatment.

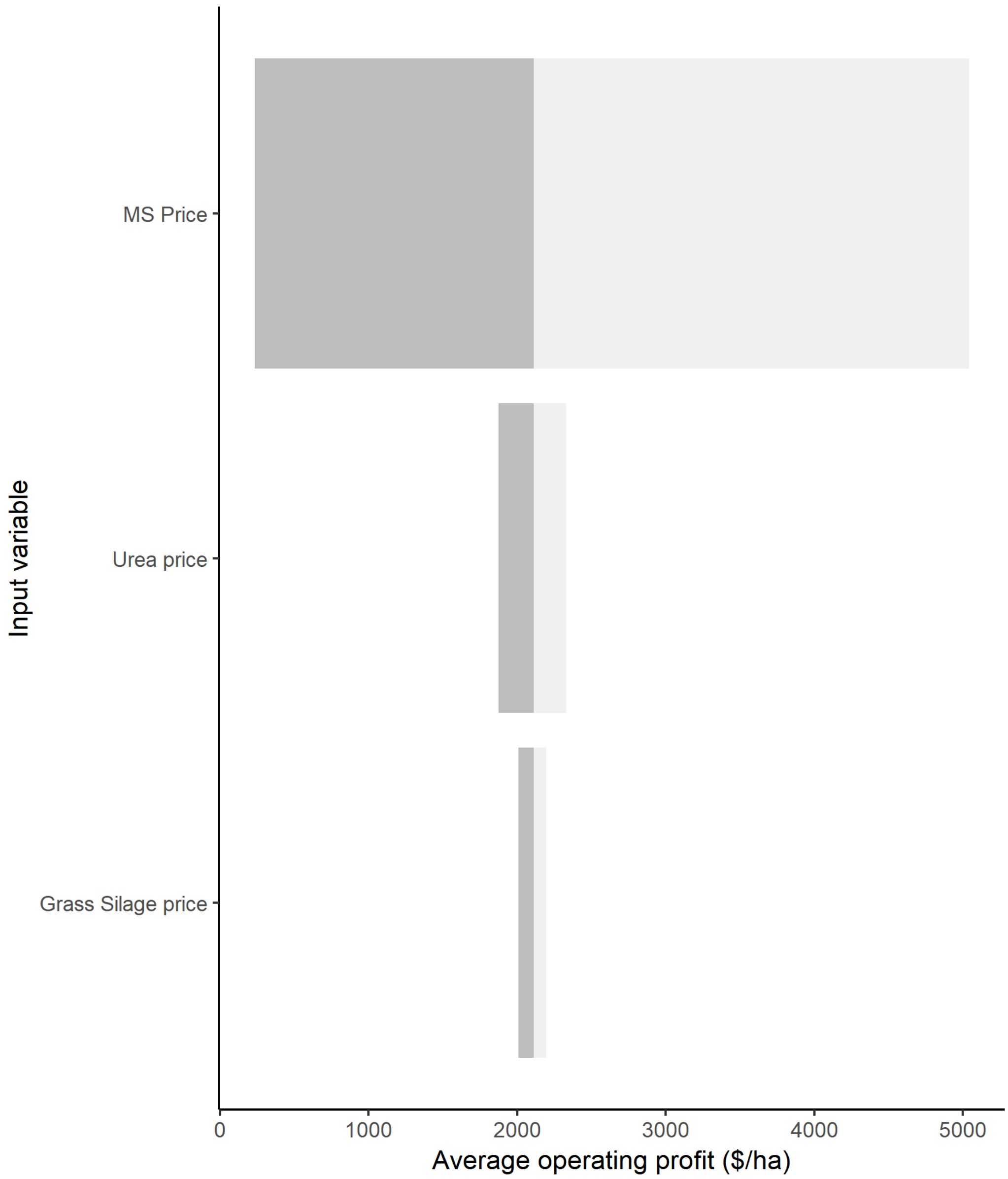

Figure 57: Tornado graph of relative effect of risky inputs on operating profit per hectare in the Pasture treatment.

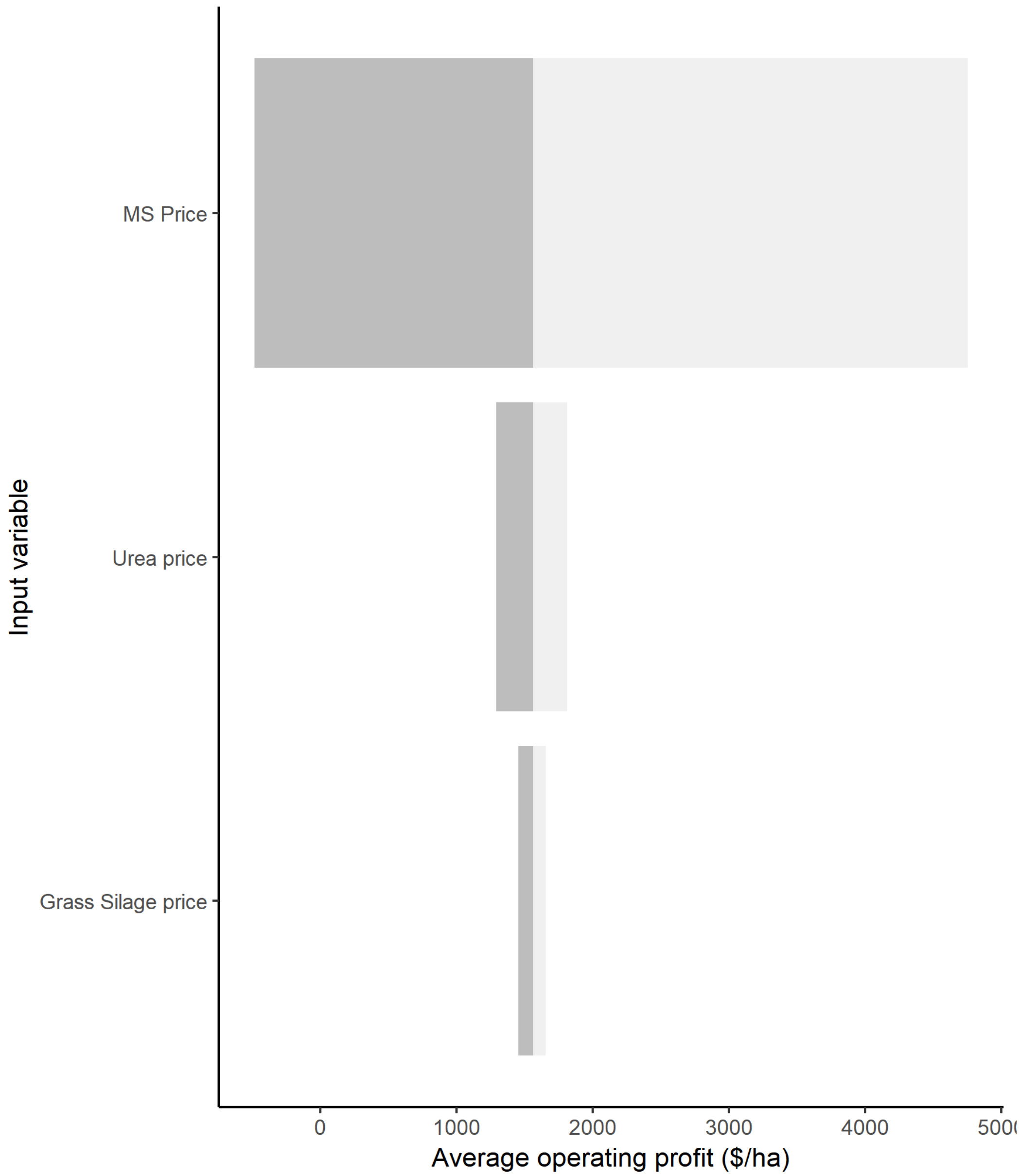

Figure 58: Tornado graph of relative effects of risky inputs on operating profit per hectare in the Cropping treatment.

5.5 Sensitivity of profitability to the biophysical response to supplementary feed

As presented in Figure 54, the difference in profitability between the PKE and Pasture treatments was sensitive to the MMPR to supplementary feed. In addition, as discussed in Chapter 3, the response to supplementary feed in the current study was 20 - 60% greater than other systems-level responses to supplementary feed reported within the literature (Bargo et al., 2003; Horan, Dillon, Faverdin, et al., 2005; Macdonald et al., 2017; Penno, Bryant, Macdonald, et al., 1996). Therefore, it is necessary to evaluate the sensitivity of these economic conclusions to lower milk production responses to supplementary feed.

In the stochastic analysis, a reduction in the response to supplementary feed by 9% to 111 g MS/kg DM, resulted in no numerical difference in median operating profit per hectare between the PKE and Pasture treatments (Figure 59). If the imputed response to supplementary feed was reduced further to the average response deduced from national farm economic performance databases (M.Neal, personal communication, March 18th, 2019) and that reported by Bargo et al. (2003) of approximately 75 g MS/kg DM, the Pasture treatment second order stochastically dominated the PKE treatment, returning a greater operating profit in approximately 90% of scenarios (Figure 60). Further to this, at a response to supplementary feed of 40 g MS/kg DM, similar to the systems-level response to supplementary feed reported by Horan et al. (2005), the Pasture treatment first order stochastically dominated the PKE treatment, returning a greater operating profit per hectare at every probability level (Figure 61).

Therefore, the economic conclusions of the current study are highly sensitive to the response to supplementary feed. Above a response to supplementary feed of 111 g MS/kg DM, a decision maker’s preference between the PKE and Pasture treatments is dependent on their risk aversion, shifting in favour of the PKE treatment, as the response to supplementary feed increases. In contrast, below this breakeven response to supplementary feed the Pasture treatment second order stochastically dominates the PKE treatment and will be a preferable system for a profit-focussed decision maker irrespective of their risk aversion.

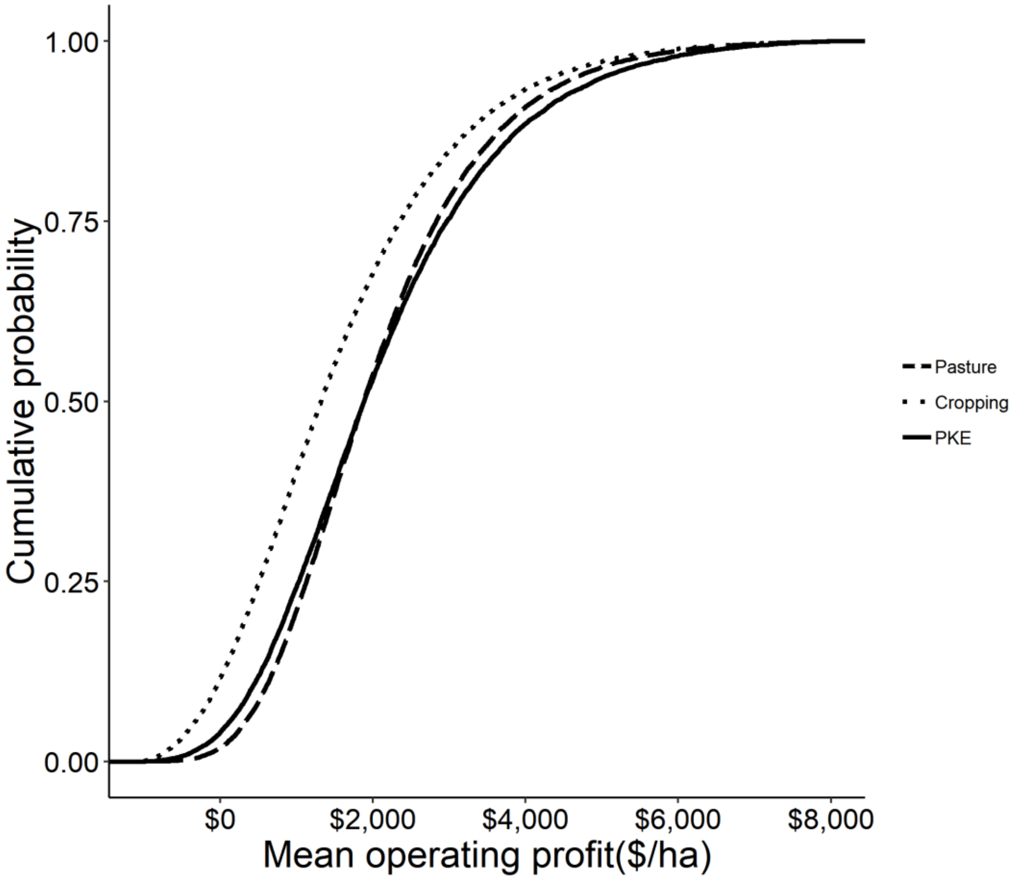

Figure 59: Cumulative probability density functions for the PKE, Pasture, and Cropping treatments at a response to supplementary feed of 111 g MS/kg DM.

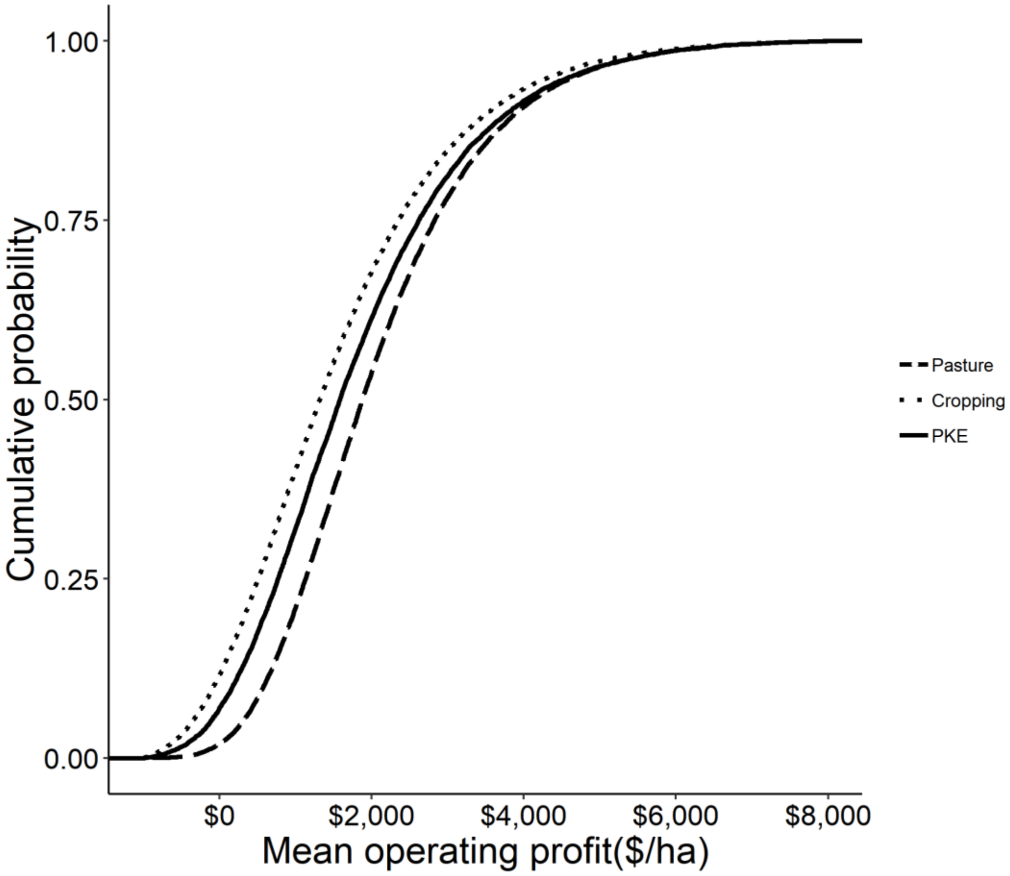

Figure 60: Cumulative probability density functions for the PKE, Pasture, and Cropping treatments at a response to supplementary feed of 75 g MS/kg DM.

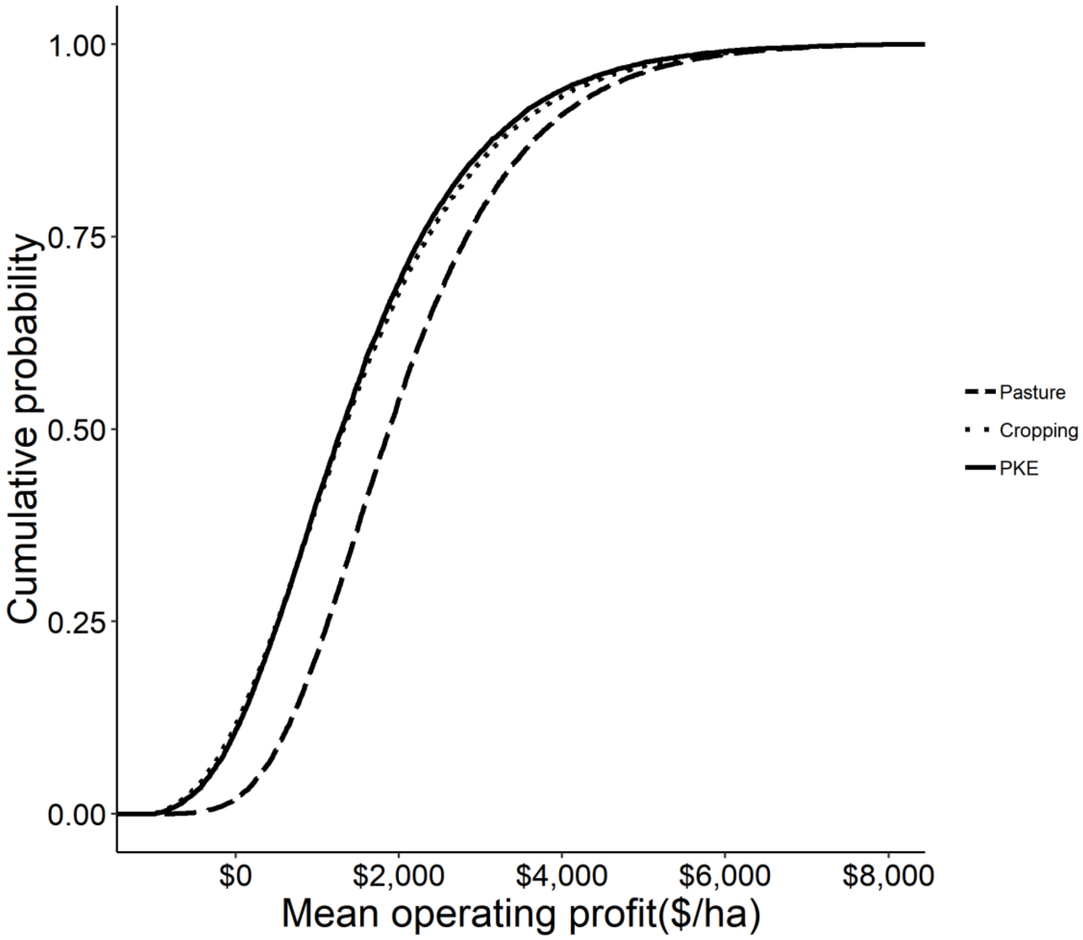

Figure 61: Cumulative probability density functions for the PKE, Pasture, and Cropping treatments at a response to supplementary feed of 40 g MS/kg DM.

5.6 Operating profit adjusted for environmental externalities

5.6.1 Deterministic analyses

As outlined in Chapter 4, treatment affected the total environmental externality associated with production, both with respect to N leached and GHG emitted per hectare. The externality adjusted operating profit, after accounting for the valuation of these differences in environmental externalities between treatments, is presented in Figure 62. Externality adjusted operating profit per hectare tended ($P < 0.1$) to be lower in the Cropping treatment relative to the PKE treatment. The value of lower GHG emissions in the Cropping treatment was insufficient to offset the cost of greater N leaching relative to the PKE treatment. As a result, the difference in externality adjusted operating profit per hectare between the PKE and Cropping treatments ($778/ha) was 11% greater than the difference in operating profit per hectare between the treatments ($701/ha).

In contrast, there was no difference in externality-adjusted operating profit per hectare between the PKE and Pasture treatments. Despite little difference in N leaching, GHG emissions were lower in the Pasture treatment relative to the PKE treatment, resulting in a lower total environmental externality in the Pasture treatment. As a result, valuation of environmental externalities further reduced the small numeric difference in operating profit between the PKE and Pasture treatments by 40% (from $151/ha to $89/ha).

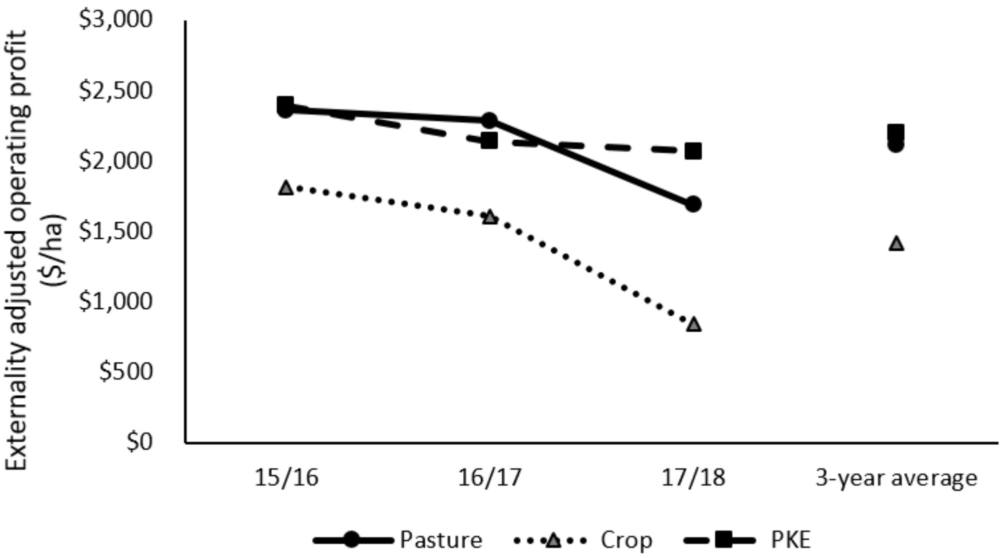

Figure 62: Effect of treatment on externality adjusted operating profit per hectare by year and 3-year average.

5.6.2 Stochastic analysis

Valuation of the difference in environmental externalities between treatments had no effect on conclusions with respect to stochastic dominance between treatments. However, despite a lack of effect on stochastic dominance between treatments, valuation of environmental externalities between treatments affected the proportion of scenarios under which the PKE treatment dominated the Pasture treatment. The PKE treatment outperformed the Pasture treatment in only 55% of scenarios (relative to 70% of scenarios for operating profit/ha).

Valuation of the difference in environmental externalities between treatments reduced the proportion of scenarios under which the PKE treatment returned a greater operating profit per. As a result, a decision maker with low-to-moderate risk aversion, paying or receiving incentives to reduce environmental externalities, would likely be indifferent between the PKE and Pasture treatments if achieving the very large MMPR to supplementary feed achieved in this study.

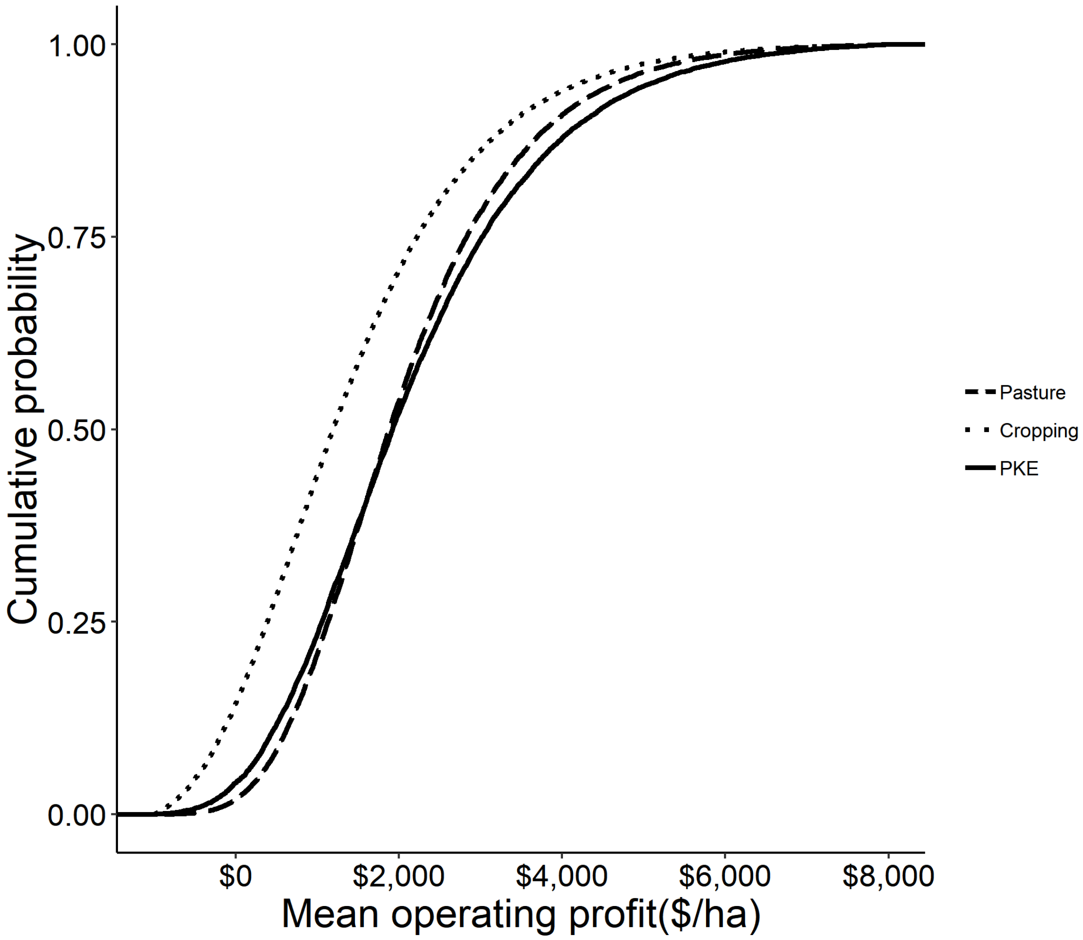

Figure 63: Cumulative probability density functions for externality adjusted operating profit for the PKE, Pasture, and Cropping treatments.

5.7 Conclusions

Despite significantly greater milk production and associated GFR in the PKE treatment, this was offset by greater operating expenses per hectare relative to the Pasture treatment. As a result, despite consistently large MMPR to supplementary feed in the PKE treatment, on average there was no significant difference in operating profit per hectare between the PKE and Pasture treatments. However, when accounting for the potential variability of key input prices, the PKE treatment returned a greater operating profit than the Pasture treatment in 70% of scenarios and, as a result, would likely provide a favourable system for a decision maker with low to moderate risk aversion.

The relative profitability of the PKE and Pasture treatments, however, was highly dependent on the MMPR to supplementary feed. A reduction in the MMPR to supplementary feed of less than 10% resulted in no numeric difference in the average operating profit of the PKE and Pasture treatments; furthermore, a reduction in the MMPR to supplementary feed to the average response reported in national databases (~75 g MS/kg supplementary feed DM) resulted in the Pasture treatment returning a greater operating profit in approximately 90% of scenarios. In addition, valuing environmental externality differences between treatments reduced the proportion of scenarios under which the PKE treatment returned a greater operating profit than the Pasture treatment. As a result, a decision maker with low to moderate risk aversion, paying or receiving incentives to reduce environmental externalities, would likely be indifferent between the PKE and Pasture treatments, even with the large MMPR to supplementary feed achieved in the current experiment.

Despite no significant effect of treatment on milk production, GFR and operating expenses per hectare, as a result of an accumulation of numeric differences, operating profit tended to be lower in the Cropping treatment relative to the PKE treatment. Further to this, valuation of the differences in environmental externalities further increased the operating advantage of the PKE treatment relative to the Cropping treatment.

Chapter 6: Experimental limitations

I had a unique opportunity to analyse the biophysical, environmental, and economic effects of removing a small quantity of imported supplementary feed (~ 550 kg DM PKE /cow/yr; ~10% of cow's annual diet) from a pasture-based dairy system. I used a quantitative case study approach in a multi-year experiment, which provides a degree of reality sometimes missing from very controlled research farm environments. I was fortunate to have large treatment herd sizes relative to published component and systems experiments, which increases the likelihood of herd-level effects that complicate real-life scenarios presenting themselves when compared with small-scale farm systems experiments undertaken previously. The current experiment was conducted on heavy-textured clay soils in Northland, New Zealand, with kikuyu forming a seasonal component of the pasture sward; this is very different to the majority of published work, where research is undertaken in centres of traditional dairy production and, therefore, better land classes and climate.

Despite the advantages of my approach, as with any applied experiment, it is important to consider the limitations of the methodology used and the associated data before extending the conclusions of this study beyond the conditions under which it was undertaken.

6.1 General experimental limitations

One of the strengths of the current experiment is that it compared three different farm system treatments over three consecutive years; this allowed for an understanding of the potential variation in treatment effects across a range of climatic conditions. However, a potential limitation of the experimental design was a lack of spatial replication (i.e., treatment replication). Spatial replication would have allowed for differentiation between natural variation and treatments effects and, therefore, provided greater statistical power to detect differences between treatments. However, this experiment was undertaken at a regional demonstration farm with limited resources. Furthermore, it has been recognised that, within a farm system context, replication across years is of greater value than replication within years due to inherently large between year variability in biophysical outcomes (Connolly, 2018; McMeekan, 1960), providing some validation of the decision to replicate across years as opposed to within year in the current content.

A further limitation relates to the length of the experiment; although the experiment was conducted for three years, it did not capture the full potential variability of climatic conditions in three years; therefore, variation in the financial conclusions across years may not be fully captured within this analysis. However, the average annual rainfall across the three years of the experiment (1,113 mm) was similar to the 10-year historic average (1,106 mm). Therefore, the three experimental years analysed are representative of expected conditions, providing relevance to long-term decision making.

If I were to conduct this experiment again with greater resources, I would spatially replicate treatments and extend the treatment period to 5 years.

6.2 Biophysical chapter limitations

Conclusions with respect to pasture-related variables were limited by the completeness and frequency of measurement of pasture data. The pre-grazing mass, post-grazing mass and grazing dates of individual paddocks were not recorded in the current study. As a result, as described in the methods section, pasture variables were estimated from farm walk data measured at weekly or fortnightly intervals. Pre-grazing and post-grazing mass were estimated from the average of the three greatest and three lowest herbage mass measurements for the day of measurement, respectively. This approach could, potentially, result in an overestimation of post-grazing mass, as two of the measures within the average would have had time to regrow after grazing and before measurement, and a slight underestimation of pre-grazing covers, as two of the measurements would have had additional time after measurement to accumulate before grazing. The size of this effect would have been affected by rotation length and, therefore, was probably seasonally dependent. However, this effect was common across all treatments and, therefore, would not be expected to materially affect conclusions.

The frequency of measurement was also a hindrance to detecting differences in pasture variables between treatments, if they existed. Pasture walks were conducted fortnightly during busy periods. During periods of high pasture growth (i.e., spring or autumn), a large number of paddocks would have been grazed during a fortnightly measurement period. As a result, fortnightly recording reduced the number of measurements from which to estimate growth, potentially reducing the likelihood of detecting differences between treatments.

In the current study, although the measurement of pasture related variables was sufficient to guide decision making from a pasture management perspective, the completeness and frequency of measurement of pasture variables limited the ability to detect differences in pasture variables between treatments. Whilst, conclusions with respect to pasture variables were not central to the objectives of the study, with hindsight, they were important for estimating the RFD and, hence, the ability to explain the large MMPRs to supplementary feed achieved in the current experiment. If I were to conduct this experiment again, in the absence of funding and resource constraints, I would ensure greater measurement of pasture variables, including the measurement and recording of all pre-grazing and post-grazing pasture mass and grazing dates for individual paddocks.

Conclusions with respect to the relatively poor financial outcomes of the Cropping treatment are not transferable to all conditions, as they were dependent on the climatic and farm physical conditions that affected the crop yields in the current study. These conclusions could, also, be affected by crop species selection and are, likely, soil type dependent. However, the wider conclusions that cropping increases production risk, and hence, market/price risk are likely transferable. In addition, the difficulties of maximising crop yields on the milking platform without comprising pasture production is universal across farming systems as extending the growth period of either pasture or crop, reduces the growing period of the other, thereby compromising growth.

6.3 Environmental chapter limitations

Environmental output variables (e.g., N leaching and GHG emissions) were not directly measured in the current experiment; instead, these were modelled through Overseer (version 6.3.1). Therefore, conclusions with respect to treatment effects on environmental outcomes are subject to the limitations and uncertainty of the model. Although concerns have been raised with regard to the use of Overseer in a regulatory framework, Overseer is widely considered the 'best available option' for estimating the environmental footprint at a farm scale (Dunbier et al., 2013; Maseyk et al., 2018).

6.4 Economic chapter limitations

Due to the research farm operating as a single entity and the resultant structure of the accounting system, published per cow and per hectare ratios were used to apportion the majority of expenses between treatments. Whilst this is a scientifically accepted method, it presents limitations to the applicability of conclusions to individual farming businesses, as the nature of many expense items may differ between businesses in reflection of unique resource bases. However, the analysis presents a reasonable approximation for an average farming business; furthermore, while between farm variations may affect the proportion of scenarios over which one treatment is favourable to another, the wider stochastic relationships between treatments are likely to be independent of farm businesses. Within the economic analyses, the distribution of key input prices was estimated from inflation adjusted historic prices. This does not account for any future trends in input or milk prices which presents a potential future limitation.

It is also important to recognise that farmers make decisions for many reasons (e.g., value-based judgements; Pannell et al., 2006); there are a number of aspects, beyond profit, that create value for individuals and may influence their preference for one type of farming system over another. For example, the numeric differences in BCS between treatments in early-lactation can be an emotive factor causing a decision maker to prefer the PKE treatment over the Pasture treatment. The many social, cultural and personal factors affecting decision making should be considered when providing farmers with advice on how to strategically optimise their businesses; however, value judgements and preferences beyond profit maximisation and environmental considerations have not been a focus of my study.

Chapter 7: General discussion

The objective of my Masters experiment was to determine the biophysical and, associated, environmental and economic effects of removing PKE from a pasture-based grazing system, by either:

1) re-aligning feed demand with pasture supply by decreasing SR; or

2) growing potentially high yielding forage crops on the dairy platform to increase feed supply above what could be produced by pasture alone and, thereby enabling the same SR to be supported.

7.1 Large milk production responses to imported supplementary feed were achieved

As presented in Chapter 3, there were consistently larger than anticipated milk production responses to imported supplementary feed. Average MMPR to supplementary feed (122 g MS/kg DM) were 60% greater than the average reported by Bargo et al. (2003) in their review of short term component analyses and approximately 20 - 60% greater than other systems-level responses reported from experiments in pasture-based grazing systems (Horan, Dillon, Faverdin, et al., 2005; Macdonald et al., 2017; Penno, Bryant, Macdonald, et al., 1996).

In the current study, due to animal ethics considerations, reduced milking frequency (OAD) was practiced in the 17/18 season for a 6-week period in early-lactation in the Pasture and Cropping treatments. Reduced milking frequency is reported to have a negative effect on mammary secretary cell number and activity, negatively affecting milk production in both the period of reduced milking frequency (immediate effect) and, subsequently, for the remainder of the lactation (carry-over effect; Grala et al., 2011; Hale et al., 2003; Nørgaard et al., 2005; Wall et al., 2006). As a result, the MMPR to supplementary feed in the 17/18 season and, hence, the average response across the experiment, were likely positively influenced by this OAD effect. Nevertheless, even after accounting for this effect of OAD milking, the average MMPR to supplementary feed in the current experiment (114 g MS/kg DM) was approximately 20% greater than other system-level responses reported in the literature (Macdonald et al., 2017; Penno, Bryant, Macdonald, et al., 1996).

The experimental design did not allow me to conclusively determine further potential causes of this comparatively large MMPR to supplementary feed. However, this large response potentially reflects differences in RFD associated with pasture species. The RFD of the cow has been reported to be the most important factor affecting the milk production response to supplementary feed (Penno, 2002). I postulated that the negative effect of kikuyu pastures on the quality of the diet contributed to a relatively larger RFD and, hence, the greater response to supplementary feed relative to what may have been achieved in a ryegrass sward, all other factors being equal. This premise is supported by Fulkerson et al. (2008), who reported similar average responses to supplementary feed over a 5-year period in a farm system with a kikuyu dominant sward.

Although I cannot determine the cause with certainty, large responses to supplementary feed were achieved in the current study and these were a fundamental factor affecting the biophysical, environmental, and economic conclusions of this study. Further research into the effect of pasture quality on the RFD and the response to supplementary feed must be undertaken to enable a better prediction of the biological response to supplementary feed.

7.2 There was no difference in nitrogen leaching between the PKE and Pasture treatments, despite differences in stocking rate and feed intensity

As presented in Chapter 4, the removal of a relatively low quantity (500 kg DM/cow/year) of a low-to-moderate CP supplementary feed from a pasture-based system was not an effective strategy to reduce modelled N leaching. Despite a lower SR and the removal of imported supplementary feed from the farm system, there was no effect of treatment on modelled N leaching between the Pasture and PKE treatments. Furthermore, although modelled N leached increased when modelled on a fine textured soil, the lack of treatment effect on N leaching between the PKE and Pasture treatments remained and was independent of soil type. Although N surplus was numerically lower, a greater proportion of surplus N was leached in the Pasture treatment relative to the PKE treatment. This was potentially due to the effect of a greater dietary CP content and, hence, greater N concentration in the urine from cows on the Pasture treatment.

The current study identified limitations to the use of N surplus to predict differences in N leaching between farm systems due to differences between farm systems in the risk of this surplus N leaching. In addition, the results of the current study support the conclusions of Roche et al. (2016) that reducing SR, per se, will not necessarily reduce N leaching within a pastoral grazing system. The effect of system changes on N leaching will be dependent on the quantity, concentration, and timing of deposited urinary N. Farm systems analyses, such as those conducted in the current study, are necessary to analyse the full potential effect of farm systems changes.

7.3 Total greenhouse gas emissions were greater in the PKE treatment relative to the Pasture treatment, largely because of methane emissions

As reported in Chapter 4, and in contrast to the conclusions discussed for N leaching, the removal of imported supplementary feed from a grazing system, alongside a corresponding reduction in SR, was an effective strategy to reduce total GHG emissions. Differences in total modelled GHG emissions were primarily due to differences in methane emissions. As milk production was lower in the Pasture treatment relative to the PKE treatment, methane emissions and, hence, total emissions, were lower in the Pasture treatment relative to the PKE treatment.

Similar to the conclusions of Ledgard et al. (2017), there were no differences in emissions intensity (CO_2-equivalents/kg MS) between treatments. This lack of difference in emissions intensity between treatments further confirms that differences in total GHG emissions between treatments were primarily affected by differences in DMI (as represented by production), as opposed to differences in environmental efficiency between treatments. The results of the current study and those of Ledgard (2017) suggest there is limited scope to reduce the emissions intensity through farm system change. As a result, in the absence of commercially available solutions to reduce methane emissions, reducing production appears to be the only available solution to decreasing total emissions from pasture-based grazing systems in the short- to medium-term.

7.4 There was no significant difference in operating profit between PKE and Pasture treatments, despite very large milk production responses to supplementary feed

As reported in Chapter 5, on average, there was no significant difference in operating profit per hectare between the PKE and Pasture treatments, despite the large responses to supplementary feed discussed in Chapter 3. Milk production and hence, GFR was greater in the PKE treatment relative to the Pasture treatment. However, total expenses per hectare were also greater, because the imported supplementary feed was used to increase cow numbers. Total expenses increased by between $1.55 and $2.13 for every $1 increase in feed expenditure; these results are similar to the those reported in the literature (DairyCo, 2012; Neal & Roche, 2018; Ramsbottom et al., 2015). The increase in fixed and variable costs associated with greater cow numbers in the PKE treatment offset the greater GFR associated with offering PKE. As a result, removing PKE and reducing SR had no effect on operating profit at average market prices. However, when accounting for the variability of market prices, the PKE treatment outperformed the Pasture treatment in approximately 70% of scenarios and, therefore, would likely provide a preferable system for a profit focussed decision maker with low-to-moderate risk aversion, if they were able to consistently achieve the large MMPR to supplementary feed achieved in this study.

The relative profitability of the PKE and Pasture treatments was highly dependent on the MMPR to supplementary feed. If the average MMPR to supplementary feed was 10% lower (i.e., the extreme effects of the third season were removed), there was no profit advantage from offering imported supplementary feed in a pasture-based grazing system, even though the responses to supplementary feed were 20% greater than the average of other system-level experiments (Macdonald et al., 2017; Penno, Bryant, Macdonald, et al., 1996). Furthermore, if MMPR was reduced to the average response deduced from the national financial benchmarking database in New Zealand, the Pasture treatment would return a greater operating profit in approximately 90% of scenarios.

The results of the current analysis suggest a trade-off between using supplementary feed to increase SR and the greater fixed and variable costs associated with increased cow numbers. This trade off requires careful consideration when analysing the economic effects of feeding imported supplementary feed within pastoral grazing systems.

7.5 Total cost benefit was similar between the PKE and Pasture treatments

As discussed in Chapter 5, when the differences in environmental externalities between treatments (reported in Chapter 4) were valued, the proportion of scenarios in which the PKE treatment returned a greater operating profit relative to the Pasture treatment were reduced. As a result, a decision maker, paying or receiving incentives to reduce environmental externalities, would likely be indifferent between the PKE and Pasture treatments, even with the large MMPRs to supplementary feed achieved in the current study.

7.6 Cropping was not a biophysically, economically, or environmentally efficient alternative to importing PKE on the soil type evaluated

Despite achieving similar responses to net additional feed supplied per MJ ME in the Cropping treatment, on average, milk production, and hence, GFR, was numerically less in the Cropping treatment relative to the PKE treatment. Nevertheless, total expenses per hectare were similar in the Cropping and PKE treatments. As a result, the Cropping treatment was first order stochastically dominated by the PKE treatment; that is, it returned a lower operating profit at every probability level. The Cropping treatment would, therefore, be considered an inferior system relative to the PKE treatment for a profit-focussed decision maker, irrespective of their degree of risk aversion. In addition, despite lower GHG emissions, associated with lower average production, N leaching was increased in the Cropping treatment relative to the PKE treatment. As a result, valuation of the difference in total environmental externalities between treatments further increased the operating profit advantage of the PKE treatment relative to the Cropping treatment.

7.7 Recommendations for future work

Concurrent increases in imported supplementary feed use and SR resulted in large MMPRs to supplementary feed, consistently greater than expected based on the average from published experiments. But, the effects of supplementary feed allowance and SR were inextricably linked; the multifactorial reasons for the MMPR to supplementary feed makes it difficult to determine, conclusively, the cause of these large responses. Increases in the quantity of supplementary feed offered within a pasture-based system are reportedly associated with an increase in SR (Silva-Villacorta et al., 2005). Therefore, I believe the results of the current study have identified a need to conduct further research to quantify the contribution of the different factors affecting the systems level MMPR to supplementary feed and, particularly, the influence of SR. This would be best achieved by conducting a two by two factorial experiment at two stocking rates (i.e. SR_1 and SR_2), with or without supplementary feeding (i.e., Pasture and PKE). With appropriate measurements, this would provide a greater understanding of the marginal value and marginal cost of stocking rate decisions and their interactions with supplementary feeding decisions in economic, environmental, social and biophysical outputs.

In addition, the current study identified potential regional differences in the MMPR, relative to responses achieved in more traditional dairying regions, potentially due to the influence of pasture species. Therefore, I believe it would be beneficial to conduct a case study analysis of national financial data, with paired farm comparisons within region; this would provide a greater understanding of the MMPR to supplementary feed being achieved within commercial operations, where management decisions likely affect the achieved MMPR when compared with heavily managed research experiments.

7.8 Conclusions

In conclusion, the results of my study suggest that milk production will likely be reduced, GHG emissions reduced and N leaching and profitability maintained by removing PKE and lowering SR in a pasture-based system. In contrast, milk production and associated GHG emissions will likely be maintained, with an increase in N leaching and a reduction in profitability by growing forage crops to maintain SR with the removal of PKE from a pasture-based system.

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Appendix I

Table 16: Profit and loss statement for the PKE, Pasture, and Cropping treatments (2015/16)

2015/16 ($/ha)	PKE	Pasture	Cropping
Income			
Income from milk	$6,380	$5,448	$6,469
Dividend (Ballance and LIC)	$48	$48	$48
Income from stock sales	$552	$508	$552
Gross farm income	$6,980	$6,004	$7,069
Farm working expenses			
Wages	$1,357	$1,191	$1,488
Animal health	$196	$182	$196
Breeding expenses	$214	$197	$214
Shed expenses	$116	$109	$116
Electricity	$194	$181	$194
Grazing	$391	$360	$391
Calf rearing	$62	$57	$62
Nitrogen	$220	$238	$225
Lime	$20	$20	$20
Regrassing- Italians	$111	$111	$70
Weed and pest	$14	$14	$14
Silage	$128	$115	$0
PKE	$425	$0	$0
Maize	$0	$0	$278
Turnips	$0	$0	$49
Fodder beet	$0	$0	$291
Total farm working expenses	$3,448	$2,776	$3,607
Vehicle expenses	$124	$99	$168
Vehicle & equipment depreciation	$398	$316	$537
Repairs and maintenance (flat-rate)	$256	$256	$256
Repairs and maintenance	$60	$48	$81
Administration	$132	$130	$132
Rates and insurance	$200	$196	$200
Non-farm working expenses	$1,169	$1,044	$1,373
Total operating expenditure	$4,617	$3,820	$4,980
Non-cash adjustments			
Value of change in silage inventory	$196	$194	$0
Value of change in BCS	$5	-$14	-$15
Cost of additional capital	$129	$0	$113
Operating profit (incl. non-cash adjustments)	$2,435	$2,364	$1,961
Environmental externality adjustments			
Nitrogen	$0	$0	$100
CO2 equivalents	$38	$0	$45
Externality adjusted operating profit	$2,397	$2,364	$1,817

Table 17: Profit and loss statement for the PKE, Pasture, and Cropping treatments (2016/17)

2016/17 ($/ha)	PKE	Pasture	Cropping
Income			
Income from milk	$6,884	$5,946	$6,504
Dividend (Ballance and LIC)	$7	$7	$7
Income from stock sales	$313	$284	$313
Gross farm income	$7,203	$6,237	$6,823
Farm working expenses			
Wages	$1,369	$1,205	$1,461
Animal health	$212	$195	$212
Breeding expenses	$187	$171	$187
Shed expenses	$86	$80	$86
Electricity	$213	$196	$213
Grazing	$393	$357	$393
Calf rearing	$85	$77	$85
Nitrogen	$253	$257	$243
Lime	$20	$20	$20
Regrassing- Italians	$140	$140	$50
Weed and pest	$36	$36	$36
Silage	$126	$137	$0
PKE	$478	$0	$0
Maize	$0	$0	$281
Turnips	$0	$0	$127
Fodder beet	$0	$0	$264
Total farm working expenses	$3,597	$2,873	$3,657
Vehicle expenses	$137	$107	$147
Vehicle & equipment depreciation	$438	$341	$471
Repairs and maintenance (flat-rate)	$256	$256	$256
Repairs and maintenance	$66	$52	$71
Administration	$132	$129	$132
Rates and insurance	$200	$196	$200
Non-farm working expenses	$1,229	$1,081	$1,277
Total operating expenses	$4,826	$3,954	$4,934
Non-cash adjustments			
Value of change in silage inventory	$3	-$9	$0
Value of change in BCS	-$17	$13	-$7
Cost of additional capital	$129	$0	$113
Operating profit (incl. non-cash adjustments)	$2,234	$2,288	$1,769
Environmental externality adjustments			
Nitrogen	$40	$0	$140
CO2 equivalents	$55	$0	$20
Externality adjusted operating profit	$2,139	$2,288	$1,609

Table 18: Profit and loss statement for the PKE, Pasture, and Cropping treatments (2017/18)

2017/18 ($/ha)	**Pasture**	**Cropping**	**PKE**
Income			
Income from milk	$5,530	$5,458	$6,934
Dividend (Ballance & LIC)	$20	$20	$20
Income from stock sales	$413	$419	$453
Gross farm income	$5,963	$5,897	$7,407
Farm working expenses	$0	$0	$0
Wages	$1,259	$1,359	$1,417
Animal health	$197	$200	$214
Breeding expenses	$210	$213	$229
Shed expenses	$75	$75	$80
Electricity	$214	$217	$232
Grazing	$368	$373	$403
Calf rearing	$75	$76	$82
Nitrogen	$368	$323	$342
Helicopter charges	$89	$89	$89
Lime	$20	$20	$20
Regrassing- Italians only	$102	$35	$113
Weed and pest	$28	$28	$28
Silage	$198	$58	$138
PKE	$0	$0	$544
Maize	$0	$353	$0
Turnips	$0	$170	$0
Fodder beet	$0	$0	$0
Total farm working expenses	$3,204	$3,586	$3,931
Vehicle expenses	$120	$133	$138
Vehicle & equipment depreciation	$382	$425	$443
Repairs and maintenance (flat-rate)	$256	$256	$256
Repairs and maintenance	$58	$64	$67
Administration	$130	$130	$132
Rates and insurance	$197	$198	$201
Non-farm working expenses	$1,143	$1,206	$1,237
Total operating expenses	$4,347	$4,792	$5,168
Non-cash adjustments			
Value of change in silage inventory	$102	$0	$59
Value of change in BCS	-$31	-$34	-$45
Cost of additional capital	$0	$113	$129
Operating profit (incl. non-cash adjustments)	$1,688	$957	$2,123
Environmental externality adjustments			
Nitrogen	$0	$120	$0
CO2 equivalents	$0	-$9	$52
Externality adjusted operating profit	$1,688	$846	$2,071

Appendix II

I presented this paper at the Australasian Dairy Science Symposium 21 - 23rd November 2018, Palmerston North, New Zealand.

Profit variability in dairy systems with differing feed bases and supplement use – a Northland case study

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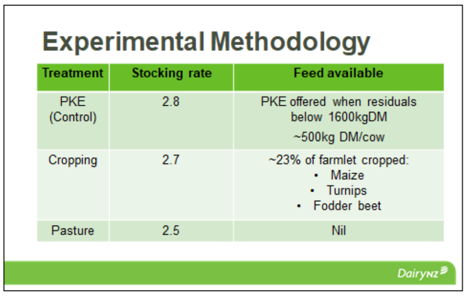
Abstract

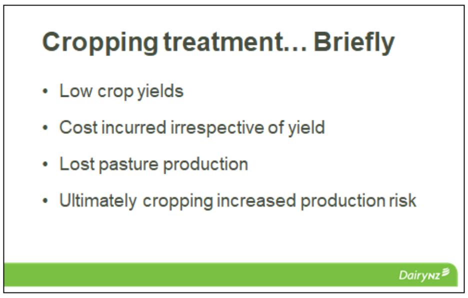
The use of supplementary feed can be an effective strategy to reduce production risk, although it simultaneously increases costs and exposure to market risk. As a result, despite the greater milk production that can be achieved by importing supplementary feed, farm profitability may not be improved. We compared three treatments differing in stocking rate and the nature of feed supply on one research farm over three years. In the Pasture treatment, the herd's diet consisted entirely of pasture grown on farm, including conserved pasture silage. This was compared with two treatments offering additional feed in the form of forage crops grown on farm or 'imported' palm kernel extract (PKE). A Monte Carlo analysis was conducted to compare profit for each treatment and associated variability over a range of market conditions. Across the three production years explored, when accounting for the likely variability of milk and input prices, and with high responses to supplement, operating profit was, on average, greatest with the PKE treatment.

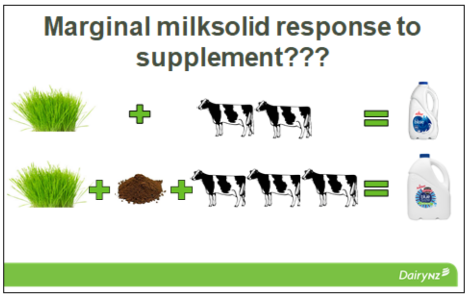
Appendix III

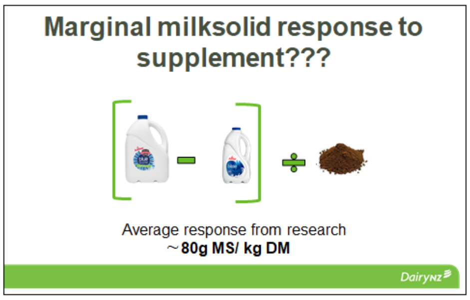
I presented this summary at the Northland Dairy Development Trust Annual Conference, 3rd April 2019, Whangarei, New Zealand.

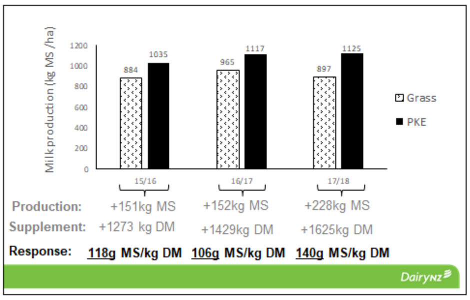


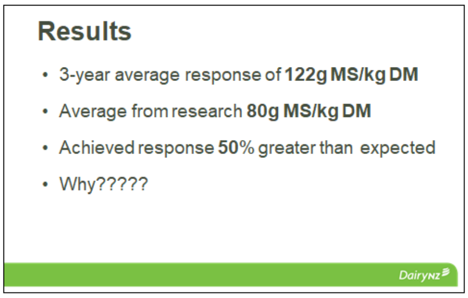
Treatment	Stocking rate	Feed available
PKE (Control)	2.8	PKE offered when residuals below 1600kgDM ~500kg DM/cow
Cropping	2.7	~23% of farmlet cropped: • Maize • Turnips • Fodder beet
Pasture	2.5	Nil

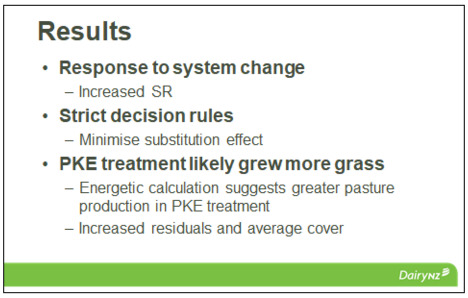


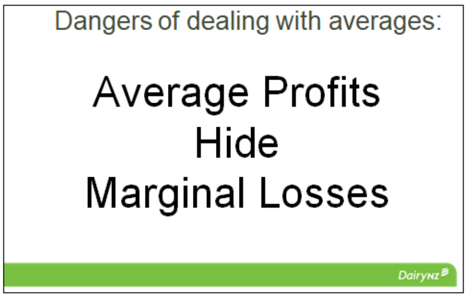


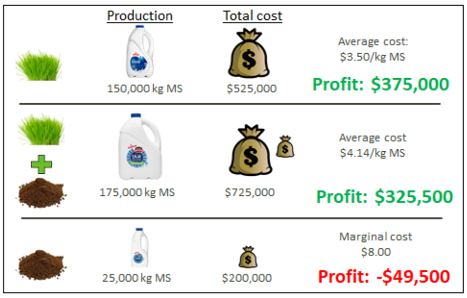


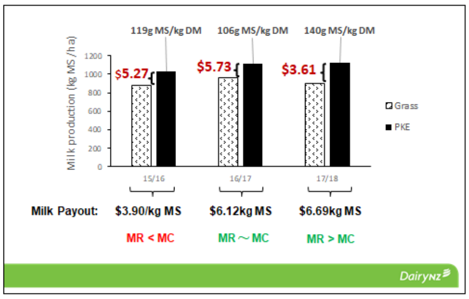


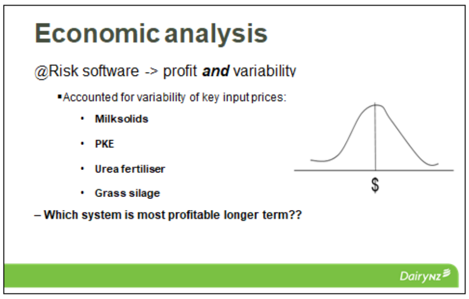


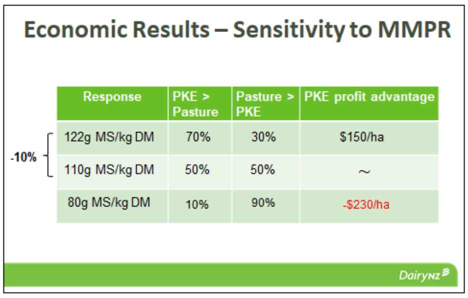












Response	PKE > Pasture	Pasture > PKE	PKE profit advantage
122g MS/kg DM	70%	30%	$150/ha
110g MS/kg DM	50%	50%	~
80g MS/kg DM	10%	90%	-$230/ha