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**Grazing and feeding management to reduce urinary nitrogen
excretion and enteric methane emissions while maintaining or
increasing milk production**

A thesis submitted in fulfilment of the requirements for the degree of

Master of Science (Research) in Biological Sciences

at

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by

Konagh Garrett



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Abstract

Rising global population is driving the requirement for more sustainable food production. Although, pastoral milk production efficiency has improved to meet demand, the intensification of practices has simultaneously increased environmental footprint by increasing methane (CH₄) emissions and urinary nitrogen (UN) excretion. Therefore, design and evaluation of practical on farm mitigation methods are required. The objective of this thesis was to explore strategic feeding managements during early and late lactation, with the aim of reducing methanogenesis and UN excretion, while maintaining milk production.

For the purpose and objective of this work, the mechanistic and dynamic dairy cow model, MINDY (Gregorini et al., 2013, 2015, in press) was used.

The first modelling experiment evaluated the effect of altering herbage allowance (HA) on dry matter intake (DMI), milk solids (MS), UN, and CH₄ production. As expected, greater HA increased DMI and MS production at a diminishing rate. Increased HA heightened consumption of fermentable carbohydrates and N containing compounds, resulting in greater emissions of both CH₄ and UN. However, with increased HA the emission intensity (g kg MS⁻¹) and CH₄ yield (g CH₄ kgDM⁻¹) declined. The results from this experiment agree with other studies and was used as a basis to add additional strategic feeding management in the following experiments.

The second experiment examined altering the time of herbage allocation to reduce methanogenesis and UN excretion while maintaining MS production. The treatments were a factorial arrangement of HA (as the first experiment) and time of pasture allocation either after the morning (AM) or afternoon (PM) milking. The PM treatments on average had a greater DMI (1.9 and 1.7%) and MS yield

(2.3 and 0.7%) as compared to AM, in EL and LL respectively. The PM treatments also produced 5.1 and 3.6% more CH₄ and 4.7 and 7.8% less UN in EL and LL, respectively. Altering the time of HA is a simple and cost-effective management practice to reduce the environmental footprint of productive grazing dairy cows.

Finally, supplementation strategies were evaluated on top of experiment two's treatments by the addition of either maize silage (MZ), maize grain (MG), or barley grain (BG) fed either prior to AM, PM, or each milking. When allocated BG, MZ, and MG in the PM rather than the AM cows respectively consumed 0.2, 8.9, and 1.2% more DM in EL and 4.0, 11.0, and 2.5% more DM in LL. Consequently, PM allocation of BG, MZ, and MG resulted in production of 0.2, 2.2, and 0.3 % more MS in EL, and 1.7, 3.6, and 1.0 % greater in LL. Similarly, the PM supplement allocation on average excreted less UN and emitted more CH₄. However, the weak positive relationship between CH₄ and UN indicates potential to simultaneously reduce their production by altering the time of herbage and supplement allocation.

Grazing and feeding management tools are inexpensive and easily integrated into practice yet aid in reaching both mitigation and production goals. Further empirical research is required to understand their usage under competitive grazing and use in conjunction with other mitigation techniques.

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Finally, a short thesis for those that told me I would never and those that never could.

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List of Abbreviations

ADF	Acid Detergent Fiber
AM	Morning
BG	Barley Grain
CH ₄	Methane
CO ₂	Carbon Dioxide
CP	Crude Protein
CT	Condensed Tannins
DCANZ	Dairy Companies Association of New Zealand
DCD	Dicyandiamide
DIM	Days in Milk
DMI	Dry Matter Intake
DNZ	Dairy New Zealand
EE	Ether Extract
EL	Early Lactation
FAO	Food and Agriculture Organization
GHG	Green House Gases
GtCO _{2e}	Gigatonnes CO ₂ equivalents
H ₂	Hydrogen
HA	Herbage Allowance
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
LIC	Livestock Improvement Cooperation
LL	Late Lactation
LULUCF	Land Use Change and Forestry sector

ME	Metabolisable Energy
MFE	Ministry for the Environment
MG	Maize Grain
MR	Marginal Milk Response
MS	Milk Solids
Mt CO ₂ e	Million Tonnes of CO ₂ Equivalent
MY	Milk Yield
MZ	Maize Grain
N ₂ O	Nitrous Oxide
NDF	Neutral Detergent Fiber
NH ₃	Ammonia
NH ₄	Ammonium
NI	Nitrogen Intake
NO ₃ ⁻	Nitrate
NPN	Non-Protein Nitrogen
NZ	New Zealand
PM	Afternoon
SR	Stocking Rate
TNC	Total Non-Structural Carbohydrates
UN	Urinary Nitrogen
UNFCCC	United Nations Framework Convention on Climate Change
VFA	Volatile Fatty Acids
WSC	Water Soluble Carbohydrates

Chapter 1. General Introduction

1.1. Introduction

Rising global population is driving the requirement for more sustainable food production. Numerous international agreements and protocols have been adopted to abate greenhouse gas (GHG) emissions, such as the Kyoto protocol; which has the goal to reduce emissions to 5% less than levels emitted in 1995 (IPCC, 2015). Agriculture of livestock has been related to high GHG emissions. However, the growing demand and consumption of foods of animal origin, such as dairy, is increasing worldwide. To meet growing demand, dairy practices have intensified i.e. increasing herd size, stocking rate, fertiliser application, and supplement use (MFE, 2015). All together enhancing environmental footprint of dairy production systems.

Although dairy farming is a universal agricultural practice, it is particularly important to New Zealand's (NZ) economy and to the lifestyle and culture of many New Zealanders. Dairy farming in NZ provides a livelihood for over 49 thousands employees excluding farm business owners; of which 70% work on farm, and the remaining in processing and wholesaling (DairyNZ, 2016). During the 2015-16 season dairy farming accounted for 26% of the value NZ earned from exported goods, and \$12 billion of export revenue, making NZ the largest dairy exporter in the world, but only the 8th largest milk producer worldwide (DairyNZ, 2016). The trend for increased milk solids (MS, sum of fat and protein yield) production both per cow and per effective hectare between the 1992/93 and 2015/16 seasons can be visualised in Figure 1.1. As dairy makes up a large part of NZs economy it is unsurprising that is also a large contributor to the countries unique emission profile. As most energy comes from renewable sources, other primary industries, such as the agricultural industry, produce most of the GHG

(MFE, 2015). The main pollutants produced by dairy farming are urinary nitrogen (UN) and the GHGs, methane (CH₄) and nitrous oxide (N₂O). Urinary N and CH₄ are mainly products of inefficiencies of rumen digestion; and therefore, feeding management aiming to reduce these innate inefficiencies are needed.

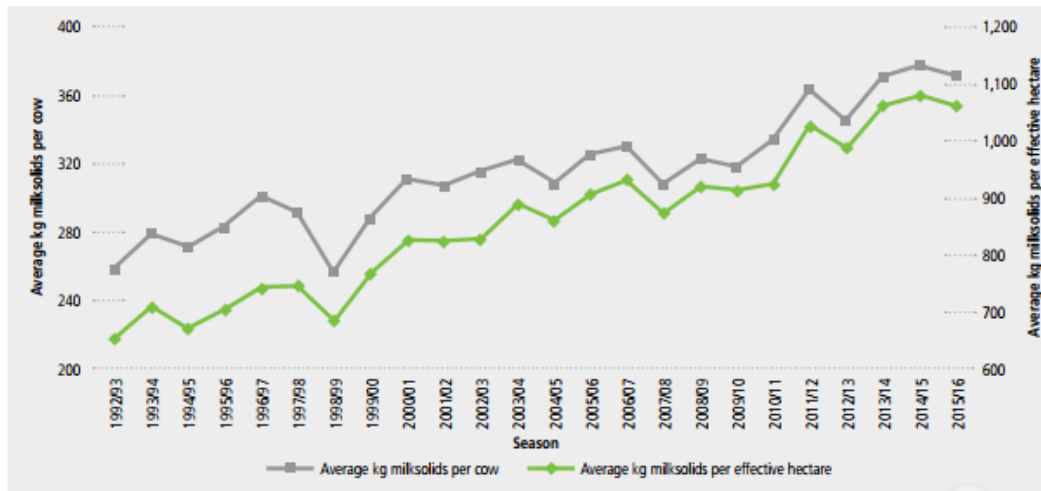


Figure 1.1. Milk solids production per cow and per effective hectare between 1992/93 and 2015/16 in New Zealand [taken from DairyNZ (2016)].

New Zealand dairy production systems are based on herbage consumption and efficient pasture utilization. Grazing and feeding management have been hypothesised to alter CH₄ production and UN excretion (Bailey, 2005; Gregorini, 2012). Strategic grazing and feeding management influences meal patterns by changes on the meal number, ingestive behaviours, grazing intensity, and temporal distribution of meals, therefore changing the dynamics and availability of nutrients supplied to the rumen and host animal (Gregorini, 2012). Although strategic grazing management has proved to increase milk production, less research has been conducted on using strategic grazing and complementary feeding management to reduce methanogenesis and UN excretion. The overall aim of this thesis was to explore the use of strategic grazing and feeding management to abate CH₄ and UN production while maintaining or increasing milk production using the model MINDY (Gregorini, Beukes, Romera, Levy, &

Hanigan, 2013; Gregorini et al. 2013; Gregorini, Villalba, Provenza, Beukes, & Forbes, 2015; Gregorini, Provenza, Villalba, & Forbes, in press). MINDY is a mechanistic model, incorporating diurnal patterns of foraging, digestion and, metabolism, dietary choice, excretion and production of a grazing ruminant. Although there is a vast array of strategic feeding managements, this thesis will examine the use and combination of three management variables: herbage allowance, time of pasture allocation and the time and type of supplement fed to MINDY. Such variables and combinations of them are of easy implementation at farm level.

1.2. Structure of thesis

In the next chapter, a short literature review on global GHG emissions, New Zealand's GHG emission profile, and mitigation methods is presented.

Chapter 3 is a simulation modelling experiment, evaluating the effect of herbage allowance on CH₄, UN, and MS production of grazing dairy cows. Four different herbage allowances (HA), 20, 30, 40, and 50 kg DM/cow per day, were tested during both early and late lactation.

Chapter 4 is the second simulation modelling experiment. In this chapter the CH₄, UN, and MS production of grazing dairy cows (in early and late lactation) allocated pasture, at the levels of HA used in Chapter 3, after either the morning (AM) or afternoon (PM) milking are compared.

The third simulation modelling experiment, Chapter 5, evaluated the effect of adding supplement (maize grain, maize silage, or barley grain) to the arrangements of grazing managements treated in chapter 4 on CH₄, UN, and MS production. Supplement input level (kg DM) differed between the different types of supplements allocated, however the total energy allocated remained the same

between treatments. The time at the supplements were fed was also examined and compared with the herbage only treatment groups.

Finally, Chapter 6 presents the conclusions on the strategic feeding management analysed within this thesis, as well as the limitations of this study and areas for further research.

Chapter 2

Literature Review

Introduction. Pastoral dairy systems is New Zealand's largest agricultural industry, producing significant wealth for the country. However, the NZ dairy industry is one of the major contributors to the GHG emission profile of the country. Therefore, its environmental footprint is examined and mitigation methods and alternatives reviewed in the context of the main pollutants produced by dairy farming, i.e. CH₄, UN, and consequently nitrous oxide (N₂O).

The link between ruminant methanogenesis and the formation of N₂O from UN and N fertilizers (e.g. urea) is detailed. Soil based abatement strategies are examined, including the use of stand-off pads, nitrification inhibitors, and level of N fertiliser applied.

The reviewed animal based CH₄ and UN mitigation methods consist of rumen function manipulation at the same resource allocation, herd size, and genetic merit. Known nutritional techniques like feeding levels of readily fermentable protein, energy supplementation, and dietary anti-microbial (methanogens) additives are briefly revised as well.

Most importantly, and due to the pastoral nature of NZ dairy production systems and the topic of this thesis, grazing and supplementation management tools such as herbage allowance and the timing of pasture and supplement. The weak positive correlation between CH₄ and UN in EL depicted in Figure 5.1 indicates there is potential to simultaneously reduce CH₄ and UN. The herbage allowance, time of herbage and supplement allocation are explored within and environmental protection and milk production context.

2.1. Climate change

Climate change is the “observed” phenomenon of the Earth’s climate patterns “changing”; such as increasing average atmospheric and oceanic temperature with increased anthropogenic activity. Since the industrial and green revolution, there has been a vast increase in the use of fossil fuels and deforestation, which is related almost linearly to the amount of GHG (Figure 2.1) entering the atmosphere (Viola, Paiva, & Savi, 2010). The rising emission of carbon dioxide (CO₂), CH₄ and N₂O from anthropogenic activities is thought to be the primary causative factor of such and increase; and thereby global warming (Houghton, 2005). Between 1970 to 2010 GHG emission rose by 22 gigatonnes CO₂ equivalents (GtCO_{2e}) to 49 (± 4.5) GtCO_{2e} per year (Figure 2.1) (IPCC, 2015). The surface temperature of the earth has risen approximately 0.6°C between 1860-2005 (Salinger, 2005); while, the global temperature rose at an elevated rate between 1910-45 and 1976-99 in increments of 0.14°C and 0.17°C, respectively. Current increasing rates of rising global temperatures and related extreme variability in patterns of precipitation will result in more severe, and longer lasting negative effects on food production (IPCC, 2015).

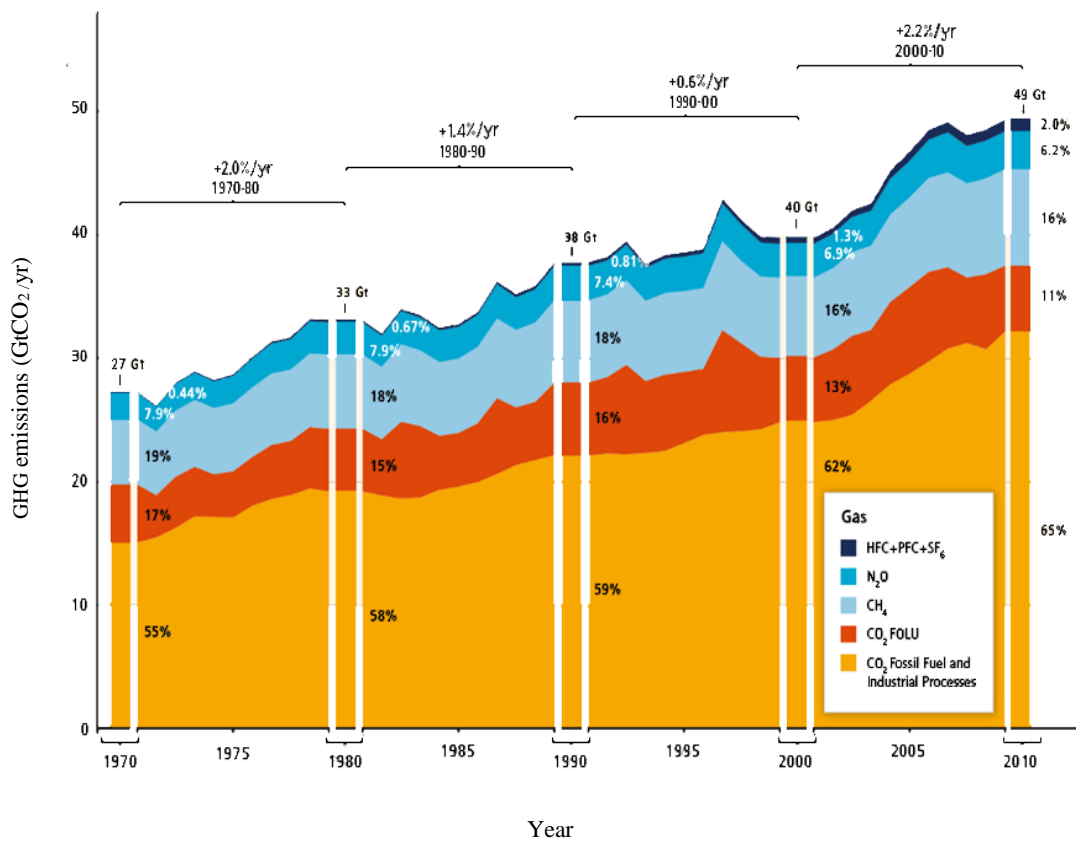


Figure 2.1. Total annual global GHG emissions by groups of gases from 1970 to 2010 (Taken from IPCC 2015).

2.2. GHG Mitigation goals

The Kyoto protocol is an international agreement to reduce GHG emissions in association with the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 2015). The UNFCCC is an international environmental treaty that was negotiated in 1992 with the goal to stabilize atmospheric GHG levels and to prevent further anthropogenic alterations to climate. Parties bound by Kyoto agreement are predominantly developed countries that have recognised that their infrastructure development is the principal cause for increased levels of GHG. The Kyoto protocol originally saw 37 developed countries, including New Zealand (NZ), agree to legally enforce limitations on their emissions of GHGs in two commitment periods. The first commitment concerned emissions from 2008-12 and the second continues until

2020. The second commitment period saw the adoption of the “Doha Amendment to the Kyoto protocol”. This amendment repaired several weaker articles of the Kyoto protocol and revised the list of GHG. Several developed countries Canada, Japan, Russia, NZ, and the United States all opted out of the second commitment period. Instead NZ, chose to meet its 2020 target under the UNFCCC rather than the Kyoto protocol. However, a Ministry for the Environment (MFE) (2017) report predicts, using current data, that NZ will meet its target to reduce emissions to 5% below that of 1990 which continues complying with the Kyoto Protocol framework.

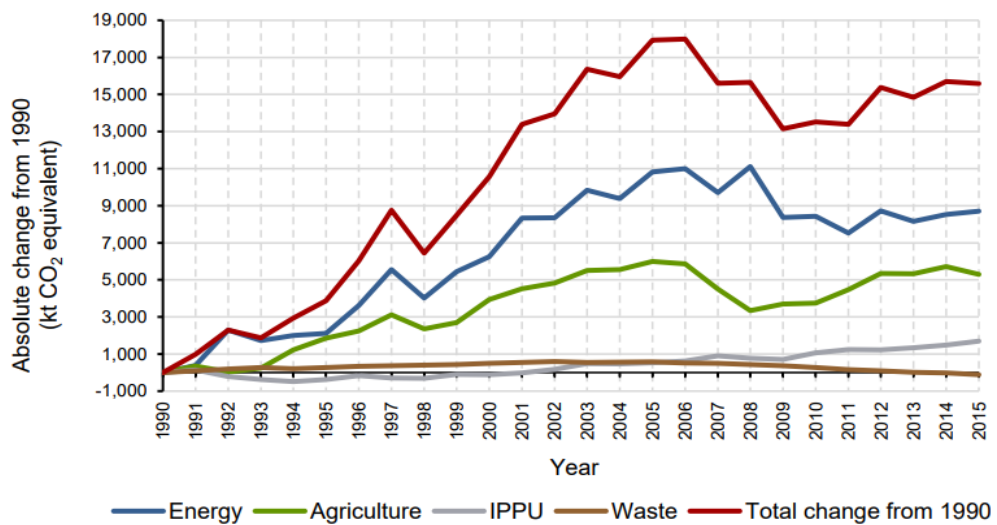
2.3. Global dairy production: the link to GHG production

The global population is predicted to rise until 2050, where the population of 9 billion will plateau (Gerber, Vellinga, Opio, Henderson, & Steinfeld, 2010; Hume, Whitelaw, & Archibald, 2011). In conjunction with the growing population, food production will need to increase at a rapid yet sustainable manner on an equal amount or less of agricultural land. The United Nations Food and Agricultural Organization (FAO) recognised in 2009 that agricultural production will need to increase by more than 70% to meet demand, placing considerable pressure on decreasing the environmental footprint of agricultural operations. Although the population prediction is an estimation and widely debated it is generally agreed that the population size will continue to grow. Global GHG emissions in 2010 were 55% greater than those of 1970. The atmospheric concentrations of GHG rose to be 55% greater in 2010 than those of 1970; the four main GHG were CO₂ (76%), CH₄ (16%), N₂O (6.2%) and halocarbons (2%) (IPCC, 2015). The combustion of fossil fuel and industrial processes contributed to approximately 78% of the global GHG emitted between 1970 and 2010. Over the same period, the global number of ruminants increased

1.4-fold, contributing largely to the increase in CH₄ emissions in the agriculture industry. Globally, the agricultural industry produced 24% of all GHGs emitted by anthropogenic activities in 2010, while producing ~50% and ~60% respectively of the total CH₄ and N₂O emitted by anthropogenic activities (Eckard, Grainger, & de Klein, 2010; IPCC, 2015). Predictions discussed within the IPCC (2015) suggest that approximately 70% of agricultural related emissions were from agricultural soil and enteric fermentation. Of these agricultural GHG emissions, 1,328 million tonnes [$\pm 26\%$] of CO₂ equivalent (Mt CO₂e) were reported to arise from dairy farms (Gerber et al. 2010).

2.4. NZ dairy and its link to NZ's high GHG emissions

New Zealand's GHG emissions have increased by 23.2% since 1990, with a level of 81.1 Mt CO₂e in 2014 (MFE, 2017). Alterations in emissions between 1990 and 2015 are depicted in Figure 2.2. The key drivers for the rise in gross emissions have been attributed to the CO₂ emissions from growth in road transport, chemical industry and food processing, as well as, enteric CH₄ from the growing livestock population. The increasing ruminant livestock population in NZ has also been associated with increased emission of N₂O from agricultural soils (MFE, 2016).



Note: Gross emissions exclude emissions from the Land Use, Land Use Change and Forestry sector (LULUCF) sector. Industrial Processes and Product Use (IPPU).

Figure 2.2. Absolute change in New Zealand's gross emissions by sector from 1990 to 2015 [Taken from MFE, 2017].

New Zealand uses an IPCC Tier two approach to predict CH₄ emissions from the average animal and its feed intake. For this calculation, a CH₄ 'yield factor' is used. Currently this factor is based on a single value for CH₄ produced per kg of dry matter intake (CH₄ g/kg DMI) (Muetzel, 2011). Based on these predictions, it has been suggested that NZ saw a 15% increase in agriculture emissions between 1990 and 2014; with the agriculture sector thought to produce 49% of NZ's total GHG emissions. New Zealand agricultural emissions are 38% greater than other developed countries (MFE, 2016). New Zealand's emission profile is peculiar, as our electricity sector is already 80% renewable, therefore NZ's reduction goals must be met in a similar unique manner, concentrating predominantly on the agricultural industry. A percentage breakdown of the

contribution by sector to NZ's gross emissions between 1990-2015 is displayed in Figure 2.3.

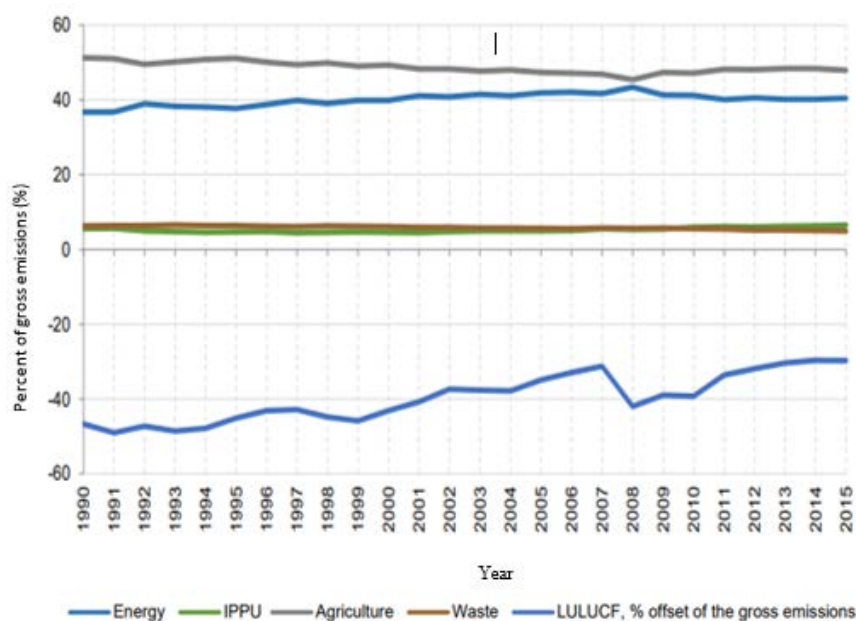
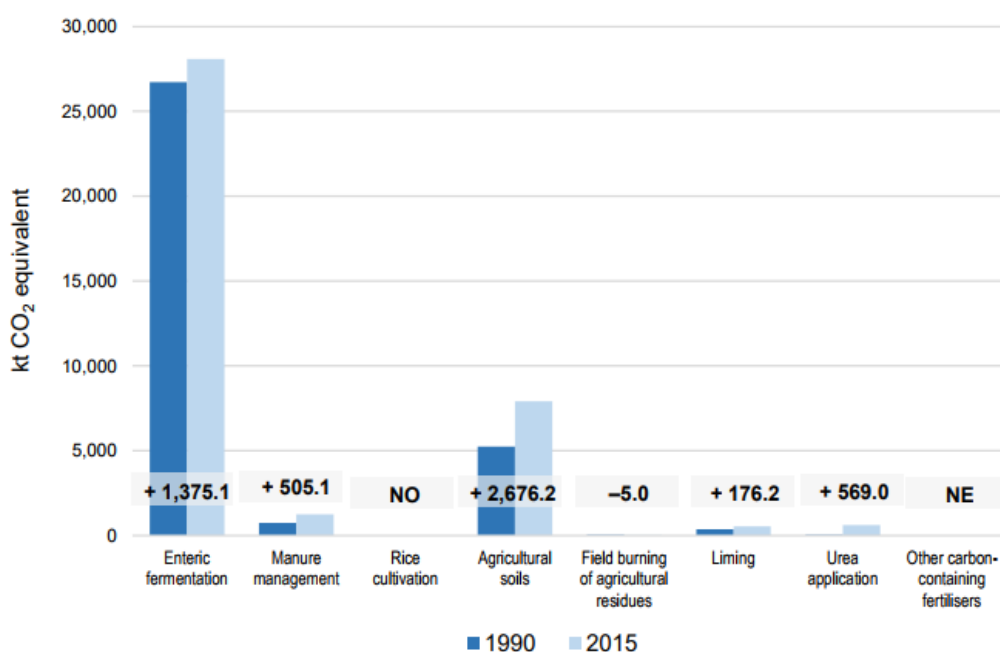


Figure 2.3. Contribution by sector to NZ's gross emissions from 1990-2015 from MFE (2017). Land Use Change and Forestry sector (LULUCF) sector. Industrial Processes and Product Use (IPPU).

The agricultural sector that was accountable for the largest percentage of emissions, a breakdown of the emissions is displayed in Figure 2.4. Within the agricultural industry, the greatest contributor to GHG emissions is the enteric fermentations of ruminants, being dairy farming operations its main source. Dairy production in NZ has grown over the past twenty years, following the trend of the growing global and national population and resulting larger food demand (Foote, Joy, & Death, 2015). The capacity to produce greater milk yields can largely be attributed to the intensification of practices by the inclusion of external inputs e.g. fossil fuel based fertilizer, feed, and water. With the intensification of farming practices further economical, societal, and environmental constraints have arisen (Gregorini, Beukes, Dalley, & Romera, 2016). Dairy is NZ's largest exported

commodity and makes a strong contribution to our economy, accounting for 26% of exported goods and 2.8% GDP (Schilling, Zuccollo, & Nixon, 2010). The production of MS inflated from 588 million kg in 1990 to 1,862 million kg in 2015 (Livestock Improvement Corporation limited & DairyNZ Limited, 2016). Which was achieved by the 94.7% increase in national dairy herd size, breeding selectively for higher yielding cows, and a five-fold increase in the use of N containing fertilisers (MFE, 2016b). The total number of cows in NZ increased from 2.4 million in 1990 to approximately 5 million in 2015.



Note: Rice cultivation does not occur (NO) in NZ. Emissions from other carbon-containing fertilisers are not estimated (NE).

Figure 2.4. Change in NZ emissions from the agricultural sector between 1990 and 2015 from (MFE, 2017).

The primary pollutants produced by the agricultural industry include N₂O, and CH₄ which are amongst an array of compounds that are associated with global warming (MFE, 2017). A breakdown of GHG emissions released from NZ dairy practices indicates that most emissions occur on farm (Figure 2.5). The N

fertilisers and UN deposit onto soils contribute to N leaching and eutrophication of water bodies. Pastoral dairy systems such as those commonly in NZ see ~70% of the 'excessive' N coming from the forage based diet. Such an excess is excreted (mainly ~ 60-70%) in urine due to the inefficient N utilisation of dairy cows (Castillo et al., 2001). Methane emissions represent a loss of approximately 6-10% of the metabolisable energy (ME) consumed, which in conjunction with the low efficiency of N utilization, enhances nutrient use inefficiencies of pastoral dairy farms in NZ (Lee, Woodward, Waghorn, & Clark, 2004). Thus, increasing nutrient use efficiencies may be beneficial to farm practices by reducing environmental impact and promoting greater energy utilisation consequently, increasing animal production.

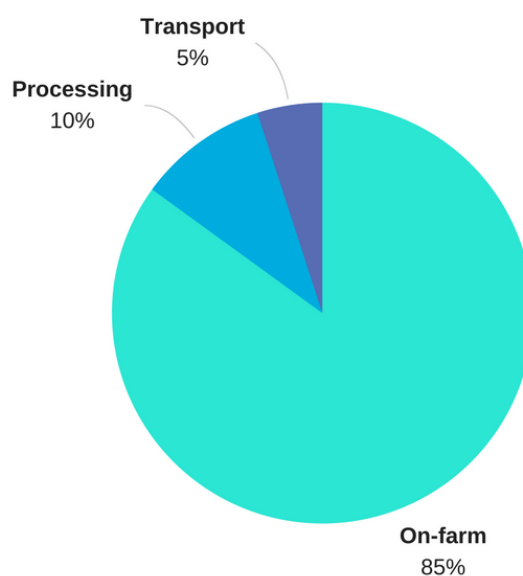


Figure 2.5. Dairy industry GHG emissions (Taken from "Greenhouse gases in the dairy industry," [MFE (2015)]).

2.5. Ruminant digestion

Cows and other ruminants ferment ingested plant material following comminution (Wolin, 1979). The ingested feed is transported to the stomach of the organism, which is also known as the rumen reticulum or rumen. The rumen is

a semi-continuous fermentation system comprised of the rumen, reticulum, omasum and abomasum. Rumen, solids (digesta) are regurgitated, chewed, re-swallowed and mixed by rumen contractions. The chewing of the solid material (cud) is a characteristic that is distinctive of a ruminant (Hungate, 1966). Rumen condition is tightly regulated to maintain anaerobic conditions, temperature and a pH of approximately 6.5 to promote steady growth of the microbial population residing within the rumen (Wolin, 1979).

A strong symbiotic relationship has formed between the host ruminants and rumen microbes. The microbial population within the rumen allows fermentation of plant material, supplying energy and amino-acids for microbial protein synthesis to the host animal, that are otherwise inaccessible and inedible to humans (Dijkstra, Oenema, & Bannink, 2011). Whilst the rumen microbes utilise the plant's carbohydrates, the volatile fatty acids (VFA, a by-product of microbial digestion) are absorbed by the rumen wall and used as energy source by the animal, turning indigestible forage (fibre) into edible food sources for humans (milk and meat).

The efficiency of nutrient utilisation by ruminants depends on a triad of elements: the animal, its diet, and the microbes within its rumen microbiome (Chilibroste, Gibb, & Tamminga, 2005). The chemical compositions and energy supplied by different feeds are not equal. Feeds have different nutritive values based on their chemical composition, energetic efficiency, and digestibility that effect the physical characteristics and true digestibility (Van Soest, 1994). The quality of feeds is further characterised by its physical characteristics, such as solubility, particle size and fibre particle properties. True digestibility is the proportion of feed available to for digestion by microbes and animals. These feed

characteristics affect the DMI and sequential microbial breakdown of feeds within the rumen.

2.6. *Methanogenesis*

It is the rumen microbes, more specifically methanogens, that produce CH₄ as a metabolic by-product. The quantity and type of food that is being digested influences the amount of CH₄ produced (Hungate, 1966). Group I anaerobes produce acetate, VFAs, hydrogen (H₂), and carbon dioxide (CO₂) (Ferry, 2010). The VFAs are degraded to H₂ and CO₂ by group II anaerobes. It is the Group III and IV methanogens that convert acetate to CH₄, as well as utilising the metabolic products of the group I and II anaerobes to form CH₄ from acetates methyl group (Group III) or reduce CO₂ (Group IV). The process of methanogenesis is largely carried out by the cohabitation of several microbial species; however, the activity of methanogenic archaea produce the final product, CH₄ (Ellis et al., 2008).

With the copious production of fermentation by-products, CH₄ and CO₂, a mechanism for its release is required to prevent toxic build (Hungate, 1966). CO₂ is released via diffusion into the lungs across the blood barrier, while, CH₄ is released by eructation as it has a low solubility in blood. The latter prevents high concentrations of CH₄ being expired alongside CO₂. Eructation of CH₄ is initiated during the rumen reticulum contractions that mix contents within the rumen.

The anaerobic decomposition of manure also contributes to the total CH₄ emissions from cattle (Dijkstra et al., 2011).

2.7. *Nitrogen excretion and emissions*

Nitrogen utilisation by cows is quite inefficient; consequently, large amounts of N (~ 70% of N intake) are expelled into the environment Gregorini et

al. (2016). It is the consumption and breakdown of true protein and non-protein nitrogen (NPN) that results in excretion of N within urine. Rumen microbes hydrolyse the peptide bonds of proteins, to oligopeptides and finally amino-acids from which ammonia (NH_3) is cleaved from (Pfeffer & Hristov, 2005). Rumen microbes are the sole utilisers of NPN, which they use to synthesis microbial crude protein. The NH_3 then diffuses across either the blood or rumen walls, following which it is taken up or transported to the liver for urea synthesis and excreted in urine.

The deposition of urine from cows is the vector for most N entering the environment, predominantly in the form of urea (50-90%), as well as allantoin (2.2-22%), hippuric acid (1.9-23.7%), uric acid (0.6-1.9%), creatine (0-6.3%) and creatinine (0-8.1%) (Bussink & Oenema, 1998; Kool, Hoffland, Hummelink, & Van Groenigen, 2006). Faecal N excretion tend to remain relatively constant at 7.8 g/kg DM independent of N intake (NI), when NI varies between 450 to 775g N per day (Bussink & Oenema, 1998).

Excessive N excretion impacts the environment negatively in two main ways: through water pollution by N leaching and acting as a GHG after being converted to N_2O . Nitrogen leaching is a considerable issue for dairy farming, as the soil type used for dairying farms is often of well drainage, allowing N to leach into waterways (Chapman et al., 2012). Ideally, N would remain in the sward root zone. High levels of N within water bodies can result in eutrophication and decreased water quality by promoting algal blooms.

Animal N excretions are responsible for 80% of N_2O in grazing dairy systems (de Klein, Shepherd, & van der Weerden, 2014). The amount of N_2O produced from UN is dependent on the concentration of N in the urine and

deposited onto the pasture, as well as the rate of N cycling within the system (mainly soil) following deposition. The amount of UN that is nitrified and/or denitrified to produce N₂O is dependent on the localised abiotic and biotic conditions, including microbial population dynamics, size, soil characteristics, and climate conditions. Urea is hydrolysed into carbamic acid, an extremely unstable acid which rapidly decomposes to ammonia (NH₃) and subsequently ammonium (NH₄). Ammonium is either nitrified to nitrate (NO₃⁻) or denitrified to N₂O or N gas (Kool et al., 2006). Often the intermediates of this process, NH₃ or NO₃⁻, are leached into water bodies and are later converted to N₂O after they are redeposited onto land. As a result, NH₃ and NO₃⁻ are considered an indirect source of emitted N₂O (Kool et al., 2006).

2.8. The relationship between N and CH₄; pollution swapping

The production of CH₄ and UN are intimately linked. Diets used to reduce UN can increase production of enteric CH₄ or vice versa; phenomenon known as pollution swapping (Gregorini et al., 2016). Dietary changes to reduce CH₄ tend to decrease the amount of fermentable polysaccharides by replacing them with protein. Numerous studies have identified that UN production can be reduced by decreasing protein concentration in the diet; consequently, increasing dietary carbohydrate content, then fermentability and consequently CH₄ (Dijkstra et al., 2011; Gregorini et al., 2016; Mulligan, Dillon, Callan, Rath, & O'mara, 2004).

2.9. Mitigation options

Previous empirical and simulation modelling research suggests that the main strategies to reduce animal GHG emissions are animal related mitigation alternatives, soil treatments, feed-based, and grazing management strategies (Gregorini, Villalba, Chilibroste, & Provenza, 2017; Gregorini et al., in press); Adler, Doole, Romera, & Beukes, 2013; Beauchemin, Kreuzer, O'mara, &

McAllister, 2008; Beukes, Gregorini, Romera, Levy, & Waghorn, 2010; Dijkstra et al., 2011; Eckard et al., 2010; Ellis et al., 2008; Hristov et al., 2013; Hume et al., 2011; Waghorn, 2008). These methods will be discussed with the goal of reducing the emissions of UN and/or CH₄. More detail will be provided for feed-based and grazing management strategies as it is the thesis focus.

2.9.1. Animal based mitigation methods

Reducing stocking rate increases individual animal and sometimes, total herd productivity by increasing the availability and feeding value feed/ herbage; whilst, simultaneously reducing total GHG and UN (Hristov et al., 2013; Waghorn, 2008). Lower stocking rates and greater herbage allowance allow for selective foraging behaviour and, thereby, increase of nutritive value of consumed herbage, which would be especially advantageous in heterogeneous swards (Bailey, 2005). The intake of herbage with greater nutritive value reduces CH₄ yield as a response to faster rumen digesta outflows; however, it may lead to greater N intakes leading to increments in UN (Gregorini et al. 2017).

Other animal-based methods include manipulating rumen archaea and bacteria via defaunation, i.e. the complete or partial removal of rumen fauna (Eckard et al., 2010). Promotion or suppression of microbes within the rumen during the early developmental stages of a ruminant's life can alter microbial colonization and development within the rumen later in life (Eckard et al., 2010). These techniques could potentially be used to reduce CH₄ yield and total production and increase N use efficiency by influencing the intimate link between microbial and protozoal activity within the rumen and residual metabolite production (Eckard et al., 2010).

Another method being examined, with the potential to minimise the production of CH₄ and UN is selective breeding for animals (e.g. sires) with faster ingestion and rumen digesta outflow rates (Gregorini et al. 2017) as well as better N use efficiencies (de Klein & Eckard, 2008; Eckard et al., 2010; Hristov et al., 2013). Priority for most dairy breeding programmes is to select for traits such as milk production, length of productive life, survival rate, and fertility; all of which have a significant effect on farm profitability (Hristov et al., 2013). If these traits were considered alongside those for reducing CH₄ and UN, milk production could be maintained whilst accelerating reduction of environmental impact by pastoral dairying in NZ.

2.9.2. Soil treatment

As temperature and soil moisture content increases, so does the generation of N₂O because of an upsurge in microbial population denitrifying NH₄ to N₂O (de Klein et al., 2014). N₂O emissions can be effectively reduced through the application of a nitrification inhibitor such as dicyandiamide (DCD) to soils and urine patches (Adler, Doole, Romera, & Beukes, 2013, 2015). Dicyandiamide reduces N loss as N₂O, allowing more N to remain in soil for plant growth. Application of the DCD has been reported to have no effect on CH₄ emissions from manure (Cahalan et al., 2015).

Management options to capture as much UN prior to deposition onto pasture soils include the use of stand-off pads, shelters, and feed pads, reducing available grazing time on pastures (Beukes et al., 2010; Monaghan & de Klein, 2014). As of N₂O emissions from animal excreta is highest during the wet seasons autumn and winter, the use of stand-off pads can reduce the amount of N lost into the environment (de Klein, Smith, & Monaghan, 2006). Reducing available time at pasture also aids in avoiding pasture damage and consequently N₂O emissions

by mitigating pugging and soil compaction. Pugging and soil compaction increase N₂O production through degradation of the soil's physical condition, leading to reduced drainage efficiency and elevated levels of N runoff (Singleton, Boyes, & Addison, 2000). In addition, pugging and soil compaction can cause other implications such as manure build-up resulting in higher N₂O emissions during manure storage (de Klein et al., 2014). Also, the addition of edge-of field capturing or reuse options such as riparian buffer, wetlands, and denitrification walls either capture and remove N, and or abate N₂O release from nitrate reduction (Monaghan & de Klein, 2014). This research indicates that the use of nitrification inhibitors, standoff pads, and denitrification walls or riparian zones can mitigate the N entering the environment.

2.9.3. Fertiliser application

Nitrogen application is an integral part of farming practices used to increase herbage production, particularly in tough growing conditions (Al-Marashdeh Gregorini, & Edwards, 2016a). A study by Delagarde, Peyraud, & Delaby (1997) reported that reduced fertilisation can manipulate the volume of herbage consumed by altering sward structure. Applying fertiliser alters sward height and green leaf mass, which can alter the grazing patterns and DMI of foraging cows. Peyraud, Astigarraga, & Faverdin, (1997) reported the effect of different levels of N fertiliser application to swards on sward structure. Their results suggest that DMI remained similar between fertilized swards; however, reduced levels of N decreased N intake and subsequently UN. The cows used in such an experiment were fed *ad libitum* fresh cut herbage within stalls. Conversely, Delagarde et al. (1997) reported that grazing dairy cows consumed less herbage and produced lower levels of MS when fertiliser application levels

were reduced. This information indicates that the addition of N fertiliser to systems increases N intake and subsequent UN excretion.

2.9.4. Nutritional manipulation of CH₄ emissions and UN excretion

Dairy cow's nutritional requirements vary throughout lactation. Therefore, management practices must be adjusted to meet metabolic demand. Nutrient deficiency decreases milk production; whilst surplus nutrient supply elevates the input costs for no more gain and nutrient loss into the environment that can be detrimental.

Nutritional strategies aimed at reducing CH₄ production predominantly aim to reduce the fermentable portion, such as rumen degradable fibre, and increase the amount of dietary starch. These dietary changes result in the formation of propionic acid rather than acetic or butyric acid as an intermediate of fermentation (Beauchemin et al., 2008; Dijkstra et al., 2011; Ellis et al., 2008). Propionic acid formation is favourable as it consumes H₂ and in turn mitigates CH₄ production by minimising the amount of CO₂ reduced by H₂ oxidation. Alternatively, acetic and butyric acid produce H₂ gas and heighten the formation of CH₄ (Dijkstra et al., 2011).

A common method to abate CH₄ emissions is to alter the ratio of fibre to starch in supplement fed, which both decreases ruminal pH and heightens formation of the fermentative substrate propionic acid (Dijkstra et al., 2011). Rumen conditions such as pH are influential on the fermentative product. Lower ruminal pH coincides with greater propionic acid production from starch and sugars.

Supplements with a high fat content have the potential to lower CH₄ production by 10-25% in commercial settings (Beauchemin et al., 2008). The

addition of lipids reduces CH₄ production by decreasing the fermentable portion of the diet; consequently, reducing the proliferation of methanogens and protozoa by limiting their main food source. For dairy cows, high-fat diets can reduce the fat content of milk and uncertainties remain about the effects of sustaining high fat diets over the entire lactation (Beauchemin et al., 2008).

A dietary option that is particularly successful at reducing UN includes the reduction of NI (dilution effect) and improve N capture in the rumen by the addition of grains, containing high concentrations of rumen degradable starch (Hume et al., 2011). The addition of a starch-rich concentrate to herbage only diet, increased DMI and although NI only differed by 20 g, the excretion of UN was 32% less (Higgs, Sheahan, Mandok, Van Amburgh, & Roche, 2013). A 2017 study by Luo *et al.* examined the effect of increasing the proportion of rumen degradable starch on nitrogen utilisation. The group with 10% more rumen degradable starch than the other retained 3.5% more nitrogen and excreted 5.1% less UN. Benchaar, Pomar, & Chiquette (2001) results showed that increasing the starch proportion of the concentrate fed reduced the emissions of CH₄ by 16.2%. The results of another experiment by Beauchemin & McGinn (2005) analysed the addition of a greater proportion of corn or barley supplements decreased CH₄ production to 62 and 80 g d⁻¹ from 171 and 130g d⁻¹.

There are numerous feed additives that have been used to reduce CH₄ emissions. For example, inhibitors, yeast, electron receptors, ionophores, plant bioactive compounds, and exogenous enzymes (Hristov et al., 2013). Monensin is an ionophore that acts as an antimicrobial agent. Ionophores are often used to regulate bloat, intake and improve production efficiency, while favouring propionate production and accordingly reducing methane production (Beauchemin et al., 2008). The effect of monensin on dairy cow's efficiency to

utilise N was analysed in a study by Gehman, Kononoff, Mullins, & Janicek, (2008). Data on N metabolism over two control and two monensin treatments were examined. Results suggested that monensin did not significantly alter DMI, proportions of propionate present within the rumen, N utilization, or faecal, milk, and urinary N excretion. Monensin is required at a high dosage to reduce CH₄ and does not persist for long lengths of time. Finally, Beauchemin et al. (2008) suggested that monensin is not a long-term solution due the increased public pressure to cease the use of antimicrobials in agriculture.

Saponines from plant sources (e.g. *Medicago sativa*) can reduce the production of CH₄ through their anti-protozoal effects (Beauchemin et al., 2008; de Klein & Eckard, 2008). Tannins are another plant secondary compound that have been reported to reduce CH₄ emission by ~12%. The majority of research has concentrated on the condensed tannins (CT) due to lower risk of toxicity (Beauchemin et al., 2008; de Klein & Eckard, 2008). Large scale usage of CT is unlikely due to the limited cultivation of CT containing legume forages. Additionally, the productivity of cows limited by high levels of CT which can negatively affect the digestibility of feeds.

Mitigating methods manipulating diet composition often result in pollution swapping; therefore, it is difficult to recommend dietary changes that reduce both UN and CH₄ emissions and maintain milk production levels. A 2016 study by Gregorini et al. screened 51 feeds and approximately 10,000 dietary combinations in a bid to find a diet that simultaneously reduces UN and CH₄, whilst maintaining or increasing milk production. The results suggested that particular diet compositions can reduce both UN and CH₄. However, a trade-off analysis between UN and CH₄ is required to decide on the optimum dietary feeds combination. Until this trade-off analysis is conducted decisions will be made by

the farm owner or manager to prioritize their practices based on their individual production and environmental goals.

2.9.5. Improved pasture and grazing management

Grazing management, the process of managing the intensity and frequency of livestock to alter herbage utilisation, is a technique that is hypothesised to reduce environmental impact of dairy farming through the improvement of herbage feeding value (Bailey, 2005; Gregorini, 2012). The improved feeding value of herbage can reduce methanogenesis by increasing rumen digesta outflow, and also compensate for less N based fertiliser use (Adler et al., 2013). Improving herbage feeding value can lower the amount of feed required to meet productivity goals per unit of land, by increasing the metabolisable energy (ME) content of the feed (Monaghan & de Klein, 2014).

Strategic grazing management is a technique that can be used to influence grazing patterns through invoking changes on the number, intensity, and temporal distribution of meals, therefore changing the availability and supply of nutrients to the rumen and grazing ruminants (Gregorini, 2012; Gregorini et al., 2017). Herbage and nutrient intake dynamics have been suggested to be influenced by a set of grazing decisions and behaviours such as ‘when’ to feed throughout the day, at ‘how’ often, and ‘what’ time to start grazing (Gregorini, 2012). Due to the accessibility of the entire daily paddock allocation the decisions of ‘where’ to graze is rendered unimportant (Bailey et al., 1996; Gregorini, 2012). In the context of an intensively grazed dairy cow, grazing management focuses on the manipulation of diurnal grazing pattern and herbage utilisation, which has been proven to increase milk production. Since such managements of grazing alter rumen function, there is potential to use strategical management practices of

grazing dairy cows to reduce CH₄ emissions, NI, and subsequent UN excretion.

However, little research if none has been conducted in this arena.

The following subsections explore how management of herbage allowance, timing of herbage and supplement allocation can alter the production of MS, emission of CH₄, and UN excretion.

2.9.6. Herbage allowance

Milk production, DM intake, and grass growth are all affected by herbage allowance (HA). Herbage allowance is the amount of herbage allocated per cow and day. Under grazing conditions HA can be managed by the combined effect of the area offered per day to individual animals and the pre-grazing herbage mass). Therefore, HA is a key grazing management tool. As HA increases, herbage DMI and milk production increase, generally in “a diminishing return” fashion. Increments in HA though, lead to reductions in herbage utilization and potentially farm profit.

Herbage allowance does not alter the nutritive value of the herbage allocated, but the nutritive value of the ingested herbage, as well as ingestive behaviour by altering the availability and accessibility of herbage (Pèrez-Prieto & Deleгарde, 2012). One of the key ingestive variables affected by HA is bite mass and rate, both determining herbage intake rate and thereby DMI (Barrett, Laidlaw, Mayne, & Christie, 2001). As HA is reduced or herbage mass depleted, intake rate diminishes, and therefore animals tend to increase grazing time. At low HA herbage mass is depleted faster and animals will graze down to levels in where ingestion of fibre increases by the consumption of pseudo-stems and dead material. All which in turn reduce DMI, MS production and influence rumen function to a greater methanogenesis.

Under restricted grazing settings (low HA or high nutrient demand) large volumes of herbage are quickly consumed, but comminuted less effectively and packed within the rumen poorly, creating a filling sensation at a lower DMI (Gregorini et al., 2017). Poor herbage/ ingesta comminution and poor rumen packing result in longer rumen retention times, and in turn non-glucogenic and methanogenic rumen fermentation. Although this concepts help to understand potential effects of HA on rumen fermentation changes and environmental impact, there still lack of detail studies on the effect of strategic grazing managements at the same resource allocation on rumen metabolic processes and excretion of metabolic by-products such as UN and CH₄ (Gregorini et al., 2017).

Numerous experiments have been conducted on the effect of HA on milk production in different seasons and stages of lactation (Chilibroste, Mattiauda, Bentancur, Soca, & Meikle, 2012; Kennedy, O'Donovan, Murphy, Delaby, & O'Mara, 2005; Peyraud, Comeron, Wade, & Lemaire, 1996). Many of which have been reviewed in two meta-analyses by Pèrez-Prieto and Deleгарde (2012, 2013), who reported that DMI, milk and milk solids production increased with HA with a diminishing return response

Research on the effect of HA on combined CH₄ and UN emissions is small, with most of the research examining these pollutants independently. Moreover, much of this small body of this research fed fresh cut herbage to cows, which eliminates the grazing context and decisions making to select for herbage of grater feeding value at high HA. Under this 'indoor' feeding conditions, greater DMI results in elevated fermentation levels and a larger supply of substrate is provided to methanogens consequently, increasing CH₄ production (Knapp, Laur, Vadas, Weiss, & Tricarico, 2014; Purcell, O'Brien, Boland, O'Donovan, & O'Kiely, 2011). Therefore, moderate feed intake of a higher nutritive quality

could be a method to reduce CH₄ emissions; however, DMI is also a major determinant in milk production and the profit of a farm system. This thesis will examine the effect of HA on production and pollution swapping between CH₄ and UN. The emission of CH₄ and UN will be examined alongside production on a per cow basis to determine if strategic grazing management can influence the GHG output of dairy cows.

2.9.7. The time of day effect

Most grazing ruminants under temperate conditions and a set stocking rate have three to five meals a day (Gregorini, 2012). This frequency, though, depends on environmental conditions, such as photoperiod and temperature (Gregorini, 2012). The major meals occur during both dawn and dusk, while less intense and shorter meals are consumed overnight. Dairy cows are not the exception and under set stocking, they display the same general meal patterns, as displayed in Figure 2.6.

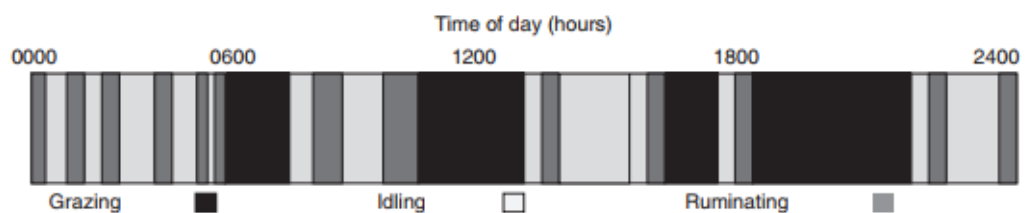


Figure 2.6. Grazing pattern of dairy cows under set stocking [Taken from Gregorini (2012)]

Chemical composition fluctuates during the day, and consequently its nutritive and feeding value (Abrahamse, Tamminga, Dijkstra, 2009; Delagarde, Peyraud, Delaby, & Faverdin, 2000; Gibb, Huckle, & Nuthall, 1998; Gregorini, 2012; Gregorini, et al., 2009; Gregorini et al., 2006; Orr, Rutter, Penning, &

Rook, 2001; Van Vuuren, Van der Koelen, & Vroons-de Bruin, 1986). As photosynthates accumulate and water evaporates from herbage the DM, starch and total non-structural carbohydrates content rises (Gregorini et al., 2008; Griggs, MacAdam, Mayland, & Burns, 2005; Mayland, MacAdam, Shewmaker, & Chatterton, 2003). Other chemical constituents, such as fibre, crude protein (CP) and N, are consequently diluted as photosynthesis and transpiration occurs during the day (Delagarde et al., 2000; Gregorini et al., 2009). Greater content of non-structural carbohydrates has been reported to increase palatability and partial preference of ruminants (Gregorini et al., 2017).

As chemical composition of herbage changes throughout the day, so does its biomechanical properties such as 'toughness' and tensile strength, both affecting ingestibility, comminution rate and rumen digestibility. The main factors affecting these changes are cell wall constituents: cellulose fibres, hemicellulose, and lignin (Gregorini et al., 2009). Toughness increases the energy expenditure in ingestive processes and consequently its herbage nutritive value (Gregorini, 2012). Diurnal changes in toughness have been reported by Gregorini et al (2009), who also related diurnal fluctuations in toughness to changes in water soluble carbohydrates (WSC), moisture content and fibres content changes over the day. Tougher herbage is hard to comminute, requiring more mastication and chewing effort, constraining bolus formation, cell breakdown, and reducing surface area for microbial populations to colonise and digest faster (Chilibroste, Dijkstra, Robinson, & Tamminga, 2008; Gregorini et al., 2009). Toughness can decline by 40% from dawn to dusk, while particle size reduction index increases (Gregorini et al., 2009). It is these biomechanical features that determine the energy required to ingest and digest forage. Therefore, the larger quantity of herbage consumed at dusk is also more readily digested.

Neuroendocrine factors controlling food ingestion fluctuate in synchronous patterns matching the light cycle (Gregorini et al., 2012). A number of hypothalamic areas are involved in the control of feeding regulation such as the paraventricular hypothalamic nucleus, stimulating intake through the release of neurotransmitters such as neuropeptide-Y. Such a neuropeptide has been reported to be present at the highest concentrations prior to dusk. The circadian rhythm of hypothalamic suprachiasmatic nucleus has also been related to secretion patterns of melatonin and its precursor serotonin. Serotonin inhibits the reward function and consequently inhibits food consumption. Serotonin levels increase from dawn to noon, and decline from noon to dusk contributing to greater motivation to feed late in the day. All of which explains the largest and most intensive meal of the day happening during late afternoon early evening.

The largest meal of the day –late afternoon early evening- is thought to maximize rumen digesta fill to stabilize the release of nutrients during night time periods of non-grazing, when predation risks is high and vigilance is required. At dusk the nutritive value, palatability, motivation to eat and particle size reduction of herbage is greater and the toughness is reduced allowing for efficient energy acquisition and utilisation (Gregorini et al., 2006).

Matching herbage supply to periods of natural motivation to eat, has been shown to increase DMI, alter rumen function, increase nutrient supply to the duodenum, and nutrient absorption from the same resource allocation (Orr et al., 2001; Gregorini et al., 2008). These increases, have been reported to enhance milk production by 2-5% (Orr et al., 2001; Gregorini 2012; Vibart et al., 2017).

While the literature abound on the effect of timing of herbage allocation of grazing cattle performance, reports on the benefit of allocating herbage in the

afternoon on the efficiency on DMI, nutrient intake, rumen function, and UN and CH₄ yield and total emissions are lacking. The reports on the effect of afternoon herbage allocations indicate that N intake and UN excretion are reduced (Vibart, Pacheco, Lowe, & Barrett, 2011; Vibart et al., 2017). Simulation modelling experiments by Gregorini et al., (2010 and 2016) report that as UN excretion reduced the production of CH₄ per kg of MS increased. Recently, Gregorini et al. (2017) suggested that afternoon herbage allocations may also reduce CH₄ yield. Although some empirical work by Gregorini et al (2008) indicates faster digesta outflow rates with cattle being allocated to the pasture in the afternoon may support that modelling outputs, there is still lack of empirical evidence of such a positive effect.

2.9.8. Supplementation

Milk production of dairy cows grazing high quality herbage is limited by the supply of metabolisable energy (Kolver & Muller, 1998). The addition of energy-rich supplements, particularly when energy demand is high or herbage availability is scarce, can offset this energy deficit. Although energy supplementation increases energy supply and subsequently milk production, its marginal milk response (MR) varies largely with supplement quantity and the type of supplement fed (Bargo, Muller, Kolver, & Delahoy, 2003; Sheahan, Gibbs, & Roche, 2013; Stockdale, 2000). Supplemental MR is also dependent on the genetic merit of the animal, rumen microbial population, and the quantity of herbage the supplement is paired with. Supplementation usually results in decreased herbage consumption, the phenomenon known as substitution (Bargo, Muller, Kolver, & Delahoy, 2003; Sheahan, Gibbs, & Roche, 2013). Substitution rate varies between supplement type and HA.

The literature abound with data and reports on the effect of supplementation of herbage with energy (mainly starchy) concentrates on milk production, MR, substitution rate, and rumen function and N metabolism (Bargo et al., 2003; Hills, Wales, Dunshea, Garcia, & Roche, 2015). Despite this body on literature, there is little research on the effect of herbage supplementation on pollution swapping. Again, the little research on these topics has focused on individual pollutants, either CH₄ emissions or UN excretion. Recent simulation modelling experiments of Dijkstra et al. (2011) and Gregorini et al. (2016), however, report how in specific situations and feeding managements, pollution swapping can be counteracted. Gregorini et al. (2016) reported that under NZ pastoral systems, dietary inclusion of cereals, grains and silages (i.e. barley) would help to dilute N, and thereby UN, as well as and at the same time reduce enteric CH₄ emissions, while maintaining or increasing MS production. Although Gregorini et al. (2016) examined numerous supplement types and thousands of dietary mixes, these authors and due to the model used in their simulations –Molly (Gregorini et al., 2015) did not considered potential benefit of managing grazing and or timing of supplementation.

2.9.9. Timing of supplementation

Timing of supplementation has been reported to not only reduce substitution rate and increase animal production, but also alter rumen function leading to potential reductions in UN and CH₄ emission. For example, Al-Marashdeh et al. (2015, 2016a, 2016b) and Sheahan et al. (2013) reported that strategic timing of supplementation reduces substitution rate, increases MS production and the MR to supplements. Timing of supplementation has been also reported to alter N utilisation efficiency of microbes and subsequent N partitioning in dairy and beef cattle (Gregorini et al., 2010; Al-Marashdeh et al.,

2015; Al-Marashdeh, et al., 2016a; Bailey et al., 1996; Gekara, Prigge, Bryan, Nestor, & Seidel, 2005; Mitani, Takahashi, Ueda, Nakatsuji, & Kondo, 2005). Al-Marashdeh et al. (2015), reported that NI of dairy cows was greatest for the herbage only treatments, while the treatment allocated supplement in the AM consumed more N than those supplied pasture in the PM. The cow's allocated herbage in the AM generally displayed a trend of reduced UN excretion and elevated N in milk. Gregorini et al. (2010) under in vitro conditions, reported that strategic timing maize silage supplementation reduce rumen ammonia N by 30% and increase glucogenic fermentation, i.e. propionate, by 13%. In view of these reports, timing of supplementation appears as a synergetic and strategic feeding management tool to reduce environmental impact. However, there is no virtually reports that evaluate the timing of supplementation and HA plus timing of herbage allocation on pollution swapping. However, the quantity of N excreted within urine remained the same despite difference in time of pasture allocation. Despite some research on the effect of altering timing of supplement allocation to optimise intake, milk production, and UN exists, further studies are required including the impact on CH₄ emissions.

2.10. Conclusions

Increasing GHG emissions and growing levels of N leaching into water bodies in NZ is placing considerable limitations on agriculture, mainly dairy production systems, which and as response of intensification practices produces the greatest amount of enteric CH₄, deposit the greatest amount of UN on NZ pastures and lead the highest levels of N leaching. There are many factors that influence intake and consequently CH₄, UN, and milk production including but not limited to animal breed, number, rumen fauna, soil moisture, soil temperature, DCD, standoff regimes, fertiliser application, dietary additives, and altering fibre, n-

containing protein, and starch concentrations there is an equally enormous area to investigate to reduce the environmental footprint of farming practices while maintaining milk production. Whilst none of the treatments described provide the perfect solution to mitigate UN and CH₄ while maintaining or increasing milk production, a much need solution may be formed when used in combination with one another. A number of the techniques described require further exploration to broaden the depth of understanding as exactly how they can be optimally utilised to reach both milk production and environmental footprint goals.

2.10.1. Knowledge gap that this thesis will fulfil

Herbage allowance does not affect chemical composition of herbage; however, it influence grazing and selective behaviour presenting the animal the opportunity to select and ingest herbage or part of it with greater nutritive value. Although much research has been conducted on HA and its effect on milk production and herbage intake. There is little data on its effect on simultaneous reductions of CH₄, UN and milk production.

As meals consumed by ruminants follow a circadian rhythm, with the largest meal consumed at dusk when feeding motivation, herbage chemical composition, and herbage physiology are optimal for increased energy intake. Managing the time of herbage allocation has been identified to increase milk production and reduce UN. However, further research is required into the time of herbage allocation simultaneously addressing UN, CH₄, and milk production.

Supplementing herbage with cereals –grains and silages- help diluting N intake and, thereby, UN with potential to reduce CH₄ emissions. Timing of supplementation can add further benefits in the reduction of these pollutants.

However, empirical and simulation modelling research is lacking to the evaluation

of simultaneous effects of HA, timing of herbage allocation and timing of supplementation, not only on milk production, but most importantly in the context of this thesis on the effects on CH₄ emissions, UN excretion of dairy cows. The following chapters of this thesis aim at exploring and evaluating the effect of HA, timing of herbage allocation and supplementation on CH₄ emission, UN and milk production of grazing dairy cows under typical dairy farm grazing conditions of Waikato, New Zealand.

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Chapter 3

The effect of herbage allowance on enteric methane emission, urinary nitrogen excretion and milk production by grazing dairy cows

Simulating the effect of herbage allowance on enteric methane emission, urinary nitrogen excretion and milk production by grazing dairy cows

Abstract.

Intensification of farming practices has impacted the environment negatively by increasing enteric methane (CH₄) emissions and urinary nitrogen (UN) excretion by dairy cows; subsequently, increasing economical, societal, and environmental constraints on dairy farming. The objective of this simulation modelling study was to investigate the effects of herbage allowance (HA), on milk solids production (MS, sum of daily fat and protein yield, kg d⁻¹), enteric methane emission (CH₄, g/d and g/kg DM intake), and urinary nitrogen (UN, g d⁻¹) excretion of dairy cows grazing a typical sward of Waikato, New Zealand. A mechanistic and dynamics model of a grazing ruminant, MINDY, was used. Eight identical instances of MINDY were allocated four different HA 20, 30, 40, and 50 kg DM d⁻¹. Four of them were initialized on early lactation (EL) and the other four in late lactation (LL). As HA increased, dry matter intake (DMI, kg DM d⁻¹), post grazing herbage mass, CH₄ production, UN, and MS production increased with a diminishing marginal response per kg of herbage DM allocated.

The average increase in CH₄, UN and MS production from 20 to 50 kg DM were 12, 23, and 6% respectively, beginning to plateau at 30 kg herbage DM. Methane yield and MS kg DMI⁻¹ declined between 20 and 50 kg DM respectively by 11 and 18%, while UN kg herbage DMI⁻¹ declined by 1%. Methane and UN kg MS⁻¹ on average rose by 6 and 16%, respectively. At the MS inflection point, CH₄ yield on average is 18.16 and 19.90 g kg DM⁻¹ and UN yield 12.80 and 17.38 g kg DM⁻¹, each in EL and LL respectively. From this point, minimal increase in MS will lead to exponential increase in UN, while increments in the MR in terms of MS production will increase CH₄ yield exponentially. The pollution swapping

between CH₄ emission and urinary N excretion is usually present, but increments in the environmental impact of increased CH₄ yield can be easily offset by reductions in urinary UN. Although setting HA is a simple and well explored grazing tool to manage MS production and herbage utilization, the results of this study suggest that HA can also sever as a tool to reduce environmental impact and manage pollution swapping.

Key words. Herbage allowance, grazing, methane emissions, urinary N

3.1. Introduction

New Zealand's agricultural greenhouse gas (GHG) emissions increased between 1990 and 2014 by 23.3%. Over this period national dairy herd size increased by 94.7%, along with fertiliser application, which grew by 500% (MFE, 2016). Alongside growing herd sized, milk solids (MS, sum of daily fat and protein yield) production increased too. The increase of MS production grossed 1.862 million tonnes in 2015-16 season, 0.572 million more tonnes than what was produced in the 1990-91 season (Livestock Improvement Corporation limited & DairyNZ Limited, 2016). Dairy products, such as milk powder, are NZ's most exported commodity, accounting for 26% of exported goods and make a strong contribution to New Zealand economy (Schilling, Zuccollo, & Nixon, 2010). The need for dairy and meat is predicted to continue rising with the growing population, until 2050 when the population is estimated to plateau at 9 billion (Hume, Whitelaw, & Archibald, 2011). For production to meet demand, practices must be conducted in a sustainable manner, thus it is important to consider sustainability alongside productivity.

Intensification of pastoral dairy farm has led to considerable increments in stocking rate, which poses challenges to grazing management, reducing the flexibility to manage herbage allowance (HA). Two meta-analyses by Pérez-Prieto and Delagarde (2012, 2013) investigated the productive and behavioural response of grazing dairy cows to HA. These analyses involved over 60 published papers from all over the world with different swards, cow breeds, stages of parity, DIM, and sward structure. Their results indicate that increments in HA lead to increases in MS and body condition score, and reductions in grazing time and herbage utilization. They also indicate a strong effect of HA on milk composition. Milk production and milk protein content increase with HA, while fat content of

milk is reduced as HA increases. Despite this big body of information, only few studies explored the effect of either stocking rate (cows ha⁻¹) or even less HA on GHG emissions and/or UN excretion on NZ dairy farms (Adler, Doole, Romera, & Beukes, 2015; Doole, 2014, 2015; Doole & Kingwell, 2014; Doole & Romera, 2013, 2014, 2015; Romera & Doole, 2016; Romera, Doole, & Khaembah, 2015). Moreover, whilst the analyses Pérez-Prieto and Delagarde (2012 and 2013) were extensive, only four of the studies used were conducted in NZ. Such a lack of information indicates that there is potential to further investigate the effect of HA on CH₄, and UN.

The analysis and relationship between herbage DMI and CH₄ production and yield reported by Muetzel (2011) suggests not only a large variability of the estimated CH₄, but also a considerable variability of CH₄ yield. Greater herbage DMI results in consumption of more fermentable carbohydrates; consequently, enlarging emissions of fermentation by-products (g CH₄ d⁻¹). However, CH₄ yield (g CH₄ kgDMI⁻¹) declines with intake, as rumen digesta outflow increases and fermentation patterns in the rumen become more glucogenic (i.e. increments in propionate production) (Bannink, Ellis, Mach, Spek, & Dijkstra, 2013; Hristov et al., 2013; Pinares-Patiño, D'hour, Jouany, & Martin, 2007; Lee, Donaghy, & Roche, 2008; O'Donovan & Delaby, 2008; Purcell, O'Brien, Boland, O'Donovan, & O'Kiely, 2011). Contrastingly to this reduction in CH₄ yield, increases in HA would lead to greater total UN excretion as a result of greater DM and, thereby, N intake (Gregorini, Beukes, Dalley, & Romera, 2016). The latter being a product of greater ingestion of green leaf (Gregorini et al., 2017).

The objective of the present simulation study was to explore the effect of a broad range of HA on CH₄ emissions and UN excretions by dairy cows, with the

purpose of analysing how HA could be used as a tool to minimise environmental impact while maintaining or increasing MS production.

3.2. Methods

3.2.1. The model

For the objective and the purpose of this study, the latest version model MINDY (Gregorini, Provenza, Villalba, & Forbes, in press) was used. MINDY is a deterministic, mechanistic and dynamic model of a dairy cow representing diurnal patterns of ingestion, digestion and metabolism, and production, as well as excretion based on explicit relationships among direct (ingestion, digestion and metabolism) and indirect (feeding environment) controls of motivation to feed. MINDY is a cluster of seven models: 1) Molly models digestion, metabolism and production of a dairy cow (Baldwin 1995 as modified by Gregorini, Villalba, Provenza, Beukes, & Forbes, 2015); 2) diurnal fluctuations in feeding motivation; 3) sward canopy structure and herbage quality; 4) grazing behaviour; 5) dietary preference and forage selection; 6) foraging bioenergetics; and 7) drinking and urination behaviour. MINDY also integrates functional relationships between forage ingestion, oral physiology and swallowing, and rumen digestion responsible for variations in liquid outflows from the rumen.

Each instance of MINDY can be initialized with unique characteristics, e.g. age, breed, BCS, high, body weight, genetic merit for milk production, calving date etc. Likewise, pasture and supplements can be chemically and physically (e.g. sward structure) designed and set by the user. In addition, MINDY simulates spatio temporal changes in herbage chemical composition. Herbage nutritive value change during the day and grazing strata.

3.2.2. Virtual experiments

Eight identical instances of MINDY were initialized as multiparous 500 kg BW Friesian dairy cows, and strip-grazed (allocated) under four different HA, 20, 30, 40, and 50 kg DM d⁻¹. Four of them were initialized to graze in Hamilton (New Zealand) in September during early lactation (EL, 31 DIM) and the other four grazed in Hamilton as well, in April during late lactation (LL, 180 DIM) (Note: MINDY's hunger and herbage chemical composition and lactation respond to changes in daylight hrs., i.e. photoperiod).

The simulated sward was a perennial ryegrass- based (80 % *Lolium perenne* L. and 20% *Trifolium repens*) typical of Waikato NZ dairy systems. The sward herbage mass was 3000 kg DM ha⁻¹, the sward surface height (extended tiller) was 30 cm. The chemical composition of herbage at each time of the year is presented in Table 3.1, and reflected the used of fertiliser applied at a level of 200 kg N/ha per year. Pasture paddocks of different sizes (according to treatments) were allocated once a day after the morning milking. MINDY was milked at 06:00 and 15:00.

Simulations were run for 30 days, the first 10 days was 'model adaptation/stabilization' and the last 20 days data collection. The outputs requested were: DMI (kg DM⁻¹d⁻¹), MS yield (kg cow⁻¹d⁻¹), milk yield (MY) (kg cow⁻¹d⁻¹), N intake (NI, g d⁻¹), UN (g d⁻¹), and CH₄ emissions (g d⁻¹).

Table 3.1. Chemical composition of herbage offered to and grazed by MINDY during early (October) and late (April) lactation.

Analyses (g kg⁻¹DM)^b	Early lactation perennial ryegrass	Late lactation perennial ryegrass
Dry matter (g/kg ⁻¹ wet weight)	183	19.4
Crude protein (%DM)	13.9	18.4
Water soluble carbohydrates (%DM)	15.9	21.3
Neutral detergent fibre (%DM)	45.5	46.1
Acid detergent fibre (%DM)	25.7	26.5
Ash (%DM)	10.9	11.6

3.3. Results

3.3.1. Herbage DMI, post-grazing herbage mass and milk production

Model outputs are presented in Table 3.2. Herbage DMI increased with HA in both EL and LL. The incremental increases in DMI diminished as HA increased. Post-grazing herbage mass, a.k.a. as ‘residual’, increased with HA. Similarly, MS and MY increased with HA, both in EL and LL. The MY increased by 9% and 24% between the lowest (20 kg DM) and highest (50 kg DM) HA during EL and LL respectively. The difference in MS production from the lowest to highest HA was 0.11 and 0.08 kg cow⁻¹d⁻¹ for EL and LL cows, respectively. The initial gains in MS production of cows with a greater HA follows a similar trend as DMI, with the incremental gains decreasing with increments in HA.

3.3.2. Methane emissions and UN

Model outputs are presented in Figure 3.1 and 3.2 (Also, see Appendix 1, for details). At both stages of lactation, UN excretion and CH₄ emissions were predicted to increase with HA at a declining rate. Excretion of UN was ~24 and

23 % greater for the highest HA compared to 20 kg DM of HA in EL and LL, respectively. Likewise, CH₄ emissions rose by 14 and 10% between the 20 and 50 kg DM HA in EL and LL, respectively. However, CH₄ yield declined with HA as DMI rose, consumption of both N and fermentable carbohydrates increased. Greater N intake resulted in a larger proportion of N being excreted within urine. Likewise, greater consumption of fermentable carbohydrates heightened the production of CH₄.

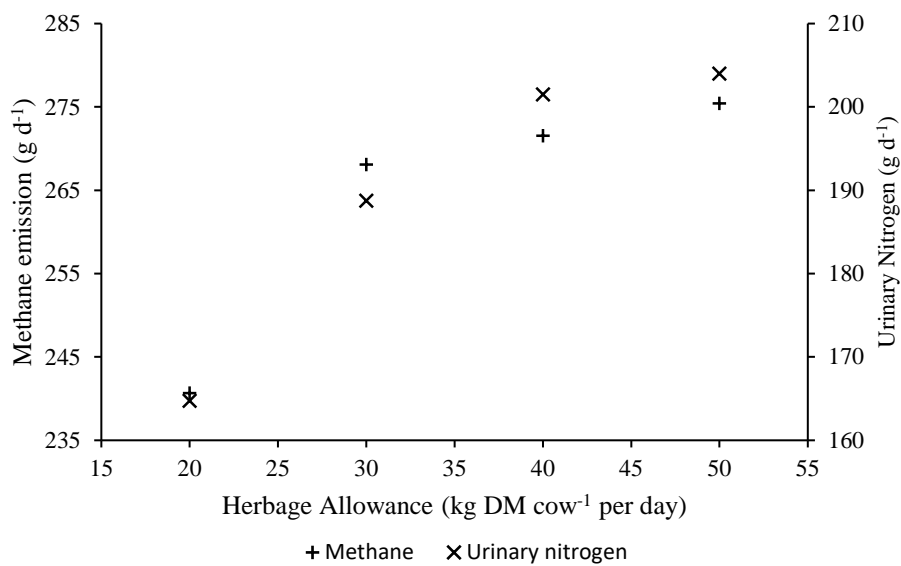


Figure 3.1. Predicted effect of HA on total CH₄ emission and UN excretion in early lactation.

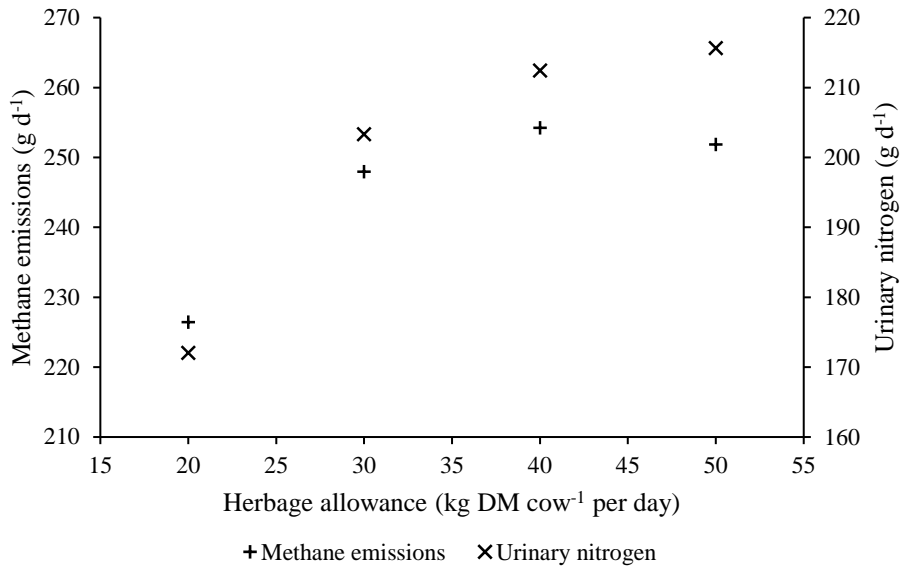


Figure 3.2. Predicted effect of HA on total CH₄ emission and UN excretion in late lactation.

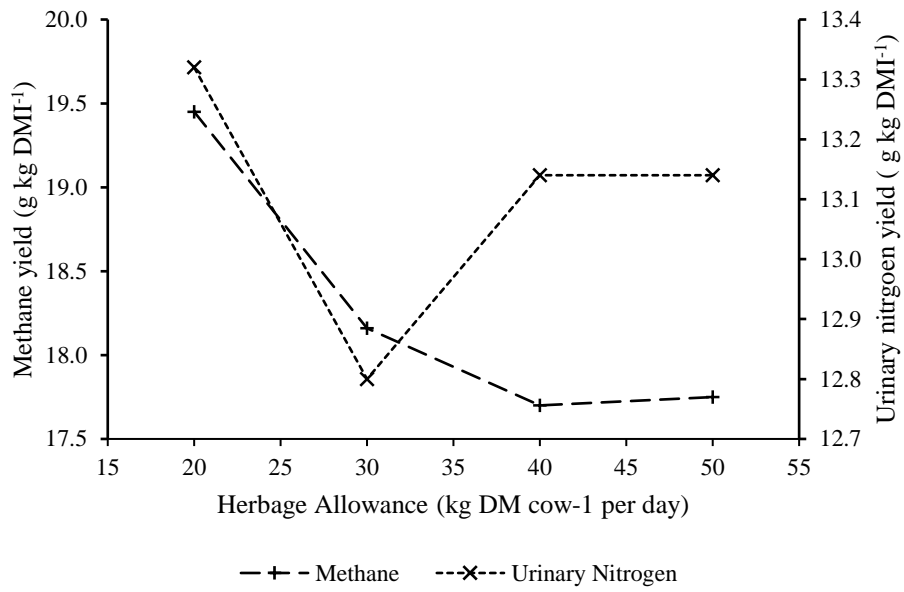


Figure 3.3. Predicted effect of HA on CH₄ and UN yield in early lactation.

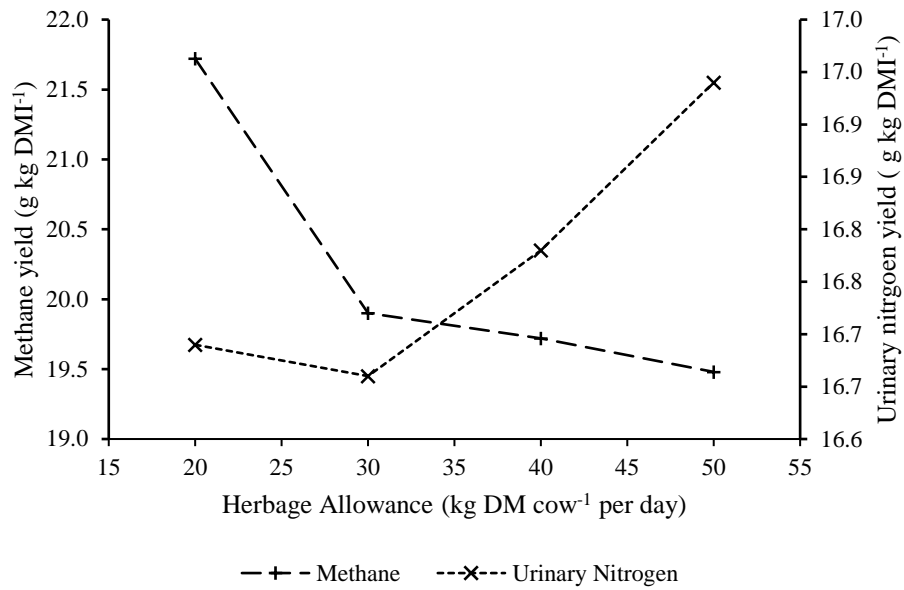


Figure 3.4. Predicted effect of HA on CH₄ and UN yield in late lactation.

Table 3.2. Predicted effect of HA on herbage DMI, post-grazing herbage mass, milk production, methane emission, N intake and UN during early and late lactation.

Variable	Units	Scenario ^o							
		EL20	EL30	EL40	EL50	LL20	LL30	LL40	LL50
Herbage DMI	kg DMI	12.37	14.76	15.34	15.52	10.2	12.37	12.6	12.69
Post-grazing herbage mass	kg DM ha ⁻¹	1,083	1,475	1,882	2,045	1,418	1,727	2,028	2,214
Milk production	kg MS	2.03	2.13	2.14	2.14	1.14	1.21	1.22	1.22
Total methane	g CH ₄	241	268	271	275	258	279	287	284
Methane yield	g kgDM ⁻¹	19.45	18.16	17.70	17.75	21.72	19.90	19.72	19.48
Emission intensity	g CH ₄ kgMS ⁻¹	119	126	127	129	194	203	203	202
N intake	g N	347	424	455	464	332	411	416	426
UN	g N	165	189	202	204	180	215	220	222
UN yield	g CH ₄ kgDM ⁻¹	13.32	12.80	13.14	13.14	16.69	16.66	16.78	16.94
UN intensity	g N kgMS ⁻¹	81	89	94	95	158	178	180	182

The intensity of CH₄ emission is presented in Table 3.2 and Figure 3.5.

Methane emission intensity rose by 8.4 and 4.1% between the 20 and 50 kg HA

for EL and LL, respectively. Methane emissions intensity was more uniform between the 20 and 50 kg DM HA during LL. The largest increase in CH₄ emission intensity occurred between the 20 and 30 kg HA regardless of stage in lactation. Between the 30, 40, and 50 kg PA, incremental increases in CH₄ emission intensity decrease; appearing to plateau with DMI and MS production.

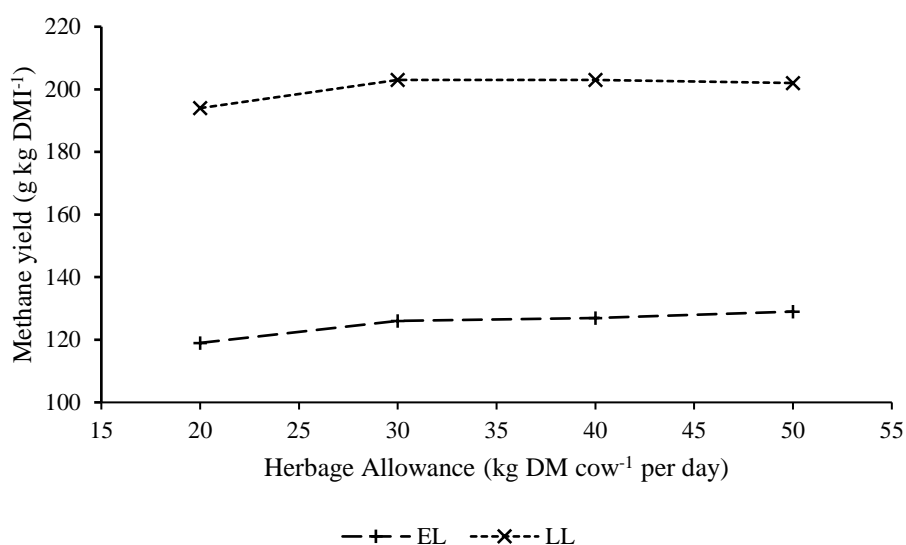


Figure 3.5. Predicted effect of HA on CH₄ emission intensity (g kg MS⁻¹) in both early and late lactation.

MINDY predicted the largest changes in milk production between the 20 kg and 30kg HA. Likewise, UN excretion and CH₄ emissions rose with the largest increment between the 20 and 30 kg DM HA.

3.4. Discussion

3.4.1. The effect of HA on milk production

Model outputs indicate that as HA increased from 20 to 40 kg DM per day, MINDY produced more MS. The 40 and 50 kg DM d⁻¹ HA had similar MS production whilst their DMI only differed by 1.1% and 0.7% respectively, for EL and LL simulations. As reported in the literature (Pérez-Prieto and Delagarde

2013), herbage DMI and milk production increased with HA at a declining rate until seemingly plateauing. The inflection point in milk production at the 30, kg DM d⁻¹ HA related to both the approximation to meeting the energy requirement and the digestive constraints presented by rumen fill and function as reported by (Poppi, Hughes, & L'huillier, 1987; Eastridge, 2006).

3.4.2. The effect of HA on post-grazing herbage mass and growth

Post-grazing herbage mass –residuals- is thought to affect herbage regrowth rates (Lee et al., 2008). The model outputs indicate that residuals increased with HA. High residual have been reported to reduce herbage feeding value as well, and thereby effect animal performance in future grazing events of the same paddock (Lee et al., 2008). Thus, and at a greater, scale increasing HA could reduce pasture herbage production and herbage nutritive value, reducing farm milk production and profitability (Macdonald, Glassey, & Rawnsley, 2010; Romera & Doole, 2015). However, there is not enough evidence to support such a premise. Herbage regrowth studies report conflicting results. Some studies identified that post grazing residual greater than 1500 kg DM ha⁻¹ have a faster herbage regrowth rate, whilst others report the same result for residuals lower than 1500 kg DM ha⁻¹. Moreover, Lee et al (2008) reported that the nutritive value and regrowth of perennial ryegrass-dominant swards was maximized when residual sward height ranged between 40 to 80 mm, which indicate that at relatively high grazing efficiencies, post grazing herbage mass or sward height may not be as important in determining herbage nutritive value .

In this model study, the post-grazing herbage mass ranged between of 1117-1602 kg DM ha⁻¹ and 1854-2301 kg DM ha⁻¹ for EL and LL, respectively. Assuming that post-grazing herbage mass has a real and significant effect on herbage regrowth and nutritive value, and the an optimal average approximates

the mark of 1500 kg ha⁻¹, during EL HA of 30 kg of herbage DM with a residual of 1475 kg DM ha⁻¹ would approximate such an ‘optimal’ threshold outlined by Lee et al. (2008). Conversely, in LL the 40 and 50 HA treatments grazed pasture down to residuals of 2028 and 2214 kg DM ha⁻¹ that were not within the range described by Lee et al. (2008) as ‘optimal’ residuals. Independent of the present considerations on ‘optimal residual’ and its effect on herbage regrowth and nutritive value, it is important to consider that, overall grazing efficiency is reduced as HA increased. There is a trade-off between grazing efficiency and the option to provide selective power to cows and increase daily herbage DMI.

3.4.3. Urinary N and CH₄ emission mitigation through HA

Herbage management affects the chemical composition of ingested herbage and the availability and accessibility of such herbage to the grazing animal (Gregorini 2012), in turn determining herbage intake, and would influence CH₄ emissions and UN excretion (Gregorini et al., 2017). Increments in HA result in greater total amount of CH₄ emissions and UN excretion per cow, which relate to the increase in herbage DM, N and fermentable carbohydrates intake. This premise can be illustrated by the lowest HA treatment, which had the lowest UN and highest CH₄ yield. Pollution swapping is evident. Often intensive grazing, as occurs at low HA, result in the consumption of lower grazing strata and thereby lower proportion of green leaves. The later increasing the amount of fibre intake (O'Donovan & Delaby, 2008). Reduced degradable protein intake lowers N emissions per cow as N utilisation by microbes within the rumen is more efficient (Kebreab et al., 2010). herbage can be limited to numerous levels of availability by altering the time available to graze or the area allocated per cow, Pinares-Patiño et al. (2007) evaluated the effect that low and high stoking rate (1.1 and 2.2

livestock units per ha, respectively) had on CH₄ production on a per hectare basis. The lower stocking rate treatment produced more CH₄ per kg digestible organic matter intake than the high stocking rate, similar to the results of the present study with HA.

Therefore, increasing HA would enhance the environmental impact of pastoral dairy farming in NZ at a cow level, despite the reductions in CH₄ yield and the incremental increases milk production. This premise indicate that lower HA would be beneficial since any increase in CH₄ yield can be easily offset by reductions in urinary UN (Dijkstra, Oenema, & Bannink, 2011; Gregorini, Beukes, Romera, Levy, & Hanigan, 2013), plus CH₄ emission intensity would be reduced.

Increments in HA would also decreases milk production per hectare as grazing efficiency and herbage production would be reduced (Glasse, Roach, Lee, & Clark, 2013; Macdonald, Penno, Lancaster, & Roche, 2008). The present simulations though were on a per cow basis to and cannot be extended to a per hectare basis as it would require too many further assumptions.

3.4.4. Practical implications

To maintain herbage feeding value, optimal intake, and high production in low GHG emission pastoral livestock production systems, management practices are often intensive and difficult to conduct. Reducing stocking rate can reduce negative environmental effects, as DMI is the main driver of CH₄ and UN emissions when paired with lower fertiliser application rates. Many dairy farms with high stocking rate find that harsh seasons result in herbage shortages, leading to shorter lactations if nutritive needs are not meet by supplementation. Lactation lengths from trials involving low stocking rates were shown to be unaffected by harsh growing seasons (Vibart et al., 2012). High stoking rates, almost inevitably

leads to low HA managements, which present the advantage of greater efficiency of herbage conversion to MS. The success of pasture-based dairy systems can be improved by increasing such conversion efficiency. Enhancing farm efficiencies was hypothesised by Beukes, Gregorini, Romera, Levy, & Waghorn (2010) to reduce emissions by increasing profitability and maintaining production.

Although Vibart et al. (2012) outlined the success of a number of competitive, highly profitable farms with low emissions, it is thought that only a few farms have remained highly competitive given the high level of management skill required to maintain profitable high HA systems. Difficulties encountered when managing high HA systems include lack of defoliation to renew photosynthetic efficiency and shading of tiller bases, which degrades herbage nutritive value due to decreased green leaf quantity, reduced amount of green leaf, number of initiating tillers, and increased the quantity of dead material (Macdonald et al., 2008). Managing profitable high HA systems involves maximising individual cow's biophysical properties such as DMI and herbage utilisation and implementing different rotation lengths throughout the year (Romera and Doole, 2015).

3.5. Conclusions

The present simulation study suggests that HA over 30 kg DM cow⁻¹ per d would not increase milk production significantly, being the MR considerably low and promoting inefficient grazing. Strategic reductions of HA, even below the inflection point for milk production, could be used as an effective and significant mitigation methods to minimise CH₄ emissions and UN excretion by grazing dairy cows. The present study suggest that increasing HA lead to greater herbage DM and N intake and, consequently, increasing rumen fermentability and the total

CH₄ emissions (despite reduction in CH₄ yield), as well as UN excretion and deposition onto pasture.

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Chapter 4

The effect of herbage allowance and timing of allocation on methane emission, urinary nitrogen excretion and milk production by grazing dairy cows.

The effect of herbage allowance and timing of allocation on methane emission, urinary nitrogen excretion and milk production by grazing dairy cows

Abstract.

New Zealand's agriculture industry produced 48% of national greenhouse gases (GHG) in 2015, 38% greater than most other developed countries. Methane (CH₄) and nitrous oxide (N₂O) are the key GHG produced by dairy farming. Methane is a by-product of enteric digestion, and N₂O is the product of nitrification or denitrification of urinary nitrogen (UN), which can also leach as nitrate into receiving water bodies, promoting eutrophication. The model MINDY was used to examine the effect of the time of day herbage was allocated, morning (AM) or afternoon (PM), on milk production, and the emissions of UN and CH₄ for different herbage allowances (HA, 20, 30, 40, and 50 kg cow⁻¹per d). Herbage allowance increased DMI, and thereby CH₄ emission and UN excretion. The HA effect, however, followed a diminishing marginal response. In the same way, HA, reduced CH₄ yield on average by 11 and 18% between the 20 and 50 kg in early and LL (EL and LL). Independent of HA, PM herbage allocation reduced UN by an average of 5%, compared to treatments allocated herbage in the AM. Allocating herbage in the afternoon led to an increase in CH₄ production by 5%, compared AM, evidencing the pollution swapping phenomena, and a trade-off decision and prioritisation of mitigation of either CH₄ or UN needs to be made. The PM herbage allocation increased DMI, and lifted milk solids (MS) production. The pollution swapping between CH₄ emission and urinary N excretion is often present, but increments in the environmental impact of increased CH₄ emission can be easily offset by reductions in urinary UN. Therefore, unnecessary increments in HA, and even reduction under the MS

production inflection point, plus simple changes to grazing management practices enhancing the natural grazing pattern of ruminants preferring to graze in the afternoon-evening help NZ dairy production systems to reduce environmental impact further.

Key words. Herbage allocation, grazing pattern, methane, urinary N.

4.1. Introduction

The dairy industry is a strong contributor to New Zealand's (NZ) economy and accounts for around 25% of all exported products (Schilling, Zuccollo, & Nixon, 2010). In 2016, more than 3.0 million tonnes of milk powder, butter, and cheese with a value of NZ \$11.2 billion were exported from NZ (Statistics New Zealand, 2017). The demand for dairy and meat products is predicted to grow until 2050, when the global population is expected to stabilise at 9 billion (Hume, Whitelaw, & Archibald, 2011). Various pollutants are produced by ruminants used for meat and dairy production. Over the period between 1990 and 2014, net greenhouse gas production (GHG) increased in NZ by 55% (Statistics New Zealand, 2016). New Zealand's agriculture industry produced 48% of GHG in 2015, 40% more than in most other developed countries (MFE, 2016). Enteric methane (CH₄) is the key GHG produced by ruminant digestion and emitted mainly by eructation. The other major GHG and pollutant produced by dairy practices is nitrous oxide (N₂O) which is produced by the nitrification or denitrification of urinary nitrogen (UN). Urinary N also acts as a pollutant through nitrate leaching into receiving water bodies, promoting eutrophication. Within pastoral based dairy settings, the N excreted by dairy cow's accounts for approximately 70% of that they consume, of which approximately 60% is excreted as UN (Castillo et al., 2001). Typically, dietary strategies to reduce UN increase methanogenesis or vice versa, the phenomena called pollution swapping (Gregorini, Beukes, Dalley, & Romera, 2016). It is thought that grazing managements to date have reached a point at which a trade-off decision must be made to optimise the use of an abatement and production strategy (the frontier),

which sometime compromises one area of either mitigation (UN or CH₄) or MS production.

Whilst dietary changes and managements typically result in pollution swapping, there may be potential to reduce environmental impact by influencing grazing patterns and thereby ingestion and digestion dynamics (Gregorini, Villalba, Chilibroste, & Provenza, 2017).

In general, either wild or domesticated ruminants have between three to five large grazing events or 'meals' during the day (Gregorini, 2012). According to Orr, Rutter, Penning, & Rook (2001), Gibb, Huckle, & Nuthall (1998) and Gregorini (2012), the dusk meal is the most intensive and longest meal of the day; at a time of day when the feeding value of herbage is the highest, with the lowest N: fermentable carbohydrates ratio. Moreover, also at that time of the day the rumen presents the fastest digesta outflow rate (Gregorini 2012). Consequently, timing of herbage appears as an alternative to reduce environmental impact. Although timing of herbage allocation in the afternoon has potential to increase nutrient supply from the rumen to the host animal (Gregorini, Gunter, & Beck, 2008) with consequent benefits in animal performance (Gregorini et al., 2006, Gregorini 2012), only few empirical works have attempted to quantify benefits on the reduction of UN, and none in methanogenesis.

The following hypothesis emerges: timing of herbage allocation will influence methanogenesis and excretion of UN. Allocation of herbage in the afternoon will reduce environmental impact and can add to HA managements. The objective of this simulation modelling was to explore the effect of timing of herbage allocation at different HA on milk production, but most importantly, the UN excretion and CH₄ emission.

4.2. Methods

4.2.1. *The model*

The latest version model MINDY (Gregorini, Provenza, Villalba, & Forbes, in press) was used. MINDY is a deterministic, mechanistic and dynamic model of a dairy cow representing diurnal patterns of ingestion, digestion and metabolism, and production, as well as excretion based on explicit relationships among direct (ingestion, digestion and metabolism) and indirect (feeding environment) controls of motivation to feed. MINDY is a cluster of seven models: 1) Molly models digestion, metabolism and production of a dairy cow (Baldwin 1995 as modified by Gregorini, Villalba, Provenza, Beukes, & Forbes, 2015); 2) diurnal fluctuations in feeding motivation; 3) sward canopy structure and herbage quality; 4) grazing behaviour; 5) dietary preference and forage selection; 6) foraging bioenergetics; and 7) drinking and urination patterns. MINDY also integrates functional relationships between forage ingestion, oral physiology and swallowing, and rumen digestion responsible for variations in liquid outflows from the rumen.

Each instance of MINDY can be initialized with unique characteristics, e.g. age, breed, BCS, high, body weight, genetic merit for milk production, calving date etc. Likewise, pasture and supplements can be chemically and physically (e.g. sward structure) designed and set by the user. In addition MINDY simulates spatio temporal changes in herbage chemical composition. Herbage nutritive value change during the day and grazing strata.

4.2.2. *Virtual experiments (simulation exercise)*

Sixteen identical instances of MINDY were initialized as multiparous 500 kg BW Friesian dairy cows, and strip-grazed under four different HA, 20, 30, 40,

and 50 kg DM d⁻¹, allocating herbage either after the morning (AM) or afternoon (PM) milking. Milking times were 06:00 and 15:00. Eight of them were initialized to graze in Hamilton (New Zealand) during September on early lactation (EL, 31 DIM) and the other eight grazed in Hamilton as well, during April during late lactation (LL, 180 DIM) (Note: MINDY's hunger and herbage chemical composition and lactation respond to changes in daylight hrs., i.e. photoperiod).

The simulated sward was a perennial ryegrass- based (80 % *Lolium perenne* L. and 20% *Trifolium repens*) typical of Waikato NZ dairy systems. The sward herbage mass was 3000 kg DM ha⁻¹, the sward surface height (extended tiller) was 30 cm. The chemical composition of herbage at each time of the year is presented in Table 4.1 and reflected the used of fertiliser applied at a level of 200 kg N/ha per year. Pasture paddocks of different sizes (according to treatments) were allocated once a day either after the morning or afternoon milking.

Each simulation was run for 30 days, being the first 10 days of 'model adaptation/stabilization' and the last 20 days of data collection. The outputs requested from MINDY were: DMI (kg DM⁻¹d⁻¹), MS production (kg cow⁻¹d⁻¹), milk yield (MY) production (kg cow⁻¹d⁻¹), N intake (NI, g d⁻¹), UN (g d⁻¹), and CH₄ emissions (g d⁻¹).

Table 4.1. Predicted CH₄ and UN values for herbage allowances allocated at different times of the day in early and late lactation.

Analyses (g kg⁻¹DM)^b	Early lactation perennial ryegrass	Late lactation perennial ryegrass
Dry matter (g/kg ⁻¹ wet weight)	183	19.4
Crude protein (%DM)	13.9	18.4
Water soluble carbohydrates (%DM)	15.9	21.3
Neutral detergent fibre (%DM)	45.5	46.1
Acid detergent fibre (%DM)	25.7	26.5
Ash (%DM)	10.9	11.6

4.3. Results

4.3.1. Herbage intake, post-grazing herbage mass, and milk

Predicted herbage DMI and milk solids production (MS, sum of fat plus protein daily yield, kg d⁻¹) are presented in Figure 4.1. The pattern of increased allowance increasing DMI and MS described in Chapter 3 remains evident in each of the AM or PM treatments groups. A rise is seen in the DMI for cow's allocated pasture in the afternoon for each allowance except the 30 kg PA, for both EL and LL treatments. In comparison to the AM pasture allocation the PM group had a 2.4, 3.2, and 2.7 % rise in DMI, respectively, for the 20, 40, and 50 kg HA's in EL. Yet within the same EL simulation the 30 kg HA treatment supplied in the evening consumed 0.7% less DM than its equivalent AM treatment group. While the PM allocation of the LL 20, 30, 40, and 50 kg HA's allocated in the PM consumed 2.2, -2.8, 1.1, and 0.7% more and less DM than their AM counterparts. As expected, those with higher DMI had corresponding lower residual covers. The trend for MS production does not follow that of DMI in EL with each PM allowance treatment producing more MS than its AM equivalent. The greatest difference between the AM and PM allocation of pasture was simulated between

the 20 kg HA which increased milk solids production by 3.2 and 1.8% individually for the EL and LL. Within both lactation settings the PM allowances: 30, 40, and 50 produced more MS than their AM equivalents. Within EL simulations, the MS production of the PM group are on average 2.3% greater than the AM treatments. Likewise, the LL PM allocation of pasture on average produces 0.7% more MS.

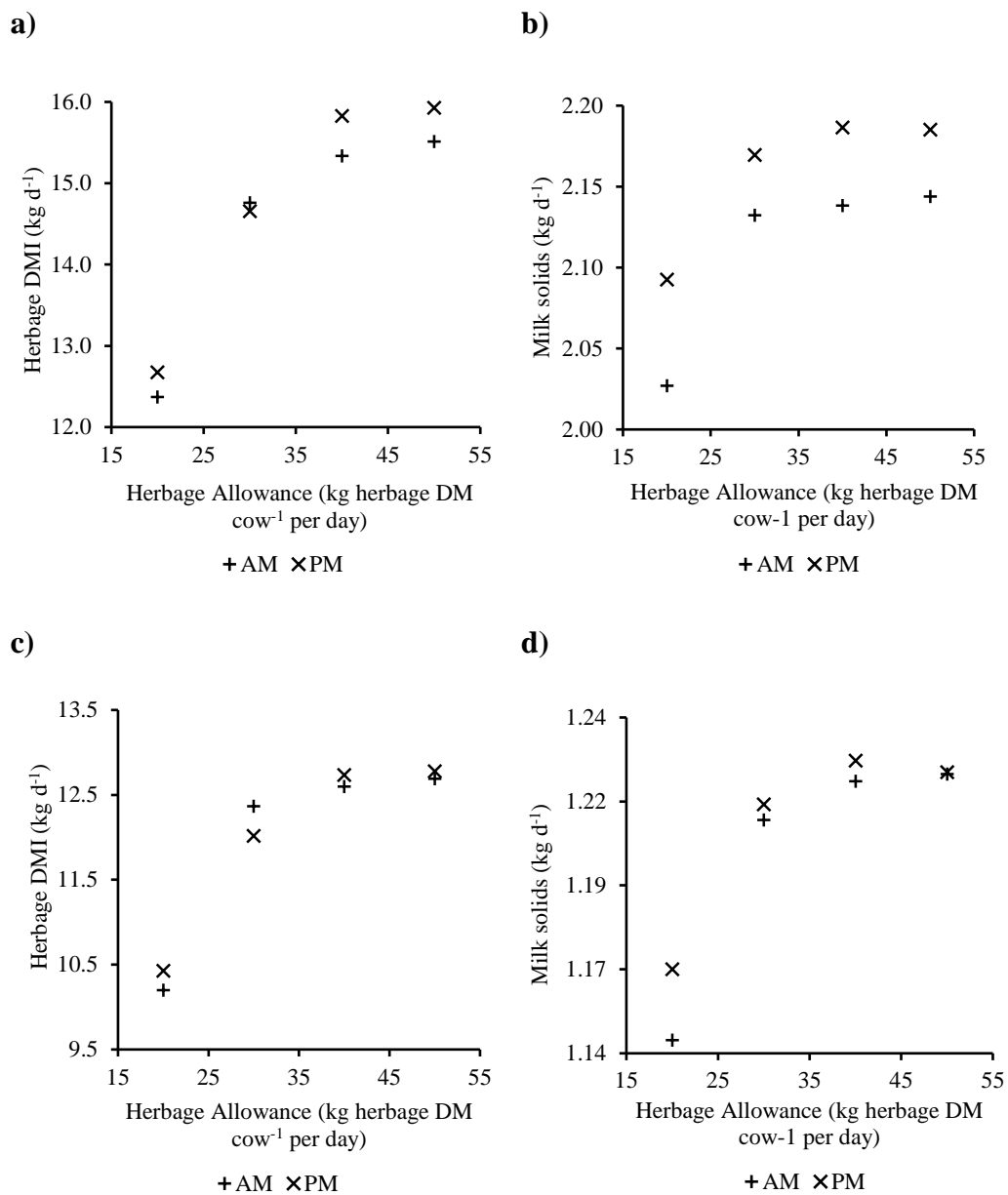


Figure 4.1: Predicted effect of timing of herbage allocation either after the morning (AM) or afternoon (PM) milking at different herbage allowances on a) Herbage DMI in early lactation b) MS in early lactation c) DMI in late lactation, and d) MS in late lactation.

4.3.2. CH₄ emission and UN excretion

Predicted UN and CH₄ emission are presented in Table 4.2. Herbage DM and N intake, and consequently emissions of UN and CH₄ (gd⁻¹) increased with HA at a declining rate, both within EL and LL. Also, the greater the HA the

greater emission intensity was, regardless of stage of lactation or timing of herbage allocation. The emission intensity ($\text{kg CH}_4 \text{ kg MS}^{-1}$) was higher for LL compared to EL.

Table 4.2. Predicted UN excretion and CH_4 emissions as a response to different HA and timing of herbage allocation (AM and PM) during early and late lactation.

Variable	Units	Stage ^a	Scenario ^o									
			20am	20pm	30am	30pm	40am	40pm	50am	50pm		
NI	kg	EL	0.35	0.33	0.42	0.41	0.46	0.44	0.46	0.46	0.46	
CH_4	gd^{-1}	EL	241	258	268	279	272	288	275	284	284	
CH_4 yield	g kgDM^{-1}	EL	19.5	20.4	18.2	19.0	17.7	18.2	17.8	17.9	17.9	
Emission intensity	$\text{g CH}_4 \text{ kgMS}^{-1}$	EL	119	123	126	129	127	132	129	130	130	
NI	kg	LL	0.33	0.32	0.41	0.38	0.42	0.41	0.43	0.42	0.42	
CH_4	gd^{-1}	LL	222	231	246	250	248	260	247	257	257	
CH_4 yield	g kgDM^{-1}	LL	21.7	22.2	19.9	20.8	19.7	20.4	19.5	20.0	20.0	
Emission intensity	$\text{g CH}_4 \text{ kgMS}^{-1}$	LL	194	199	203	206	203	212	202	210	210	

The AM allocations increased NI in comparison PM; except for the 50kg HA in EL in which both the AM and PM allocations had equal NI values. The differences in NI between the AM and PM allocations were 10-20 g. For the LL treatments the NI for the 30 kg HA was 20 g greater for AM than PM. The AM HA for 20, 40, and 50 kg increases NI by 10 g compared to PM. Within EL and LL, each AM HA produced on average 4.7 and 7.8% more UN, respectively, than their equivalent PM (Figures 4.2 and 4.3). The amount of extra UN in AM compared to PM as HA increase from 20 and 50 kg, with the exception on the 30 kg HA, which had the largest UN difference between the AM and PM. The previous statement is true for both stages of lactation; however, the LL PM 30 kg HA was particularly effective at reducing the amount of UN excreted in comparison to AM.

The greater the HA, the greater the CH₄ yield (g kg DM⁻¹) was in EL (Figure 4.4) and LL (Figure 4.5). Regardless of lactation stage the PM had greater CH₄ yields in comparison to AM. The EL PM produced 4.8, 4.8, 2.6, and 0.6% more CH₄/ kg DM than AM, respectively for the 20, 30, 40, and 50 kg. While the LL PM 20, 30, 40, and 50 kg HA produced 2.2, 4.5, 3.6, and 3.1% greater CH₄ yields than AM. The PM of each HA emitted more CH₄ per kg of MS than AM. Within EL, the difference between the AM and PM CH₄ yields, diminished as HA increased. The LL 20 kg HA varied from the prior trend, with the AM and PM CH₄ yields being the most similar. The remaining LL treatments showed the diminishing divergence in CH₄ yields between AM and PM pasture allocation with HA.

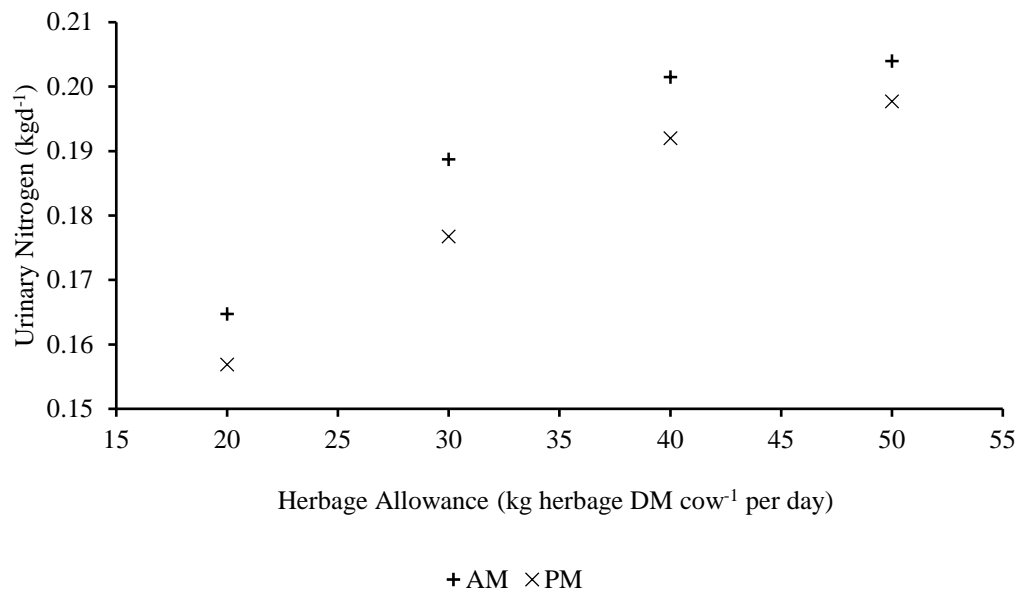


Figure 4.2. Predicted effect of timing of herbage allocation either after the morning (AM) or afternoon (PM) milking at different herbage allowances on UN during early lactation.

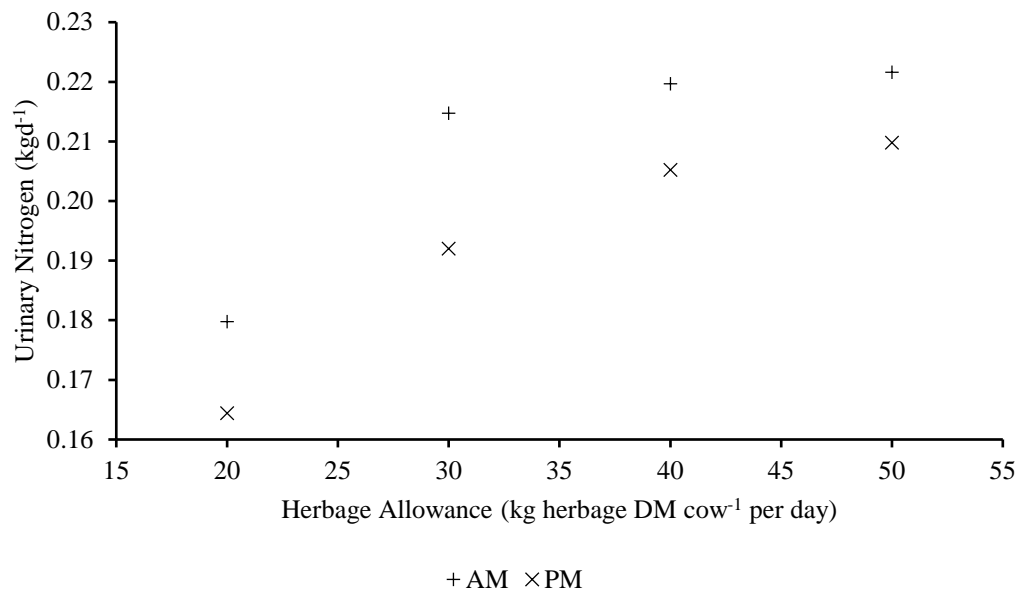


Figure 4.3. Predicted effect of timing of herbage allocation either after the morning (AM) or afternoon (PM) milking at different herbage allowances on UN during late lactation.

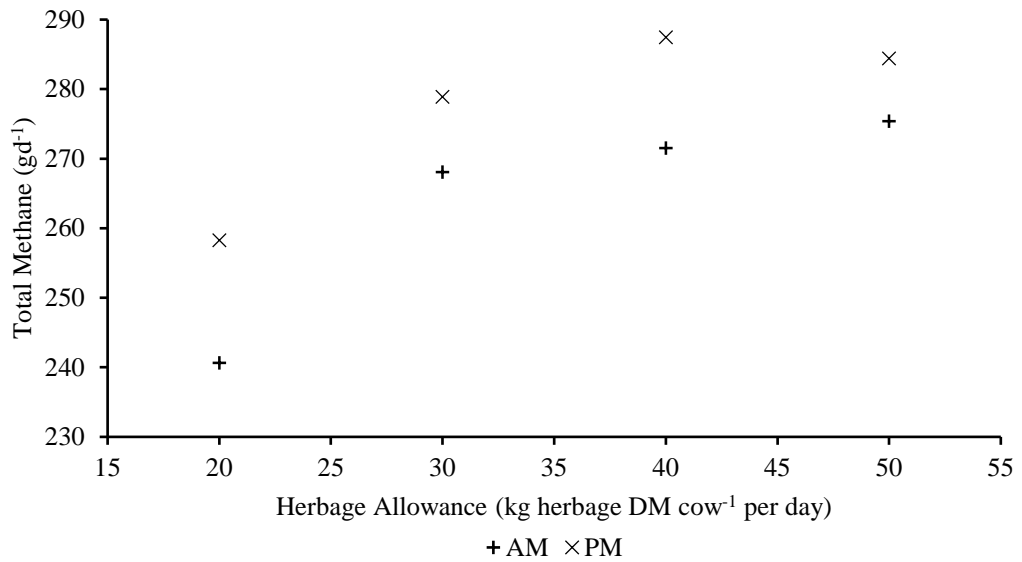


Figure 4.4. Predicted effect of timing of herbage allocation either after the morning (AM) or afternoon (PM) milking at different herbage allowances on CH₄ emission during early lactation.

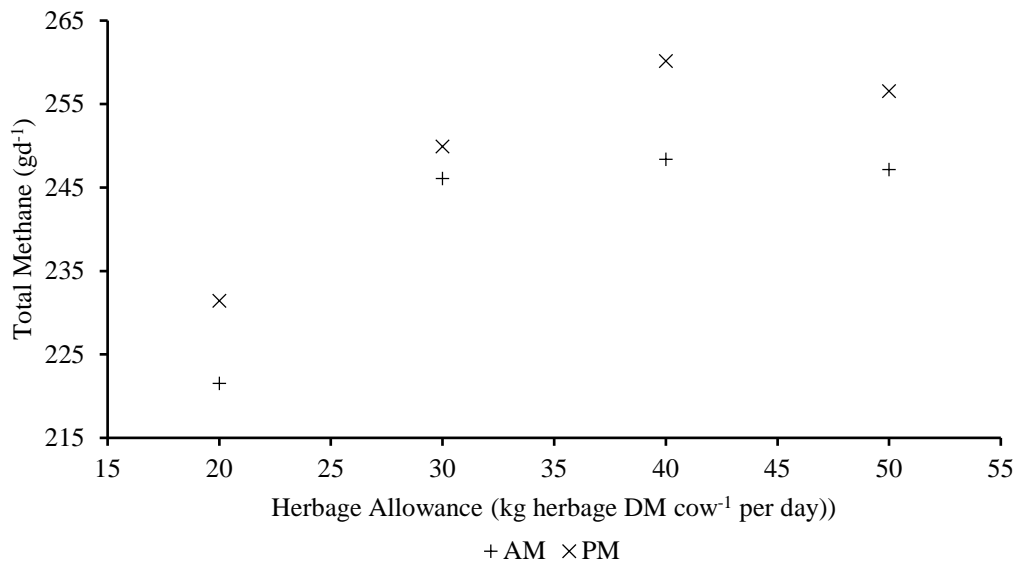


Figure 4.5. Predicted effect of timing of herbage allocation either after the morning (AM) or afternoon (PM) milking at different herbage allowances on CH₄ emission during late lactation.

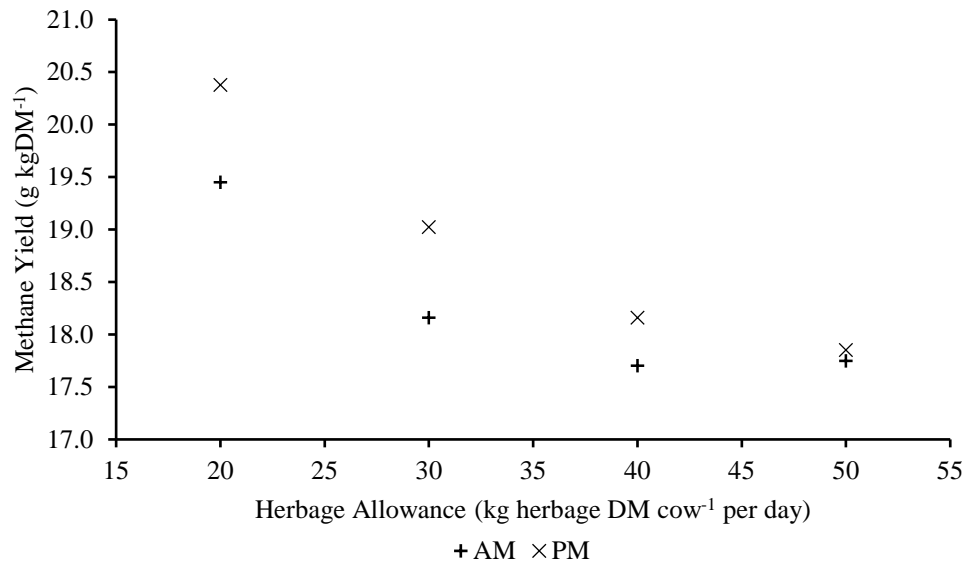


Figure 4.6. Predicted effect of timing of herbage allocation either after the morning (AM) or afternoon (PM) milking at different herbage allowances on CH₄ yield during early lactation.

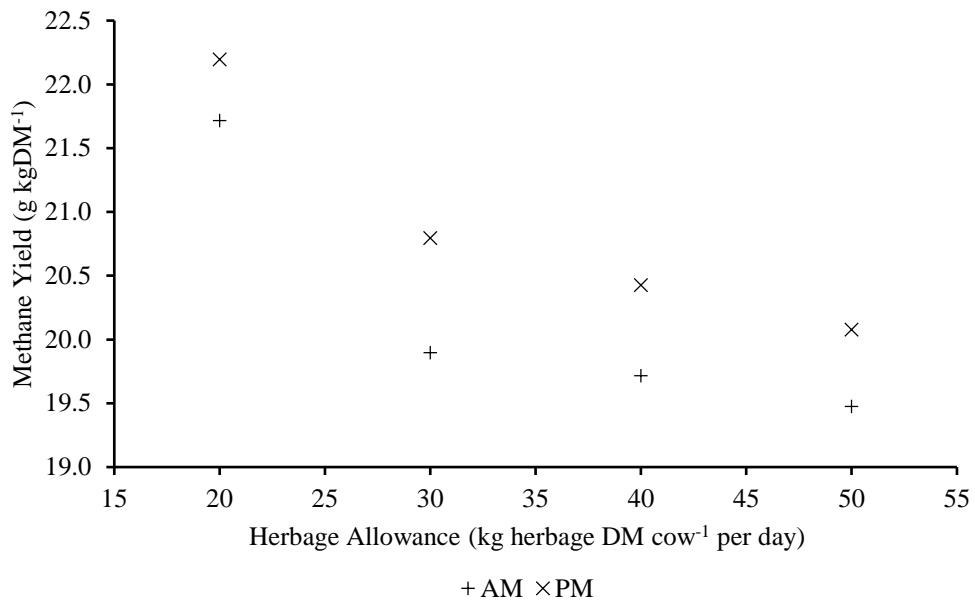


Figure 4.7. Predicted effect of timing of herbage allocation either after the morning (AM) or afternoon (PM) milking at different herbage allowances on CH₄ yield during late lactation

4.4. Discussion

4.4.1. Time of herbage allocation on DMI and milk production

The results of the present study suggest that cows allocated the same HA in the PM increased herbage DMI, on average, 1.9% in EL and 0.3% in LL, compared to AM. These results are supported by Orr et al. (2001), who examined how grazing behaviour of dairy cows was affected by timing of herbage allocation either AM or PM. Similar to our results, the mean DMI for the PM was 1.1% greater than the intake of the cows in AM. The daily herbage DM intake within Orr et al. (2001) experiment was broken into two intake periods, from the morning to afternoon milking (07:45-16:45) and between the afternoon milking (16:45-07:45 h). The cows consumed the most herbage within the period the herbage was allocated, for example the AM cow consumed 12.1 kg of its total DMI (17.8 kg DM) after the morning milking. Alternatively, the cow grazing the PM pasture allocation consumed 15.8 kg of its total DMI (18 kg DM) during the 16:45-07:45 h grazing slot (Figure 4.8.). Orr et al. (2001) also reported that the PM led to longer afternoon meals and less rumination time. Despite such longer afternoon meal cows spent nearly the same amount of time grazing (AM, 461 vs. PM, 462 min day⁻¹) and had similar DMI (AM, 17.8 vs. PM, 18 kg DMI). The lack of effect on these variables may have been related by a dilution effect of by the supplements fed to the cows. However, milk yields with the PM herbage allocation increased by 5%.

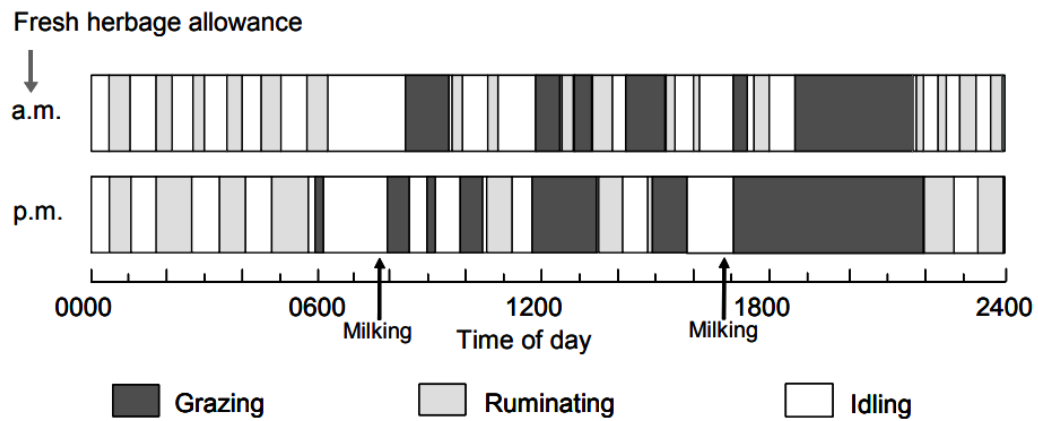


Figure 4.8. The temporal grazing, ruminating, and idling activity of grazing ruminants supplied the same allowance after either the morning (AM) or afternoon (PM) milking [Orr et al., 2001. as taken from Gibb (2007)].

The chemical composition of herbage fluctuates over the day, with the DM content of being highest in the afternoon [AM, 178 vs PM, 197 g DM kg⁻¹ fresh matter (Orr et al., 2001)]. Higher DM content in the afternoon as fresh herbage is allocated may contribute to the slightly greater intake and MS production estimated for the treatments allocated herbage in the PM. The concentration of water-soluble carbohydrates (WSC) are also significantly higher within the same sward in the PM (Gregorini 2012). The CP content of herbage is lower in the evening as opposed by the morning (Delagarde, Peyraud, Delaby, & Faverdin, 2000; Gregorini 2012). The reduction in the CP: WSC ratio in PM herbage can also influence rumen fermentation, increase DMI and MS production. The latter due to an increase in nutrient supply from the rumen to the host animal (Gregorini 2012), which supports the outcomes of the present modelling study.

The effect of the time of year, season, regrowth age, and time of day, on chemical composition was analysed in perennial ryegrass by Delagarde et al. (2000), who showed that in spring the top strata of pasture had the greatest soluble carbohydrate levels. These changes in chemical composition are associated with the water lost during transpiration, and the concentration of photosynthates as the

day progresses (Gregorini et al., 2008; Griggs, MacAdam, Mayland, & Burns, 2005; Mayland, MacAdam, Shewmaker, & Chatterton, 2003). Such differences in chemical composition, energy requirements, and intake demands of cows between seasons contribute to the differences in intake and by-products produced from dairy cows as seen within the present study. Similarly, changes in the chemical composition of forage have been shown to have profound effects on the physical characteristics, such as reduced toughness between dawn and dusk (Gregorini, Soder, Sanderson, & Ziegler, 2009). Key cellular constituents known to affect the toughness of herbage are the structural carbohydrates, hemicellulose, cellulose, and lignin (Gregorini et al., 2009). The 2009 study by Gregorini et al. evaluated the variation in herbage chemical composition, particle size, and toughness between dawn and dusk at, 06:50, 11:10, 15:30, and 19:25 h. As the day progressed both the DM and TNC content present within the herbage grew, displaying the opposite trend NDF and ADF concentrations declined. Consequently, herbage toughness has a negative correlation with both DM and TNC content, and a positive correlation for NDF and ADF. The proportion of large particles declined linearly over the day, subsequently the medium and small particle portion increased. The particle size is significant as it was suggested by Casler, Schneider, & Combs (1996) to be indicative of ease of comminution, this theory was supported by the proceeding results of the Gregorini et al. (2009) study. Greater ease of breakdown in the afternoon may contribute to the increased intake and differences in milk production seen in the cows allocated pasture within the afternoon. The increased ease of breakdown would reduce the amount of chewing required to begin the process of particle size reduction which promotes, bolus formation, swallowing, and herbage damage that allows for microbial colonisation within the rumen (Chilibroste, Dijkstra, Robinson, &

Tamminga, 2008; Gregorini et al., 2009). As well as affecting the biochemical properties such as the toughness the time of day pasture is allocated also affects the amount of energy required to harvest and chew forage during ingestion and rumination (Gregorini, 2012). MINDY simulates changes in fibre content during the day, as well as toughness (easy to forage particle breakdown), as well as changes in ingestive and rumination behaviour as response to fibre content and toughness. All of this research evidence supports the results of the present simulation study.

4.4.2. The effect of time of herbage allocation on CH₄ emission and UN excretion

The NI for the AM for HA was on average 4.7 and 7.8% greater than that of the PM HA. The 50 kg HA in EL for both AM and PM, however, lead to practically the same NI and then UN. The AM produced more UN than their equivalent PM allowances, between the 20 and 50 kg HA. The difference in UN produced by the AM and PM diminished with HA. The exception to this statement is the 30kg HA which had the largest disparity between the two times of herbage allocation, with the LL 30 kg HA PM showing the largest difference compared to the parallel AM.

The pattern of heightened NI for the AM HA was also reported by Bryant, Dalley, Gibbs, & Edwards (2014), who estimated NI using information of DMI and herbage N concentration. It was estimated that the cows allocated herbage in the AM consumed 52 g more N per cow per day than the PM allocation. Bryant et al. (2014) reported a numerical difference of 20 g, this is about 10% of reported UN excreted a day by NZ dairy cows. This reductions are obtained simply by matching the natural grazing pattern of ruminants with natural fluctuations in herbage chemical composition during the day. Upscaling this effect to whole herds and farms make this simple changes in grazing management an attractive

tool/ method to reduce environmental impact. Since it has no cost, and in addition increase MS production. A recent study by Vibart et al. (2017) also estimated AM cows ingested more N. Similar to the results of the present study, Vibart et al. (2017) also found that MS production was greater for the PM treatment group; however, they also reported that PM cows had a greater milk fat and protein yield and excreted larger amounts of N within milk. Timing of herbage allocation was evaluated in term of IN and enteric CH₄ emission by Gregorini et al. (2017), who reported that UN excretion was 292 and 271 kg for the AM and PM respectively, and CH₄ emission was 215 and 198 g/d for the AM and PM respectively. Differences in MINDY versions used account for the different patterns of intake and CH₄ emissions between the present study and results reported by Gregorini et al. (2017).

Pollution swapping was evidenced by the present, the abatement of UN through PM herbage allocation culminated in greater CH₄ production. At a greater HA more CH₄ is emitted and more UN excreted. Treatments with the same HA but allocated in the PM emitted more CH₄ than the AM HA. Within EL the CH₄ yield became increasingly similar between the AM and PM as the HA increased from 30 to 50 kg, although the 20 and 30 kg HA had the same CH₄ yield. Furthermore, the same trend was predicted between the 30 kg AM and PM HA for LL. Greater herbage DMI results in greater fermentation levels and a larger supply of substrate for methanogens; consequently, increasing CH₄ production (Knapp, Laur, Vadas, Weiss, & Tricarico, 2014). The PM herbage allocation lead to greater herbage DMI, and as a result emitted greater amount CH₄. Similarly Gregorini, Beukes, Bryant, & Romera (2010) reported that cow's allocated herbage in the PM produced 9.2% more CH₄ per kg DM compared to the AM allocation.

4.5. Conclusion

Reduction of UN excretion, greater DMI, and more MS production were achieved by allocating herbage in the afternoon. But allocation in the PM lead to greater methanogenesis, impairing the goal to mitigate both UN and CH₄ at the same time –“pollution swapping mitigation”. However, the magnitude of UN reduction was greater than the increase in CH₄ emission and yield, especially at the inflection point of MS production. The latter might be taken as an approach to cope with pollution swapping, as increments in the environmental impact of increased CH₄ yield can be easily offset by reductions in urinary UN. Therefore, simple changes to grazing management as PM herbage allocation accompanied by strategic (according to the farming context) reductions in HA could evolve and help traditional grazing managements in NZ pastoral dairy farming systems to reduce environmental impact. This study examined a single cow, therefore, it is likely that the results would differ on a per hectare basis, due factors such as HA being related to stocking rate and changes emerging in grazing behaviour as competition is introduced. The work used a model, which despite its breadth and detail of the biological processes and behaviours of grazing dairy remains a simplification of the system. Future research could conduct empirical research within the area.

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Chapter 5

Effect of type and time of supplement allocation, herbage allowance and time of pasture allocation on methane emission, urinary nitrogen excretion and milk production of dairy cows grazed in early and late lactation

Effect of type and time of supplement allocation, herbage allowance and time of pasture allocation on methane emission, urinary nitrogen excretion and milk production of dairy cows grazed in early and late lactation

Abstract.

Dairy farming in New Zealand has a large and growing impact on the environment, through the release of greenhouse gases (GHG's) such as methane (CH₄) and nitrous oxide (N₂O), as well as nitrogen to the waterway through leachates from urinary N (UN). The objective of this simulation modelling study was to investigate the effects of supplement type (maize silage (MZ), maize grain (MG), and barley grain (BG) and the time of allocation at different herbage allocations (HA, 20, 30, 40 and 50 kg DM cow⁻¹ per day) allocate either in the AM or PM, on UN and CH₄ emissions, during early and late lactation. A mechanistic and dynamic model of a grazing ruminant, MINDY, was used. MINDY was initialized to represent typical grazing conditions and managements of a Waikato, New Zealand, dairy farm. Although the supplements comprised a small portion of MINDY's diet, the differences in chemical composition altered intake, and subsequent output of MS, UN and CH₄. On average the BG, MZ, and MG treatments produced 2.24, 2.76, and 2.08 kg of milk solids (MS) in EL and 1.22, 1.71, 1.21 kg of MS in LL, respectively. The average amount of UN excreted by the BG, MZ, and MG was respectively, 167, 168, and 172 g in EL and 184, 184, and 182 g in LL. While the average total CH₄ emissions for the BG, MZ, and MG were 277, 288, and 284 g in EL and 246, 272, and 246 g in LL. Altering the time of BG allocation on average increased MS, reduced UN, and CH₄ production by 5, 3, and 4 %, respectively. While the time of MZ allocation on average increased MS, reduced UN, and CH₄ production by 3, 7, and 4 %, respectively. Equally time of MG allocation increased on average production of

MS, reduced UN, and CH₄ production by 4, 2, and 1 %, respectively. As HA was increased the effects of supplying supplement and the time it was allocated remained. The present results indicate that, using supplementation as a strategy to reduce environmental impact is more effective regardless of HA. At 20 kg HA, and based on the results of this the present study, supplementing with MZ at any time was the most effective at mitigating UN, CH₄, while maintaining or increasing MS production.

Key words. Dairy cattle, supplementation, herbage allowance, methane, urinary

N

5.1. Introduction

Milk and meat consumption is increasing rapidly due to rising income and growing population and urbanisation (Steinfeld, Gerber, Wassenaar, Castel, & de Haan, 2006). Farming livestock to produce milk and meat has a large and growing impact on many areas of the environment, including but not limited to contributing to climate change and polluting the air, soil, and water; reducing biodiversity; and inducing habitat fragmentation e.g. swamps (Steinfeld et al., 2006). And, the release of greenhouse gases (GHGs), such as enteric methane (CH₄) and nitrous oxide (N₂O), and nitrogen excreted within urine (UN) leaching into water bodies (Foote, Joy, & Death, 2015) by intensive dairy farming has put dairy production under a considerably societal scrutiny.

In New Zealand (NZ), dairy contributes largely to the economy, making up 18% of all goods and service exports, which were worth \$12.4 billion in 2016 (Dairy Companies Association of New Zealand (DCANZ), 2017). To meet growing demand milk solids (MS) production increased by 326 % between the 1989-1990 season to the 2015-2016 season (Livestock Improvement Corporation & DairyNZ, 2016). To meet milk production goals practices intensified, national herd size doubled, and the application of fertiliser increased by more than five times. Together these practices increased GHG emissions by 23.3% (MFE, 2016). Alongside the intensification of farming and increased GHG emissions, societal, economic, and environmental constraints have grown in strength to challenge the social license for NZ dairy production (Gregorini, Beukes, Dalley, & Romera, 2016).

Pasture-based farming harnesses an energy resource, herbage, that otherwise remains unavailable to humans (Hume, Whitelaw, & Archibald, 2011). In situations where herbage is in high demand, supplements are fed to maximise

energy intake and milk production. At the same time, some supplements can alter the ratio fibre to starch within the diet, reducing CH₄ production by decreasing rumen pH and elevating the proportion of the fermentative substrate propionate synthesised (Dijkstra, Oenema, & Bannink, 2011). The formation of propionate is favourable over other volatile fatty acids (VFAs) such as acetate and butyrate, as it uses hydrogen (H₂) that would otherwise reduce carbon dioxide (CO₂) to form CH₄ (Dijkstra et al., 2011). In addition, starchy supplements also alters the production of rumen ammonia by not only capturing more N in microbial protein, but also diluting N supply and intake; and thereby reduce UN (Hume et al., 2011; Castillo et al 2001).

While research on the type of supplement has been conducted with the goal of reducing the environmental footprint of practices, less research has been focused on the effect of time of supplementation. A study by Ueda, Mitani, and Kondo (2017) examined the effects of the time that supplements were allocated, on DMI, milk production, and nitrogen utilisation. Their study determined that regardless of the time supplement is allocated DMI, milk production and nitrogen utilisation remained similar between treatments. However, grain supplements and CH₄ production emissions were omitted from their study.

In the present study, the hypothesis that not only type, but also timing of supplementation reduce CH₄ emission and UN is explored. The objective of this simulation modelling study was to investigate the effects of supplement type (maize silage (MZ), maize grain (MG), and barley grain (BG) and the time of allocation at different herbage allowances (HA, 20, 30, 40 and 50 kg DM cow⁻¹ per day) at two times of herbage allocation (AM and PM), on UN and CH₄ emissions, during early and late lactation.

5.2. Methods

5.2.1. *The model*

For the objective and the purpose of this study, the latest version model MINDY (Gregorini, Provenza, Villalba, & Forbes, in press) was used. MINDY is a deterministic, mechanistic and dynamic model of a dairy cow representing diurnal patterns of ingestion, digestion and metabolism, and production, as well as excretion based on explicit relationships among direct (ingestion, digestion and metabolism) and indirect (feeding environment) controls of motivation to feed. MINDY is a cluster of seven models: 1) Molly models digestion, metabolism and production of a dairy cow (Baldwin 1995 as modified by Gregorini, Villalba, Provenza, Beukes, & Forbes, 2015); 2) diurnal fluctuations in feeding motivation; 3) sward canopy structure and herbage quality; 4) grazing behaviour; 5) dietary preference and forage selection; 6) foraging bioenergetics; and 7) drinking and urination behaviour. MINDY also integrates functional relationships between forage ingestion, oral physiology and swallowing, and rumen digestion responsible for variations in liquid outflows from the rumen.

5.2.2. *Virtual experiments (simulation exercise)*

A factorial arrangements of treatments was designed to represent the interaction amongst HA, time of pasture allocation, type of supplement and timing of supplementation. Individual and identical instances of MINDY were allocated to each treatment. Each instances of MINDY were initialized as multiparous 500 kg BW Friesian dairy cows, and strip-grazed under four different HA, 20, 30, 40, and 50 kg DM d⁻¹, allocating herbage either after the morning (AM) or afternoon (PM) milking. Treatments that were supplemented were allocated barley grain (BG), maize grain (MG), or maize silage (MZ) prior to the AM or PM milking or

in two equal proportions fed prior to each of the milking times. Each of the supplements MG, MZ, and BG were fed in different quantities, 1.37, 1.81, or 1.50 kg DM respectively, to maintain the same level of metabolisable energy (25% supplementation).

Milking times were 06:00 and 15:00. All MINDY instances were initialized to graze in Hamilton (New Zealand) during September on early lactation (EL, 31 DIM) and the other eight grazed in Hamilton as well, during April during late lactation (LL, 180 DIM) (Note: MINDY's hunger and herbage chemical composition and lactation respond to changes in daylight hrs., i.e. photoperiod).

The simulated sward was a perennial ryegrass- based (80 % *Lolium perenne* L. and 20% *Trifolium repens* L.) typical of Waikato NZ dairy systems. The sward herbage mass was 3000 kg DM ha⁻¹, the sward surface height (extended tiller) was 30 cm. The chemical composition of herbage at each time of the year is presented in Table 5.1 and reflected the used of fertiliser applied at a level of 200 kg N/ha per year. Pasture paddocks of different sizes (according to treatments) were allocated once a day either after the morning or afternoon milking. Table 5.1 also presents the chemical composition of MG, BG, and BG supplements.

Each simulation/ treatment was run for 30 days, being the first 10 days of 'model adaptation/stabilization' and the last 20 days of data collection. The outputs requested from MINDY were: DMI (kg DM⁻¹d⁻¹), MS production (kg cow⁻¹d⁻¹), milk yield (MY) production (kg cow⁻¹d⁻¹), N intake (NI, g d⁻¹), UN (g d⁻¹), and CH₄ emissions (g d⁻¹).

Table 5.1. Chemical composition of herbage and supplements offered to and grazed by MINDY during early (October) and late (April) lactation.

Analyses (g kg ⁻¹ DM) ^b	Early	Late	Maize grain	Maize silage	Barley grain
	lactation perennial ryegrass	lactation perennial ryegrass			
Dry matter (g/kg ⁻¹ wet weight)	183	194	860	330	870
Crude protein (%DM)	13.9	18.4	9.2	9.3	11.5
Water soluble carbohydrates (% DM)	15.9	21.3	1.3	4.6	2.8
Starch (%DM)	2.0	1.9	73.4	20.6	59.7
Neutral detergent fibre (% DM)	45.5	46.1	12.0	48.6	20.7
Acid detergent fibre (% DM)	25.7	26.5	3.0	29.6	6.4
Ash (% DM)	10.9	11.6	1.4	4.8	2.6

5.3. Results

5.3.1. Type of supplement: intake and milk production

The average total DMI, herbage and supplement intake, milk yield, MS, CH₄ and UN emissions for each supplement fed are reported in Table 5.2.¹ Herbage DMI increased with HA. The estimated average DMI for non-supplemented EL cows was 14.50 kg DM d⁻¹, with the addition of either MG, BG, or MZ supplement total DMI increased by 3, 8 and 22%, respectively. In LL the non-supplemented cows consumed 11.97 kg DM d⁻¹, while those supplemented

¹ Individual treatment results for DMI, pasture intake, supplement intake, CH₄ yield, and UN are presented in a table in Appendix 1.

with MZ, BG, or MG consumed 24, 6 and 4% more. In EL regardless of the time, both herbage and supplement were allocated the herbage only, BG, MG, and MZ treatments led MINDY to produce an average of 23.9, 24.9, 26.3, and 26.9 kg milk d⁻¹ and average MS of, 2.11, 2.24, 2.08, and 2.76 kg d⁻¹, respectively. Similarly, in LL, regardless of the time, both herbage and supplement were allocated the herbage only treatment had a lower predicted mean milk yield (14.1 kg d⁻¹) than that of each of the treatment-fed supplement, MG (14.4 kg d⁻¹), BG (14.6 kg d⁻¹), and MZ (19.1 kg d⁻¹). The average estimated MS production for the herbage only, MG, BG, and MZ fed treatment at LL was, on average, for 1.20, 1.21, 1.22 and 1.71 kgd⁻¹, respectively, regardless of the time both herbage and supplement were allocated.

Table 5.2. Predicted effect of supplement type average intake, milk production CH₄ emission and UN.

Treat ment	Stage ^a	DMI (kg DM)	Pasture intake (kg DM)	Supple ment intake (kg DM)	MY (kgd ⁻¹)	MS (kgd ⁻¹)	UN (gd ⁻¹)	Total CH ₄ (gd ⁻¹)
--	EL	14.50	14.50	--	23.9	2.11	190	264
BG	EL	15.70	14.2	1.50	24.9	2.24	167	277
MZ	EL	17.69	16.34	1.35	26.9	2.76	168	288
MG	EL	14.93	13.56	1.37	26.3	2.08	172	284
--	LL	11.97	11.97	--	14.1	1.20	201	245
BG	LL	12.66	11.2	1.50	14.6	1.22	184	246
MZ	LL	14.82	13.57	1.26	19.1	1.71	184	272
MG	LL	12.48	11.11	1.37	14.4	1.21	182	246

--Herbage only

a) Stage of lactation

5.3.2. *Type of Supplement: UN and CH₄ emission*

The greatest estimated mean CH₄ quantity produced in EL was by the treatment supplemented with MZ (288 g d⁻¹), followed by treatments fed MG, BG, and the herbage only which produced 284, 277, and 264 g CH₄ d⁻¹. On average UN excretion from treatments fed herbage only was 0.190 kg d⁻¹, while just five grams differentiated the estimated UN of the supplemented treatments, MG (0.172 kg d⁻¹), MZ (0.168 kg d⁻¹), and BG (0.167 kg d⁻¹). Comparing the effect on average of different supplement types in EL with the goal of reducing the environmental impact and optimising milk production, BG treatments were estimated to produce the lowest UN and CH₄ of the treatments fed supplement and the second highest amount of MS.

The pasture herbage only treatments within LL emitted on average the least CH₄ (245 g d⁻¹) compared to the other treatments that were fed supplement; MG, BG, and MZ produced 246, 246, and 272 g d⁻¹ of CH₄, respectively. In LL, treatments feeding MG produced the lowest mean quantity of UN (0.182 kg d⁻¹); however, only two grams lower than MZ treatments (Table 5.2.). The herbage only treatments, on average, produced an estimated 0.201 kg d⁻¹ of UN during LL; therefore, producing the largest amount of UN in both EL and LL. The types of supplement in LL that were most effective at reaching the mitigation goal were treatments fed MG or BG, which were predicted on average to produce similar low quantities of UN and CH₄, while also producing more MS than the herbage only treatment. The MZ fed treatments produced a similar quantity of UN to the

other supplemented treatments; however, it produced 25 g more CH₄ and ~0.50 kg MS daily.

5.3.3. Time of supplement allocation: the effect on MS, UN, and CH₄ emission

The effect of the time of herbage allocation alone was discussed in chapter 4 of the present thesis. Allocation of herbage in the PM lead to reductions in UN (Chapter 4) and increments in MS production as compared to than AM herbage allocations.

The different CH₄, UN, and MS production of treatments allocated supplements and herbage at different times of the day in EL are compared in Figure 5.1, while Figure 5.2 compares the same parameters and treatments in LL. These figures show that treatments that enhance production of MS production may intensify the production of either CH₄ or UN, or both. Similarly, those treatments aimed at mitigating UN or CH₄, may further increase the excretion of the other pollutant and/or lessen MS production. However, some PM allocated treatments were more effective at yielding greater MS, while simultaneously emitting lower quantities of UN and insignificant slightly more CH₄.

The EL estimations indicated some treatments may be suitable at both abating CH₄ and UN, while maximizing the output of MS. This included the treatments allocated 20 kg of herbage and BG in the PM which produced 2.45 kg d⁻¹ of MS, 280 g d⁻¹ of CH₄ and a low 0.137 kgd⁻¹ of UN. The EL treatments that saw 20 kg HA allocated in the PM and supplemented BG in the AM, produced the same quantity of UN, lower amounts of CH₄ (266 g d⁻¹) and a comparable quantity of MS (2.40 kg d⁻¹). The 30 kg HA allocated in the PM and supplemented in the AM was also a fairly successful treatment at producing high MS yield (2.5 kg) and low quantities of UN (152g) and CH₄ (299). Similarly, the

30 kg HA allocated in the PM and supplemented with BG in the PM produced a high MS yield (2.51 kg), and a low amount of UN (146 g) and CH₄ (301 g). However, the other EL treatments fed a 20 kg HA and MZ at different times of the day were more successful at producing a high MS yield while emitting a similar amount of CH₄ and UN as the BG treatments. Although these six treatments produced more MS, they also emitted greater amounts of CH₄ compared to the herbage only treatments, yet smaller quantities of UN. Of these six effective MZ treatments, four remained suitable for reaching the aim of reducing UN, CH₄, and improving production of MS in LL. These four LL treatments were those allocated 20 kg HA in the AM alongside MZ, and those allocated 20 kg HA in the PM with MZ in the AM, PM, or twice a day MZ supplementation. These treatments produced between 1.63-1.67 kg of MS, a quantity not achieved by any of the herbage only treatments, and excreted 0.141-0.150 kg of UN and emitted 259-270 g of CH₄. Treatments fed the same HA at the same time and allocated the same type of supplement, but at a different time, had different intakes yet emitted similar quantities of CH₄ and UN.

The weak positive correlation between CH₄ and UN in EL depicted in Figure 5.1 indicates there is potential to reduce CH₄ and UN simultaneously. The correlation between CH₄ and UN becomes weaker still in LL (Figure 5.2). Equally treatments that mitigated CH₄ and UN tended to produce lower quantities of MS; although not all high producing treatments resulted in greater emissions of UN and CH₄.

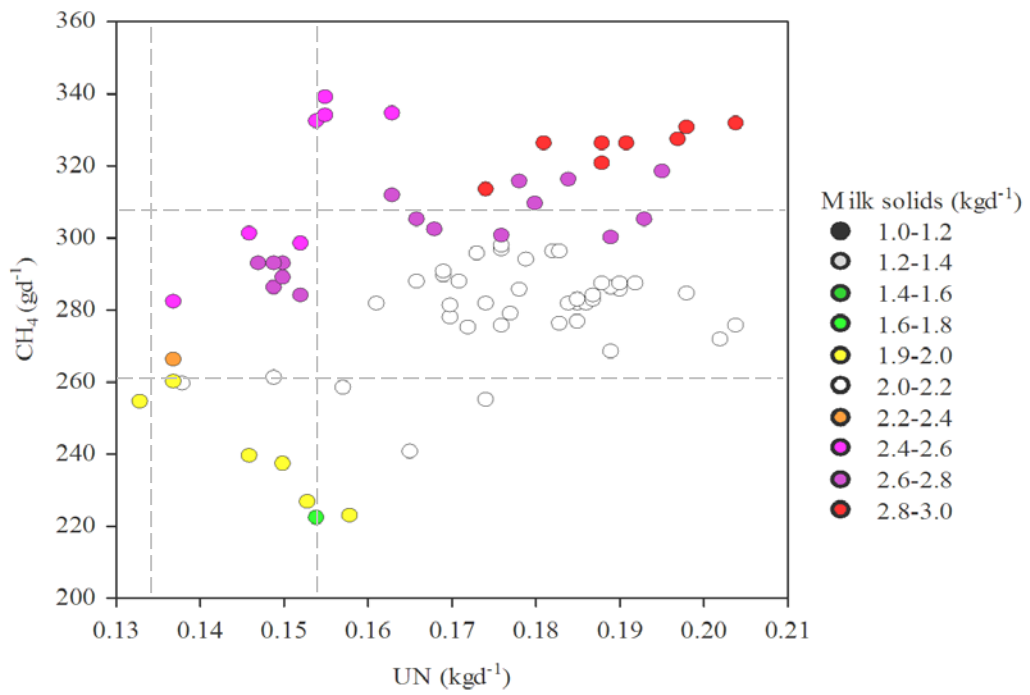


Figure 5.1. Simulated effect of different herbage allowances, time of herbage and supplement allocation on MS production, UN excretion, and CH_4 emission in EL (note --- draws attention to the centre square window where treatments produce high MS, low UN and CH_4).

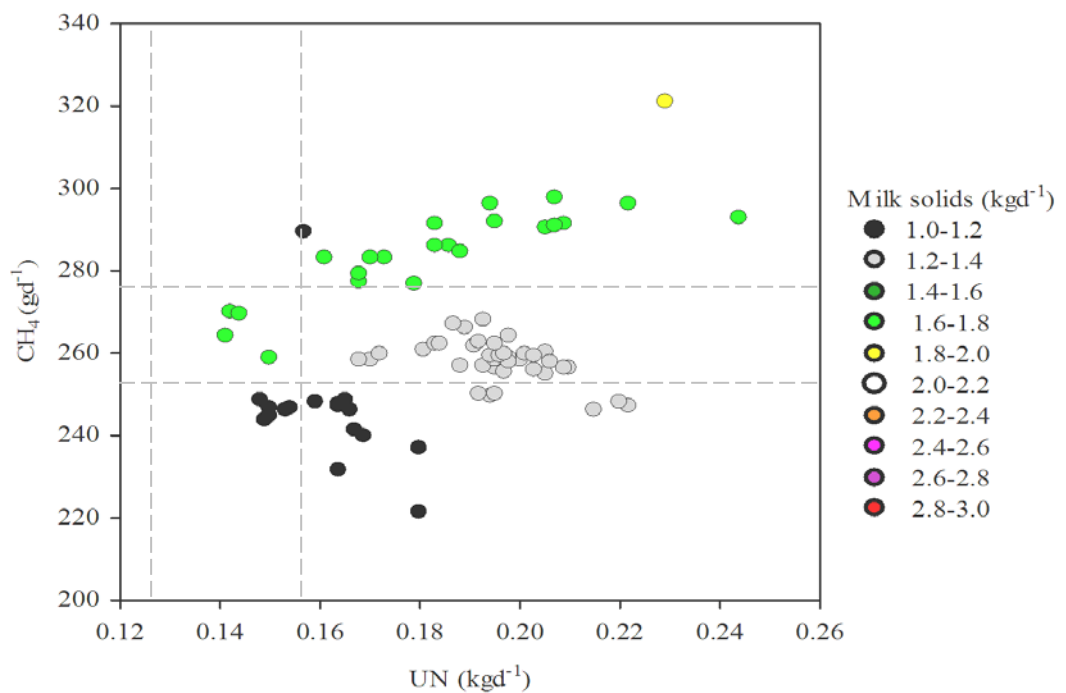


Figure 5.2. Simulated effect of different herbage allowances and time of herbage and supplement allocation on MS production, UN excretion, and CH_4 emission in LL

(note --- draws attention to the centre square window where treatments produce high MS, low UN and CH₄).

5.4. Discussion

5.4.1. Type of supplement: the effect on intake and milk production

The variation in DMI between the treatments supplied different HA can be attributed to the discrepancies in intake and chemical composition when the herbage available to graze is altered. As HA is increased DMI rises. Within lower HA low HA sward is often depleted to a lower strata, increasing the consumption of pseudostem and dead material with a lower nutritive value which in turn may also decrease grazing motivation and time spent grazing. Likewise, the incremental increases in DMI diminish as HA increase. The herbage DMI plateaus as the nutritive and energy requirements are either satisfied or digestive constraints appear (Poppi, Hughes, & L'huillier, 1987). Disparity in DMI between the treatments fed the same HA and different supplements MG, MZ, or BG may be attributed to the alterations in intake (1.37, 1.81, and 1.5 kg, respectively) and grazing behaviours associated with feeding each supplement. Although each treatment was fed a different supplement, MG, MZ, or BG at a different quantity, the total ME allocated was equal between supplement treatments.

The DMI rose from smallest to greatest for the supplemented treatments in the order: MG < BG < MZ at both stages of lactation. Consequently, average milk production for the different supplement-based treatment groups followed the same trend. Differences in DM, NDF, and ether extract (EE) digestibility may alter intake by impacting digestion kinetics, comminution efficiency, and rumen conditions (Poorkasegaran & Yansari, 2014). Generally, grains (BG or MG) have greater digestibility than silages, perhaps resulting in lower DMI than silage fed

treatments, as energy and nutrient uptake occurs more efficiently for grain fed treatments. However, digestibility is not the only factor effecting intake other differences between treatments such variation in the dietary chemical composition may impact subsequent grazing events. The MZ treatments consumed on average 22 and 13% more herbage than the herbage only and BG treatments, perhaps due to lower digestibility of MZ compared to grains. The greater intake for the MZ fed treatments is potentially a positive associative effect; however, is an unusual result. Although substitution occurred for each treatment with both the MG and BG treatments consuming less herbage than the control as seen in previous experiments (Al-Marashdeh, Gregorini, & Edwards, 2016). As the model used is an exploratory tool, it is predicted that although values may not be exact they indicate an approximate trend to change emissions and production by introducing strategic grazing and feeding management techniques.

5.4.2. Type of supplement: the effect on UN and CH₄ emissions

In the present study greater CH₄ emissions from MZ compared to herbage only, agrees with the results reported by Waugh, Clark, Waghorn, & Woodward (2005), who evaluated CH₄ emissions when feeding increasing proportions of MZ to dairy cows. Contrastingly the treatments consuming grains emitted lower amounts of CH₄ than both the MZ and herbage only treatments. The addition of such grain supplements to an herbage based diet can mitigate CH₄ production by altering the ratio of fibre to starch and protein (Dijkstra et al., 2011). The MZ may be less successful at doing that, as silage also incorporates leaves of the maize plant, altering such a ratio less. Degradation of high concentrations of protein and fermentation of large quantities of starch within diets coincides with lower ruminal pH, heightening the formation of propionate which uses H₂, preventing its use in reducing CH₄ producing CO₂ (Dijkstra et al., 2011). Lower ruminal pH can

also inhibit the growth of methanogenic bacteria, favourable for CH₄ abatement (Beauchemin & McGinn, 2005). The success of grain use to mitigate CH₄ is dependent on the type of grain fed. When cows were fed a diet composed predominately of MG, CH₄ emissions were 30% less than those fed a diet rich in BG (Beauchemin & McGinn, 2008). The difference between BG and MG was not seen within the present study, potentially due to herbage making up most of the treatments diet and the small quantity of each supplement fed (MG 1.37, MZ 1.81, and BG 1.5 kg).

To ensure substantial CH₄ mitigation grains must be fed at a high proportion (80-90% of DMI) (Beauchemin & McGinn, 2005; Pinares-Patiño, Waghorn, Hegarty, & Hoskin, 2009). However, incorporation of grains into ruminant diets uses an edible energy source for humans that can also be incorporated into biofuels. Therefore, it is disadvantageous to feed these dairy cows within large quantities (Beauchemin & McGinn, 2008; Hume et al., 2011). Another risk associated with large quantities of high starch grains or feeds are consumed by ruminants is the onset of acidosis, disrupting rumen function partially or altogether (Beauchemin & McGinn, 2008). The current study included supplement feeding as it is required to optimise both intake and animal production particularly when herbage availability is scarce. It is important to consider that although supplement use is associated with CH₄ mitigation, it can increase the total GHG cost compared to herbage only situations due to additional emissions from supplement growth, harvesting, and transportation (Beauchemin & McGinn, 2005; Pinares-Patiño et al., 2009). Previous works also shows that economic levels of supplement use also depend strongly on system intensity, milk price, and input prices, such as those for fertiliser of supplement (Lovett, Shalloo, Dillon, & O'Mara, 2008; Romera & Doole, 2016; Vibart et al., 2012). Thus, while

abatement can occur through changing the ratio of herbage: supplement, the economic cost of this can vary depending on the circumstances (Doole, 2014).

The incorporation of protein and starch into the diet to abate CH₄ production can consequently heighten UN, an example of pollution swapping where the mitigation of one pollutant subsequently drives an increase in another (Dijkstra et al., 2011; Gregorini et al., 2016). It is the surplus intake and usage inefficiency of nutrients such as N that result in its excretion within urine or faeces, although it is UN that is more susceptible to loss (Dijkstra et al., 2011). As the proportion of CP incorporated into the diet is increased, the N efficiency is decreased which in turn amplifies the quantity of UN excreted (Colmenero & Broderick, 2006). However, not all protein supplements and even proteins contain the same N quantity. Additionally, proteins are not the only N-containing compounds (e.g. nucleic acids) (Pacheco & Waghorn, 2008). Higher levels of dietary N can reduce DMI, as can absorption of large quantities of ammonia (Pacheco & Waghorn, 2008). Other treatments with lower N concentrations, e.g. MZ can also lowered NI and consequently the excretion of N (Al-Marashdeh, Greenwood, Hodge, & Edwards, 2015; Valk, 1994). Within the present study the potential of lowered NI was offset by increased consumption of herbage containing high N concentrations by the MZ treatment groups. This may have occurred as the quantity of supplement fed, each making up just 14% of the required ME within the present study was low.

Previous studies have reported that the relationship between UN and CH₄ emissions is weak and variable (Dijkstra et al., 2011; Gregorini et al., 2016). The relationship seems to be variable between stages of lactation as determined by Gregorini et al. (2016) and the present study (Table 5.2). It is also shown by the strength of the relationships between these factors identified in Figures 5.1 and

5.2. This indicates that CH₄ and UN could be reduced simultaneously. The results of the present study suggest that different treatments are more suitable for lowering CH₄ or increasing MS production.

5.4.3. Time of supplement allocation: the effect on DMI, MS, UN and CH₄ emission

The EL 20, 40, and 50 kg HA's treatments allocated in the AM and supplemented BG treatment in the AM consumed more DM, and consequently produced more MS than those allocated BG in the PM. In contrast, the EL treatments within the present study allocated 20, 40, or 50 kg of HA and BG in the PM consumed more herbage, resulting in MS production that were greater or equal to treatments fed BG in the AM. A study by Ueda et al. (2017) also examined the effects of time and type of supplement allocation, 6 kg of BG was supplemented in different morning: afternoon ratios, either 75:25 or 25:75 to dairy cows. The cows allocated more supplement in the morning consumed 0.5 and 1 kg more DM in spring and summer, respectively than the cows fed more of the supplement in the afternoon (Ueda et al., 2017). In the present study the LL treatments allocated herbage (40 and 50 kg HA) and BG in the AM on average consumed 0.35 kg more DM and produced more MS same treatments allocated supplement within the PM BG. While when herbage was allocated in the PM, DMI and MS production were greater for treatments allocated BG in the PM compared to those allocated BG earlier in the day. The MG treatments allocated herbage at the same time in most cases consumed more DM and produced greater MS. The increased DMI may have been an effect associated with the time MG is fed or reducing the time between herbage and MG allocation. Within both EL and LL scenarios regardless of the time herbage was allocated, cows consumed more DM and produced more MS when MZ was fed in the PM. Supplying supplement

in either the AM or PM alters grazing events, compared to that of the cows fed herbage only (Sheahan, Gibbs, & Roche, 2013). The time supplement is allocated can alter the supply of nutrients, proteins and energy entering the rumen, in turn altering subsequent grazing events and grazing behaviour (Scaglia, Boland, & Wyatt, 2009; Gregorini 2012). Therefore, this easy to implement management strategy with no cost is worth further investigation.

While the BG and MG treatments had great intake and high production, the objective of this study was to determine if the diurnal variation in herbage chemical composition and intake patterns of dairy cows can be manipulated by altering the time of herbage and supplement allocation to abate UN, CH₄, and maintain or increase MS production. Within EL eight treatments were more effective at both mitigating UN and CH₄, and producing a high level of MS, whereas in LL there were only four more effective treatments. The treatments that emitted lower UN and CH₄ were those fed the 20 kg HA. To meet energy demands cows grazed lower herbage strata, likely consuming more stems that are higher in NDF, ADF and lignin but lower protein (O'Donovan & Delaby, 2008). Reduced degradable protein mitigates UN as the efficiency of microbial N utilisation rises (Kebreab, Strathe, Fadel, Moraes, & France, 2010). However, the greater fibre intake may result in greater production of CH₄ per kg of DM consumed. In general, allocating more herbage resulted in greater DMI; however, intake seemingly plateaued between 40 and 50 kg DM of HA, with the inflection point at 30 kg DM HA. The smaller intake associated with the 20 kg HA treatments is also partially responsible for the lower levels of CH₄ and UN emitted. It lowers the amount of fermentable carbohydrates and N-containing proteins entering the rumen and results in alterations to the amount of CH₄ and UN emitted. Despite disparity in the amount of UN excreted between the

treatments fed supplements at different times of the day, the differences were small, on average 7 and 13 g regardless of supplement type in EL and LL, respectively. Similar results were determined in an earlier study by Al-Marashdeh et al. (2016), which also found minimal differences in UN between treatments allocated MZ two or nine hours prior to evening herbage allocation. Likewise, while variation in CH₄ production between treatments fed the same supplement at a different time of day was present, the differences were small, on average 12 and 9 g regardless of supplement type in EL and LL. Thus, the results of this study indicated that a simple strategy of changing timing of herbage and supplement allocation can reduce UN and CH₄ by 6 and 4%, respectively. Interestingly, this reduction happens at the same result allocation and as consequence of simply management of feeding with no extra cost.

5.5. Conclusions

The time herbage is allocated to cow's impacts intake and subsequent metabolic processes that affect milk production and emissions of CH₄ and UN excretion. The addition of supplement to grazing regimes can alter grazing behaviours and meal distribution, consequently impacting on intake, milk production, emissions of GHGs and UN excretion. The time of supplement allocation had a slight impact on intake, milk production, and emissions, as a mitigatory strategy for UN and CH₄ implemented with ease, at the same resource allocation at no extra cost, these slight alterations could be used in conjunction with other mitigation strategies. Further research examining the impact of time that a greater quantity of supplement feeding has on abating CH₄ and UN, while maintaining or increasing milk production, is worthwhile. The 20 kg HA treatment allocated in PM and supplemented with MZ (AM or PM) holds promise to achieve the aim of

simultaneously mitigating UN and CH₄, while maintaining or increasing milk production.

5.6. References

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Chapter 6

Conclusions

6.1. Study Outline

To meet the growing demand for food as the global population rises, its production needs increase by more than 70% in a more sustainable manner on an equal amount or less of agricultural land, according to predictions made by the United Nations FAO in 2009. The morphing population and demographic changes have altered and grown the demand for agriculture products and advances in technologies such as dairy (Steinfeld, Gerber, Wassenaar, Castel, & de Haan, 2006). Worldwide the livestock sector uses ~30% of all ice-free land, consequently making it a major source of pollution and nutrient loss. Livestock and farming activities related to their care can directly and indirectly, impact all environmental aspects, such as climate change, land, water, and biodiversity (Steinfeld et al., 2006). As agricultural practices namely dairy farming are a large sector in New Zealand (NZ), also accounting for most of NZ's emissions, it is unsurprising that exploration of greenhouse gas (GHG) mitigatory methods are required to ensure the sustainability of practices.

The objective of this thesis is to explore and evaluate grazing and feeding managements to reduce enteric CH₄ emissions and UN excretion, while maintaining or increasing MS production.

6.2. Methodology

Exploratory studies using complex mechanistic and dynamic simulation models allow for a cost effective and timely method to analyse a vast number of treatments, derived from factorial arrangements, that would otherwise remain unfeasible in the real world. Use of such models are important for future research

for New Zealand's dairy industry. For purpose of this work, we used the model MINDY (Gregorini, Provenza, Villalba, & Forbes, in press). MINDY is a comprehensive mathematical, mechanistic, and dynamic simulation model of a grazing ruminant as represented by a dairy cow. MINDY captures the underlying biological mechanisms of rumen form and function, as well as grazing, urination, and drinking patterns. Moreover, MINDY represent preference and selective behaviours. MINDY responds to chemical, structural and biomechanical features of herbage and other feeds as supplements. MINDY can be initialized with different genetic merits for milk production, and also with different morphological features. MINDY can grazed, fed supplements, milked, stud-off pasture with endless combinations.

In this thesis we use a factorial arrangement of HA, time of herbage and supplement allocation and type of supplement to design a vast arrange of grazing and feeding managements to explore and evaluate the effect of feeding management based on technologies of processes as grazing and feeding on milk, CH₄ emission and UN production. The use of grazing scenarios is important as it is the dominant form of feeding within NZ's temperate climate. Such explorations and management in terms of mitigating CH₄ and UN has been largely unexplored.

6.2.1. Per cow analysis

The present thesis examines the response of a single Friesian dairy cow to simple management techniques. Per cow analysis is important prior to empirical whole farm analysis as it allows for exploration of a greater range of techniques. While modelling and analysis could have been conducted on a farm scale, the introduction of more assumptions and parameters would further the potential for errors and increase the complexity and narrow the understanding of results. Larger scenarios require further labour and increased computing power, all factors of

which were not available within the present exploratory study. For these reasons this thesis explored strategic feeding management alterations on a per cow level to scope the field prior to larger empirical studies.

6.3. Key findings

6.3.1. Strategic feeding management: Herbage allowance

The quantity of herbage allocated to cows in grazing systems can alter the response and production of GHGs and pollutants excreted within urine as metabolic waste. Alterations to the area and consequently amount of herbage allocated (20, 30, 40 or 50 kg DM) to grazing cows can alter grazing events, DMI, herbage regrowth and subsequent grazing events. As expected, increasing herbage availability, increased DMI and the total emissions of CH₄ and UN. The incremental increases in DMI, MS, CH₄, and UN production declines with increasing allowances, seemingly plateauing as energetic and nutritional demands are met. De-intensification of practices by increasing the HA available to each cow increased the emission intensity (g CH₄ kgMS⁻¹). De-intensification is a key strategy that can contribute to reducing the environmental footprint of practices; however, exploration in grazing scenarios is somewhat limited. Residual herbage mass, a.k.a. pasture covers were also analysed as it is important as it determines how soon stock can be reintroduced into a paddock and the nutritional value of the herbage as its regrown. The high residual covers when allowance is greater may be problematic as the proportion of dead matter within pasture increases and the feeding value of herbage decreases. Increments in HA in the present simulation study increased residual covers and thereby grazing efficiency. Further modelling is required to evaluate and analyse the effects of HA on CH₄ and UN at farm level

6.3.2. *Strategic feeding management: time of herbage allocation*

After altering how much cows were fed, the next chapter examined the time at which the HA was allocated, i.e. AM vs PM herbage allocation. In other words after either the morning or afternoon milking. As the chemical and biomechanical properties of herbage fluctuate over the day, allocating herbage at different times of the day alters intake patterns and DMI, as well as nutrient supply to the rumen; and thereby, milk production, CH₄ emission and UN. Afternoon herbage allocation resulted in greater DM and WSC intake, while CP intake declined and subsequently production of MS by 1.5% and CH₄ rose by 5%, while UN production declined by 5%, compared to the treatments. While, the treatments allocated herbage in the morning consumed less herbage, but greater concentrations of CP and consequently excreted UN and less CH₄. Although the morning or afternoon herbage allocations, respectively, produced less CH₄ or UN, neither achieved the original goal of mitigating both pollutants. The pollution swapping between CH₄ emission and urinary N excretion is always present, but increments in the environmental impact of increased CH₄ yield can be easily offset by reductions in urinary UN. Simple management changes, such as altering the temporal distribution of meal by timing of herbage allocation, could evolve traditional grazing systems to be more environmentally friendly, at a time where every change counts.

Altering the time of pasture allocation provides an inexpensive low input method to alter production of CH₄, UN, and MS. Exploring temporal distribution of HA at different allowances indicated that at greater stocking rates (Lower HA) the time of day effects are more prominent.

6.3.3. Strategic feeding management: Supplement type and time of allocation

The nutritive value and energy content of different feed types alters intake as energetic and nutrient demands for survival, growth, reproduction, and production are met (Van Soest, 1994). The addition of supplement to grazing based systems alters the chemical composition and energy content of DM consumed, in turn altering rumen responses in subsequent grazing events. Influencing dietary chemical composition by feeding different types of supplement had considerable impact of grazing behaviours, intake, milk production and emissions of CH₄ and UN. Timing of supplement allocation had a lesser effect on intake, MS, CH₄, and UN production. However, this research was aimed at analysing herbage dominant situations with low levels of supplementations, the addition of more supplement at different times may have a greater impact on abating CH₄ and UN, while maintaining or increasing MS. Of the treatments analysed the lowest (20 kg DM) HA supplemented with maize silage (MZ) was the most promising at mitigating UN and CH₄, while maintaining or increasing milk production. Despite the lack of a 'perfect' strategy to meet the aim of reducing CH₄ and UN while maintaining or increasing MS production, results suggest that the correlation between CH₄ and UN is only weak.

Although CH₄ and UN production can be reduced respectively by 6 and 4% by altering the time of herbage and supplement allocation may be of significant importance, as it results from a simple alteration to the feeding management strategy used, for no extra cost, at the same resource allocation.

6.4. References

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Appendix 1

Time of 20 kg DM PAEL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ ¹)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	12.37	12.37	-	22.5	2.03	165	19.45	241
PM	-	-	12.67	12.67	-	22.5	2.09	157	20.38	258
AM	BG	AM	12.33	10.83	1.50	22.9	1.97	150	19.25	237
AM	BG	PM	11.69	10.19	1.50	22.4	1.94	158	19.06	223
AM	BG	Both	11.78	10.28	1.50	22.5	1.94	153	19.26	227
PM	BG	AM	14.04	12.54	1.50	25.6	2.40	137	18.95	266
PM	BG	PM	14.45	12.95	1.50	25.8	2.45	137	19.56	283
PM	BG	Both	12.73	11.23	1.50	22.8	2.01	149	20.53	261
AM	MS	AM	15.29	13.48	1.81	26.3	2.68	150	18.91	289
AM	MS	PM	15.94	15.52	0.42	26.1	2.72	152	17.80	284
AM	MS	Both	16.53	15.21	1.32	26.9	2.73	149	17.73	293
PM	MS	AM	14.23	12.42	1.81	25.2	2.66	149	20.12	286
PM	MS	PM	15.00	13.19	1.81	25.6	2.69	150	19.52	293
PM	MS	Both	14.91	13.10	1.81	25.5	2.69	147	19.62	293
AM	MG	AM	12.31	10.94	1.37	22.7	1.94	146	19.40	240
AM	MG	PM	11.52	10.15	1.37	22.0	1.87	154	19.23	222
AM	MG	Both	11.57	10.20	1.37	22.4	1.91	153	19.51	227
PM	MG	AM	12.14	10.77	1.37	22.3	1.96	133	20.87	254
PM	MG	PM	12.55	11.19	1.37	22.7	2.00	138	20.57	259
PM	MG	Both	12.37	11.00	1.37	22.5	1.97	137	20.95	260

Time of 30 kg DM PAEL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ day)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	14.74	14.74	-	24.0	2.13	189	18.16	268
PM	-	-	14.69	14.69	-	23.8	2.17	177	19.03	279
AM	BG	AM	14.30	12.80	1.50	24.3	2.07	174	17.85	255
AM	BG	PM	15.41	13.91	1.50	24.9	2.12	176	17.87	275
AM	BG	Both	15.70	14.20	1.50	25.0	2.13	174	17.94	282
PM	BG	AM	16.41	14.91	1.50	27.1	2.50	152	18.18	299
PM	BG	PM	16.18	14.68	1.50	26.9	2.51	146	18.61	301
PM	BG	Both	15.75	14.25	1.50	25.2	2.15	169	18.38	289
AM	MS	AM	16.65	14.84	1.81	27.2	2.70	176	18.06	301
AM	MS	PM	18.62	18.19	0.43	28.4	2.79	180	16.62	310
AM	MS	Both	18.82	17.50	1.32	28.8	2.81	174	16.64	313
PM	MS	AM	16.32	14.51	1.81	26.6	2.72	168	18.53	302
PM	MS	PM	16.93	15.30	1.63	27.0	2.75	166	18.03	305
PM	MS	Both	17.58	15.77	1.81	26.7	2.74	163	17.76	312
AM	MG	AM	15.34	13.97	1.37	24.5	2.09	170	18.07	278
AM	MG	PM	15.22	13.85	1.37	24.7	2.10	172	18.03	275
AM	MG	Both	15.39	14.02	1.37	24.7	2.10	170	18.21	281
PM	MG	AM	14.96	13.59	1.37	24.4	2.10	161	18.79	282
PM	MG	PM	15.86	14.49	1.37	25.2	2.14	169	18.29	291
PM	MG	Both	15.44	14.07	1.37	24.9	2.12	166	18.61	288

Time of 40 kg DM PAEL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ h)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	15.34	15.34	-	24.5	2.14	202	17.70	272
PM	-	-	15.83	15.83	-	24.9	2.19	192	18.16	288
AM	BG	AM	16.49	14.99	1.50	25.6	2.16	190	17.34	286
AM	BG	PM	15.87	14.37	1.50	25.2	2.12	185	17.45	277
AM	BG	Both	16.20	14.20	1.50	25.5	2.15	187	17.50	284
PM	BG	AM	18.59	17.09	1.50	28.6	2.59	155	17.97	334
PM	BG	PM	18.65	17.15	1.50	28.8	2.59	155	18.17	339
PM	BG	Both	16.55	15.05	1.50	25.8	2.19	176	18.00	298
AM	MS	AM	17.19	15.38	1.81	28.1	2.70	189	17.45	300
AM	MS	PM	19.27	18.83	0.44	29.1	2.80	195	16.51	318
AM	MS	Both	19.97	18.61	1.36	29.8	2.81	191	16.33	326
PM	MS	AM	17.60	15.79	1.81	28.2	2.77	178	17.94	316
PM	MS	PM	19.06	18.69	0.37	29.0	2.82	188	16.82	321
PM	MS	Both	19.19	17.76	1.43	29.3	2.82	181	16.99	326
AM	MG	AM	16.12	14.75	1.37	25.3	2.12	185	17.42	282
AM	MG	PM	15.69	14.32	1.37	25.1	2.10	183	17.57	276
AM	MG	Both	15.86	14.49	1.37	25.2	2.12	184	17.72	282
PM	MG	AM	15.75	14.38	1.37	25.1	2.13	171	18.22	288
PM	MG	PM	16.57	15.20	1.37	25.7	2.16	176	17.86	297
PM	MG	Both	16.16	14.79	1.37	25.5	2.15	173	18.24	296

Time of 50kg DM PAEL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ h)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	15.52	15.52	-	24.6	2.14	204	17.75	275
PM	-	-	15.93	15.93	-	25.0	2.19	198	15.85	284
AM	BG	AM	16.68	15.18	1.50	25.8	2.17	190	17.21	287
AM	BG	PM	16.45	14.95	1.50	25.4	2.15	189	17.40	286
AM	BG	Both	16.49	14.99	1.50	25.5	2.15	188	17.44	289
PM	BG	AM	18.43	16.93	1.50	28.5	2.57	154	18.01	332
PM	BG	PM	18.81	17.31	1.50	28.9	2.58	163	17.77	334
PM	BG	Both	16.78	15.28	1.50	25.9	2.19	183	17.66	296
AM	MS	AM	17.71	15.90	1.81	28.5	2.72	193	17.23	305
AM	MS	PM	20.39	19.93	0.46	30.1	2.83	204	16.27	332
AM	MS	Both	20.48	19.12	1.36	30.3	2.82	198	16.15	331
PM	MS	AM	17.94	16.13	1.81	28.6	2.78	184	17.63	316
PM	MS	PM	19.59	19.20	0.39	29.8	2.81	197	16.77	327
PM	MS	Both	19.23	17.79	1.44	29.6	2.81	188	16.95	326
AM	MG	AM	16.26	14.89	1.37	25.4	2.13	187	17.36	283
AM	MG	PM	16.05	14.68	1.37	25.2	2.12	186	17.51	282
AM	MG	Both	16.00	14.63	1.37	25.2	2.11	185	17.63	283
PM	MG	AM	15.98	14.61	1.37	25.2	2.14	178	17.81	285
PM	MG	PM	16.78	15.41	1.37	25.8	2.17	182	17.60	296
PM	MG	Both	16.39	15.02	1.37	25.6	2.16	179	17.88	294

Time of 20 kg DM PALL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ ¹)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	10.20	10.20	-	13.32	1.14	180	21.72	222
PM	-	-	10.43	10.43	-	13.48	1.17	164	22.20	231
AM	BG	AM	11.82	10.32	1.50	14.01	1.18	165	21.05	249
AM	BG	PM	11.65	10.15	1.50	13.95	1.18	169	20.60	240
AM	BG	Both	11.74	10.24	1.50	13.99	1.18	166	20.97	246
PM	BG	AM	11.19	9.69	1.50	13.83	1.17	150	21.89	245
PM	BG	PM	11.54	10.04	1.50	14.07	1.19	154	21.40	247
PM	BG	Both	11.20	9.70	1.50	13.91	1.18	150	22.03	247
AM	MS	AM	12.09	10.28	1.81	17.59	1.63	150	21.43	259
AM	MS	PM	14.67	14.45	0.27	18.71	1.71	168	18.65	277
AM	MS	Both	16.09	14.37	1.72	19.04	1.12	157	18.45	290
PM	MS	AM	12.18	10.37	1.81	17.72	1.65	142	22.19	270
PM	MS	PM	12.45	10.63	1.81	17.86	1.67	144	21.66	270
PM	MS	Both	11.98	10.17	1.81	17.75	1.66	141	22.07	264
AM	MG	AM	11.67	10.30	1.37	13.90	1.17	164	21.12	247
AM	MG	PM	11.51	10.14	1.37	13.86	1.17	167	20.91	241
AM	MG	Both	11.62	10.25	1.37	13.90	1.17	164	21.25	248
PM	MG	AM	11.01	9.64	1.37	13.74	1.17	149	22.06	244
PM	MG	PM	11.30	9.93	1.37	13.94	1.18	153	21.69	246
PM	MG	Both	11.05	9.68	1.37	13.80	1.17	148	22.44	249

Time of 30 kg DM PALL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ ¹)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	12.37	12.37	-	14.21	1.21	215	19.90	246
PM	-	-	12.02	12.02	-	14.11	1.22	192	20.79	250
AM	BG	AM	13.05	11.55	1.50	14.63	1.22	194	19.85	259
AM	BG	PM	12.80	11.30	1.50	14.46	1.20	195	19.53	250
AM	BG	Both	13.22	11.72	1.50	14.75	1.23	197	19.64	260
PM	BG	AM	12.40	10.90	1.50	14.37	1.21	168	20.84	258
PM	BG	PM	13.11	11.61	1.50	14.85	1.24	184	20.00	262
PM	BG	Both	12.61	11.11	1.50	14.54	1.22	172	20.61	260
AM	MS	AM	14.45	12.64	1.81	18.79	1.70	183	19.81	286
AM	MS	PM	16.85	16.52	0.33	19.81	1.79	207	17.57	298
AM	MS	Both	16.28	14.99	1.29	19.83	1.79	194	18.15	296
PM	MS	AM	13.66	11.85	1.81	18.38	1.69	161	20.72	283
PM	MS	PM	13.88	12.78	1.10	18.73	1.72	170	19.66	283
PM	MS	Both	13.88	12.34	1.54	18.90	1.72	168	19.75	279
AM	MG	AM	12.85	11.48	1.37	14.52	1.21	193	19.93	257
AM	MG	PM	12.67	11.30	1.37	14.34	1.20	194	19.65	250
AM	MG	Both	12.96	11.59	1.37	14.58	1.21	195	19.89	258
PM	MG	AM	11.59	10.22	1.37	14.07	1.19	159	21.32	248
PM	MG	PM	12.79	11.42	1.37	14.66	1.22	181	20.31	261
PM	MG	Both	12.33	10.96	1.37	14.40	1.21	170	20.88	258

Time of 40 kg DM PALL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ ¹)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	12.60	12.60	-	14.36	1.22	220	19.72	248
PM	-	-	12.74	12.74	-	14.41	1.23	205	20.43	260
AM	BG	AM	13.14	11.64	1.50	14.69	1.23	196	19.72	259
AM	BG	PM	13.47	11.97	1.50	15.02	1.25	206	19.15	258
AM	BG	Both	13.32	11.82	1.50	14.83	1.23	201	19.49	260
PM	BG	AM	12.94	11.44	1.50	14.64	1.22	183	20.26	262
PM	BG	PM	13.46	11.96	1.50	15.00	1.25	193	19.93	268
PM	BG	Both	13.18	11.68	1.50	14.80	1.23	187	20.26	267
AM	MS	AM	14.52	12.71	1.81	18.86	1.70	186	19.68	286
AM	MS	PM	16.45	16.11	0.34	20.12	1.79	222	17.91	296
AM	MS	Both	16.20	14.91	1.29	19.88	1.78	205	17.87	291
PM	MS	AM	14.18	12.37	1.81	18.63	1.70	173	19.97	283
PM	MS	PM	15.53	15.16	0.37	19.39	1.76	195	18.79	292
PM	MS	Both	15.61	14.22	1.39	19.48	1.77	183	18.63	292
AM	MG	AM	12.93	11.56	1.37	14.57	1.21	195	19.75	256
AM	MG	PM	13.15	11.78	1.37	14.73	1.23	203	19.40	256
AM	MG	Both	13.09	11.72	1.37	14.65	1.22	198	19.71	259
PM	MG	AM	12.73	11.36	1.37	14.54	1.21	181	20.43	261
PM	MG	PM	13.15	11.78	1.37	14.82	1.23	189	20.17	266
PM	MG	Both	12.96	11.59	1.37	14.67	1.22	191	20.21	262

Time of 50kg DM PALL	Supplement type	Time of supplement	DMI (kg DM cow ⁻¹ per day)	Pasture intake (kg DM cow ⁻¹ per day)	Supplement intake (kg DM cow ⁻¹ per day)	MY (kg cow ⁻¹ per day)	Milk solids (kg cow ⁻¹ per day)	UN (g cow ⁻¹ per day)	CH ₄ yield (g kgDM ⁻¹ day)	Total CH ₄ (g cow ⁻¹ per day)
AM	-	-	12.69	12.69	-	14.40	1.22	222	19.48	247
PM	-	-	12.78	12.78	-	14.37	1.22	210	20.08	257
AM	BG	AM	13.18	11.68	1.50	14.73	1.23	198	19.57	258
AM	BG	PM	13.54	12.04	1.50	15.10	1.25	209	18.93	256
AM	BG	Both	13.38	11.88	1.50	14.90	1.24	203	19.37	259
PM	BG	AM	11.32	9.82	1.50	14.38	1.18	180	20.94	237
PM	BG	PM	13.41	11.91	1.50	14.99	1.24	198	19.71	264
PM	BG	Both	13.17	11.67	1.50	14.80	1.23	192	19.95	263
AM	MS	AM	14.55	12.74	1.81	18.90	1.71	188	19.58	285
AM	MS	PM	16.38	16.04	0.34	20.12	1.78	244	17.77	293
AM	MS	Both	16.32	15.03	1.29	19.96	1.78	207	17.74	291
PM	MS	AM	14.23	12.42	1.81	18.65	1.70	179	19.47	277
PM	MS	PM	15.69	15.31	0.38	19.55	1.75	209	18.68	292
PM	MS	Both	17.63	17.16	0.47	20.94	1.88	229	17.25	321
AM	MG	AM	12.99	11.62	1.37	14.62	1.22	197	19.60	255
AM	MG	PM	13.22	11.85	1.37	14.83	1.23	205	19.23	255
AM	MG	Both	13.13	11.76	1.37	14.71	1.22	200	19.61	258
PM	MG	AM	12.72	11.35	1.37	14.53	1.21	188	20.14	257
PM	MG	PM	13.12	11.75	1.37	14.83	1.23	195	19.93	262
PM	MG	Both	12.91	11.54	1.37	14.67	1.22	191	20.21	262