# Bulk milk urea as an indicator of herd dietary nitrogen surplus and nitrogen use efficiency on Canterbury dairy farms

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## Abstract

Managing herd dietary nitrogen surplus (DNS) remains a core challenge on pasture-based dairy farms to reduce the risk of nitrogen loss to the environment. To manage their herd's DNS, farmers need readily available, practical indicators. In an observational longitudinal study of five Canterbury dairy farms over five seasons (2014/15 to 2018/19), we explored the usefulness of bulk milk urea concentration (BMU; mg/dL) and bulk milk urea nitrogen to milk protein nitrogen ratio (BMU-N:milk-N) to assess estimated herd DNS and dietary nitrogen use efficiency (DNUE). The analyses included correlations, linear and quadratic regression, and multivariate modelling to determine relationships of herd DNS and DNUE with BMU and BMU-N:milk-N and factors affecting BMU and BMU-N:milk-N. Herd DNS was moderately positively correlated with BMU and BMU-N:milk-N ($r = 0.48$-$0.56$, and $r = 0.46$-$0.61$, respectively). In contrast, herd DNUE was moderately negatively correlated with BMU and weakly to moderately correlated with BMU-N:milk-N ($r = -0.48$ to $-0.56$, and $r = -0.38$ to $-0.49$, respectively). Final multivariate models accounted for 51.6-52.8% of the variation in BMU, and 43.6-46.2% of the variation in BMU-N:milk-N. The results suggest that BMU can be used as a near real-time indicator of herd DNS and DNUE in current New Zealand dairy farm systems.

**Keywords:** bulk milk urea, decision support nitrogen management

## Introduction

The dairy sector is a critical part of the New Zealand economy, with an export value of $26 billion in 2023 (Ministry for Primary Industries 2023). However, agricultural production can put pressure on natural resources and can have a detrimental impact on the environment including the emission of greenhouse gases and the leaching of contaminants to waterways. In New Zealand, the National Policy Statement for Freshwater Management mandates environmental objectives for freshwater receiving environments (Ministry for the Environment 2024), which provides direction to local authorities (e.g. regional councils) who impose regulation and set out the rules for farming activities in their area. The dairy sector has acknowledged the impact that it can have on the environment and is committed to improving this through the Dairy Tomorrow strategy (Dairy Tomorrow 2022).

In grazed ruminant production systems, typically 5-30% of the nitrogen (N) ingested is converted into products such as meat and milk; the remaining 70-95% that is surplus to the animal's requirements is excreted as urine and faeces (Oenema et al. 2005). Urine patch N loadings range between 200 and 2000 kg N/ha (mean of 613 kg N/ha) in dairy cattle (Selbie et al. 2015). These rates frequently exceed pasture requirements. In pasture-based systems, excess urinary-N that is not taken up by plants is at risk of loss via leaching where it can reach and contaminate waterways or be lost to the atmosphere through ammonia volatilisation and the emission of nitrous oxide, a potent greenhouse gas (Cameron et al. 2013). Autumn presents the highest risk period for N leaching due to high rainfall and low N uptake by plants (Selbie et al. 2015), coupled with pastures typically having a higher N content from late autumn to early spring relative to other times of the year (Shepherd & Lucci 2013) while dairy cow N requirements are lower in the predominant spring-calving system.

Urinary N excretion is difficult to measure at a farm scale, and currently New Zealand farmers receive little feedback on their herd's dietary N surplus (DNS) throughout the lactation season. Farmers have some tools available to estimate farm N surplus such as the Overseer nutrient budget model (Watkins & Selbie 2015), and annual insights reports from milk processors. These reports allow them to retrospectively examine their environmental performance and make strategic decisions for the future, but neither provide feedback during the lactation season for making tactical management decisions. There is evidence from overseas studies that suggests that milk urea nitrogen (MUN) concentration is a good predictor of urinary N excretion in lactating dairy cows (Ciszuk & Gebregziabher 1994; Jonker et al. 1998; Nousiainen et al. 2004; Zhai et al. 2005; Spek et al. 2013; Bougouin et al. 2022) or dietary N use efficiency (DNUE; Aizimu et al. 2021).

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**Table 1** Average annual characteristics of the five Canterbury dairy farms monitored as part of the FRNL programme across lactation seasons 2014/15 to 2018/19. Lactation seasons were August to May; wintering is not included. Range presented in brackets.

| Farm | Milksolids (kg/ha) | Stocking rate (cows/ha) | Nitrogen fertiliser (kg N/ha) | Pasture N (%) | Pasture proportion (%) | Pre-grazing pasture mass (kg DM/ha) | Supplements used (kg DM/cow/day) |
|---|---|---|---|---|---|---|---|
| A | 1710<br>(1649-1841) | 3.3<br>(3.0-3.5) | 280<br>(268-313) | 3.9<br>(3.6-4.2) | 79<br>(71-84) | 2864<br>(2839-2904) | 3.9<br>(3.4-5.1) |
| B | 2076<br>(2024-2147) | 3.8<br>(3.5-4.1) | 241<br>(165-293) | 3.6<br>(3.3-4.0) | 80<br>(76-85) | 2873<br>(2721-2984) | 3.7<br>(2.8-4.9) |
| C | 1411<br>(1285-1660) | 2.8<br>(2.4-3.4) | 290<br>(245-367) | 4.0<br>(3.8-4.4) | 85<br>(76-92) | 2712<br>(2625-2788) | 2.3<br>(1.2-3.7) |
| D | 1760<br>(1687-1821) | 3.4<br>(3.1-3.9) | 294<br>(260-323) | 4.1<br>(3.6-4.5) | 77<br>(72-82) | 2852<br>(2767-3019) | 3.1<br>(2.6-3.6) |
| E | 1594<br>(1518-1770) | 3.2<br>(3.0-3.5) | 273<br>(209-300) | 4.2<br>(3.7-4.7) | 83<br>(75-90) | 2685<br>(2651-2747) | 3.0<br>(2.0-3.7) |
| **Overall mean** | 1710 | 3.3 | 276 | 4.0 | 81 | 2797 | 3.2 |

However, few studies (Aizimu et al. 2021; Bougouin et al. 2022; Tavernier et al. 2023) have included data from grazed pasture systems and the study by Tavernier et al. (2023) indicated that MUN was weakly correlated with N excretion (correlation coefficient of 0.06), and with DNUE (correlation coefficient of -0.01) in grazing systems. In contrast to this, Aizimu et al. (2021) evaluated the use of parameters to predict DNUE for cows grazing ryegrass pasture and reported that MUN was one of the best and most practical parameters, alongside water soluble carbohydrate to crude protein ratio of the diet.

Currently, New Zealand dairy farmers have near real-time access to concentrations of milk urea through bulk milk testing at the farm-level by their milk processors. The aim of this study was to utilise an existing monitor farm dataset consisting of five pasture-based dairy farms from Canterbury, New Zealand, with information collected over five years, to determine whether bulk milk urea (BMU) or the ratio of BMU nitrogen to milk protein nitrogen (BMU-N:milk-N) could be useful indicators of herd DNS or DNUE. The ratio BMU-N:milk-N, the proportion of bulk milk N that is made up by MUN, may provide a better indicator for herd DNS or DNUE than BMU alone, since it also accounts for efficiency of absorbed true protein utilisation, which is lacking if using BMU only (Hof et al. 1997). The following hypothesis was tested at the farm level: BMU concentration and BMU-N:milk-N are correlated with and explain a significant proportion of the variation in herd DNS (positive correlation) and DNUE (negative correlation).

## Materials and Methods

In 2014, a network of monitor farms was established in Canterbury as part of the Forages for Reduced Nitrate Leaching (FRNL) research programme (Pinxterhuis & Edwards 2018). The FRNL programme focussed on reducing N loss by utilising diverse pasture mixtures (Bryant et al. 2017), supplementary feeds with low N content, such as fodder beet (Dalley et al. 2017), and catch crops to mitigate N loss following a grazed fodder crop (Malcolm et al. 2020). The participating farms implemented to varying extents these and other mitigation options during the programme.

In this paper, we analysed data from the milking platforms of the five dairy monitor farms. These farms were monitored over five lactation seasons (2014/15 to 2018/19) between August and May as part of an observational longitudinal study. Data on wintering is not included in this study. Farmers recorded detailed data in a comprehensive spreadsheet, which included: paddock herbage mass estimates from regular pasture walks using rising plate meters and standard conversion equations, the type and amount of supplement fed, the timing and amount of fertiliser applied, effluent and irrigation applications, and stock movements. A researcher visited the farms approximately monthly to ensure data recording was complete and accurate.

Characteristics of the five monitor farms are given in Table 1 averaged across the five years. Detailed information on the monitor farm systems and the changes the farmers made can be found here: www.dairynz.co.nz/frnl. Results from the first three years were summarised in Pinxterhuis and Edwards (2018).

Each month, three pasture samples were taken, one from each of the next three paddocks to be allocated to the herd. Samples consisted of a representative subsample of herbage collected via snip cuts to grazing height, taken along a transect across the paddocks.

Samples were also taken of any supplementary feeds being offered to the herd at the time of the visit. All feed samples were analysed for feed quality (including metabolisable energy (ME) and N content) at Lincoln University (2014/15 to 2015/16) and Hill Laboratories (Hamilton, New Zealand; 2016/17 to 2018/19). In brief, samples were oven dried at 60-62°C, ground to 1 mm and analysed by near infrared spectroscopy (NIR; Lincoln University: FOSS NIRSystems 5000, MD USA; or Hill Laboratories: MPA FT-NIR Analyzer, Bruker Optics, Billerica, MA USA). Dry matter content was determined by drying samples at 105°C for ≥ 24 hours.

Milk production volume and bulk milk composition data (protein %, fat %, milk urea in mg/dL) for each Fonterra tanker consignment were obtained with farmer permission from Fonterra's Farm Source records, and monthly means were calculated. The ratio of BMU-N:milk-N was calculated as the monthly total kg MUN produced (milk urea × 0.47) divided by the monthly total kg milk protein N produced (milk protein ÷ 6.38). Herd mean liveweight was estimated by weighing 10% of the herd up to twice per year around December and May.

The final dataset contained pasture, supplement and milk data summarised per month for each farm and year. Mean monthly herd DNS (expressed as kg N/cow/day) was calculated per farm as the difference between estimated monthly dietary N intake (pasture + supplements; kg N/cow/day) and monthly milk-N production (milk-N production as milk protein ÷ 6.38; kg N/cow/day). Mean monthly herd DNUE was calculated as the ratio of total monthly milk-N production to the estimated total monthly dietary N intake.

Pasture dry matter intake is inherently difficult to estimate from grazing cattle; hence, we used two methods to estimate this variable: 1) pasture disappearance and 2) back-calculation of ME requirements of the herd. Our rationale for reporting both methods was to ensure that the predictions of BMU and BMU-N:milk-N and of herd DNS and DNUE were not dependent on the way pasture dry matter intake was estimated and thus if both analyses showed consistency, we could be more confident in the relationships obtained. Pasture disappearance was calculated from the difference between pre- and post-grazing herbage mass estimated with rising plate meters and standard conversion equations during the regular farm walks (weekly to fortnightly, depending on season). We used equations 1, 2, 3, 4, 6, and 7 for maintenance, chewing, walking associated with grazing, activity (including walking to and from the milking parlour), pregnancy and lactation, respectively, from Nicol and Brookes (2007) to back-calculate the total ME requirements of the herd. Assumptions included: 2 km daily horizontal walking distance, 0.1 km vertical km climbed per day, pregnancy requirements based on a standard conception date of 31 October, and liveweight change of zero.

### Statistical analysis

Data analyses were performed in R (version 4.3.0, R software, R Core Team 2022) and R Studio (2023.06.0+421) using tidyverse, readxl, broom, GGally, knitr, MVQuickGraphs, emmeans, pls, plsRglm, and plsdof packages. Analysis of variance was used to investigate the effects of Farm, Season, Month, and the interaction of Month and Season on BMU and BMU-N:Milk-N. Pearson correlation coefficients were calculated for all pairs of the variables of interest (Table 2) and BMU concentration (mg/dL), BMU-N:milk-N, DNS and DNUE. Correlations with an absolute value of r>0.7 were considered strong, between 0.4 and 0.69 were considered moderate, and r<0.39 were considered weak correlations (Schober et al. 2018). Linear and quadratic regressions were used to determine the relationships between BMU concentration (mg/dL) or BMU-N:milk-N and DNS, DNUE.

Partial least squares (PLS) regression modelling was used to predict BMU and BMU-N:milk-N using 11 variables of interest (see Table 2). All variables were included as linear, and additionally as quadratic terms if regression analysis showed a significant quadratic relationship, resulting in 19 predictors in the starting (full) models. Three of the 11 variables were included either based on pasture disappearance or back-calculation estimates (diet_n_me, past_kgcd, and past_prop; see Table 2), resulting in four starting models (BMU or BMU-N:milk-N and pasture disappearance or back-calculation for those variables where this is relevant; see Table 2). All predictors were scaled to a mean of 0 and standard deviation of 1, and leave-one-out cross-validation and a permutation approach (selectNcomp() in plsr()) were used to determine the appropriate number of components. After fitting the starting models, predictors were removed one at a time based on the smallest scaled coefficient, and the model re-run with n-1 predictors until the final model was found. The final models were defined as explaining the greatest proportion of variation in y ($R^2$-value) with the smallest number of predictors, and all remaining predictors being similarly important in predicting the response (i.e. having very similar scaled coefficients). Original (raw) coefficients are presented for each full and final model. See Table 2 for description of variables used for correlation and regression analyses and predictive modelling.

## Results and Discussion

The Canterbury FRNL monitor farms were highly

**Table 2** Description of farm variables. Data used in the analyses were means per month; overall monthly means and the associated coefficient of variations (CV) are presented for the monitoring period August to May 2014/15 to 2018/19. Where relevant, variables were calculated using pasture intake estimates based on pasture disappearance or back-calculation (_bc) of metabolisable energy requirements.

| Variable abbreviation | Variable description | Mean | CV |
|---|---|---|---|
| BMU | Bulk milk urea concentration (mg/dL) | 28.4 | 23.1 |
| BMU-N:milk-N | Bulk milk urea nitrogen to milk protein nitrogen ratio | 0.021 | 21.9 |
| diet_n* | Diet nitrogen content on a dry matter basis (%) | 3.6 | 15.8 |
| diet_n_bc* | Diet nitrogen content on a dry matter basis using back-calculation of pasture intake (%) | 3.5 | 18.0 |
| diet_n_me | Diet nitrogen to metabolisable energy ratio (N% ÷ MJ ME/kgDM) | 0.34 | 14.1 |
| diet_n_me_bc | Diet nitrogen to metabolisable energy ratio using back-calculation of pasture intake (N% ÷ MJ ME/kgDM) | 0.34 | 14.1 |
| dmi* | Dry matter intake (kg DM/cow/day) (pasture + supplements) | 18.8 | 23.4 |
| dmi_bc* | Dry matter intake using back-calculation of pasture intake (kg DM/cow/day) (pasture + supplements) | 14.9 | 15.1 |
| DNS | Herd dietary nitrogen surplus (dietary N – milk N) (kg N/cow/day) | 0.58 | 36.2 |
| DNS_bc | Herd dietary nitrogen surplus using back-calculation of pasture intake (diet N – milk N) (kg N/cow/day) | 0.42 | 27.1 |
| DNUE | Herd nitrogen use efficiency ratio (milk N ÷ diet N) | 0.17 | 31.2 |
| DNUE_bc | Herd nitrogen use efficiency ratio using back-calculation of pasture intake (milk N ÷ diet N) | 0.21 | 17.6 |
| month* | Month of the year (1 being June, start of a new milking season) | | |
| mp* | Milk protein content (%) | 4.02 | 11.9 |
| mp_cd* | Milk protein production per cow per day (kg/cow/day) | 0.74 | 18.5 |
| ms_cd* | Milksolids (fat + protein) production per cow per day (kg MS/cow/day) | 1.67 | 17.9 |
| my_cd | Milk yield production per cow per day (L/cow/day) | 18.9 | 25.3 |
| n_fert | Nitrogen fertiliser applied (kg N/ha) | 27.8 | 48.2 |
| past_kgcd | Pasture intake estimated using pasture disappearance (kg DM/cow/day) | 15.4 | 33.1 |
| past_kgcd_bc | Pasture intake estimated using back-calculation (kg DM/cow/day) | 11.5 | 33.0 |
| past_me | Pasture metabolisable energy content (MJ ME/kg DM) | 11.8 | 4.5 |
| past_n | Pasture nitrogen content on a dry matter basis (%) | 4.0 | 14.8 |
| past_prop | Proportion of pasture in the diet (%) | 80.7 | 17.6 |
| past_prop_bc | Proportion of pasture in the diet using back-calculation of pasture intake (%) | 76.0 | 25.5 |
| pregraze_mass | Pre-graze pasture mass offered (t DM/ha) | 2.83 | 7.3 |
| supp_kgcd | Supplement intake (kg DM/cow/day) | 3.4 | 72.6 |
| supp_me | Supplement metabolisable energy content, weighted average of supplements offered (MJ ME/kg DM) | 12.1 | 14.7 |
| supp_n | Supplement nitrogen content on a dry matter basis, weighted average of supplements offered (%) | 2.0 | 25.0 |

* Variable was not included in PLS because they were used to calculate other variables, were calculated from other variables, or were highly correlated with another variable.

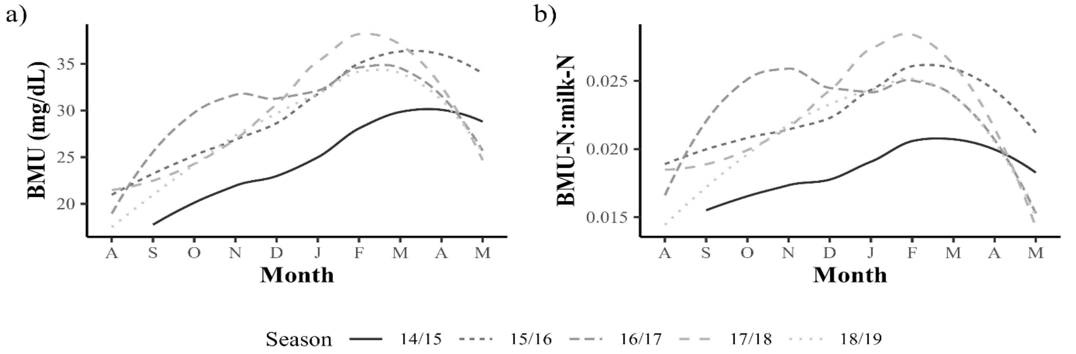

**Figure 1** a) Bulk milk urea concentration (BMU; mg/dL), and b) bulk milk urea nitrogen to milk protein nitrogen ratio (BMU-N:milk-N) across five Canterbury dairy farms from lactation seasons 2014/15 to 2018/19. Locally weighted non-linear line of best fit based on monthly means.

productive, irrigated farms producing, on average 1,710 kg MS/ha or 516 kg MS/cow with relatively high annual inputs of fertiliser N and supplementary feeds during the five seasons from 2014/15 to 2018/19 (Table 1). In comparison, national average milksolids produced was between 1,048 and 1,082 kg/ha or 368 and 381 kg/cow in these seasons, and 2018/19 averages for the North Canterbury region were 1,469 kg MS/ha or 427 kg MS/cow (LIC & DairyNZ 2019). The relatively high input is reflected in the higher predicted farm-gate N surplus and lower predicted farm-gate NUE as estimated for farms in, for example, the Waikato (Pinxterhuis & Edwards 2018).

Visualisations of BMU and BMU-N:milk-N across the lactation season for each of the five years of the observational study are presented as locally weighted non-linear lines of best fit in Figure 1. Analysis of variance indicated that there were significant Season × Month interactions, confirming that the month-to-month shapes of the curves vary between years. On average, regardless of month, BMU and BMU-N:milk-N were significantly lower in 2014/15 (means of 24.3 mg/dL and 0.0181 for BMU and BMU-N:milk-N, respectively) than any other season. The greatest values were observed in 2015/16 and 2016/17 (monthly means 29.8 to 29.9 mg/dL and 0.0225 to 0.0226), which were significantly greater than those in 2018/19 (27.7 mg/dL and 0.0206). The lower BMU and BMU-N:milk-N in the 2014/15 season may partially be explained by the monthly mean N content of pasture, which was significantly lower in 2014/15 at 3.6% DM, compared with 3.9 to 4.4% DM for the other seasons. Pasture ME content was also significantly lower in 2014/15, averaging 11.3 MJ ME/kg DM, compared with 11.7 to 12.1 MJ ME/kg DM for the other seasons. Note the use of two different laboratories for feed analysis in this study is likely to have introduced variation in the estimation of ME content between the first two years and the final three years. Annual N fertiliser application rate decreased over the years and was significantly greater in the 2014/15 season (307 kg N/ha) than the 2018/19 season (240 kg N/ha). Nitrogen content of supplement and dry matter intake based on pasture disappearance were not significantly different between seasons, but diet N:ME ratio was lower in the first year. Dry matter intake estimated from back-calculation was significantly greater in the 2014/15 season (average of 15.9 kg DM/cow/day) than in the other seasons (14.4 to 14.9 kg DM/cow/day), likely due to the lower pasture ME content in the first season. These results suggest that an unintended consequence of regular farm walks and pasture quality assessments, as prescribed by the project, and reduced N fertiliser rates could have been improved grazing management, with more even and possibly lower pre-grazing pasture covers in subsequent years. Unfortunately, collected data were insufficient to estimate pre-grazing pasture covers for the first year of the project, but modelling results presented in Table 4 indicate a higher pre-grazing mass was associated with a lower BMU and BMU-N:milk-N ratio. A recent assessment of farm management differences between groups of farms with relatively low versus high BMU also indicated that a higher pre-grazing herbage mass (2893 kg DM/ha vs 2740 kg DM/ha P = 0.052; associated with longer grazing intervals (40 days vs 29 days; P= 0.026) and a more advanced leaf stage (2.28 leaves vs 2.15 leaves; P = 0.084)) was associated with lower BMU (Glassey et al. 2023). This was reflected in a 2.7% lower pasture crude protein for the low BMU group but with no difference in pasture ME (Glassey et al. 2023). This is expected, with grass and herb crude protein content declining with greater regrowth interval (e.g. Martin et al. 2017).

Another striking result seen in Figure 1 is the trend for a decline in BMU and BMU-N:milk-N ratio during autumn, especially in the final three years of the

**Table 3** Coefficients of correlation for farm variables, see Table 2 for full variable descriptions. Strength of correlation indicated by colour (dark grey = strong, light grey = moderate, white = weak).

| | Month | n_fert | pregraze_mass | dmi_bc | dmi | supp_kgcd | supp_me | supp_n | past_kgcd_bc | past_kgcd | past_me | past_n | past_prop_bc | past_prop | my_cd | ms_cd | diet_n_bc | diet_n | diet_n_me_bc | diet_n_me | DNUE_bc | DNUE | DNS_bc | DNS | BMU-N:milk-N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BMU | 0.57 | 0.29 | -0.20 | 0.18 | 0.37 | -0.27 | 0.04 | 0.20 | 0.26 | 0.45 | -0.26 | 0.42 | 0.29 | 0.42 | -0.21 | -0.07 | 0.52 | 0.59 | 0.52 | 0.51 | -0.48 | -0.56 | 0.48 | 0.56 | 0.89 |
| BMU-N:milk-N | 0.16 | 0.38 | -0.24 | 0.31 | 0.27 | -0.42 | 0.10 | 0.35 | 0.44 | 0.43 | -0.14 | 0.28 | 0.46 | 0.52 | 0.17 | 0.22 | 0.61 | 0.60 | 0.35 | 0.34 | -0.49 | -0.38 | 0.61 | 0.46 | |
| DNS | 0.36 | 0.20 | -0.18 | 0.23 | 0.87 | -0.19 | 0.15 | 0.06 | 0.24 | 0.84 | -0.07 | 0.57 | 0.23 | 0.48 | -0.02 | 0.09 | 0.53 | 0.73 | 0.60 | 0.61 | -0.32 | -0.80 | 0.50 | | |
| DNS_bc | -0.02 | 0.47 | -0.21 | 0.69 | 0.24 | -0.66 | 0.22 | 0.35 | 0.80 | 0.53 | -0.20 | 0.40 | 0.74 | 0.70 | 0.50 | 0.60 | 0.90 | 0.79 | 0.52 | 0.49 | -0.57 | -0.19 | | | |
| DNUE | -0.53 | -0.05 | 0.11 | 0.15 | -0.67 | -0.04 | 0.00 | 0.02 | 0.12 | -0.56 | 0.09 | -0.55 | 0.06 | -0.24 | 0.40 | 0.34 | -0.32 | -0.57 | -0.59 | -0.60 | 0.39 | | | | |
| DNUE_bc | -0.14 | -0.13 | 0.07 | 0.06 | 0.09 | 0.50 | 0.03 | -0.19 | -0.28 | -0.17 | 0.19 | -0.44 | -0.44 | -0.39 | 0.14 | 0.15 | -0.73 | -0.66 | -0.57 | -0.53 | | | | | |
| diet_n_me | 0.47 | 0.10 | -0.30 | 0.03 | 0.27 | 0.05 | 0.10 | -0.05 | -0.03 | 0.21 | -0.05 | 0.95 | -0.03 | 0.08 | -0.23 | -0.12 | 0.59 | 0.79 | 0.99 | | | | | | |
| diet_n_me_bc | 0.46 | 0.12 | -0.29 | 0.05 | 0.26 | 0.01 | 0.11 | -0.04 | 0.00 | 0.22 | -0.07 | 0.94 | 0.01 | 0.10 | -0.21 | -0.11 | 0.62 | 0.80 | | | | | | | |
| diet_n | 0.19 | 0.29 | -0.29 | 0.23 | 0.34 | -0.43 | 0.16 | 0.16 | 0.39 | 0.50 | 0.09 | 0.79 | 0.45 | 0.56 | 0.15 | 0.22 | 0.91 | | | | | | | | |
| diet_n_bc | 0.00 | 0.36 | -0.21 | 0.36 | 0.15 | -0.66 | 0.19 | 0.27 | 0.61 | 0.45 | 0.02 | 0.57 | 0.69 | 0.66 | 0.32 | 0.38 | | | | | | | | | |
| ms_cd | -0.51 | 0.40 | -0.09 | 0.78 | 0.12 | -0.38 | 0.23 | 0.32 | 0.69 | 0.29 | 0.08 | -0.09 | 0.51 | 0.42 | 0.94 | | | | | | | | | | |
| my_cd | -0.72 | 0.34 | -0.09 | 0.64 | 0.01 | -0.37 | 0.23 | 0.32 | 0.60 | 0.18 | 0.20 | -0.16 | 0.46 | 0.35 | | | | | | | | | | | |
| past_prop | 0.02 | 0.39 | -0.01 | 0.55 | 0.38 | -0.89 | 0.16 | 0.15 | 0.86 | 0.75 | -0.25 | 0.00 | 0.91 | | | | | | | | | | | | |
| past_prop_bc | -0.15 | 0.38 | 0.03 | 0.58 | 0.10 | -0.97 | 0.18 | 0.20 | 0.93 | 0.56 | -0.26 | -0.11 | | | | | | | | | | | | | |
| past_n | 0.33 | 0.02 | -0.34 | -0.10 | 0.21 | 0.12 | 0.07 | -0.10 | -0.14 | 0.12 | 0.25 | | | | | | | | | | | | | | |
| past_me | -0.42 | -0.24 | -0.14 | -0.46 | -0.17 | 0.21 | -0.08 | -0.15 | -0.36 | -0.25 | | | | | | | | | | | | | | | |
| past_kgcd | 0.22 | 0.29 | -0.02 | 0.49 | 0.88 | -0.50 | 0.20 | 0.09 | 0.58 | | | | | | | | | | | | | | | | |
| past_kgcd_bc | -0.15 | 0.46 | -0.01 | 0.82 | 0.19 | -0.86 | 0.21 | 0.27 | | | | | | | | | | | | | | | | | |
| supp_n | -0.18 | 0.28 | -0.06 | 0.32 | 0.02 | -0.15 | 0.39 | | | | | | | | | | | | | | | | | | |
| supp_me | -0.09 | 0.17 | -0.08 | 0.26 | 0.14 | -0.16 | | | | | | | | | | | | | | | | | | | |
| supp_kgcd | 0.16 | -0.34 | -0.06 | -0.42 | -0.02 | | | | | | | | | | | | | | | | | | | | |
| dmi | 0.35 | 0.15 | -0.06 | 0.33 | | | | | | | | | | | | | | | | | | | | | |
| dmi_bc | -0.06 | 0.47 | -0.06 | | | | | | | | | | | | | | | | | | | | | | |
| pregraze_mass | 0.01 | -0.14 | | | | | | | | | | | | | | | | | | | | | | | |
| n_fert | -0.07 | | | | | | | | | | | | | | | | | | | | | | | | |

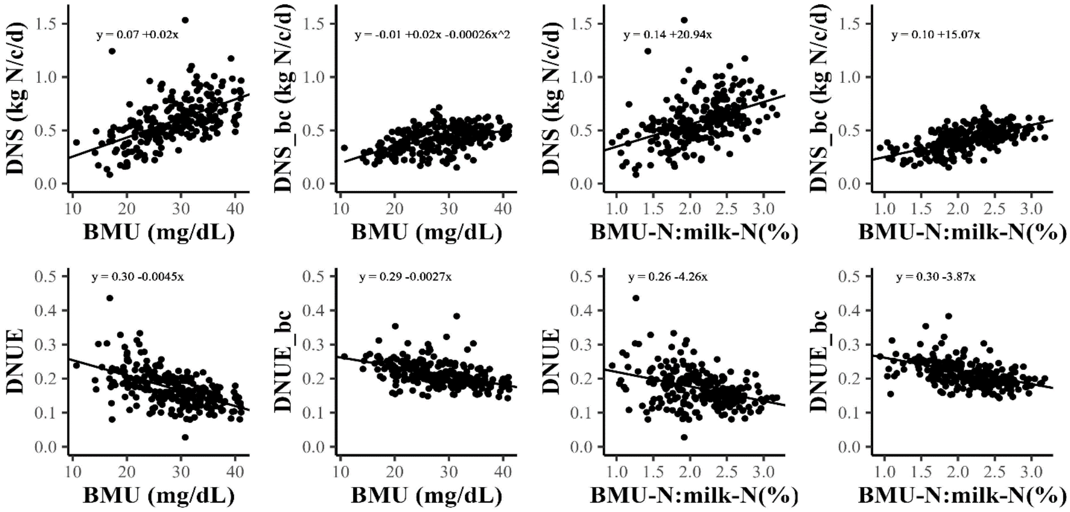

**Figure 2** Regression relationships between response variables: herd dietary nitrogen surplus (DNS, based on pasture disappearance, and DNS_bc, based on back-calculated pasture intake) and dietary nitrogen use efficiency (DNUE, based on pasture disappearance, and DNUE_bc, based on back-calculated pasture intake) with predictors: bulk milk urea concentration (BMU; mg/dL) and bulk milk urea nitrogen to protein nitrogen ratio (BMU-N:milk-N; %). Regression equations are presented in the graphs and are linear ($P<0.001$) apart from the BMU vs DNS_bc regression, which had a significant quadratic effect ($P<0.05$).

project. All farms started to use fodder beet in autumn to transition their cows before drying off and moving to fodder beet crops for winter grazing (Pinxterhuis & Edwards 2018). Fodder beet has a low protein content and high sugar content, thus reducing N intake and excretion (Dalley et al. 2020). This effect of supplement N content on BMU is also apparent in the models presented in Table 4.

Correlation coefficients for variables are described in Table 3 as a matrix of all variables analysed. Unsurprisingly, BMU and BMU-N:milk-N were strongly positively (Table 3). Herd DNS was moderately positively correlated ($r \geq 0.46$) with BMU and with BMU-N:milk-N. By comparison, herd DNUE was moderately negatively correlated with BMU ($r \leq -0.48$) and was weakly to moderately negatively correlated with BMU-N:milk-N ($r \leq -0.38$). Values for correlations with the back-calculated herd DNS and DNUE were weaker for BMU but stronger for BMU-N:milk-N in comparison to those based on pasture disappearance. Interestingly, herd DNS and DNUE were strongly negatively correlated when calculated using the pasture disappearance method ($r = -0.80$), but this relationship weakened to a moderate negative correlation when these variables were estimated using the back-calculation method ($r = -0.57$). Other variables that were moderately positively correlated with BMU included N content of the diet, month, the ratio of N to ME in the diet, pasture intake calculated using pasture disappearance, the proportion of pasture in the diet calculated using pasture disappearance, and N content of pasture (Table 3). Other variables that were moderately positively correlated with BMU-N:milk-N included N content of the diet, proportion of pasture in the diet, and pasture intake. Supplement intake was moderately negatively correlated with BMU-N:milk-N, but weakly negatively correlated with BMU concentration (Table 3).

Linear regression relationships for response variables herd DNS and DNUE, with BMU and BMU-N:milk-N as predictors, are presented in Figure 2. Back-calculated herd DNS had a quadratic relationship with BMU and is also presented in Figure 2. Despite weak to moderate correlations between BMU or BMU-N:milk-N with herd DNS or DNUE (Table 3), the significant linear and quadratic regressions (Figure 2) indicate that BMU and BMU-N:milk-N could be used to predict herd DNS and DNUE on commercial Canterbury dairy farms. The average herd DNS was 0.58 kg N/cow/day in our study, using the pasture disappearance method to estimate pasture intake, or 0.42 kg N/cow/day using the back-calculation method. Average herd DNUE was 0.17 and 0.21 for these two methods, respectively. In a summary of published field experiments (22 were conducted in New Zealand and four overseas), DNUE was on average 0.23 (minimum 0.18, maximum 0.33) for Friesian cows and 0.25 (minimum 0.16, maximum 0.47) for Jersey × Friesian crossbred cows (Aizimu et al. 2021). The average DNS derived from their data was 0.36 kg N/cow/day for Friesian cows and 0.32 kg N/

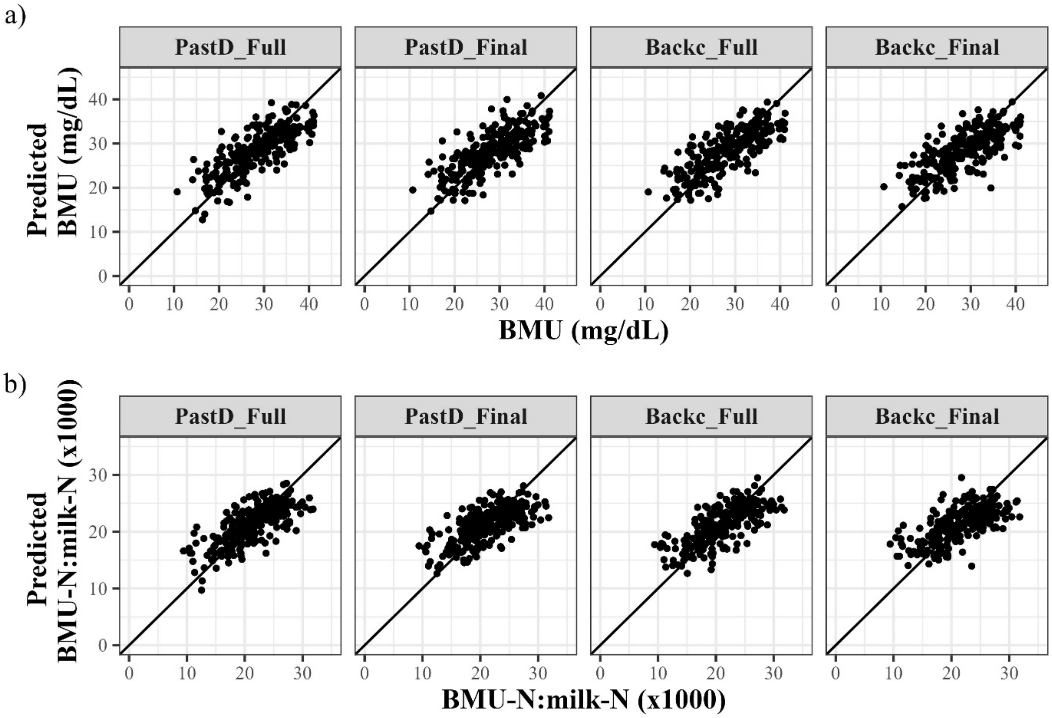

**Figure 3** Measured versus predicted a) bulk milk urea concentration (BMU; mg/dL), and b) bulk milk urea nitrogen to milk protein nitrogen ratio (BMU-N:milk-N; ×1000) for models described in Table 4. PastD = pasture intake estimated using difference between pre- and post-grazing herbage mass to calculate pasture disappearance; Backc = pasture intake estimated using back-calculation relative to animal requirements. Full = model with all 19 variables; Final = model explaining the greatest proportion of variation with the smallest number of predictors.

cow/day for Jersey × Friesian crossbred cows. A higher DNUE and lower DNS than in the current study can be explained by the lower N content and similar ME of the diets in the experiments analysed by these authors.

The PLS regression produced predictive models for BMU and BMU-N:milk-N (Table 4; Figure 3). The full models with all 19 predictors, based on pasture disappearance or back-calculation, accounted for 61.6% and 56.9% of the variation in BMU, and 53.2% and 51.7% of the variation in BMU-N:milk-N, respectively. Thus, the models based on pasture disappearance explained slightly more of the variation than those based on back-calculation. The final models included 6 to 10 predictors and explained between 43.6% and 52.8% of the variation in BMU and BMU-N:milk-N. Predictions for BMU were again slightly better than those for BMU-N:milk-N, and models based on pasture disappearance explained slightly more of the variation than those based on back-calculation. The two methods (pasture disappearance and back-calculation) resulted in different estimates for pasture intake, averaging 15.4 and 11.5 kg DM/cow/day, respectively, which meant that the correlation coefficient between these two variables was only moderate, at r = 0.58. It appears the estimates based on pasture disappearance might have been slightly better, and more accurate data were needed for the back-calculations of pasture intake based upon animal ME requirements. Estimates using the back-calculation method could be improved in future projects by using consistent laboratory estimates of ME, reducing the number of assumptions used, such as including more accurate estimates of cow liveweights (e.g. from walk-over weigh scales, or more frequent liveweight measurements), and using actual distances walked each day.

The $R^2$ of the final models indicate that apart from the inherent inaccuracies in farm-level observations, factors other than those included in the models may be responsible for up to half of the variation in BMU and BMU-N:milk-N. Possibilities include variation between farms, seasons and months in management or systems variables that were not included in the PLS models. Analysis of variance showed significant effects of farm, month, season for both BMU and BMU-N:milk-N ($P<0.001$; results not shown), and including them in the PLS models was masking effects of variables of interest. Variables that were not included in our analysis but are known to influence the relationship between BMU and urinary N excretion, are breed, genetic merit, type of protein in the diet (rumen degradable, soluble), protein

**Table 4** Partial least squared regression model equations (raw coefficients) for predicting bulk milk urea concentration (mg/dL) or bulk milk urea nitrogen to milk protein nitrogen ratio (×1000) on five Canterbury dairy farms from lactation seasons 2014/15 to 2018/19. See Table 2 for variable descriptions; Sq = denotes that the variable was squared. Full = model with all 19 variables; Final = model explaining the greatest proportion of variation with the smallest number of predictors. Where relevant, variables were calculated using pasture intake estimates based on pasture disappearance or back-calculation of metabolisable energy requirements.

| | **Bulk milk urea (mg/dL)** | | | | **Bulk milk urea nitrogen to milk protein nitrogen ratio (×1000)** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Pasture disappearance** | | **Back-calculation** | | **Pasture disappearance** | | **Back-calculation** | |
| **Variable** | **Full** | **Final** | **Full** | **Final** | **Full** | **Final** | **Full** | **Final** |
| $R^2$ (%) | 61.6 | 52.8 | 56.9 | 51.6 | 53.2 | 46.2 | 51.7 | 43.6 |
| Intercept | 16.696 | 1.333 | -3.314 | 24.307 | 11.241 | 8.252 | -3.092 | 3.690 |
| diet_n_me | 13.180 | 26.432 | 9.797 | 26.051 | 8.940 | 12.403 | 9.384 | 34.704 |
| diet_n_meSq | 12.363 | 36.542 | 2.688 | | 5.224 | | -6.844 | |
| my_cd | -0.261 | -0.260 | -0.332 | -0.217 | 0.038 | | 0.124 | |
| my_cdSq | -0.011 | -0.009 | -0.016 | -0.007 | -0.003 | | -0.008 | |
| n_fert | 0.107 | 0.069 | 0.170 | 0.075 | 0.094 | 0.050 | 0.219 | |
| n_fertSq | -0.001 | | -0.002 | | -0.001 | | -0.003 | |
| past_kgcd | 0.283 | 0.254 | 0.563 | 0.271 | 0.121 | 0.148 | 0.216 | 0.117 |
| past_kgcdSq | -0.003 | | 0.012 | | -0.003 | | -0.007 | |
| past_me | 0.086 | | 0.591 | -1.963 | 0.270 | | 0.463 | |
| past_meSq | -0.001 | | 0.017 | | 0.008 | | 0.011 | |
| past_n | 1.025 | | 1.736 | 1.480 | 0.669 | 0.836 | 1.402 | |
| past_nSq | 0.086 | | 0.173 | 0.176 | 0.027 | | 0.055 | |
| past_prop | 0.151 | 0.108 | 0.086 | 0.063 | 0.109 | 0.065 | 0.105 | 0.063 |
| pregraze_mass | -4.257 | | -2.951 | | -4.712 | -2.080 | -4.121 | -2.234 |
| supp_kgcd | -0.133 | | 0.089 | | -0.171 | -0.302 | -0.265 | |
| supp_kgcdSq | -0.003 | | 0.062 | | -0.004 | | 0.053 | |
| supp_me | -0.268 | | 0.079 | | -0.349 | | -0.119 | |
| supp_n | 2.819 | 3.554 | 4.486 | 3.032 | 3.015 | 1.647 | 6.197 | 2.480 |
| supp_nSq | 0.060 | | -0.047 | | -0.066 | | -0.720 | 0.176 |

reserves in the cows, milking interval, and water intake (Spek et al. 2012). These variables may, therefore, also affect any relationship between BMU and herd DNS or DNUE.

The most important predictors of BMU, which were also retained in the final models, were proportion of pasture in the diet, pasture DM intake, N fertiliser rate, diet N:ME ratio and N content of the supplements (positive relationship), and milk yield (negative relationship). Hence, it was the combination of higher milk production, lower pasture intake and proportion of pasture in the diet, lower N fertiliser rate, lower diet N:ME ratio and lower N content of supplements that was associated with lower BMU. Higher pre-grazing mass also tended to reduce BMU but did not remain in the final model as a predictor, possibly because it was negatively correlated with pasture N content and diet N:ME ratio. This result was consistent with findings from a recent study comparing farms divergent in BMU where farms with high BMU (mean 31.4-35.0 mg/dL) tended to have a lower pre-grazing herbage mass, which was associated with higher pasture crude protein content; farms with low BMU (mean 21.5 mg/dL) tended to have higher pre-grazing herbage mass, which was associated with lower pasture crude protein (Glassey et al. 2023).

Pasture N content, protein composition and N:ME ratio can also be altered by using alternative pasture species (i.e. other than perennial ryegrass and clover), and this also alters MUN content. For example, Cosgrove et al. (2014) reported lower MUN when cows were fed chicory or sulla, and higher MUN when fed lucerne, red or white clover. Moreover, Minnée et al. (2020) reported lower MUN in late-lactation cows fed increasing proportions of plantain, which had lower crude protein and non-protein N and higher insoluble N and ME than the ryegrass-dominant pasture fed alongside it. From Minnée et al. (2020), it can be deducted that DNS reduced from 0.48 kg N/cow/day for a ryegrass-dominant diet to 0.44 kg N/cow/day for a diet with 45% plantain; whereas DNUE increased from 0.12 to 0.17, MU reduced from 16.8 to 13.7 mg/dL and urine N excretion reduced from 0.26 to 0.20 kg N/cow/day.

The predictive models for BMU-N:milk-N were very similar to those for BMU, with the exception of the relative importance of milk yield. Here, it was the combination of higher pre-grazing mass combined with lower pasture intake and proportion of pasture in the diet, higher supplement intake, lower N fertiliser rate, lower diet N:ME ratio and lower N content of pasture and supplements that was associated with a reduced BMU-N:milk-N. Higher milk yield was associated with an increased BMU-N:milk-N ratio, but not enough so to remain in the final model as a predictor.

Because of the similarity in results between BMU and the ratio BMU-N:milk-N (correlations and models), we suggest the latter does not provide any obvious advantage alongside BMU to estimate herd DNS and DNUE and assess risk of N loss from these Canterbury dairy farm systems.

## Conclusions and Practical implications

Currently farmers only have strategic tools available to help manage their N loss risk, such as either retrospective annual data in reports received from their milk processors or the use of modelling. The use of practical milk-based indicators of herd DNS and DNUE, such as BMU and BMU-N:milk-N presented in the current study, would provide farmers with a tool to assess the risk of high urine N excretion in near real-time and they may be able to adjust their management accordingly. Our correlation, linear and quadratic regression analyses indicate that BMU and BMU-N:milk-N could be used to predict herd DNS and DNUE on commercial Canterbury dairy farms; however, BMU-N:milk-N ratio did not provide any obvious advantage over BMU. This study provided insight into factors that likely affect BMU and BMU-N:milk-N and thus where farmers could target N loss mitigations; for example, reducing diet N:ME ratio, N fertiliser rate, N content of supplements, N content of pasture, and proportion of pasture in the diet, or increasing pre-grazing herbage mass.

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## REFERENCES

Aizimu W, Al-Marashdeh O, Hodge S, Dewhurst RJ, Chen A, Zhao G, Talukder S, Edwards GR, Cheng L. 2021. Estimation of nitrogen use efficiency for ryegrass-fed dairy cows: model development using diet- and animal-based proxy measures. *Dairy 2(3)*: 435-451. https://doi.org/10.3390/dairy2030035

Bougouin A, Hristov A, Dijkstra J, Aguerre MJ, Ahvenjärvi S, Arndt C, Bannink A, Bayat AR, Benchaar C, Boland T, Brown WE, Crompton LA, Dehareng F, Dufrasne I, Eugène M, Froidmont E, van Gastelen S, Garnsworthy PC, Halmemies-Beauchet-Filleau A, Herremans S, Huhtanen P, Johansen M, Kidane A, Kreuzer M, Kuhla B, Lessire F, Lund P, Minnée EMK, Muñoz C, Niu M, Nozière P, Pacheco D, Prestløkken E, Reynolds CK, Schwarm A, Spek JW, Terranova M, Vanhatalo A, Wattiaux MA, Weisbjerg MR, Yáñez-Ruiz DR, Yu Z, Kebreab E. 2022. Prediction of nitrogen excretion from data on dairy cows fed a wide range of diets compiled in an intercontinental database: a meta-analysis. *Journal of Dairy Science*. https://doi.org/10.3168/jds.2021-20885

Bryant RH, Miller ME, Greenwood SL, Edwards GR. 2017. Milk yield and nitrogen excretion of dairy cows grazing binary and multispecies pastures. *Grass and Forage Science 72*: 806-817. https://doi.org/10.1111/gfs.12274

Cameron KC, Di HJ, Moir JL. 2013. Nitrogen losses from the soil/plant system: a review. *Annals of Applied Biology 162*: 145-173. https://doi.org/10.1111/aab.12014

Ciszuk P, Gebregziabher T. 1994. Milk urea as an estimate of urine nitrogen of dairy cows and goats. *Acta Agriculturae Scandinavica, Section A - Animal Science 44*: 87-95. https://doi.org/10.1080/09064709409410187

Cosgrove GP, Taylor PS, Lowe KA, Foote AG, Jonker A. 2014. Milk urea estimates of nitrogen excretion by dairy cows grazing forage species with contrasting chemical and morphological characteristics. *Proceedings of the 5th Australasian Dairy Science Symposium 2014*: 249-251.

Dairy Tomorrow. 2022. *Protecting our environment*. Retrieved 25 March 2024 from: https://www.dairynz.co.nz/media/jp1dzgml/sustainable-dairying-annual-report-protecting-our-environment-2022-v141.pdf

Dalley D, Waugh D, Griffin A, Higham C, de Ruiter J, Malcolm B. 2020. Productivity and environmental implications of fodder beet and maize silage as supplements to pasture for late lactation dairy cows. *New Zealand Journal of Agricultural Research 63*: 145-164. https://doi.org/10.1080/00288233.2019.1675717

Dalley DE, Malcolm BJ, Chakwizira E, de Ruiter JM. 2017. Range of quality characteristics of New Zealand forages and implications for reducing the nitrogen leaching risk from grazing dairy cows. *New Zealand Journal of Agricultural Research 60*: 319-332. https://doi.org/10.1080/00288233.2017.1345762

Glassey C, Woods R, Reed C, Puriri N, Scott G, Hodgkinson A, Bryant R. 2023. Grazing management practices on Waikato and Canterbury dairy farms diverging in bulk milk urea content. *Journal of New Zealand Grasslands 85*: 273-281. https://doi.org/10.33584/jnzg.2023.85.3649

Hof G, Vervoorn MD, Lenaers PJ, Tamminga S. 1997. Milk urea nitrogen as a tool to monitor the protein nutrition of dairy cows. *Journal of Dairy Science 80*: 3333-3340. https://doi.org/10.3168/jds.S0022-0302(97)76309-4

Jonker JS, Kohn RA, Erdman RA. 1998. Using milk urea nitrogen to predict nitrogen excretion and utilization efficiency in lactating dairy cows[1]. *Journal of Dairy Science 81*: 2681-2692. https://doi.org/10.3168/jds.S0022-0302(98)75825-4

LIC, DairyNZ. 2019. *New Zealand Dairy Statistics 2018-19*. Retrieved 5 February 2020 from https://www.dairynz.co.nz/media/5792393/nz-dairy-statistics-2018-19-web.pdf

Malcolm BJ, de Ruiter JM, Dalley DE, Carrick S, Waugh D, Arnold NP, Dellow SJ, Beare MH, Johnstone PR, Wohlers M, Brown H, Welten B, Horrocks AJ. 2020. Catch crops and feeding strategy can reduce the risk of nitrogen leaching in late lactation fodder beet systems. *New Zealand Journal of Agricultural Research 63*: 44-64. https://doi.org/10.1080/00288233.2019.1704422

Martin KE, Bryant RH, Hodge S, Edwards GR. 2017. Effect of autumn regrowth interval and nitrogen fertiliser on dry matter yield and plant characteristics of six forage species. *Journal of New Zealand Grasslands 79*: 67-72. https://doi.org/10.33584/jnzg.2017.79.560

Ministry for Primary Industries. 2023. *Situation and outlook for primary industries December 2023*. Retrieved 13 March 2024 from https://www.mpi.govt.nz/dmsdocument/60526/direct

Ministry for the Environment. 2024. *National Policy Statement for Freshwater Management 2020 - Amended January 2024*. Retrieved 26 March 2024 from https://environment.govt.nz/publications/national-policy-statement-for-freshwater-management-2020-amended-january-2024/

Minnée EMK, Leach CMT, Dalley DE. 2020. Substituting a pasture-based diet with plantain (*Plantago lanceolata*) reduces nitrogen excreted in urine from dairy cows in late lactation. *Livestock Science 239*: 104093. https://doi.org/10.1016/j.livsci.2020.104093

Nicol AM, Brookes IM. 2007. The metabolisable energy requirements of grazing livestock. In: Rattray PV, Brookes IM, Nicol AM Ed. *Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production. Occasional Publication No. 14*. pp. 151-172. Hamilton, New Zealand Society of Animal Production (Inc.).

Nousiainen J, Shingfield KJ, Huhtanen P. 2004. Evaluation of milk urea nitrogen as a diagnostic of protein feeding. *Journal of Dairy Science 87*: 386-398. https://doi.org/10.3168/jds.S0022-0302(04)73178-1

Oenema O, Wrage N, Velthof G, van Groenigen JW, Dolfing J, Kuikman P. 2005. Trends in global nitrous oxide emissions from animal production systems. *Nutrient Cycling in Agroecosystems 72*: 51-65. https://doi.org/10.1007/s10705-004-7354-2

Pinxterhuis JB, Edwards JP. 2018. Comparing nitrogen management on dairy farms - Canterbury case studies. *Journal of New Zealand Grasslands 80*: 201-206. https://doi.org/10.33584/jnzg.2018.80.329

R Core Team. 2022. *A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Schober P, Boer C, Schwarte LA. 2018. Correlation coefficients: appropriate use and interpretation.

*Anesthesia & Analgesia 126*: 1763-1768. https://doi.org/10.1213/ane.0000000000002864

Selbie DR, Buckthought LE, Shepherd MA. 2015. The challenge of the urine patch for managing nitrogen in grazed pasture systems. *Advances in Agronomy 129*: 229-292. https://doi.org/10.1016/bs.agron.2014.09.004

Shepherd M, Lucci G. 2013. A review of the effect of autumn nitrogen fertiliser on pasture nitrogen concentration and an assessment of the potential effects on nitrate leaching risk. *Proceedings of the New Zealand Grassland Association 75*: 197-202. https://doi.org/10.33584/jnzg.2013.75.2900

Spek JW, Dijkstra J, Van Duinkerken G, Bannink A. 2012. A review of factors influencing milk urea concentration and its relationship with urinary urea excretion in lactating dairy cattle. *The Journal of Agricultural Science 151*: 407-423. https://doi.org/10.1017/S0021859612000561

Spek JW, Dijkstra J, van Duinkerken G, Hendriks WH, Bannink A. 2013. Prediction of urinary nitrogen and urinary urea nitrogen excretion by lactating dairy cattle in northwestern Europe and North America: A meta-analysis. *Journal of Dairy Science 96*: 4310-4322. https://doi.org/10.3168/jds.2012-6265

Tavernier E, Gormley IC, Delaby L, McParland S, O'Donovan M, Berry DP. 2023. Cow-level factors associated with nitrogen utilization in grazing dairy cows using a cross-sectional analysis of a large database. *Journal of Dairy Science 106*: 8871-8884. https://doi.org/10.3168/jds.2023-23606

Watkins N, Selbie D. 2015. *Technical description of OVERSEER for regional councils. Report prepared for Bay of Plenty regional council, September 2015* [RE500/2015/084]. 40 p. https://overseer.org.nz/support-and-training

Zhai SW, Liu JX, Ma Y. 2005. Relation between milk urea content and nitrogen excretion from lactating cows. *Acta Agriculturae Scandinavica, Section A - Animal Science 55*: 113-115. https://doi.org/10.1080/09064700510009289