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Farm systems and diet modelling of Greenhouse gas emissions, nitrogen losses and economic performance of differing diet and land use scenarios for a Waikato dairy farm

H Tacoma (DVM), B Rys (B. Agr., M.Sc.Trop.Ag.), W Morritt (B. Agr.) & Sophie Davison (B. Agr. Sci, Hons)

Reviewed by Dave Clark (formerly Principal Scientist, DairyNZ, Hamilton, NZ)

Abstract

Whole farm systems modelling was undertaken to investigate the impacts of multifactorial alterations within a farming system to Greenhouse gas (GHG) emissions, nitrogen (N) losses, farm productivity and profitability. The control farm was created using data from a DairyNZ economic survey (DairyNZ, 2019), with the intention of representing an 'average farm' for the Waikato region for the 2018/19 season. Whilst the physical farm parameters remained constant across the scenarios, progressive alterations were made to variables such as stocking rate, cow size, genetic merit and concentrate feed input. Modelling software Udder (version 3.19.1), RedSky (version 5.04.02) plus Excel spreadsheet and Overseer (version 6.4.0) were used to predict the productive, economic and environmental outcomes of 4 scenarios each with increasingly fewer, but larger cows of higher genetic merit whilst being fed increasing amounts of a concentrate feed, to a maximum of 18.5% of the diet (Pasture, forage, concentrate diet; PFC diet). Whilst maintaining the same physical parameters as the control farm, these four alternative scenarios were constructed with the express aim to keep farm milk production similar to the control scenario, whilst varying parameters such as stocking rate, cow size and cow genetic merit. A fifth alternative scenario was also modelled with the aim of reflecting current industry advice; this consisted of the same baseline farm system as the control farm, with a 15% reduction in stocking rate, without use of concentrate feeds (pasture /forage diets, PF).

Critically, the purpose of utilising concentrate feeds in this modelling was not to intensify the system by increasing the stocking rate or total farm milk production; rather, concentrate feeds were utilised to increase the per cow production compared to the lower level of production per cow that would be possible in a forage only system, allowing the total annual production to remain the same across the scenarios.

Whole farm systems modelling showed compounding effects of the multifactorial farm system alterations; by moving to a PFC diet (reducing the forage content and increasing the concentrate portion of the diet to a maximum of 18.5%), using larger cows of higher genetic merit, and maintaining the same farm milk solid production, GHG emissions (including youngstock) and N losses (leaching, volatilisation, and denitrification) each decreased by 15-16%, whilst profitability increased by 22% (at the modelled concentrate and milk prices) in the most developed scenario, compared to the control farm. Cow body condition score (BCS), an important indicator of animal welfare, was higher throughout the season in the PFC scenarios than the lower input scenarios. The most developed scenario (4) reduced

total farm feed requirement by 13% which was a primary driver for reducing GHG emissions and N losses. There was an additional benefit of an 8.5% reduction in land area required on the dairy platform to maintain production in scenario 4. This retired land could be used for GHG mitigation or carbon sequestration or other revenue generating purposes. The stocking rate of 2.94 cows per hectare in the control farm was able to be reduced to 2.06 cows per hectare in scenario 4, thereby also reducing the requirement for replacement stock numbers.

Cornell Net Carbohydrate Protein System (CNCPS) modelling was undertaken to predict methane emissions for the control farm and scenarios 4 & 5. Enteric methane emissions were reduced by 13.9% (CNCPS) and total methane emissions by 15.2% (Overseer) by incorporating 18.5% of the diet as concentrates and eliminating imported forages from the diet (scenario 4). Methane emissions calculated as kg methane /kg fat corrected milk (FCM) also reduced by 15% (CNCPS). This was due to increased per-cow milk production and greater efficiency of conversion of feed to milk.

This modelling showed that by incorporating concentrate feeds into a pasture-forage diet and simultaneously increasing cow size and genetic merit, as well as reducing stocking rate, GHG emissions and nitrogen losses can be reduced substantially; area of land farmed can be reduced and profitability and productive efficiency of farm-land and animals increased.

Introduction

In accordance with New Zealand's commitment to the Paris Agreement on climate change, by 2030 the New Zealand dairy industry must reduce Greenhouse gas (GHG) emissions to 30% below 2005 emission levels. Current advice to the industry is indicating that the mechanism for reducing GHG emissions should be to reduce reliance on imported feeds and for the industry to move back to a lower stocked, pasture /forage-only system.

The New Zealand dairy industry has historically been a predominantly pasture-based system. However, over the past two decades, farmers have introduced concentrate feeds into their farming systems to optimise the productivity of their cows and land. Nevertheless, the New Zealand dairy industry is still largely pasture based, with approximately 85% of feed grown on farm, and 15% of feed imported from outside the farm (Ledgard et al., 2020), with New Zealand farmers being held in high regard internationally for their highly efficient farm systems.

Both domestically and internationally, there has been a large amount of research into strategies to reduce GHG emissions over the last two decades due to the growing concern surrounding climate change. Particular focus has been on reducing enteric methane emissions from ruminants. Methane is naturally produced during fermentation in the rumen as it is an end product in the fermentation of carbohydrate feed sources (Beauchemin et al., 2008; O'Neill et al., 2011). There have been a number of products which claim to reduce enteric methane production through modification of rumen function, however, there is yet to be a commercially available product in New Zealand which is recognised for significantly reducing methane production and which is suitable for grazing systems.

Nitrogen losses are also an important environmental factor requiring optimisation. Nitrogen losses from NZ dairy systems can be very high due to the high quantities of soluble and degradable protein in high quality pasture (Higgs et al., 2013).

The challenge before New Zealand dairy farmers is to reduce their environmental footprint whilst maintaining or increasing productivity and profitability. Environmental and economic sustainability are needed to underpin the resilience of New Zealand's dairy businesses, whilst continuing to supply large volumes of high quality and nutritious food to countries which don't have the ability to produce food with the efficiency New Zealand enjoys. It is pertinent to the global food system that the New Zealand agricultural industry maintains its high level of land use efficiency, whilst always striving to improve current practices. Knapp et al. (2014) emphasized that GHG mitigation strategies which reduce agricultural productivity would be at least partly counterproductive as they would simultaneously increase the cost of food or reduce the availability of high-quality animal products.

The primary objective of this investigation was to use modelling software (Udder, Overseer and Red Sky) to analyse productivity and profitability, as well as GHG emissions and nitrogen outputs through modelling a series of multi-factor alterations to the average farm in the Waikato region as defined by the 2018 /2019 DairyNZ economic survey (DairyNZ, 2019). The secondary objective of this investigation was to use CNCPS software to verify the accuracy of the trends in GHG emissions obtained from modelling through Overseer. Given the large contribution of enteric methane production to total GHG emissions in NZ dairy systems, using a separate, internationally respected model helped to corroborate the results from the Overseer model.

Methodology

Whole systems analysis

Udder

A whole-farm model was developed in the farm modelling software Udder, to represent an 'average farm' in the Waikato, based on information from a 2018-19 DairyNZ economic survey (DairyNZ, 2019). This farm (control farm) model consisted of a 117 ha, Spring calving dairy farm with a start of calving date of 15th July, a calving period of approximately 11 weeks, an annual heifer replacement rate of 25% of peak cow numbers and a feeding system consisting of ryegrass /white clover pasture and imported silage (pasture silage was chosen for this exercise) and palm kernel expeller (PKE).

Pasture grazing decision rules are discussed in detail by Macdonald et al. (2010). The decision rules used in the current modelling was in accordance with these rules, with the aim of optimising quality and quantity of pasture production. Macdonald et al. (2010) also reported that these rules have been tested using the Udder model, and results were similar between the modelled simulation and results observed in the field.

Briefly, the decision rules applied ensured that maximum pre-grazing pasture covers were approximately 3,000 kg DM /ha, and post-grazing pasture residuals were 1,500 kg DM /ha. In situations where there was a feed deficit, pasture silage and /or palm kernel were supplemented to cows, and in situations of feed surplus, surplus pasture was harvested for silage.

Rotation lengths were set in accordance with a template designed to reach the end of the first grazing round by approximately September 25 (Figure 1). The rotation length from September 25 to March 1, was primarily designed with the intention to graze plants at the 2.5 – 3 leaf stage, maximizing pasture harvested without impacting pasture quality. However, from late October to early January, a 19-day round was chosen, aiming to graze plants at 2 to 2.5 leaves, thus avoiding some of the seedhead accumulation that would occur with slower late spring/early summer rotation lengths. After the risk of seedhead accumulation had reduced in January, rotation length returned to 23 days until early March. In autumn the rotation length was 30 days (March), 40 days (April) and finally 50 days (May) in order to re-build average pasture cover to a level similar to the initial average pasture cover.

Initial and final average body condition score (BCS) of the herd was the same in each scenario to ensure annual milk production wasn't at the cost of body fat reserves. Ensuring the average pasture cover and BCS of the herd are the same at the model start date, and end date, ensures that the model is feasible and has long term sustainability.

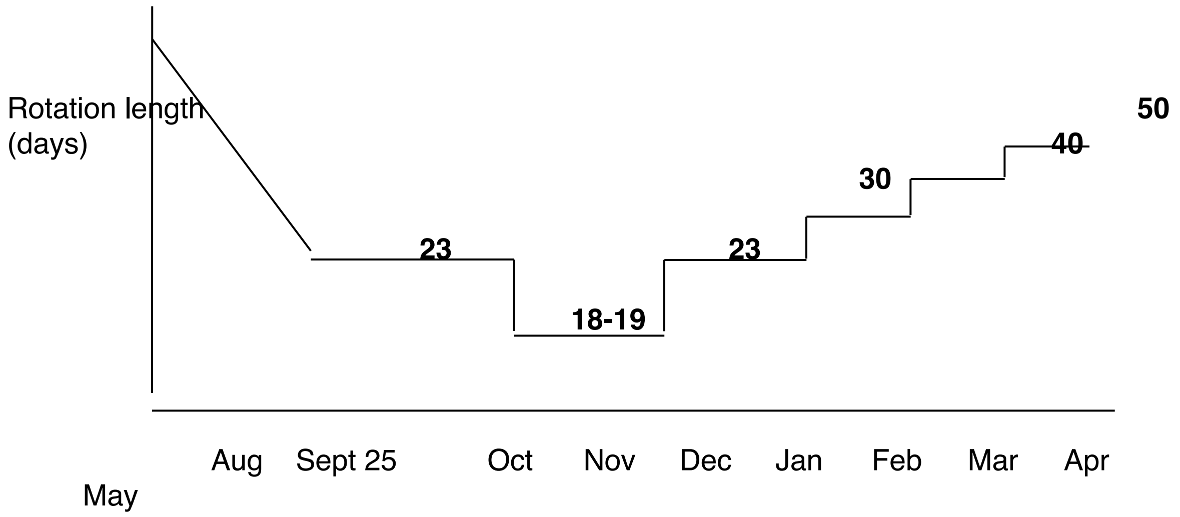


Figure 1. Schematic of round lengths modelled in Udder.

Financial Analysis

The economic performance of the control farm was extrapolated from Red Sky Farm Performance Financial Analysis software (version 5.04.02). Red Sky software provides a platform for analysing the financial performance of a farm, and provides the opportunity to benchmark different farms or farm systems against one another. Red Sky also allows for financial data to be matched to physical production data to ensure that the economic analysis is accurate.

The financial analysis was performed in a spreadsheet, extrapolating the expenses from the control scenario and allocating costs to a per cow or per hectare basis in accordance with the method used by Macdonald et al. (2011). In their paper, there was no entry for irrigation; we have allocated this particular cost to 100% per-hectare basis.

Table 1. Various costs used within the models

Milk Price	\$6.50 /kg MS
Concentrate price	\$500 /t DM
Imported forage	\$350 /t DM
Home-made forage	\$120 /t DM
Nitrogen	\$1,850 /t N

Analysis of environmental parameters

Greenhouse gas (GHG) emissions and nitrogen (N) losses were calculated using Overseer farm modelling software (version 6.4.0). Overseer is a nutrient budgeting tool which is commonly used on dairy farms to predict outcomes of varying nutrient use and different management systems, such as variable stocking rate, stock class or use of crops. Overseer evaluates key inputs, outputs and nutrient recycling in a farm system, and provides users with information to assess the outcomes of nutrient use, nutrient flows within a farm, and losses of nutrients and GHG in the farm system.

Total farm GHG emissions are calculated in Overseer by estimating methane, nitrous oxide and CO_2 emissions which are presented as CO_2 equivalents; this method is largely based on the method used by the New Zealand GHG emissions national inventory. Global warming potential (GWP) on a 100-year basis and standard Intergovernmental Panel for Climate Change (IPCC) 2007 factors were used for methane and nitrous oxide of 25 and 298 kg CO_2 equivalent /kg respectively.

Embedded Life Cycle Analyses (LCA) values for concentrate feeds used in Overseer are taken from the National Inventory for New Zealand GHG emissions, which is managed and updated by the Ministry for the Environment.

LCA for inputs such as fertiliser, fuel and concentrate feeds were used to determine embodied GHG emissions. Other GHG emissions included in the calculations are those associated with effluent management, enteric and non-enteric methane emissions, agrichemicals, and refrigerants. Overseer appropriately allocates embodied GHG emissions for day-to-day farm management such as fuel, electricity and supplementary feed to appropriate units of product, such as milk and meat. Product emissions resulting from Overseer estimations can then be classed as an estimation of the LCA for emissions associated with the product up to a specific point, such as the farm gate in our case. GHG emissions relating to the rearing of young stock off-farm were not included in Overseer's original calculations as it is not industry standard practice to rear youngstock on farm from weaning until Rising 2 year olds. However, the authors created a separate scenario in Overseer to determine the GHG emissions of rearing the young stock and combined this with the on-farm GHG emissions to give the total GHG emissions for the whole farm system including young stock grazing.

The model can be used without specific inputs by using default settings, or the user can input information specific to the farm for key information such as fuel and electricity usage, transport distances and fertiliser application methods. LCA emissions for supplementary feeds are based on typical LCAs for growing the supplement, given that the source of different supplements varies. Default values for fuel, electricity and transport were used in this research which is based on a national average values. Changes in soil or plant carbon stocks are not included in the model.

N losses calculated in Overseer account for the N losses from leaching, volatilisation and denitrification. N losses which occurred during the rearing of the replacement heifers off the dairy platform were calculated and reported for each scenario.

More detailed descriptions of Overseer and the GHG section of the Overseer model are given by Wheeler et al. (2006) and Wheeler et al. (2008).

Nitrogen losses from land outside the farm required to grow supplementary feed (forage or concentrate) were not accounted for in the current modelling. Biologically, N losses in a soil profile are non-linear and are influenced by a large number of factors. Furthermore, N losses associated with the growth of the crop would occur in the soil where the crop is grown and hence should not be attributed to the soil on the dairy platform. N losses from the production of concentrate feeds should be allocated to the nutrient and environmental budgets of the farms where they are physically occurring. N losses associated with the consumption of the concentrate feeds are accounted for in the current modelling.

The authors note that there is an inconsistency in the approaches taken for GHG production and nitrogen losses in Overseer; GHG production associated with feed production outside the farm area are added to the dairy farm's GHG profile, while N losses associated with same feed are not. It could be argued that there appears to be double counting of GHG.

Effluent was collected during milking on the concrete yard, and an in-shed feeding system was used to feed concentrates where appropriate; there was not a feed-pad or barn on the farm. Therefore, the majority of the dung and urine was deposited directly onto pasture. Liquid effluent collected from the yard is stirred and spread regularly throughout the year.

The soil types chosen in Overseer were Peat/ Organic Utuh_31a.2 (59% of farm); Sedimentary/Brown Airf_7a.1 (24%) and Sedimentary/Gley Temu_57b.8 (17%). The pasture selection used was the default ryegrass /white clover option in Overseer, and the ME content (MJ ME/kg DM) was the default setting for the Northern North Island. Overseer uses an annual average N concentration in pasture of 3.7% for flat dairy land. This then fluctuates throughout the season depending on N fertilisation.

Scenario 1 – 4

Using the same software and methodology used to model the control farm, four alternative scenarios were modelled. For these scenarios, the physical farm parameters were kept the same as the control farm and milk production was controlled to remain very similar to the control farm model. However, variations in cow size, genetic merit, stocking rate and the level of concentrate feeding were incorporated into the systems (Table 3). After modelling in Udder to ensure the feasibility of each scenario, these alternative farm system scenarios were then modelled through the Overseer program and the financial spreadsheet. The same methodology was used as in the control scenario, in order to analyse the impacts of the variable factors on GHG emissions, N losses, productivity and profitability compared with the control farm.

The same decision rules were applied to the scenarios surrounding pasture management as were used in the control farm, and careful control of supplementation and surplus pasture conservation was practised to ensure post-grazing pasture levels didn't exceed or fall below 1,500 kg DM /ha, in order to maintain optimum pasture quality in all scenarios.

In scenario 1, the concentrate included in the ration was 100% maize grain. In scenarios 2-4, the concentrate was a blend of soybean hull (42%), maize grain (42%) and dried distillers grain (16%). These supplements were chosen to represent common supplements used and readily available supplements in this region. The chemical composition of the two concentrate feeds are displayed in Table 2. Maize grain was sourced from within the Waikato region, soybean hull and dried distillers grain were sourced from overseas. Life cycle analysis (LCA) figures used in the model for maize grain were the model default value of 0.267kgCO2/kgDM emission. Soya Hull and Dried distillers grains did not have default figures available in the Overseer program, therefore these feeds were set to 'user defined feed – concentrate', which defaults to 0.502kgCO2/kgDM emission.

Table 2. Chemical composition of concentrate feeds used in scenarios 1-4

	Scenario 1	Scenario 2-4
MJME	12.99	12.9
CP %	9	13.6
Starch %	75	33

In contrast to previous studies where constant-rate feeding was employed (Kolver et al., 2005), the level of concentrate fed to milking cows was varied throughout the season, with higher levels fed in the first half of lactation and lower levels in the second half of lactation. This was done in order to obtain the most efficient milk yield responses to the concentrates fed, as the intention for scenarios 1-4 was to optimise production per cow, diluting maintenance energy costs. Harvesting of silage was utilised as a pasture management tool to ensure optimal levels pasture quantity and quality throughout the season. The substitution ratio adopted in the modelling was 0.45, the midpoint between the substitution rates of 0.4 and 0.5 used in the Netherlands (*Tabellenboek Veevoeding* 2016).

Scenario 5

Scenario five was created to represent current industry advice for reducing GHG emissions through reduced stocking rate (15% reduction) and reduced imported feed input, using pasture and forage-based supplements only. For scenario 5, the physical farm parameters were the same as control and scenarios 1-4. As a result of a 15% reduction in stocking rate and the use of forage supplements only, the production level of this scenario was 11% lower than that of the other scenarios, as modelled utilising the supply and demand of feed in Udder.

Table 3. Metrics of the control farm and the five scenarios

	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Peak Cow Numbers	344	306	258	247	220	293
Farm Area (ha)	117	117	117	114	107	117
Cow LW (kg)	450	475	500	500	550	450
Kg LW / ha	1,323	1,242	1,103	1,083	1,131	1,127
Relative cow genetic merit	100%	101%	104%	105%	107%	100%
Total feed consumed (t DM) **	1,944	1,881	1,762	1,738	1,688	1,686
Feed consumed vs. control		-3.2%	-9.3%	-10.6%	-13.2%	-13.2%
Stocking Rate (cows/ha)	2.94	2.62	2.21	2.17	2.06	2.5

Comparative SR (kg LW/t DM) *	94.1	90.5	84.8	81.9	82.4	92.0
Farm production (kg MS)	124,890	124,839	124,819	124,941	124,954	111,308
Concentrate fed (% of diet)	0%	4.0%	9.9%	15.8%	18. 5%	0%

LW = Liveweight

kg MS = kilogram of milk solids

* Excluding young stock

** Including young stock

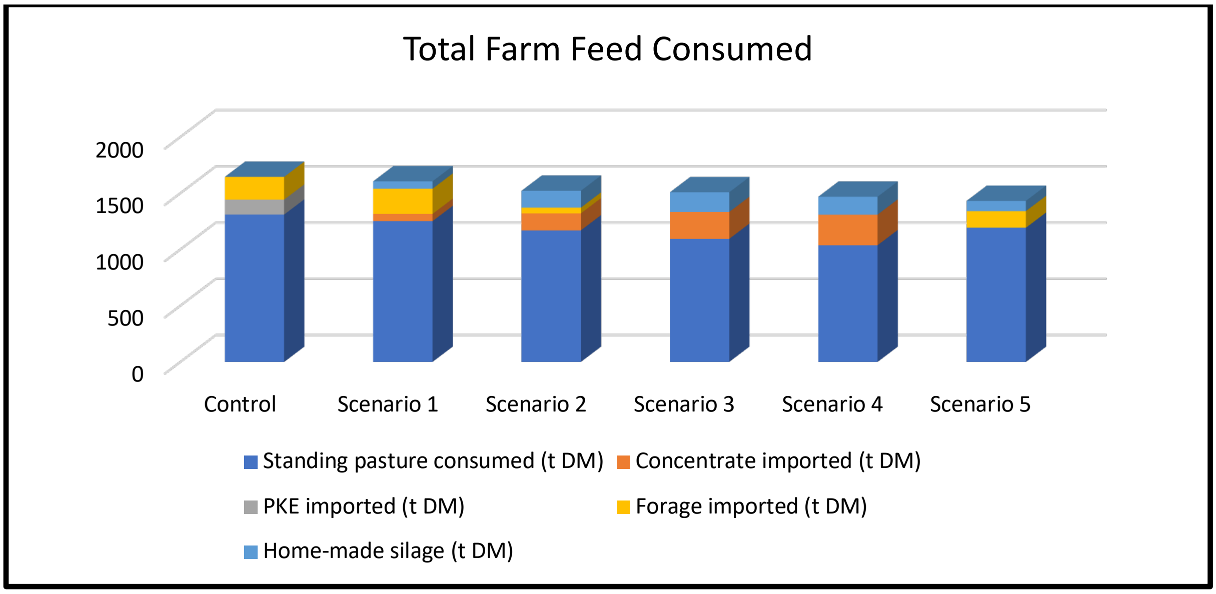


Figure 2. Reduction in the total feed requirement when concentrates are utilised (excluding young stock)

In each of the five alternative scenarios modelled in Udder, the same base pasture growth rates, total pasture production, pasture quality parameters, and level of nitrogen and fertiliser per hectare as in the control farm was applied. An important differentiation between the scenarios was the timing and area of silage harvesting and N applications. Where dairy platform land area was reduced, total N and fertiliser use was reduced to maintain the same application rate per hectare.

Cow size and genetic merit were important variable factors (Table 3). For each scenario, BCS at the end of the season was very similar to the beginning of the season. This was approximately BCS of 5 for scenarios 2, 3 & 4, and BCS 4.5 for scenarios 1 & 5, and control.

In all scenarios (including control), the Rising 1-year-old calves grazed off-farm from 1st December, to return as Rising 2-year-old heifers on June 1 the following season. This is considered standard industry practice in the Waikato region.

Various outcomes of the Udder simulations are shown in appendices 1 - 8.

Where farm model scenarios reduced land area, the area of each soil type modelled in the control Overseer model was adjusted proportionally to ensure the percentage of each soil type on the farm was maintained in each of the Overseer models.

Whilst the land required to grow the supplemental feed (concentrate) was not accounted for in the reduction of land required in scenarios 3 & 4, this is consistent with the control farm and scenarios 1, 2 & 5 which did not account for additional land required to grow pasture silage which was purchased from other farms.

Methane emissions CNCPS

The Cornell Net Carbohydrate and Protein System (CNCPS) was used to model the methane emissions of three of the dairy systems described in the whole farm systems analysis above (control, scenario 4 and scenario 5). CNCPS is a modelling tool to enable farmers and nutritionists to predict nutrient supply and demand of cattle in different management conditions (Van Amburgh et al., 2019). The model is a mechanistic mathematical model which accounts for animal, environmental, and feed compositional information to estimate requirements and supply of nutrients for cattle. In recent years, the model has been modified to incorporate equations which predict nitrogen, phosphorus, methane and carbon dioxide emissions.

The CNCPS nutritional model is designed to accurately evaluate diets and performance for cattle, using principles of ruminant nutrition and animal physiology such as digestion of feed, particle passage and microbial growth. The modelling software predicts total enteric methane emissions per cow as well as milk production (and numerous other KPI's) in different diet scenarios, which allows a comparison of methane efficiency; methane production plotted against milk production for different feed sources. CNCPS uses the metric of fat corrected milk (FCM) to a standardised level of 4% milkfat. While this isn't the standard metric used for measurement of milk production in New Zealand, it nevertheless allows for a fair comparison of milk production between different diets, therefore it is appropriate to use in this situation.

The CNCPS modelling software calculates methane emissions based on specific diets, feeding level and dietary component interactions within the animal. The total monthly methane emissions were calculated, which allowed for comparison between different stages of lactation, and diet composition through the season, and across the 3 scenarios that were modelled (control, scenario 4 and scenario 5).

The diet on the control farm consisted of pasture, conserved forage and PKE; approximately 80% standing pasture, 12% imported pasture silage on DM basis annually, and 8% imported PKE. This diet was designed to be representative of an average Waikato farm using DairyNZ survey data (DairyNZ, 2019). In scenario 4, the annual diet consisted of approx. 72 % standing pasture, 10% silage (home-grown pasture silage only) and 18.5% imported concentrates. Scenario 5 consisted of approx. 84% standing pasture, 11% imported- and 5% home-grown silage.

CNCPS has been previously evaluated in an invited review and found to accurately predict GHG emissions under a range of production systems (Van Amburgh et al., 2019). CNCPS has been continuously improved since its inception to ensure accuracy by incorporating the most up to date, scientifically robust equations.

Results

Whole systems analysis

Whilst maintaining total farm milksolids production, each of the four alternative scenarios (1-4) decreased the GHG emissions and N losses, and increased profitability in comparison with the control farm (Table 5-7).

By progressively decreasing the stocking rate but increasing cow size and genetic merit in each of the scenarios, the total DM consumed (t) reduced gradually through scenario 1-4 (Table 3). This reduction in total DM consumed was reflected by a progressive reduction in GHG emissions and N losses from scenario 1-4 (Table 6, Table 7). As stocking rate decreased and cow size and genetic merit increased, the total energy and the percentage of total energy required for cow maintenance decreased, and the percentage of feed energy partitioned towards milk production increased, increasing the feed conversion efficiency (FCE; Figure 3).

There were inverse relationships between milk production per cow as % LW and methane production, and between concentrate fed (% of diet) and methane production (Table 4, Table 5 & Table 6). There were also inverse relationships between concentrate imported (t) and total GHG (t eCO_2 /yr), and between concentrate imported (t) and total GHG (kg eCO_2) /kg MS until a plateau of methane efficiency for scenarios 3 & 4 (Table 5, Table 6 & Table 7).

Table 4. Production responses from changing system parameters

	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Peak Cow Numbers	344	306	258	247	220	293
Production /cow (kg MS)	363	408	484	506	568	380
Production / cow as % liveweight	81%	86%	97%	101%	103%	84%
Production /ha (kg MS)	1,067	1,067	1,067	1,096	1,168	951
FCE - kg DM feed per kg MS *	13.2	12.9	12.2	12.1	11.8	12.9
MS per kg DMI *	0.076	0.078	0.082	0.083	0.085	0.078
Feed energy partitioned to MS**	44.6%	46.7%	50.1%	51.2%	52.6%	45.7%

MS – Milk-solid
FCE – Feed conversion efficiency
* Excluding young stock
** Including young stock

Table 5. Requirement for imported feed and operating profit (OP)

	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Concentrate imported (t)	0	66	150	239	272	0
Concentrate as % of diet	0%	4.0%	9.9%	15.8%	18.5%	0%
PKE imported (t)	133	0	0	0	0	0
PKE as % of diet	8.1%	0%	0%	0%	0%	0%
Forage imported (t DM)	202	224	51	0	0	148

Home grown silage (t DM)	0	66	150	175	159	91
Farm area retired	0%	0%	0%	2.6%	8.5%	0%
Operating Profit	$270,777	$291,263	$331,657	$315,970	$330,970	$250,753
OP vs. control*		7.6%	22.5%	16.7%	22.2%	-7.4%

*Milk price of $ 6.50/kg MS, concentrate cost of $ 500/t.

Table 6. Impacts on GHG emissions and N losses of control farm compared with scenarios 1-5, including footprints of concentrates*, excluding young stock as modelled in Overseer

	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Methane (t eCO2 /yr)	924.9	888.4	840.9	813.5	802.7	813.6
N2O (t eCO2 /yr)	304.3	287.6	271.6	258.2	250.7	278.6
CO2 (t CO2 /yr)	222.5	179.9	180.6	198.6	204.7	150.5
Total GHG (t eCO2 /yr)	1,451.7	1,355.9	1,293.1	1,270.3	1,258.1	1,242.7
Total GHG emissions vs. control		-6.6%	-10.9%	-12.5%	-13.3%	-14.4%
Total GHG (kg eCO_2) /kg MS	11.6	10.9	10.4	10.2	10.1	11.2
N loss (kg N /yr)	5,199	5,225	4,853	4,842	4,670	4,754
N loss vs. control		+0.5%	-6.7%	-6.9%	-10.2%	-8.6%

*Overseer includes embodied emissions of imported supplements in its GHG calculations, see Appendix 9.

Table 7. Impacts on GHG emissions and N losses of control farm compared with scenarios 1-5, including footprints of concentrates*, including young stock, as modelled in Overseer

	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Methane (t eCO_2/yr)	1095	1049.3	977.2	950.5	928.8	958.5
N_2O (t eCO_2/yr)	378.1	357.4	331	317.3	303.3	342.2
CO_2 (t CO_2 /yr)	245.2	202	198.8	217	217.7	170.8
Total GHG (t eCO_2/yr)	1718.3	1608.8	1507	1484.8	1449.8	1,471.5
Total GHG emissions vs. control		-6.4%	-12.3%	-13.6%	-15.6	-14.4%
Total GHG (kg eCO_2) /kg MS	13.8	12.9	12.1	11.9	11.6	13.2
Total kg GHG /kg MS vs. control		-6.3%	-12.2%	-13.6%	-15.7%	-3.9%
N loss (kg N/yr)	6,829	6,661	6,114	6,067	5,769	6,165
N loss vs. control		-2.5%	-10.5%	-11.2%	-15.5%	-9.7%

*Overseer includes embodied emissions of imported supplements in its GHG calculations, see Appendix 9.

Scenario 4 showed the largest reduction in total farm GHG emissions and N losses compared with the control farm, 13.3% and 10.2% respectively excluding contribution from young stock (Table 6); 15.7% and 15.5% respectively including young stock (Table 7). Scenario 4 utilised a diet with the highest concentrate inclusion (18.5%) of the scenarios modelled and utilised larger, more genetically efficient cows, with a lower SR than any of the other scenarios and the control farm (Table 3). This also resulted in a decrease in total farm feed requirement (incl. YS) of 13.2% compared to the control farm. Due to the lower SR, the concentrate feed inputs and their higher genetic capacity, the cows in scenario 4 had the highest MS production per cow, and the lowest methane production per kg MS (Table 4 & Table 6).

Furthermore, scenario 4 had the largest improvement in operating profit (22.2%) compared with the control farm (Table 5), notwithstanding the fact that in this scenario, 8.5% of the productive farmland was able to be retired from dairy production. The retired land area in scenarios 3 & 4 has the potential to be utilised for alternative land uses which could offset GHG emissions from the dairy operation and/or act as an additional profit centre. However, for the purposes of this research, the retired land has been assumed to provide net zero GHG emissions, N losses and financial contribution.

Scenario 5 was designed to represent the implications of current recommendations for reducing GHG emissions on the control farm. A 15% reduction in SR was implemented, and no concentrate feed was imported. Whilst scenario 5 did reduce total farm GHG emissions by 14.4%, farm milk production was reduced by 11% (Table 3 & Table 7). This causes methane efficiency to be similar to that of the control farm; 11.6 vs. 11.2 kg GHG (e CO_2) /kg MS for control and scenario 5 respectively, whilst scenarios 2, 3 and 4 reduced total GHG emissions to 10.4-10.1kg GHG (e CO_2) /kg MS. Furthermore, profitability of Scenario 5 was approximately 7.4% lower than the control farm and 20-24% lower than that of Scenarios 2-4.

Scenarios 3 & 4 had a stronger reduction in N losses compared with scenario 5, whilst achieving 20-24% higher operating profit than scenario 5. Total land area for the milking platform was able to be reduced despite maintaining productivity in scenarios 3 & 4, whereas the full land allocation was required to produce the results of scenario 5 (Table 3).

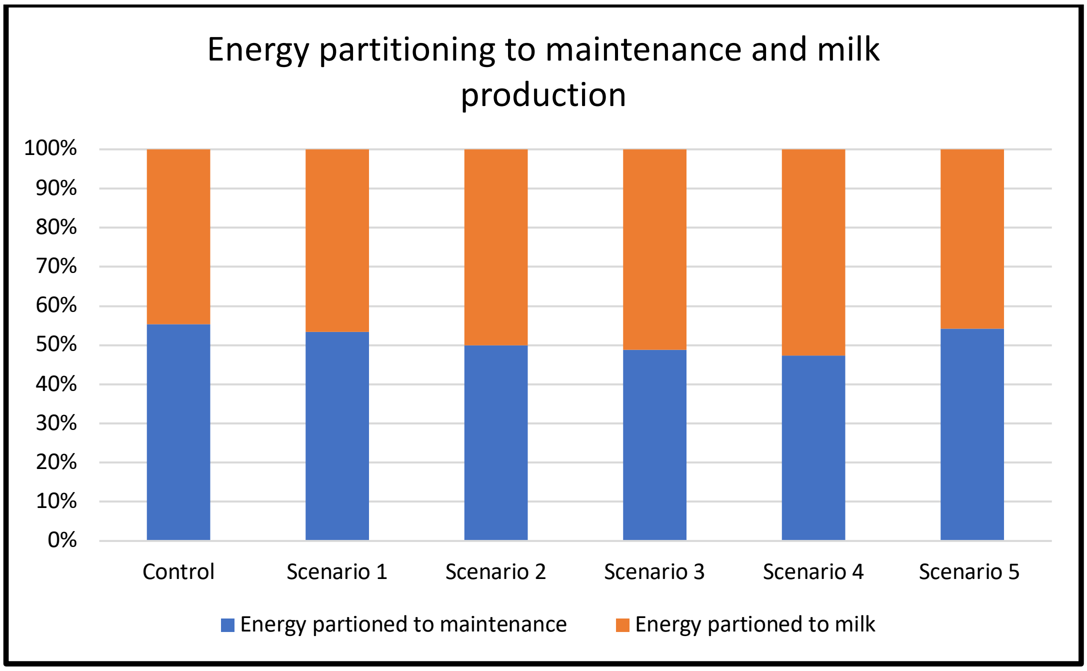


Figure 3. Increase in energy partitioned towards milk production rather than maintenance energy in each scenario

Due to the higher feed allocation per cow and higher genetic merit of the cows in scenario's 3 & 4, there is a substantially higher proportion of feed partitioned to milk production than for the control and scenario 5 (Figure 3). There is a progressive increase in feed energy partitioned to milk productions as the scenarios progress towards higher concentrate utilisation, higher genetic merit and larger cow size.

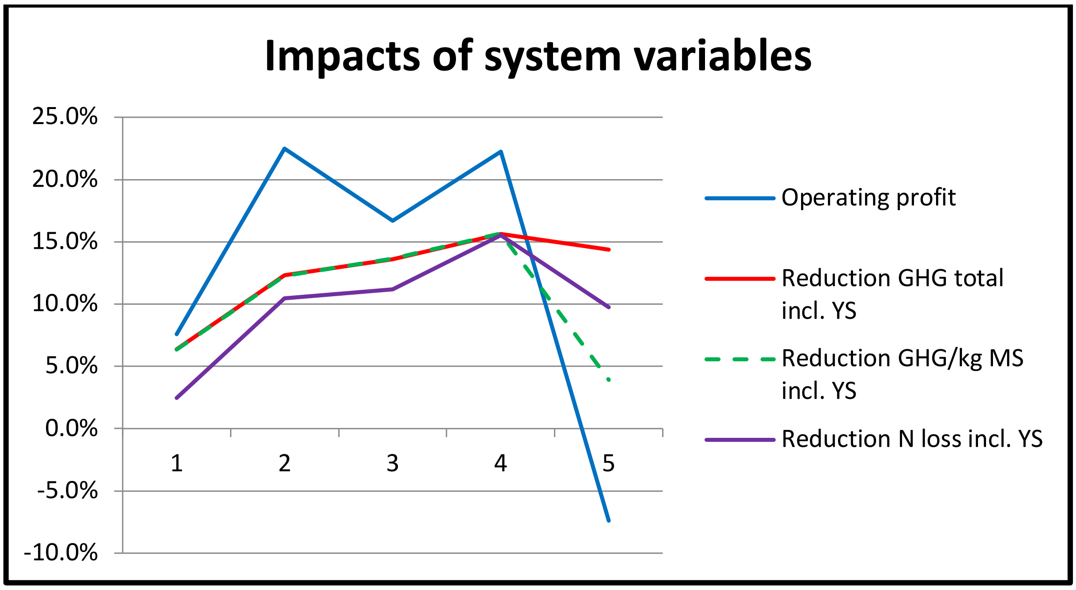


Figure 4 Relative performance of systems 1 through to 5 compared to Control.

Note: Milk pay-out of $6.50 /kg MS and concentrate price of $500 /t

The operating profit for scenarios 1-4 showed robust profit margins at variable concentrate prices and milk pay outs, when compared with scenario 5. Due to the low operating profit of scenario 5, scenario 1 was more profitable than scenario 5 at all calculated concentrate prices for a milk pay-out of $5.00 and higher, and at a milk pay-out of $4.50 until the concentrate price reached $650 /t.

Scenario 2 was more profitable than scenario 5 at all calculated milk pay-outs and concentrate prices. Scenarios 3 & 4 were more profitable than scenario 5 at most concentrate and milk prices. It was only when there was a combination of the milk price being very low and the concentrate price being very high where system 5 would challenge the profitability of scenarios 3 & 4.

In each scenario, milk pay-out had a more profound impact on operating profit than did concentrate price.

Table 8a. Sensitivity analysis of operating profit at variable milk pay-out and concentrate prices for Scenario 1 compared with Scenario 5

	Concentrate price				
	$ 350	$ 450	$ 550	$ 650	$ 750

Milk Pay-out	**$ 4.50**	$ 51,185	$ 44,785	$ 38,385	$ 31,985	$ 25,585
	$ 5.50	$ 176,024	$ 169,624	$ 163,224	$156,824	$ 150,424
	$ 6.50	$ 300,863	$ 294,463	$ 288,063	$281,663	$ 275,263
	$ 7.50	$ 425,702	$ 419,302	$ 412,902	$406,502	$ 400,102
	$ 8.50	$ 550,541	$ 544,141	$ 537,741	$531,341	$ 524,941

Numbers in red denote OP of Sc. 1 is lower than that of Sc. 5 with the same milk pay out.

Table 8b. Sensitivity analysis of operating profit at variable milk pay out and concentrate prices for Scenario 2 compared with Scenario 5

		Concentrate price				
		$ 350	**$ 450**	**$ 550**	**$ 650**	**$ 750**
Milk Pay-out	**$ 4.50**	$ 104,669	$ 89,569	$ 74,469	$ 59,369	$ 44,269
	$ 5.50	$ 229,488	$ 214,388	$ 199,288	$ 184,188	$ 169,088
	$ 6.50	$ 354,307	$ 339,207	$ 324,107	$ 309,007	$ 293,907
	$ 7.50	$ 479,126	$ 464,026	$ 448,926	$ 433,826	$ 418,726
	$ 8.50	$ 603,945	$ 588,845	$ 573,745	$ 558,645	$ 543,545

Table 8c. Sensitivity analysis of operating profit at variable milk pay out and concentrate prices for Scenario 3 compared with Scenario 5

		Concentrate price				
		$ 350	**$ 450**	**$ 550**	**$ 650**	**$ 750**
Milk Pay-out	**$ 4.50**	$ 101,504	$ 77,604	$ 53,704	$ 29,804	$ 5,904
	$ 5.50	$ 226,662	$ 202,762	$ 178,862	$ 154,962	$ 131,062
	$ 6.50	$ 351,820	$ 327,920	$ 304,020	$ 280,120	$ 256,220
	$ 7.50	$ 476,978	$ 453,078	$ 429,178	$ 405,278	$ 381,378
	$ 8.50	$ 602,136	$ 578,236	$ 554,336	$ 530,436	$ 506,536

Numbers in red denote OP of Sc. 3 is lower than that of Sc. 5 with the same milk pay out.

Table 8d. Sensitivity analysis of operating profit at variable milk pay out and concentrate prices for Scenario 4 compared with Scenario 5

Milk Pay-out	Concentrate price: $ 350	$ 450	$ 550	$ 650	$ 750
$ 4.50	$ 121,862	$ 94,662	$ 67,462	$ 40,262	$ 13,062
$ 5.50	$ 246,816	$ 219,616	$ 192,416	$ 165,216	$ 138,016
$ 6.50	$ 371,770	$ 344,570	$ 317,370	$ 290,170	$ 262,970
$ 7.50	$ 496,724	$ 469,524	$ 442,324	$ 415,124	$ 387,924
$ 8.50	$ 621,678	$ 594,478	$ 567,278	$ 540,078	$ 512,878

Numbers in red denote OP of Sc.4 is lower than that of Sc. 5 with the same milk pay out.

Methane emissions CNCPS

The use of a pasture, forage and concentrate system in scenario 4, with 18.5% of the diet as concentrate feed reduced the total farm methane production by 13.9% compared with the control farm (Table 9a and 9b). Scenario 5 resulted in a 9.6% reduction in methane production, but there was also an 11% reduction in milk production (Table 3).

There was a 15% reduction in methane production per kg FCM for scenario 4 whilst in scenario 5, there was a 1.9% increase in methane production per kg FCM (Table 9a, 9b & 9c). The decrease in methane production per kg FCM in scenario 4 corresponded with increased levels of concentrate in the diet which resulted in an increase in milk production per cow, and decreased energy (%) partitioned towards maintenance (Figure 3). The level of methane produced per kg FCM is at its lowest when cows are at peak levels of milk production, consuming a diet of pasture and concentrates, without supplementary forages (Scenario 4). The increase in methane production per kg FCM in scenario 5 is due to the reduction in milk production and the low feed conversion efficiency in this scenario.

Table 9a. CNCPS-predicted monthly methane production, Control.

Month	Cow numbers	Milk production (kg FCM /cow)	Methane produced (g/kg milk)	Total Methane (kg /month /herd)
July	11	17.44	24.23	51
August	168	22.50	19.76	2,315
September	307	26.10	17.75	4,267
October	344	27.09	17.57	5,076
November	344	24.08	19.46	4,836
December	334	20.68	22.04	4,719
January	329	18.11	25.36	4,685

February	329	16.45	27.78	4,210
March	329	15.25	29.37	4,568
April	268	14.97	32.92	3,963
May	56	15.12	34.19	289
Total kg CH_4				**38,979**
Average grams methane /L FCM				**22.51**

Table 9b. CNCPS-predicted monthly methane production, Scenario 4.

Month	Cow numbers	Milk production (kg FCM /cow)	Methane produced g/kg milk	Total Methane (kg /month /herd)
July	7	23.74	21.52	39
August	104	31.16	16.74	1,682
September	197	36.76	14.57	3,165
October	220	37.63	14.48	3,716
November	220	33.97	15.67	3,513
December	218	29.59	18.12	3,623
January	217	26.21	18.95	3,341
February	217	24.21	21.31	3,134
March	217	23.75	23.69	3,785
April	217	22.68	25.92	3,827
May	197	20.72	30.45	3,729
Total kg CH_4				**33,555**
Average grams methane /L FCM				**19.14**
Total methane vs. control (Table 4)				**-13.9%**

Table 9c. CNCPS-predicted monthly methane production, Scenario 5.

Month	Cow numbers	Milk production (kg FCM /cow)	Methane produced g/kg milk	Total Methane (kg /month /herd)
July	9	16.88	25.78	43
August	141	21.94	20.46	1,962
September	262	26.10	18.27	3,748
October	293	27.09	17.72	4,360
November	293	24.30	19.18	4,096
December	290	20.46	20.46	3,763
January	288	17.78	25.59	4,061
February	288	16.33	28.56	3,762
March	288	15.25	30.33	4,129

April	255	15.24	30.93	3,605
May	159	14.45	36.77	1,689
Total kg CH_4				**35,219**
Average grams methane /L FCM				**22.94**
Total methane vs. control (Table 4)				**-9.6%**

Discussion

The primary objective of this research was to use modelling software to analyse the effects of multi-factor alterations to farm systems on GHG emissions, N losses, productivity and profitability. These alterations included diet, stocking rate, cow liveweight, cow genetic merit, timing of N fertiliser and timing of silage harvesting. Rather than try to develop 'the ideal farm system', which is an impossibility due to the extremely complex and multifactorial nature of farming, the aim was to show a logical progression of change and effect in a series of farm scenarios.

The modelled scenarios in Udder were chosen to represent progressive variation in farm systems which could achieve environmental benefits, whilst maintaining flexibility and profitability in farming businesses. When given flexibility, farmers will seek innovative and efficient means of achieving targets. What has been demonstrated in this research is the ability to use multiple parameters within a farming system to improve environmental outcomes across a range of environmental parameters, whilst maintaining high productivity and improving profitability.

The mechanism involved in reducing GHG emissions and N losses in the modelled scenarios was reducing the total dry matter consumed on each farm (Table 3). Reducing the total quantity of feed consumption is a commonly accepted method for reducing enteric methane production (O'Neill et al., 2011). As stocking rate was decreased, and cow size and genetic merit increased, proportionally less energy was required for maintenance, and a higher proportion of energy was partitioned towards milk production (Figure 3). In the farm systems modelled, as a lower percentage of the feed energy was partitioned to maintenance and more towards milk production increasing FCE; increased production per cow resulted in similar total farm milk production with fewer cows and less total feed consumption. As total feed consumption progressively reduced, GHG production and N losses also progressively reduced. This result is in accordance with the concept described by Hristov et al. (2013) who reported that on a per cow basis, whilst methane emissions increase as feed intake increases, the efficiency of methane emissions per kg dry matter intake (DMI) also increases with increasing feed intake above maintenance level. Therefore, when there is a low stocking rate combined with high production per cow, as is the case with scenario's 3 and 4, the maintenance energy requirements have been diluted by high DMI per cow, the efficiency of methane production per kg MS is high, and total farm methane production is low. This concept is also supported by Knapp et al. (2014) and Boadi et al. (2004) who both reported that lower methane production in scenarios where milk production remains constant with reducing cow numbers should be expected.

For scenarios 2-4, N losses were inversely correlated with concentrate feed % in the diet (Table 5 & Table 6). This is because the concentrate feed had lower average CP content than the pasture (Overseer default of 3.7% N for pasture). As concentrate proportion of the diet increased, the overall CP content of the diet decreased, which reduced the N losses. Higgs et al. (2013) reported that a primary method of reducing N losses is through reducing N content in feed. With progressively increasing levels of concentrate in scenarios 2-4, N losses progressively reduced from a 6.7% reduction from control for scenario 2, to a 10.2% reduction from control for scenario 4 (excl. YS). Scenario 1 had high N losses due to the high reliance on pasture silage as a supplementary feed.

The feed conversion efficiency (FCE) in the current modelling improved from 13.2 kg DMI /kg MS for control, to 11.8 kg DMI /kg MS for scenario 4 (excl. YS). This increase is due to the increased genetic merit of cows, the reduction in stocking rate and the increased levels of concentrate feeding. This resulted in higher milk production per cow which reduced the proportion of feed required for maintenance energy for the herd. In a recent attempt to use higher genetic merit cows and lower stocking rate to mitigate N leaching, Clark et al. (2020) recorded an FCE of 13kg DMI /kg MS, which is substantially lower efficiency than the predicted FCE in the current modelling. Whereas, Chapman et al. (2021) reported FCE of 10.88 and 10.9 kg DMI /kg MS on an irrigated Canterbury dairy system. This is an increased FCE compared to our modelling which is likely to be due to increased pasture quality in Canterbury compared with the Waikato. Furthermore, Chapman et al. (2021) achieved this level of FCE with cows in which 94% of the lactating diet was grazed pasture, whereas in the present modelling, approximately 75-80% of the lactating diet was grazed pasture. Increasing the intake of concentrate feed in the diet will aid in maximising dry matter and energy intake, which will promote a high FCE. Whilst the authors acknowledge that this FCE is challenging for an average Waikato farm, the authors believe this can be achieved with strong adherence to pasture grazing rules described by Macdonald et al. (2010), which combined with supplementing with low levels of high energy density feeds will support optimal dry matter intake. These factors combined with increased cow size, increased genetic merit and selecting for increased feed conversion efficiency will support this level of production and feed conversion efficiency. The harvesting of silage at critical pasture growth vs. demand thresholds will be essential to maintaining pasture quality in this low stocking rate system. Maximising pasture quality will ensure optimal energy consumption is achieved which will increase the FCE.

A further advantage of decreasing stocking rate is the decrease in replacement heifers required each season. Each scenario's herd was replaced at 25% of peak cow numbers, so in scenarios with the lowest total cow numbers, replacement heifer numbers were correspondingly the lowest.

The objective of scenario 5 was to create a scenario to model the effects of current industry recommendations for reducing GHG emissions and N losses to compare with alternative system alterations made to achieve similar environmental results. Scenario 5 uses the base model of the control, but implements lower SR (15%) and utilises pasture and forage-based supplements only; no PKE is fed. Whilst scenario 5 did decrease total GHG emissions and N losses compared to the control (14.4% and 9.7% respectively), productivity was reduced by 11% compared to the control. Operating profit was lower than control and scenarios 1-4; the modelling indicated 20-24% higher operating profit for scenarios 2-4 than scenario 5(Table 5). Clark et al. (2020) implemented a number of strategies, including reduced stocking rate and higher genetic merit cows in an attempt to reduce nitrogen leaching on a 'typical' Waikato farming system. These authors found that whilst N leaching was reduced, mitigation strategies also reduced profit by $279 /ha /yr on average, and decreased the operating return on assets from 4.2% to 3.5%. Chapman et al. (2021) observed a reduction in estimated N leaching from implementing a low N and low supplement system compared with a high N and high supplement system, however milk production was also reduced by the low input system. Profitability was similar for the two systems at a milk solid pay-out of $6.46, above which the high input system was more profitable, and the inverse was true for the low input system.

The intensity of dairy emissions have decreased over the past three decades due to increased milk production from a reduced number of cows (Clark & Journeaux, 2021). As well as reducing the total farm GHG emissions, scenario's 1-4 progressively reduce the intensity of GHG emissions per unit of milk production through increased FCE and optimising milk production on the land area and feed available. Scenario 5 only marginally reduces the intensity of GHG emission per unit of milk produced compared to control, and still has a higher intensity than scenario 1, the worst of the 4 alternative scenarios in terms of GHG /kg MS.

An important distinction to make is that in this research concentrate feeds are not being included in the diet to increase the stocking rate. Concentrate feeds are being utilised to optimise the per cow production compared to what would be possible in a forage only system, therefore, allowing a lower stocking rate than the control scenario but maintaining milk production. As has been discussed, optimising the per cow production causes a dilution effect on methane produced in association with the consumption of maintenance energy (Hristov et al., 2013; Knapp et al., 2014). This optimisation of per cow production is where scenarios 3 and 4 have major advantages over scenario 5. Whilst scenario 5 does achieve environmental benefits, it is at the cost of milk production and profit. In addition, scenarios 2, 3 and 4 all have lower SR than scenario 5. In terms of the global food supply, New Zealand milk has a low Carbon footprint compared to internationally produced milk (Knapp et al., 2014; Ledgard et al., 2020), therefore, it is better to maximise our efficient milk production as is demonstrated in scenario 4, rather than achieve similar environmental goals by sacrificing milk production as shown with scenario 5.

In previous research, a flat rate of supplementation was used for the entire season and substitution rates were high (Kolver et al., 2005). However, in the current research, supplementation levels were variable and silage was harvested in time to ensure substitution rates were minimised. Furthermore, in the research by Kolver et al. (2005), DM offered was unlimited, whereas in this research there will be more competition between cows for feed, which will reduce substitution. Had DM offered been unlimited, pasture quality would have declined, and efficiencies and financial performance outcomes would have reduced. Supplementation levels in the current research were carefully managed and silage was harvested when pasture surpluses occurred to ensure high pasture quality throughout the season and to optimise production. It was imperative that the annual rotation planner and pasture grazing rules in Udder, such as pre- and post-grazing average pasture covers were adhered to. This is in contrast to residual grazing rules used in the experiment by Kolver et al. (2005), where residuals higher than industry best practice were allowed (followed by non-treatment cow grazing or topping).

Whilst the cost structure of the farm may seem counterintuitive to current understanding and assumptions around the dilution or inflation of costs in differing systems, a careful distinction should be made with the systems being modelled; where historically farmers have utilized supplements to intensify the system by increasing the stocking rate and increasing overall production, a key systematic feature of the current modelling is that the supplements are being utilised to optimise production on a per cow basis and reduce the stocking rate, maintaining the same total farm milk production. In the current modelling, despite the production level remaining constant, the profitability increased with the increase of concentrate percentage in the diet, whereas Neal and Roche (2019) reported that for every $1 increase in spending for feed costs, there was a corresponding $1.66 increase in the operating expenses for Waikato farms, from analysis of DairyBase data. However, in the current modelling, as concentrate use progressively increases in the scenarios (% of diet), stocking rate progressively decreases. Historically, as concentrate percentage of the diet increased, so did the stocking rate. Hence, as stocking rate decreased in the current modelling, there was a reduction in costs correlated to the number of cows. For example, animal health costs and breeding costs which are highly weighted towards cow numbers both reduced substantially as the systems reduced cow numbers. Freight, labour, electricity, shed expenses and vehicle costs which all have a higher weighting towards per cow rather than per hectare factors will also decrease with the decreasing stocking rate and concurrent increase in concentrate supplementation. Whereas, traditionally, if concentrate supplements were utilised to increase the stocking rate, these costs would all have increased, which explains the discrepancy between the financial results in this modelling and the report of Neal and Roche (2019).

Furthermore, the report by Neal and Roche (2019) has retrospectively analysed information inputted into DairyBase from commercial farms which likely had key focusses of profitability and/or productivity with few constraints outside of these two parameters. Whereas, the systems within the current modelling exercise have been created with express aims of reducing the environmental implications of the farming system, whilst maintaining profitability and productivity. In attempting to optimise productivity and profitability on farm, trade-offs may be made for different reasons, but historically, GHG emissions and N losses have not been factors for farmers when considering different farm systems options. Therefore, with a shift in mindset to adopt principles highlighted in this modelling of aiming to optimise per cow production whilst minimising the environmental implications of each system, we believe it is possible for farmers to utilise supplemental feeds without having a subsequent rise in operating costs in their system, and simultaneously reduce the environmental impacts of their system.

The decision was made to use a blend of soybean hull, maize grain and dried distillers grain as the concentrate supplements rather than palm kernel expeller (PKE). This decision was made to align with the likely future direction of the industry in reducing reliance on PKE due to perceived environmental issues with PKE, and manufacturing issues encountered in the processing of milk produced from cows fed high levels of PKE. Soybean hulls, maize grain and dried distillers grain are readily available and commonly used as parts of feed blends for dairy farmers in the Waikato region. Substituting this blend for PKE would increase the financial performance of the scenarios as PKE is approximately $80 per tonne cheaper than the chosen blend. From the experience of the authors, it would be likely that the use of PKE would support the desired high levels of production. Where possible, concentrates were sourced from New Zealand to minimize the environmental footprint.

It is pertinent to note that many feeds utilized in the stock feed industry are by-products from the manufacturing or processing of other products such as energy, human food or -food oil production. Soybean hulls, dried distillers grains and PKE all fit into this category. Were these feeds not upcycled and used as stockfeed, they would have to be disposed of, which would likely be by burning, burying or rotting in landfill. Alternative disposal of by-product feed potentially result in negative environmental implications (Russomano et al., 2012); hence it should be considered that utilizing these products as stockfeed increases efficiency of the overall food system, which means that the production of greenhouse gases from their use is for a productive purpose, rather than a wasteful purpose.

Limitations

In designing a modelling experiment, limitations are inevitable and are discussed in the following section.

Pasture grazing rules in Udder were chosen to maintain 1,500 kg DM /ha residuals in each scenario in order to comply with the accepted standard for maximizing pasture growth and quality (Macdonald et al., 2010). However, as we have used the average pasture harvested value from DairyNZ (2019) information for the average of pasture harvested in the Waikato region and no information regarding residual levels was available, we cannot be sure that this same principle was utilized by farmers to achieve this quantity of pasture harvested. Accepting that, it is important that the quantity of pasture harvested accurately represents what is achievable and realistic for this region.

The pasture harvested quantity of 11 t DM /ha /year was the average for the Waikato region for the 2018/2019 season (DairyNZ, 2019). Overall, the season was considered to be an average season for pasture growth, without major unusual climatic constraints to pasture production. This is supported by pasture growth rates (net pasture accumulation as opposed to pasture harvested rates) recorded by DairyNZ between 2009 and 2017 from across the Waikato region ranging from 13.8 t DM /ha /year to 15.4 t DM /ha /year (excluding the outlier of DairyNZ research farm at Newstead of 17.7 t DM /ha /year) (DairyNZ, 2009-2017). All scenarios modelled utilized the same pasture growth rates to ensure consistency across each scenario.

The authors acknowledge that the scenarios modelled will require careful management to optimise production and profitability whilst minimising environmental impacts. As stocking rate is decreased, grazing pressure on pasture reduces which can cause critical pasture quality issues, highlighting the need for precise pasture management. The pasture grazing rules outlined in Macdonald et al. (2010) surrounding management of residuals, rotation speeds and harvesting of surplus pasture as high-quality silage are critical to the success of the system.

Milk production has been capped in the farm systems modelled for two important reasons; firstly, this allows for a fair comparison of the difference in feed requirements and financial outcomes of systems differing in feed quality and quantity. Secondly, despite historical trends for continually striving to increase milk production, it is apparent that milk production is going to be required to stabilize in order to mitigate the environmental impacts of farming systems. As discussed previously, it is pivotal to the global food system that food production is not reduced, however whilst systems and technologies are created to reduce detrimental impacts of food production, it is likely that the trends for continually increasing production will be halted – at least in the short term.

The accuracy of the Overseer model for predicting N losses has been called into question by Johnson et al. (2021). Whilst these reviewers have valid concerns regarding the accuracy of Overseer's prediction of N losses, we are confident that due to the same physical parameters being modelled on each farm, and lack of differing uses of crops or difference in fertiliser applications, the limitations of the model will be equal for each scenario, and therefore maintain the relevance of the current research.

Methane emissions CNCPS

The secondary objective of this investigation was to use CNCPS software to verify the accuracy of the trends in GHG emissions obtained from modelling through Overseer. Given the large contribution of enteric methane production to total GHG emissions in NZ dairy systems, using a separate and internationally respected model helped to corroborate the results from the Overseer model.

CNCPS was also used to predict the methane production in each month of lactation, comparing the control farm with scenario 4 which included 18.5% concentrate inputs in the diet, and scenario 5 which reduced stocking rate by 15% and utilised a pasture and forage only diet.

The significant reductions in methane production for scenario's 4 & 5 compared with the control farm align with the trends observed in the Overseer modelling. The modelling of the systems through CNCPS also confirms the feasibility of the systems which were originally modelled through Udder.

Scenario 4 resulted in the lowest methane emissions of the three scenarios modelled (Table 9a, 9b and 9c). This scenario had the lowest stocking rate whilst producing the same amount of milk as the control, and 12.3% more milk than scenario 5 (Table 3 & Table 4). Reducing stocking rate, increasing cow size and genetic merit, and including concentrate in the diet resulted in an increase in milk production per cow (Table 4). This causes an effect of dilution of maintenance (Hristov et al., 2013) and increased the efficiency of methane production per kg FCM produced. Boadi et al. (2004) also reported that by increasing feeding levels, methane losses as a % of gross energy intake will reduce. The level of methane produced per kg of milk is at its lowest (14.48g /kg FCM) when cows are at peak milk production, consuming a diet of pasture and concentrates, without supplementary forages (Table 9b). Reducing the quantity of feed being consumed is a widely accepted mechanism for reducing methane production (O'Neill et al., 2011).

In all three scenarios modelled, there was substantial seasonal variation in methane production (Table 9a, 9b, and 9c). It is likely that both cow physiological factors (stage of lactation, gestation) and seasonal feed quality factors impact fluctuations in seasonal methane production. Methane production per kg FCM was lowest when per cow production was highest, and pasture quality at its peak. As lactation progresses and pasture quality declines through the warmer, drier parts of the season, milk production reduces and there is an increase in methane production (Table 9a, 9b, and 9c). This is in accordance with Robertson and Waghorn (2002) who also reported that as pasture matured throughout the season, methane production increased in a pasture based system, despite having similar DMI from spring to summer.

When CNCPS incorporated equations into their model to predict GHG emissions, Van Amburgh et al. (2015) reported that in 1,252 studies, there was a non-significant difference in the observed compared to the predicted GHG emissions from the model. The CNCPS modelling system has previously been validated as an accurate tool for the prediction of productive and environmental outcomes for New Zealand pasture based dairy systems (Higgs et al., 2013; Kolver et al., 1998).

Results have not been presented in this paper, but given the substantially lower SR of scenario 4 than scenario 5 and control, it is likely that scenario 4 will also result in considerably lower methane emissions through the dry period during winter.

Animal Welfare

The Udder models show that the average BCS of control and scenario 5 are consistently below those of scenarios 2 to 4 (Appendix, figure 8). Whilst CS is by no means the only indicator of animal welfare, it is an important one. The inclusion of concentrates in a pasture-based diet allows for energy and protein supplementation at times when pasture supply may be low and/or of lower quality (e.g. dry summer conditions), thereby maintaining cow CS and production levels. The farms with forage-only systems are more limited in their options and more often will face the dilemma of either to continue milking and sacrifice cow condition and possibly impacting animal welfare, or to dry off and sacrifice economic performance.

Conclusions

The modelling undertaken shows that a multi-faceted approach to tackling environmental problems on dairy farms will yield the most beneficial outcomes with substantial reductions in GHG emissions and nitrogen losses whilst improving profitability and land use efficiency in New Zealand.

Progressive improvements in environmental parameters can be achieved with the incorporation of concentrates into the farm system in conjunction with reducing the stocking rate and land area employed, as well as increasing size and genetic merit of cows to optimise intake and production on a per cow basis. This resulted in lower total feed requirements for similar milk production, resulting in reduced GHG emissions and N losses. Utilising concentrates in the diet enabled high DMI and high milk production per cow, which dilutes maintenance requirements and increases the efficiency of methane production per unit of milk produced. Animal welfare may be improved compared to systems relying on forages only.

Carefully designed and executed PFC systems improved economic performance over a wide range of pay-outs and concentrate prices and increased the productive efficiency of land and animals without reducing farm production. Designing these PFC systems requires a whole-system approach, analysing various levels of concentrate feed inputs, stocking rates, cow liveweight, cow genetic merit and land use, in order to achieve the most efficient milk production whilst maintaining or improving profitability on farm.

These scenarios are not intended to be interpreted as ‘recipes’; rather they mean to show the consistent logic of increasing efficiency on a per cow and per hectare basis leading to better environmental and financial outcomes.

This study has highlighted that there are further factors that must be taken into consideration when assessing the opportunity to reduce the GHG footprint of a dairy farm system:

- The use of a fixed standard rate of methane production per kg of milk solids for a dairy cow cannot be used as an industry standard for accurately calculating total methane emissions from a herd.
- The exclusive use of GHG emissions per hectare is not a good measurement for comparison between systems. Other metrics that should be included are GHG emission per unit of milk and particularly total farm system GHG emissions. GHG emissions should be calculated on an individual farm basis as each farm will differ in their emissions according to their farming practices.

Due to ever improving technology and farmer engagement in strategies to optimise production, increases in GHG emissions have been less sharp in the last 3 decades than had been predicted (Clark & Journeaux, 2021). This research group supports the adoption of progressive, scientifically based strategies to optimise farm scenarios which simultaneously reduce GHG emissions. Reducing overall productivity of farms is counterproductive as the efficiency of GHG emissions remains virtually stable. If given a clear set of parameters and freedom to optimise their systems, farmers will continue to be innovative and to strive for excellence, supported by world class research.

Future Research

With respect to the reduction of enteric methane production, this research solely focused on farm systems approaches, however, there is the potential to further reduce enteric methane production using feed sources such as fat supplements (Hristov et al., 2013), bypass proteins and readily fermentable carbohydrates. However, this was out of the scope of the current research and warrants further research. Furthermore, Russomano et al. (2012) investigated the environmental advantages of the dairy industry utilising by-products from other industries such as the fuel industry as feed sources for livestock, rather than these by-products being disposed of in landfill or burnt. This concept is also discussed by Van Amburgh et al. (2019). Whilst this was not accounted for in the current research, the environmental efficiency gained in this practice should be investigated further in order to accurately measure the environmental footprint of livestock feeds, to allow nutritionists and farmers to utilise feeds with the lowest environmental impact.

References

Beauchemin, K., Kreuzer, M., O'mara, F., & McAllister, T. (2008). Nutritional management for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture*, *48*(2), 21-27.

Boadi, D., Benchaar, C., Chiquette, J., & Massé, D. (2004). Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Canadian Journal of Animal Science*, *84*(3), 319-335.

Chapman, D. F., Dalley, D. E., Edwards, G. R., Cameron, K. C., Malcolm, B. J., Clement, A., Romera, A. J., Pinxterhuis, I. B., Beukes, P. C., & Di, H. J. (2021). Production, profit and nitrogen flows in irrigated dairy systems representing different industry development pathways: The Pastoral 21 experience in Canterbury. *New Zealand Journal of Agricultural Research*, *64*(1), 3-35.

Clark, D. A., Macdonald, K. A., Glassey, C. B., Roach, C. G., Woodward, S. L., Griffiths, W. M., Neal, M. B., & Shepherd, M. A. (2020). Production and profit of current and future dairy systems using differing nitrogen leaching mitigation methods: the Pastoral 21 experience in Waikato. *New Zealand Journal of Agricultural Research*, *63*(4), 505-528.

Clark, H., & Journeaux, P. (2021). *Greenhouse gas emissions on New Zealand farms*.

DairyNZ. (2009-2017). *Average pasture growth data (kg DM/ha/day)* https://www.dairynz.co.nz/feed/pasture/growing-pasture/pasture-growth-data/

DairyNZ. (2019). *DairyNZ Economic Survey 2018-19*. https://d1r5hvvxe7dolz.cloudfront.net/media/documents/2018-19_New_Zealand_Dairy_Statistics.pdf

Higgs, R., Sheahan, A., Mandok, K., Van Amburgh, M., & Roche, J. (2013). The effect of starch-, fiber-, or sugar-based supplements on nitrogen utilization in grazing dairy cows. *Journal of dairy science*, *96*(6), 3857-3866.

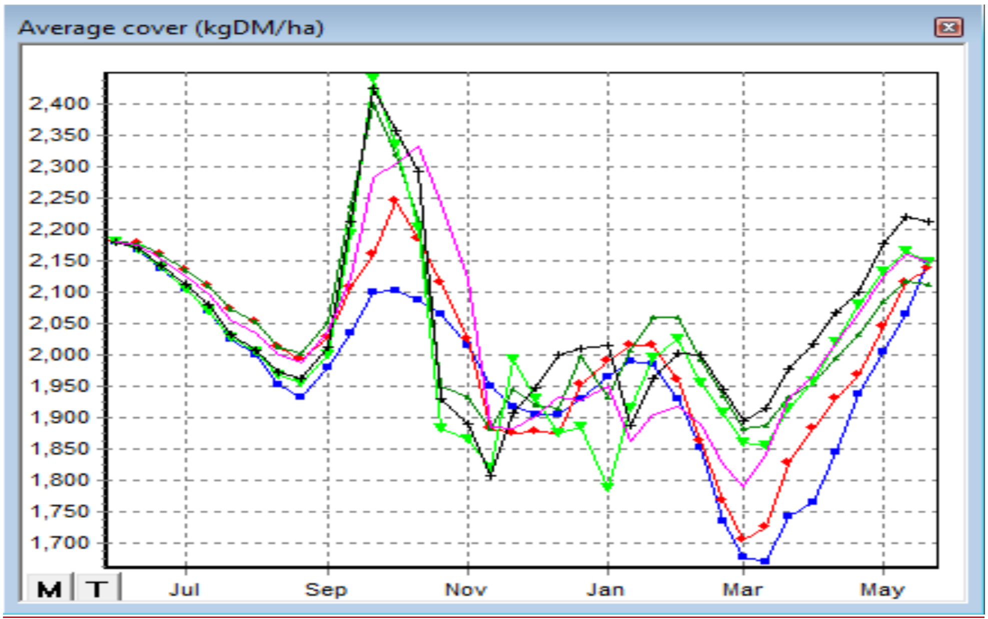
Hristov, A., Oh, J., Firkins, J., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H., Adesogan, A., Yang, W., & Lee, C. (2013). Special topics—Mitigation of methane and nitrous oxide emissions from

animal operations: I. A review of enteric methane mitigation options. *Journal of animal science*, *91*(11), 5045-5069.
Johnson, I., Clark, D., Clothier, B., Giltrap, D., Rissman, C., Roskruge, N., Thorburn, P., & White, R. (2021). *Overseer whole-model review. Assessment of the model approach*.
Knapp, J. R., Laur, G., Vadas, P. A., Weiss, W. P., & Tricarico, J. M. (2014). Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *Journal of dairy science*, *97*(6), 3231-3261.
Kolver, E., Muller, L., Barry, M., & Penno, J. (1998). Evaluation and application of the Cornell Net Carbohydrate and Protein System for dairy cows fed diets based on pasture. *Journal of dairy science*, *81*(7), 2029-2039.
Kolver, E., Roche, J., Burke, C., & Aspin, P. (2005). Influence of dairy cow genotype on milksolids, body condition and reproduction response to concentrate supplementation. Conference of the New Zealand Society of Animal Production,
Ledgard, S., Falconer, S., Abercrombie, R., Philip, G., & Hill, J. (2020). Temporal, spatial, and management variability in the carbon footprint of New Zealand milk. *Journal of dairy science*, *103*(1), 1031-1046.
Macdonald, K., Beca, D., Penno, J., Lancaster, J., & Roche, J. (2011). Effect of stocking rate on the economics of pasture-based dairy farms. *Journal of dairy science*, *94*(5), 2581-2586.
Macdonald, K., Glassey, C., & Rawnsley, R. (2010). The emergence, development and effectiveness of decision rules for pasture based dairy systems. Australasian Dairy Science Symposium: Meeting the Challenges for Pasture-Based Dairying,
Neal, M., & Roche, J. R. (2019). Profitable and resilient pasture-based dairy farm businesses in New Zealand. *Animal Production Science*, *60*(1), 169-174.
O'Neill, B., Deighton, M., O'loughlin, B., Mulligan, F., Boland, T., O'donovan, M., & Lewis, E. (2011). Effects of a perennial ryegrass diet or total mixed ration diet offered to spring-calving Holstein-Friesian dairy cows on methane emissions, dry matter intake, and milk production. *Journal of dairy science*, *94*(4), 1941-1951.
Robertson, L., & Waghorn, G. (2002). Dairy industry perspectives o methane emissions and production from cattle fed pasture or total mixed rations in New Zealand. Proceedings-new zealand society of animal production,
Russomano, K., Van Amburgh, M., & Higgs, R. (2012). Utilization of byproducts from human food production as feedstuffs for dairy cattle and relationship to greenhouse gas emissions and environmental efficiency.
Tabellenboek Veevoeding (2016). Wageningen Livestock Research.
Van Amburgh, M., Collao-Saenz, E., Higgs, R., Ross, D., Recktenwald, E., Raffrenato, E., Chase, L., Overton, T., Mills, J., & Foskolos, A. (2015). The Cornell Net Carbohydrate and Protein System: Updates to the model and evaluation of version 6.5. *Journal of dairy science*, *98*(9), 6361-6380.
Van Amburgh, M., Russomanno, K., Higgs, R., & Chase, L. (2019). Invited Review: Modifications to the Cornell Net Carbohydrate and Protein System related to environmental issues—Capability to evaluate nitrogen and phosphorus excretion and enteric carbon dioxide and methane emissions at the animal level. *Applied Animal Science*, *35*(1), 101-113.
Wheeler, D., Ledgard, S., & DeKlein, C. (2008). Using the OVERSEER nutrient budget model to estimate on-farm greenhouse gas emissions. *Australian Journal of Experimental Agriculture*, *48*(2), 99-103.
Wheeler, D., Ledgard, S., Monaghan, R., McDowell, R., & De Klein, C. (2006). OVERSEER nutrient budget model–what it is, what it does. *Implementing sustainable nutrient management strategies in agriculture*, 231-236.

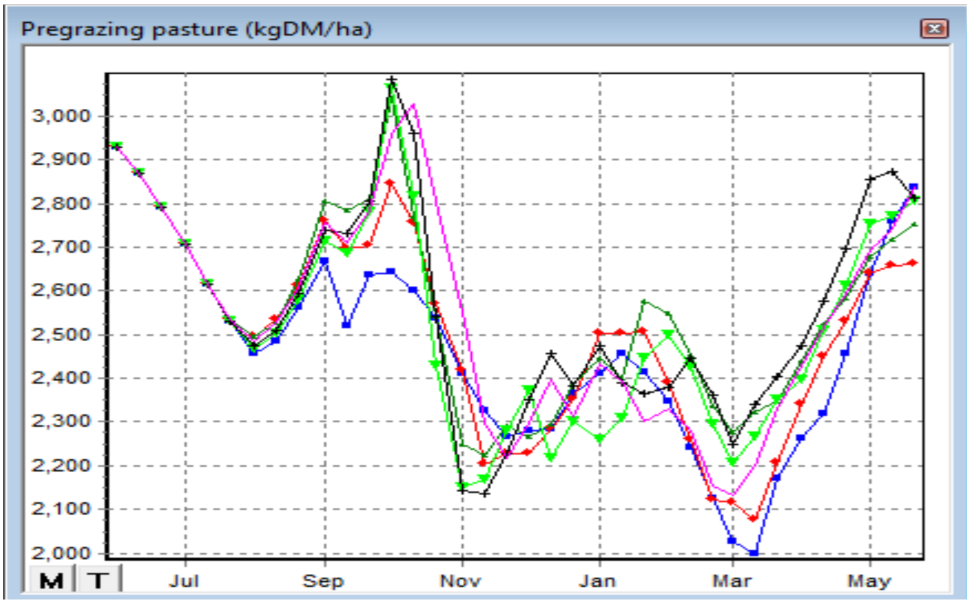
Appendices

Udder simulation graphs.

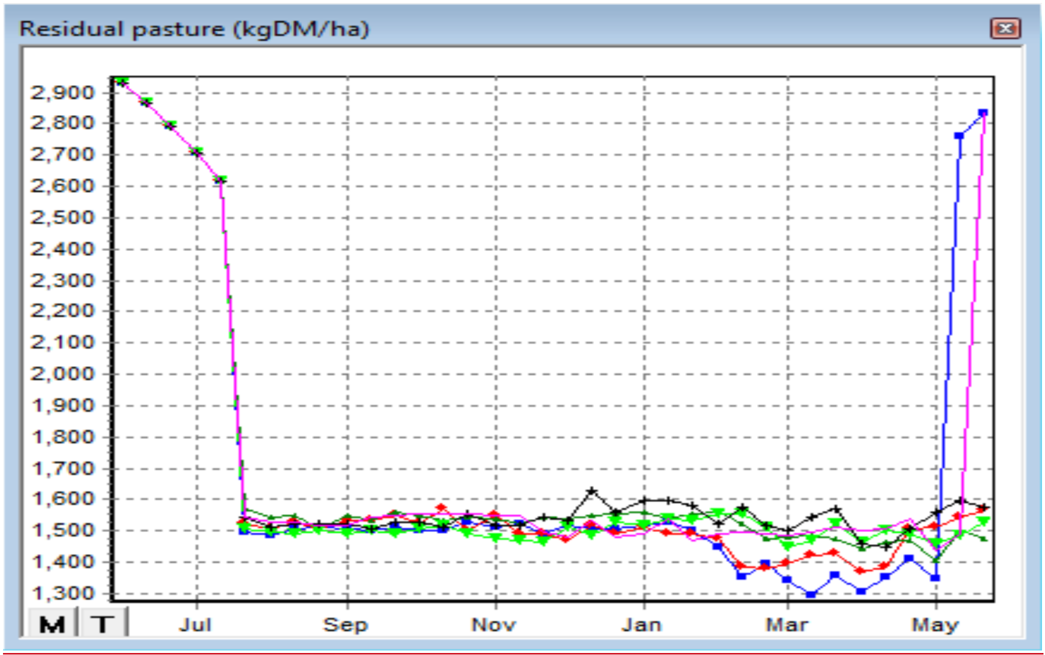
Appendix 1. Average Pasture Covers



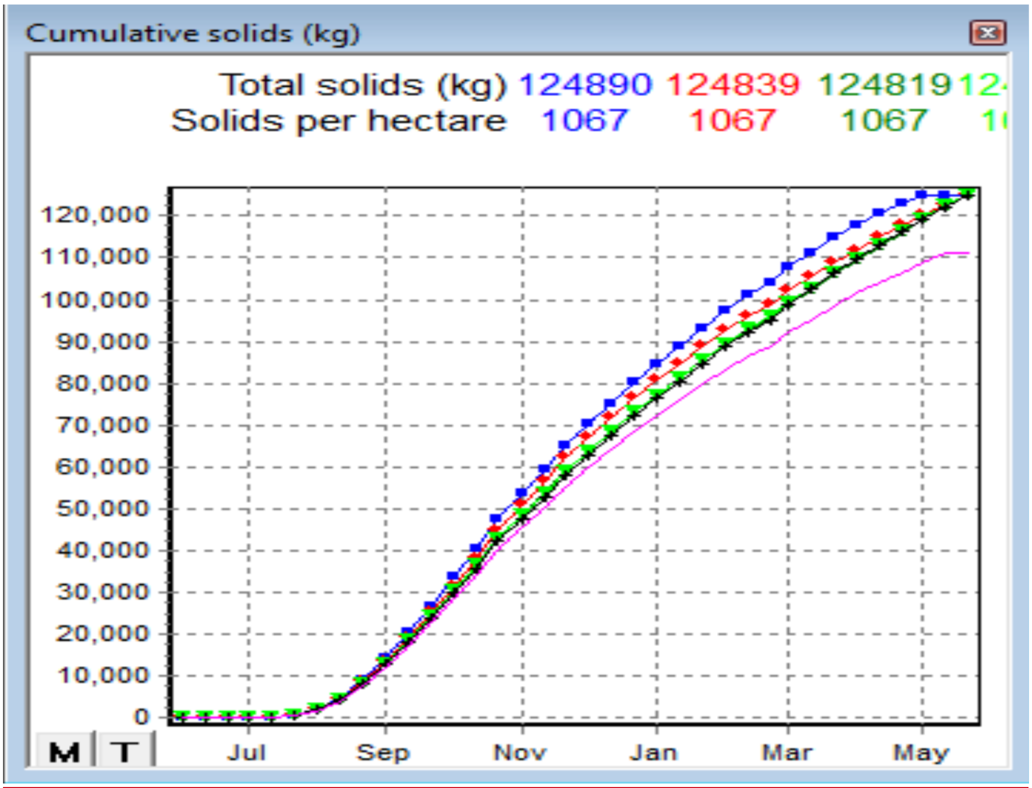
Appendix 2. Pre-grazing pasture covers (kg DM /ha)



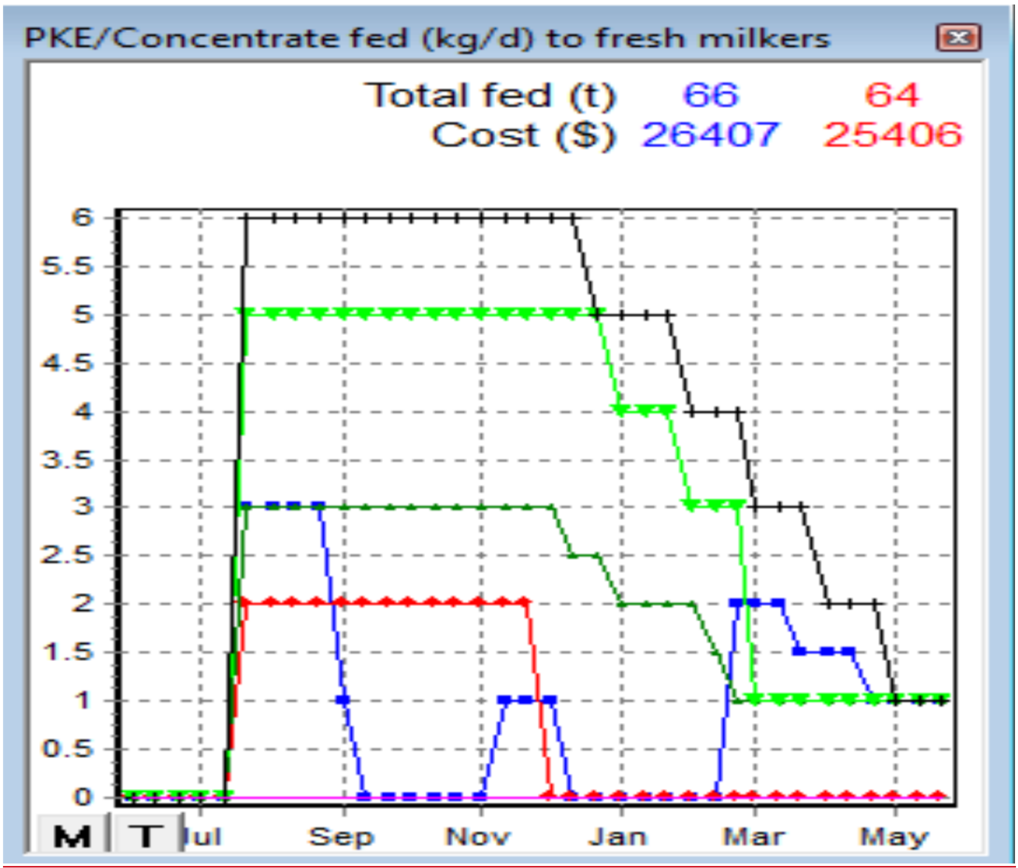
Appendix 3. Pasture residuals (kg DM/ha)



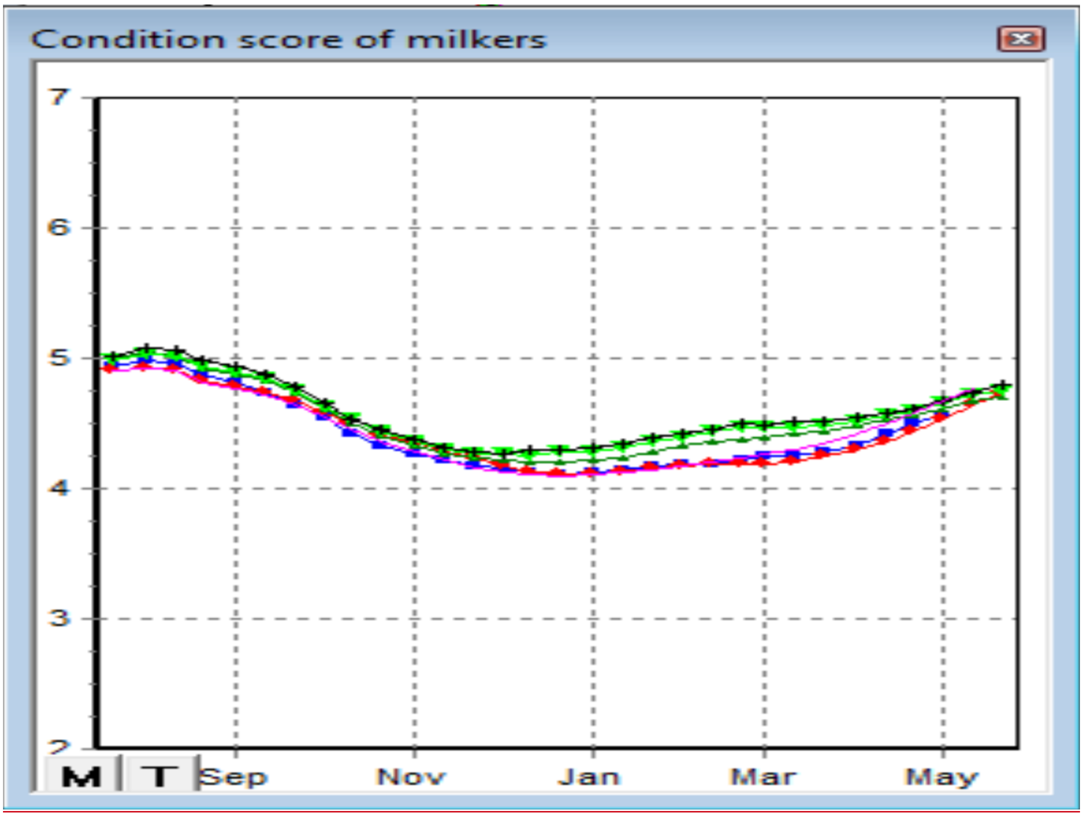
Appendix 4 . Cumulative farm milk production.



Appendix 5. Concentrate feeding levels.

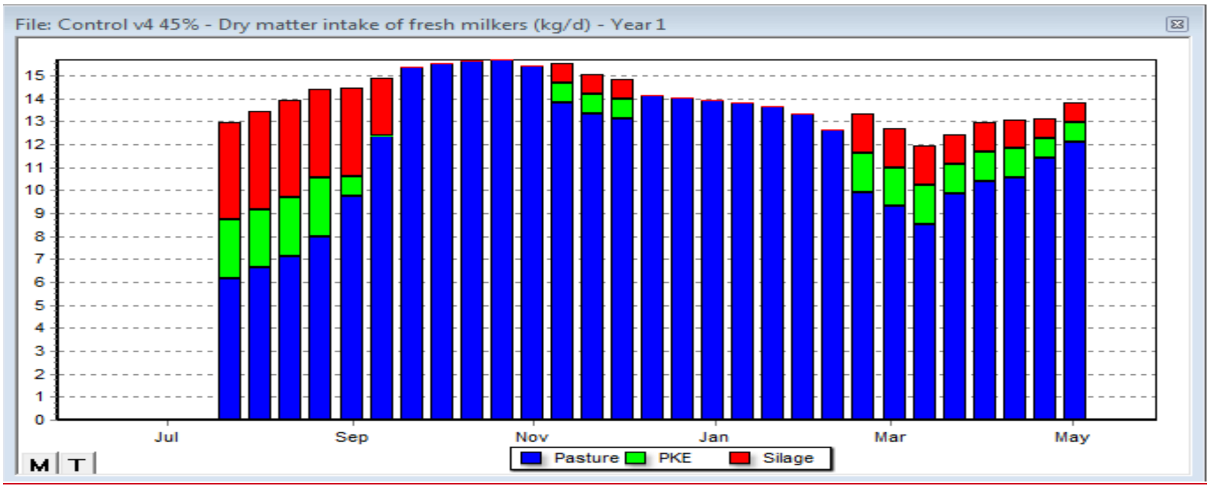


Appendix 6. Condition score of cows

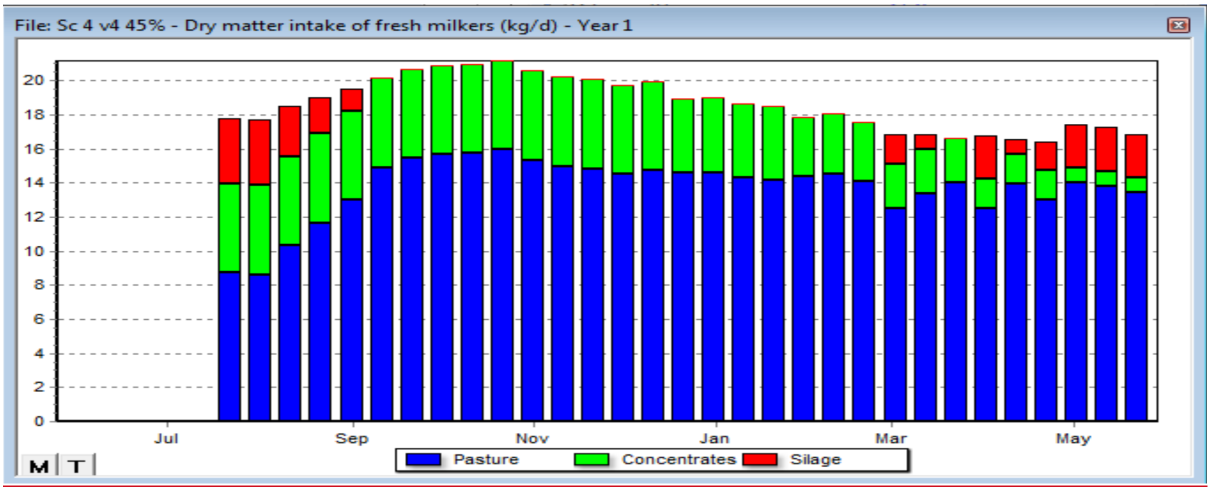


For Udder graphs above, blue represents Waikato Av. 18-19; red Sc1; dark green Sc 2; light green Sc 3; black Sc 4 and purple Sc 5.

Appendix 7. Diets through time, Waikato average 18-19



Appendix 8. Diets through time, Scenario 4.



Appendix 9. Imported supplement embodied emissions. Source: Overseer (Version 6.3.0)

3.3. Supplements imported

Embodied emissions of imported supplements include emissions for growing the supplement, and emissions associated with manufacturing and transport the supplement to a central depot. Emissions associated with fuel use for transport from the primary depot to the farm and feeding out are estimated separately (section 3.2.5.5 and 3.2.5.2 respectively).

A farmer generally knows the amount of supplement purchased, and possibly the location of the primary depot, but not necessarily the conditions under which a supplement is produced. For example, embodied emissions from palm kernel depend on whether deforestation occurred for growing the palm kernel. If it does, then under PAS 2050 guidelines (BIS 2008), the

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OVERSEER® Nutrient Budgets Technical Manual for the Engine (Version 6.3.0) 31
Carbon dioxide, embodied and other gaseous emissions June 2018