New Zealand Society of Animal Production online archive

This paper is from the New Zealand Society for Animal Production online archive. NZSAP holds a regular annual conference in June or July each year for the presentation of technical and applied topics in animal production. NZSAP plays an important role as a forum fostering research in all areas of animal production including production systems, nutrition, meat science, animal welfare, wool science, animal breeding and genetics.

An invitation is extended to all those involved in the field of animal production to apply for membership of the New Zealand Society of Animal Production at our website www.nzsap.org.nz

View All Proceedings | Next Conference | Join NZSAP

The New Zealand Society of Animal Production in publishing the conference proceedings is engaged in disseminating information, not rendering professional advice or services. The views expressed herein do not necessarily represent the views of the New Zealand Society of Animal Production and the New Zealand Society of Animal Production expressly disclaims any form of liability with respect to anything done or omitted to be done in reliance upon the contents of these proceedings.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.

You are free to:

Share— copy and redistribute the material in any medium or format

Under the following terms:

Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

NonCommercial — You may not use the material for commercial purposes.

NoDerivatives — If you remix, transform, or build upon the material, you may not distribute the modified material.

http://creativecommons.org.nz/licences/licences-explained/

Effect of grazing system on nitrogen partitioning in lactating dairy cows grazing irrigated pastures in Canterbury, New Zealand

AR Clement [a]*, DE Dalley [a], DF Chapman [a], GR Edwards [b] and RH Bryant [b]

[a]*DairyNZ, Canterbury Agriculture and Science Centre, Gerald Street, PO Box 85066, Lincoln University7647, Canterbury, New Zealand;* [b]*Faculty of Agriculture and Life Sciences, Lincoln University, PO Box 85084, New Zealand*

**Corresponding author.* Email: anna.clement@dairynz.co.nz

Abstract

Regulations currently being developed by Regional Councils throughout New Zealand to manage freshwater quality may require substantial reductions in nitrate leaching from dairy farms in many regions. The objective of this study was to quantify nitrogen intake, partitioning, and excretion in two irrigated farming systems in Canterbury, comparing different possible pathways for future industry development. A 'higher input' system (HI, n = 34 cows) was characterised by a stocking rate of 5 cows per/ha, ~300 kg/ha/year fertiliser N and ~1t DM/cow/year purchased supplement fed on the milking platform. The 'lower input' system (LI, n = 29 cows) used a stocking rate of 3.5 cows/ha, 150 kg/ha/year fertiliser N, and minimal purchased supplement. Urine, faeces, plasma, and milk samples were collected for N determination at consecutive afternoon and morning milkings once per month for four years. Estimated N intake did not differ between HI and LI (537 g N/cow/day and 557 g N/cow/day respectively, P = 0.29). No differences were recorded for N parameters and estimated milk and urine N output/cow was not affected by farm system. When scaled to per hectare, urinary N excretion was 33% greater for HI compared with LI (1.1 kg/ha/day and 0.8 kg/ha/day, respectively, P = 0.02).

Keywords: nitrogen partitioning; pasture; dairy cows; grazing

Introduction

Urinary nitrogen (UN) excreted by grazing livestock is a significant source of environmental pollutants from the New Zealand dairy industry because nitrate (NO_3^-) derived from UN contributes to ground and surface water contamination (Di & Cameron 2002). High-quality temperate forages, such as perennial ryegrass and white clover pastures, typically have metabolisable energy (ME) concentrations greater than 11.5 MJ/kg DM and crude protein contents between 20% and 30% of DM (Waghorn et al. 2007). This high-protein diet provides an excess of nitrogen (N) relative to animal requirements, and excretion of excess N increases the risk of environmental pollution.

Only 10 to 40% of the N ingested by dairy cows is converted to animal product (Haynes & Williams 1993). Previous studies have suggested that about 50% of the total N eaten is excreted in the urine and around 25% in the dung (Pacheco & Waghorn 2008). The amount of N deposited in urine patches (average 613 kg N/ha for dairy cattle (Selbie et al. 2015)) is much greater than the capacity of pasture plants to assimilate, therefore, the N is eventually lost from the system via ammonia volatilisation, nitrate leaching and denitrification.

Urinary nitrogen output is strongly correlated with N intake, with several studies (Kebreab et al. 2001; Huhtanen & Hristov 2009) reporting reduced UN excretion when the protein content of the diet is reduced. Kebreab et al. (2001) recommended several diet adjustments to reduce UN excretion e.g., grass grown with moderate fertiliser application and maize-based energy supplements formulated to provide slowly degradable protein.

The objective of this paper is to quantify N intake, partitioning, and excretion of cows grazing two contrasting pasture-based dairy systems. The systems were designed to demonstrate the effect of management, particularly differences in levels of feed and nitrogen fertiliser input, on production, profit, and N leaching. Results are discussed in relation to the N mass balance of contrasting dairy systems and possible implications for the ability of farmers to meet environmental targets.

Materials and methods

Experimental design

Two systems were compared, both with a strong focus on management efficiency: one based on the 'traditional' pathway of intensification, through increasing inputs of feed and fertiliser (HI), and one based on reducing those inputs to lower the amount of N imported to the farm (LI). The LI pathway results in less feed available and requires that feed supply and demand be re-balanced to maintain a sustainable system with high rates of pasture utilisation. In the LI system reported here, a reduction in stocking rate was required to achieve this, and tactical management decisions targeted greater per-cow production, through increased pasture intake/cow, to off-set some of the expected reduction in milk solids per hectare. The LI system also incorporated diverse pastures as an additional N mitigation option. Details of the two management systems are shown in Table 1. Both systems were irrigated, as required, from late spring to mid-autumn using a lateral sprinkler irrigator.

Fifty-one Holstein-Friesian cows and 12 heifers were allocated to two farmlets in October 2011. The number of animals in each farmlet was 29 and 34 for the lower input (LI) and higher input (HI) farmlets, respectively (Table 1). All cows calved in spring with planned start of calving

Table 1 Key management features of Higher Input (HI; n = 34 cows) and Lower Input (LI; n = 29 cows) farmlet systems in Canterbury, comprising lactating Holstein-Friesian dairy cows grazing irrigated perennial pasture, from October 2011 to May 2015

	HI	LI
Stocking rate	5.0 cows/ha	3.5 cows/ha
Cow genetic merit	Breeding Worth 133	Breeding Worth 140
N fertiliser use	Up to 400 kg N/ha/year	Up to 150 kg N/ha/year
Supplement use	Up to 800 kg/cow/year grain	Up to 100 kg/cow/year grain
Pasture base	10 paddocks diploid ryegrass / white clover; 8 paddocks tetraploid ryegrass / white clover	8 paddocks diploid ryegrass / white clover; 8 paddocks tetraploid ryegrass / white clover; 6 paddocks diverse pasture mix, including chicory, plantain, red clover and prairie grass.

30 July each year. All procedures were approved by the Lincoln University Animal Ethics Committee (AEC 419, AEC 473, AEC 523).

Fifteen hectares of pasture were subdivided into two farmlets of 6.75 (HI) and 8.25 ha (LI), respectively. Pastures were in several non-contiguous blocks; areas within each block were allocated to the two treatments to achieve balanced topography, soil fertility and distance from the farm dairy. Approximately twice the amount of fertiliser N was applied to the HI pasture (mean 304 kg N/ha over the four years of the study) compared with LI (156 kg N/ha). Pastures in the HI farmlet were predominantly perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*); whereas, in the LI farmlet, 27% of the area comprised diverse pastures containing perennial ryegrass (*Lolium perenne*), white clover (*Trifolium repens*), chicory (*Cichorus intybus*), plantain (*Plantago lanceolata*), red clover (*Trifolium pratense*) and prairie grass (*Bromus willdenowii*). The remaining 73% of the LI farmlet was perennial ryegrass-white clover pasture.

Pasture measurements

Pasture mass in each paddock was assessed weekly from calving to drying-off, using the rising-plate meter (RPM, Jenquip, Fielding, New Zealand). The RPM measurements were calibrated weekly against 12-16, 0.26 m^2 quadrats, cut to ground level, washed and dried at 65ºC for 48 hours. A four-week rolling calibration curve was used to predict weekly farm pasture mass and growth. Pre- and post- grazing mass was measured with the RPM on a selection of paddocks. Pasture DM intake was estimated by difference between pre- and post-grazing pasture mass (Bryant et al. 2014):

Equation 1 Pasture intake (kgDM/cow/day) = (pre mass (kgDM/ha) – post mass (kgDM/ha)) x area of paddock (ha)/ (No. of animals * No. of days the paddock was grazed).

Every fortnight, pre-grazing pasture samples were collected to grazing height, from four paddocks in each farmlet to estimate DM%, and botanical and chemical composition. A 20 g subsample was separated into ryegrass, white clover, red clover, prairie grass, herbs and weed species components, dried at 65°C for 48 h, and the dry weight of each component recorded. Whole sample DM% was determined by adding the DM% of the respective components. A second sample of approximately 100 g was dried at 65°C for 48 h and ground to 1 mm for analysis of nutritive components using near-infrared spectrophotometry (Foss NIRSystems 5000: FOSS NIRSystems Inc., Laurel, MD (Corson et al. 1999)). Pasture N (%) was calculated by dividing the crude protein by 6.25.

Animal measurements

Cows were milked at approximately 0630 h and 1500 h. Individual cow milk yields were automatically recorded at each milking (DeLavalAlpro Herd Management System, DeLaval, Tumba, Sweden). Milk composition (fat and protein) was analysed on individual p.m. and a.m. samples at fortnightly intervals, throughout lactation (Livestock Improvement Corporation Ltd., Christchurch, New Zealand) using a Milkoscan milk analyzer (Foss Electric, Hillerød, Denmark). Once per month, coinciding with blood, urine and faecal sampling, a subsample was collected for milk urea determination. Subsamples were centrifuged at 4000 x *g* for 10 min at room temperature and refrigerated for 10 min to allow the fat to solidify on the top and be removed. Skim milk was then pipetted into a microcentrifuge tube and frozen at -20°C until analysed. Live weight (LW) was measured twice daily immediately following milking on an automatic walk-over weighing system (DeLaval AWS100).

Immediately after the afternoon and morning milkings, once per month between August and May, urine, faeces and blood samples were collected from individual cows. Urine samples were taken midstream after manual stimulation of the vulva, acidified below pH 4 with concentrated sulphuric acid to prevent volatilisation, and then frozen at -20°C until analysed. Faeces samples were collected by rectal stimulation or as the animal defecated and frozen at -20°C until analysis. Blood samples were collected from the coccygeal vein or artery using 10 ml of EDTA Vacuette tubes (Greiner Bio-one, Kremsmunster, Austria). Blood samples were placed on ice, and then centrifuged at 3000 x g at 4°C for 15 min, and the separated plasma stored on ice at -20°C until analysis.

Urine, faeces, plasma and milk urea N analyses were

performed by Lincoln University Analytical Services (Lincoln University, Christchurch, New Zealand). One subsample of thawed faeces was dried at 100°C for 48 h for DM determination and the second was freeze dried, and ground to 1 mm. Urine and freeze-dried faeces were analysed for N concentration using a Variomax CN Analyser (Elementar Analysensysteme GmbH, Hanau, Germany). Blood urea N, milk urea, urine urea, NH_3 and creatinine were quantified using a kinetic UV and colorimetric assay (RX Daytona Randox, Antrim, Northern Ireland). Milk urea N was calculated by multiplying molar milk urea by 2.

For each urine sampling event, total nitrogen intake was calculated by multiplying the average N content (%) of the pasture by the estimated average weekly pasture intake (kg) for the week that coincided with urine sampling. If supplement was fed that week it was added to the equation. Milk N secretion (g/day) was calculated using individual cow data by dividing the milk protein content (%) by 6.38 to give N (%), which was then multiplied by the seven-day average milk yield (kg/d), for the week. Urinary nitrogen excretion was estimated using Equation 2 (Pacheco et al. (2007):

Equation 2 UN (g of N/d) = 21.9 (mg/kg) x LW (kg) x (1/ urinary creatinine (mg/kg)) x urine N (g/kg)

Statistical Analysis

The consistency of farmlet differences over the duration of the trial was tested using GenStat 16.2 (Payne 2011). Farmlet means for all reported variables were calculated for each month of each year and, when measurements were made p.m. and a.m., for each of these sample times. These farmlet monthly means for each year were then analysed as mixed models including month, farmlet and the interaction of month and farmlet as fixed effects and year, farmlet within year, and month within farmlet within year, as random effects. When p.m. and a.m. samples were taken for a variable, sampling time (a.m. vs p.m.) was also included in the model as a fixed effect. Urinary nitrogen excretion per-ha was calculated by multiplying the UN excretion per-cow by the appropriate stocking rate for each farmlet and the standard error of the farmlet difference per ha calculated from the standard error of the difference per-cow from the mixed-model analysis. A t-test was then used to test the significance of the differences per ha.

Results

Cows in the HI system consumed significantly less pasture per cow per day than LI ($P < 0.01$, Table 2). HI cows consumed, on average, 523 kg DM/cow barley grain (N content 1.8%) each season, compared with 64 kg DM/cow for LI. Pasture N% was greater ($P = 0.02$) in the HI system, by 0.1% of total DM. The LI system produced more milk solids (fat + protein) per cow, but due to the difference in stocking rate they produced significantly less than HI per hectare (Table 2).

There were no differences in plasma, milk, urine or faecal N variables between farm systems (Table 3). Urea concentration in the plasma, milk, and blood tended to be greater from December onwards compared with the first half of the lactation. Diurnal differences were observed in cows from both systems, with a greater concentration of urea N in plasma and milk measured in the afternoon. Conversely, urea concentration in the urine was elevated in the morning.

Estimated daily N intakes did not differ between systems, averaging 537 g N/cow/day for HI and 557 g N/cow/day for LI (Table 4), and there was no effect of system on estimated UN excretion. Milk N secretion was significantly greater in LI ($P = 0.02$). UN excretion constituted 42 and 43% of the total N eaten for LI and HI, respectively. The UN excreted as a percentage of total N intake tended to be greater for the months of December through to May (average 47%) compared with August to November (average 36%).

When scaled from per cow to per hectare, N intakes were significantly greater on the HI farmlet than LI (2.7 kg/ha/day and 2.0 kg/ha/day respectively, $P < 0.01$). Likewise, UN excretion was markedly greater in the HI system, at 1.1 kg/ha/day compared with 0.8 kg/ha/day for LI ($P = 0.02$).

Table 2 Key physical performance of Higher Input (HI; 5 cows/ha, 400 kg N/ha/year, 800 kg/cow/year grain) and Lower Input (LI; 3.5 cows/ha, 150 kg N/ha/year, 100 kg/cow/year grain) irrigated dairy systems in Canterbury, averaged over four seasons from October 2011 to May 2015. Milking platform data only, wintering off excluded. N leaching estimates were modelled in OVERSEER® Version 6.2

	HI	LI	SED	P value
Pasture grown (t DM/ha)	18.0	16.5	582	0.08
Daily pasture intake (kg DM/cow)	12.4	15.1	0.6	<0.01
Grain fed (kg DM/cow)	523	64	170	0.07
Total supplement fed (kg DM/cow)	940	325	220	0.07
N fertiliser applied (kg/ha)	304	156	-	-
Pasture N%	3.6	3.5	0.1	0.02
MS/cow (kg)	449	486	7	0.01
MS/ha (kg/ha)	2242	1700	60	<0.01
N leaching OVERSEER® (kg/ha)	48	33	-	-

Table 3 Average monthly nitrogen parameters (October 2011-May 2015) pertaining to partitioning in plasma, milk, urine, and faeces, of lactating cows managed in Higher Input (HI; 5 cows/ha, 400 kg N/ha/year, 800 kg/cow/year grain) and Lower Input (LI; 3.5 cows/ha, 150 kg N/ha/year, 100 kg/cow/year grain) irrigated dairy systems, in Canterbury. Mean p.m./a.m. results with farmlets combined are included to display diurnal variation

	Plasma urea (mmol/L)		Milk urea N (mmol/L)		Urine urea (mmol/L)		Urine N%		Faeces N%	
	HI	LI	HI	LI	HI	LI	HI	LI	HI	LI
Aug	8.4	8.4	6.5	6.5	88.0	97.1	0.39	0.42	3.15	3.40
Sep	8.7	8.4	6.8	6.9	97.3	93.0	0.43	0.44	3.62	3.69
Oct	9.2	9.7	7.0	7.5	109.7	131.8	0.48	0.55	3.82	3.69
Nov	7.7	6.4	5.6	4.5	88.7	77.8	0.45	0.44	3.27	3.30
Dec	12.5	10.9	9.5	8.5	146.2	141.3	0.58	0.57	3.45	3.33
Jan	11.5	9.5	9.5	8.2	135.1	128.7	0.54	0.54	3.19	3.20
Feb	13.3	12.5	10.7	10.3	141.5	157.3	0.53	0.60	3.25	3.32
Mar	11.5	15.9	9.2	12.6	120.1	157.9	0.46	0.56	3.39	3.22
Apr	12.8	12.4	10.4	10.4	134.3	126.6	0.49	0.47	3.44	3.47
May	13.9	14.9	9.3	12.1	101.2	110.2	0.37	0.40	2.93	3.08
Farmlet mean	10.9	10.9	8.5	8.7	116.2	122.2	0.47	0.50	3.35	3.37
Farmlet SED	0.8		0.6		6.3		0.02		0.03	
Farmlet P Value	1.0		0.8		0.3		0.18		0.74	
p.m.	11.49		8.98		99.9		0.42		3.34	
a.m.	10.35		8.21		138.4		0.55		3.38	
p.m./a.m. SED	0.25		0.25		4.2		0.01		0.02	
P Value p.m./a.m.	<0.01		<0.01		<0.01		<0.01		0.12	

Table 4 Daily estimated per-cow nitrogen (N) intake, excretion, and partitioning, calculated for one week each month (averaged across four years from October 2011-May 2015), coinciding with urine, faecal, and plasma N measurements of Higher Input (HI; 5 cows/ha, 400 kg N/ha/year, 800 kg/cow/year grain) and Lower Input (LI; 3.5 cows/ha, 150 kg N/ha/year, 100 kg/cow/year grain) irrigated dairy systems in Canterbury

	Total N intake (g/day)		Milk N secretion (g/day)		Urine N excretion (g/day)		Milk N secretion (% of N intake)		Urine N excretion (% of N intake)	
	HI	LI	HI	LI	HI	LI	HI	LI	HI	LI
Aug	403	447	139	146	159	156	33	32	39	36
Sep	500	520	128	144	174	184	26	29	37	38
Oct	640	631	140	149	208	211	22	24	34	35
Nov	481	502	137	139	174	151	30	29	38	32
Dec	557	574	133	137	263	232	25	24	49	42
Jan	469	494	125	130	254	220	27	26	54	45
Feb	668	646	115	124	277	264	18	20	43	42
Mar	565	688	113	113	244	340	20	17	43	51
Apr	601	619	106	107	248	251	18	18	42	41
May	492	469	78	87	264	287	16	20	54	62
Farmlet mean	537	559	121	128	226	230	23	24	43	42
Farmlet SED	20		3		15		1		2	
Farmlet P Value	0.29		0.02		0.84		0.73		0.76	

Discussion

Estimated total daily N intake per cow averaged 548 g and was unaffected by system, despite differences in the pasture-to-supplement ratio and pasture species between the two systems. The HI diet included an average of 523 kg DM/cow/year of a low-N supplement in the form of barley grain, which was considerably more than LI at 64 kg DM/cow/year. Although daily HI grain intake during the week of sampling averaged 2.5kg DM/cow, total N intake still averaged 537 g/d. Kebreab et al. (2001) concluded that the inclusion of maize-based energy supplements formulated to provide low degradable protein can reduce N intake to less than 400 g/d and, in turn, reduce UN excretion. In a pasture-based system, feeding supplements that are low in N content, such as grain, to dilute the high N content of the pasture, may reduce per-cow UN excretion (Higgs et al. 2013). However, the effect of grain feeding on per hectare UN excretion by the HI herd in this study cannot be determined because the systems also differed in stocking rate and N fertiliser input. The amount and timing of grain feeding was not based on environmental considerations but rather pasture supply and feed deficits.

Doubling the amount of N fertiliser applied to HI pasture compared with LI pasture while maintaining similar rotation lengths in both systems led to only a small increase in the N content of the pastures (+ 0.1% of DM). In this study it appears that the additional N in the HI system was used by the plants to drive pasture DM yield (Table 2). This is consistent with the physiology of grass growth response to additional N: in situations where serious N deficits do not apply, increased N supply results in faster rates of cell division at a constant rate of new leaf initiation, leading to more cells per leaf (therefore increased leaf size) with the same N concentration (Gastal & Durand 2000). Moreover, LI pasture contained significantly more white clover (data not presented), which would normally increase total pasture N%. These results suggest that the pasture management practices imposed in the LI farmlet, i.e., moderate N fertiliser application (150 kg N/ha), and the inclusion of diverse pasture species, only had a marginal effect on reducing pasture N%. Other pasture management practices such as increasing rotation length (Bryant et al. 2012) are known to reduce pasture N%.

Given that per-cow N intake did not differ between systems, it is not surprising that N parameters in plasma, milk, urine, and faeces were not significantly different. Furthermore, there were no per-cow differences in the partitioning of total N intake to milk and urine, with approximately 43% of total N eaten excreted as urine. This value is below the range for partitioning to UN (48 to 56%) reported from studies where N intake and milk N secretion were similar to those reported here (Mackle et al. 1996; Rius et al. 2012; Bryant et al. 2014) but near the top end of the range of 30 to 45% reported for feeding studies where concentrates or silage made up a large proportion of the diet (Moorby et al. 2006). Estimating total urinary N excretion from grazing studies is problematic, and while a close relationship between N intake and UN excretion has been demonstrated (Kebreab et al. 2002), limitations do exist. The method of Pacheco et al. (2007) was chosen for this study because it was developed in systems similar to those reported here.

Despite the absence of per-cow differences between farm systems, seasonal trends in N excretion can be surmised. The partitioning of N to milk tended to be greater through the spring and early summer for both systems (Table 3), reducing UN excretion during this period. Conversely, as milk production declined in late summer and autumn, a greater proportion of the total N intake was excreted in urine. Computer simulation modelling (AJ Romero and PC Beukes, unpublished data) using data from two years of this trial, supports this trend. The modelling predicted that 75% of the N leached from urinary N came from urine deposited between January and April. Plant growth is often restricted in autumn and, therefore, N uptake is low, and with winter/spring rainfall, excess nitrate is carried below the root zone in the drainage (Di & Cameron 2002). Identifying months when the risk of nitrate leaching from urine is highest is crucial for the design of efficient and targeted N leaching mitigation strategies such as the use of stand-off pads for duration-controlled grazing (Christensen et al. 2012).

On a per hectare basis, UN excretion was 33% greater in HI than LI. The relationship between urinary N loading and higher input systems is worthy of attention, as the density of animals on a given area will affect the urine patch coverage. Estimated N leaching (modelled using OVERSEER® 6.2) was greater for HI (49 kg N/ha) than LI (34 kg N/ha), primarily due to greater N inputs through fertiliser and bought in feed.

In conclusion, estimated N intake/cow did not differ between the farm systems despite differences in feed and fertiliser inputs. Furthermore, estimated UN excretion/cow was not affected by farm system. However, the LI system had lower UN excretion/ha, as feed demand was adjusted in response to lower inputs of N fertiliser and purchased feed. This project has highlighted the challenges associated with reducing UN excretion per cow through farm input changes in pasture-based systems, and the limitations of estimating UN excretion.

Acknowledgements

This work was conducted through the Pastoral 21 Programme (C10X1117), jointly funded by the Ministry of Business, Innovation and Employment, DairyNZ, Fonterra, Beef + Lamb New Zealand and the Dairy Companies Association of New Zealand. Special thanks to Jeff Curtis for managing the farmlets at Lincoln University Research Dairy Farm. We thank Brenda Lynch, the DairyNZ team, and the Lincoln University technicians for assistance with sampling during the project. Thanks also to Barbara Dow (DairyNZ) for the statistical analysis.

References

Bryant R, Gregorini P, Edwards G 2012. Effects of N fertilisation, leaf appearance and time of day on N fractionation and chemical composition of Lolium perenne cultivars in spring. Animal Feed Science and Technology 173: 210-219.

Bryant RH, Dalley DE, Gibbs J, Edwards GR 2014. Effect of grazing management on herbage protein concentration, milk production and nitrogen excretion of dairy cows in mid-lactation. Grass and Forage Science 69: 644-654.

Christensen C, Hedley M, Hanly J, Horne D 2012. Nitrogen loss mitigation using duration-controlled grazing: Field observations compared to modelled outputs. Proceedings of the New Zealand Grassland Association 74: 115-120.

Corson D, Waghorn G, Ulyatt M, Lee J 1999. NIRS: Forage analysis and livestock feeding. Proceedings of the New Zealand Grassland Association: 127-132.

Di H, Cameron K 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. Nutrient Cycling in Agroecosystems 64: 237-256.

Gastal F, Durand JL 2000. Effects of nitrogen and water supply on N and C fluxes and partitioning in defoliated swards. In: Lemaire G, Hodgson J, Moraes AD, Carvalho PDF, Nabinger C (eds.) Grassland ecophysiology and grazing ecology. Wallingford, UK, CAB International. Pg. 15-29

Haynes R, Williams P 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Advances in Agronomy 49: 119-199.

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: 3857-3866.

Huhtanen P, Hristov AN 2009. A meta-analysis of the effects of dietary protein concentration and degradability on milk protein yield and milk N efficiency in dairy cows. Journal of Dairy Science 92: 3222-3232.

Kebreab E, France J, Beever DE, Castillo AR 2001. Nitrogen pollution by dairy cows and its mitigation by dietary manipulation. Nutrient Cycling in Agroecosystems 60: 275-285.

Kebreab E, France J, Mills J, Allison R, Dijkstra J 2002. A dynamic model of N metabolism in the lactating dairy cow and an assessment of impact of N excretion on the environment. Journal of Animal Science 80: 248-259.

Mackle T, Parr C, Bryant A 1996. Nitrogen fertiliser effects on milk yield and composition, pasture intake, nitrogen and energy partitioning, and rumen fermentation parameters of dairy cows in early lactation. New Zealand Journal of Agricultural Research 39: 341-356.

Moorby JM, Evans RT, Scollan ND, Macrae JC, Theodorou MK 2006. Increased concentration of water-soluble carbohydrate in perennial ryegrass (Lolium perenne L.). Evaluation in dairy cows in early lactation. Grass and Forage Science 61: 52-59.

Pacheco D, Burke J, Death A, Cosgrove G 2007. Comparison of models for estimation of urinary nitrogen excretion from dairy cows fed fresh forages. Meeting the challenges for pasture-based dairying. Proceedings of the Australasian Dairy Science Symposium: 18-20.

Pacheco D, Waghorn GC 2008. Dietary nitrogen - definitions, digestion, excretion and consequences of excess for grazing ruminants. Proceedings of the New Zealand Grassland Association 70: 107-116.

Payne RW, Murray DA, Harding SA, Baird DB & Soutar, DM 2011. An Introduction to GenStat for Windows (14th Edition). Hemel Hempstead, UK: VSN International.

Rius A, Kittelmann S, Macdonald K, Waghorn G, Janssen P, Sikkema E 2012. Nitrogen metabolism and rumen microbial enumeration in lactating cows with divergent residual feed intake fed high-digestibility pasture. Journal of Dairy Science 95: 5024-5034.

Selbie DR, Buckthought LE, Shepherd MA 2015. Chapter Four-The Challenge of the Urine Patch for Managing Nitrogen in Grazed Pasture Systems. Advances in Agronomy 129: 229-292.

Waghorn G, Burke J, Kolver E 2007. Principles of feeding value. In: Rattray P, Brookes I, Nicol A (eds.) Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production, Occasional Publication 14. 35-59.