Simulating the intake and nitrogen excretion from cows grazing forages fertilised with increasing rates of nitrogen

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Abstract

The dry matter intake (DMI), production, and urinary nitrogen (N) excretion of dairy cows grazing forage grown under increasing N fertiliser rates were explored using a mechanistic model of a grazing ruminant. The MINDY cow model was initialised to represent a multiparous Holstein-Friesian dairy cow in late lactation (age 3.5 years, 212 days in milk). Simulated cows were offered a common allowance (30 kg DM/cow/d) of chicory, plantain, lucerne, or perennial ryegrass, fertilised at rates of 0, 100, 200, 350 and 500 kg N/ha/y (0N, 100N etc.) for 20 days in March. Forage physical and chemical composition data were obtained from a Waikato experimental field site. When N rate increased from 0–500N, predicted DMI of cows grazing plantain and ryegrass increased by 5.2 and 2.7 kg DM/cow/day (43 and 20% increase), respectively, facilitated by increased sward height and mass, and reduced herbage strength. Predicted DMI of cows grazing chicory peaked at 200N and, for cows grazing lucerne, declined with N fertilisation. Intake of highly fertilised (>200N) chicory and lucerne diets were potentially affected by high herbage soluble N content resulting in high predicted rumen ammonia concentrations (>18 mmol/L), reducing incentive for grazing. While predicted milk production from cows grazing chicory, plantain and ryegrass increased, the efficiency of dietary N used for milk production declined, with increasing N applied. Increasing N rate also increased predicted urine N concentration, and urinary N excretion from simulated cows fed chicory, plantain, and ryegrass. This study suggests that N fertiliser rates of 200N for chicory, plantain and ryegrass provides a balance between cow production and N excretion.

Keywords: ammonia; intake; milk production; urinary nitrogen

Introduction

Declining fresh water quality in New Zealand, since the 1950s, has become a significant concern (Scarsbrook & Melland 2015). Nitrogen (N) loss from agriculture has been identified as a source of freshwater pollution, and as such, reducing N loss has become a focus for industry bodies and local government. Nitrogen loss from forage-based systems is primarily due to the N content of forage exceeding that which is required by the animal, and because the efficiency of N utilisation by ruminant livestock for product (i.e., milk) is low (Delagarde et al. 1997). Because animals cannot store surplus dietary N, the excess is excreted, primarily in urine. The quantity of N that is excreted in urine on to pasture often exceeds what plants can uptake, and the remaining N is susceptible to leaching to groundwater (Jarvis 1993).

The strong positive relationship between dietary N intake and N excreted in urine (Castillo et al. 2000) indicates that reducing dietary N is a potential mitigation strategy for N loss to the environment. This may be achieved through reducing the N content of herbage. Studies have shown that reducing the amount of fertiliser N applied to swards can reduce herbage N concentration (Martin et al. 2017). However, reducing N fertiliser application may also decrease herbage growth rate and sward height, and increase herbage strength, which may affect livestock grazing behaviour and intake (Laca et al. 1992). These are important considerations for farmers. Therefore, an optimal fertiliser rate for forage species is sought to balance productivity with livestock N use efficiency.

Because key elements required to measure the N excretion of livestock fed different forages, are difficult and expensive to measure, the mechanistic model 'MINDY' was used as an initial approach to explore outcomes of increasing fertiliser N applied to four common forages on feed intake, milk production and N excretion from grazing dairy cows.

Materials and methods

Model and inputs

In this study, the MINDY model was used to simulate effects of feeding dairy cows diets of four forages, each fertilised at five rates of N fertiliser. MINDY is a deterministic, mechanistic and dynamic model of a dairy cow, representing diurnal patterns of ingestion, digestion and metabolism, excretion and production (Gregorini et al. 2015; Gregorini 2016).

Forage physical and chemical composition data (Table 1) were obtained from measurements collected in April 2015 from a small plot trial in Hamilton, New Zealand, where seven forages were grown under six fertiliser N rates in a randomised split-plot design with three replicates (JB Pinxterhuis, Unpublished data). The forages selected for the simulation exercise reported here were perennial ryegrass (ryegrass), lucerne, chicory, and plantain; and the N application rates selected were 0, 100, 200, 350 and 500 kg N/ha/y (hereafter referred to as 0N, 100N, etc.). Fertiliser N was applied as urea (46% N) in 12 even applications over the year.

Herbage strength was determined using a digital force gauge to measure the force (Newtons/mm^2) to punch 2-mm diameter holes in herbage (100 per plot). Values were normalised by assuming that the strength of ryegrass herbage fertilised at 200N = 1.0; strength of other herbages were then calculated relative to 200N ryegrass. Extended leaf height was measured from ground level using a ruler, collecting 100 measurements per plot. Herbage mass was estimated by harvesting one 1.5 m^2 strip per plot using a Haldrup® forage harvester set to a cut height of 50 mm, and drying a 150 g sub-sample of cut herbage at 95°C for 36 hours before reweighing to determine herbage dry matter (DM) content. A 200 g sub-sample was freeze dried, and ground to pass through a 1 mm sieve (Christy & Norris Mill, United Kingdom) for chemical analysis. Neutral detergent fibre (NDF) was measured using the method of Van Soest et al. (1991), and acid detergent fibre (ADF) by method 973.18 (AOAC Int. 2000). Total N concentration was determined by combustion (method 990.03; AOAC Int. 2000), and non-protein N components by the urease (941.04; AOAC Int. 2000) and potentiometric (986.31; AOAC Int. 2000) methods. Total ash concentration was determined by combustion (method 942.05; AOAC Int. 2000). Non-structural carbohydrate (NSC) concentration was calculated using the equation: NSC = 100 – (CP + NDF + Lipid + Ash).

Simulation methods

Simulation runs were set in Hamilton, New Zealand, and spanned 20 days, from 1-20 March 2014, with the last 5 d taken as the 'measurement' period. The physical characteristics and chemical composition of each forage is described in Table 1. The model was initialised as a 3.5-year-old Friesian dairy cow, weighing 423 kg, at a body condition score of 4.5, and calving in August 2013 (late-lactation). Simulated cows were offered a new break of forage each day, with an area allocated to provide 30 kg DM/cow/d based on herbage mass, and were considered to be grazing within a simulated herd of 200 cows, milked twice daily.

Results

Simulated effect of N fertilisation rate on intake and milk production

Compared with the 0N treatments, increasing fertiliser to 500N increased the prediction of DMI by 4.8, 5.2 and 2.7 kg DM/cow/d on chicory, plantain, and ryegrass diets respectively (20–43% increase) (Table 2). Correspondingly, predicted N intake increased in these forages with increasing fertiliser N applied, ranging from 198–293 g N/cow/day (Table 3). Dry matter intake of lucerne was not predicted to change as a result of N fertiliser rate.

Herbage intake rate (g DM/min) of cows was predicted to increase with increasing fertiliser N application to diets of chicory, plantain and ryegrass. The greatest increase was predicted when cows were offered chicory, increasing by 35 g DM/min when N fertiliser increased from 0–500N, followed by ryegrass (19 g DM/min increase) and plantain (13 g DM/min increase).

Table 1 Chemical composition, nutritive and physical characteristics of herbage from the four species and five rates of fertiliser N application (kg N/ha/y) used in the simulation.

Species	N rate	DM[1] (%)	CP[2]	Fat	NSC[3]	NDF[4]	Ash	CPS[5]	RUP[6]	NPN[7]	Herbage strength	Extended leaf height (cm)	Herbage mass (kg DM/ha)
			(g/g DM)					(Proportion of CP)					
Chicory	0	12.4	0.136	0.039	0.238	0.207	0.240	0.270	0.400	0.001	0.8	22.3	2060
Chicory	100	11.4	0.144	0.039	0.238	0.216	0.230	0.278	0.351	0.001	0.8	33.3	2670
Chicory	200	11.3	0.167	0.039	0.228	0.215	0.220	0.283	0.348	0.001	0.7	35.7	3300
Chicory	350	10.2	0.198	0.039	0.209	0.232	0.188	0.306	0.330	0.002	0.7	39.4	3830
Chicory	500	9.5	0.209	0.039	0.211	0.239	0.167	0.379	0.312	0.002	0.6	47.9	4060
Lucerne	0	17.7	0.270	0.045	0.095	0.477	0.118	0.401	0.28	0.002	0.6	37.0	3070
Lucerne	100	17.3	0.302	0.045	0.096	0.439	0.116	0.417	0.291	0.003	0.6	34.5	3040
Lucerne	200	17.5	0.307	0.045	0.098	0.430	0.118	0.436	0.282	0.003	0.6	33.4	3105
Lucerne	350	17.2	0.295	0.045	0.091	0.452	0.116	0.451	0.274	0.003	0.6	35.8	3126
Lucerne	500	17.9	0.284	0.045	0.099	0.451	0.120	0.452	0.279	0.005	0.6	34.7	3115
Plantain	0	18.2	0.147	0.042	0.211	0.393	0.164	0.104	0.493	0.007	1.0	21.5	2140
Plantain	100	17.4	0.151	0.042	0.222	0.380	0.161	0.109	0.468	0.007	1.0	33.7	2410
Plantain	200	16.7	0.153	0.042	0.224	0.377	0.160	0.250	0.490	0.009	0.9	36.4	2885
Plantain	350	15.8	0.170	0.042	0.231	0.361	0.153	0.255	0.487	0.009	0.8	39.4	3135
Plantain	500	15.5	0.180	0.042	0.238	0.346	0.150	0.320	0.484	0.010	0.8	42.9	3640
P. ryegrass	0	23.9	0.171	0.045	0.157	0.484	0.108	0.333	0.320	0.001	1.2	20.0	1790
P. ryegrass	100	20.1	0.183	0.045	0.154	0.470	0.112	0.370	0.315	0.015	1.0	23.0	2300
P. ryegrass	200	19.4	0.184	0.045	0.159	0.461	0.116	0.368	0.316	0.015	1.0	25.3	2580
P. ryegrass	350	17.8	0.220	0.045	0.138	0.448	0.111	0.390	0.305	0.021	0.9	30.3	2710
P. ryegrass	500	17.6	0.220	0.045	0.138	0.447	0.113	0.390	0.300	0.032	0.9	35.2	3210

[1] DM, dry matter; [2] CP, crude protein; [3] NSC, non-structural carbohydrate; [4] NDF, neutral detergent fibre, [5] CPS, soluble crude protein; [6] RUP, rumen undegradable protein; [7] NPN, non-protein nitrogen.

Predicted milk (L/cow/d) and milk solids (MS) yield (kg/cow/d) increased with increasing N fertiliser application, for cows grazing chicory, plantain, and ryegrass (Table 2), with MS increasing by 20, 17 and 8%, respectively, as fertiliser increased from 0N to 500N. Unlike plantain and ryegrass, where the milk-production response continued to increase, no further improvement was predicted for chicory when fertiliser application rate exceeded 200N. Predicted milk and MS yield appeared unaffected when N fertiliser was applied to lucerne swards. Partitioning of N to milk, and the efficiency of MS production (g MS/g N eaten) was predicted to decline (mean 35%) when N fertiliser increased from 0N to 500N in diets of chicory, lucerne, and plantain (Table 3).

Simulated effect of N fertilisation on N metabolism and excretion

The model predicted increasing mean rumen ammonia concentration with increasing N fertiliser applied to chicory, plantain and ryegrass. The greatest increases were predicted in chicory, and ryegrass diets where fertiliser application exceeded 200N (from mean 11-17 mmol/L). Predicted plasma urea N concentrations followed a similar pattern as rumen ammonia concentration. On average, predicted mean rumen ammonia was least from cows fed plantain, and greatest from cows fed lucerne (6 vs. 21 mmol/L, respectively).

Predicted urinary N concentration, and total daily N excretion from cows grazing chicory, plantain, and ryegrass increased with increasing fertiliser N application (Fig. 1). Predicted urine N concentration and excretion from cows fed lucerne did not appear to be affected by N fertiliser.

Partitioning of N was predicted to increase under high (>350N) rates of N fertiliser, accompanied with a predicted decrease in N partitioned to product. Unfertilised chicory and plantain was predicted to result in a negative N balance.

Discussion

Overall, the model predicted DMI and MS production within the range observed in studies from cows grazing similar diets under similar N fertiliser regimes, at the same stage of lactation (Woodward et al. 2010; Minneé et al. 2017).

Intake and feeding behaviour

In agreement with the literature (Delagarde et al. 1997; Valk et al. 2000) predicted DMI of cows was increased when grazing swards fertilised at greater rates of N applied (>350N) compared with swards grown under low N fertiliser (<200N). Greater predicted intakes of highly fertilised ryegrass and plantain swards may have been due to increased sward height and mass, and reduced herbage strength at greater N application. This would permit easier access to, and prehension of, herbage (Laca et al. 1992) as suggested by the greater intake rates predicted. Despite increasing sward height and mass of chicory with increasing N application, predicted DMI plateaued at rates exceeding 200N. The lack of further DMI increases from

Table 2 Predicted daily dry matter intake, dry matter intake rate and milk production from simulated cows grazing swards of chicory, lucerne, plantain and perennial ryegrass fertilised with increasing rates of nitrogen.

	N fertiliser rate (kg N/ha/y)					
	0	100	200	350	500	SEM
Dry matter intake (kg/cow/d)						
Chicory	11.3	14.9	15.9	15.1	16.2	0.9
Lucerne	17.8	17.3	16.7	17.1	17.1	0.2
Plantain	11.9	13.4	14.8	16.4	17.1	1.0
P. ryegrass	13.3	14.1	14.5	14.3	16.0	0.4
Herbage intake rate (g DM/min)						
Chicory	24	39	43	49	59	5.9
Lucerne	33	33	33	35	32	0.4
Plantain	33	36	38	43	46	2.4
P. ryegrass	16	18	19	31	35	3.9
Milk yield (L/cow/d)						
Chicory	11.1	12.2	13.1	13.2	13.6	0.5
Lucerne	16.5	16.4	16.0	16.1	15.9	0.1
Plantain	12.3	12.9	13.4	14.5	14.8	0.5
P. ryegrass	12.4	12.7	12.7	12.9	13.4	0.2
Milk solids yield (kg/cow/d)						
Chicory	0.94	1.05	1.11	1.09	1.13	0.04
Lucerne	1.45	1.40	1.38	1.40	1.40	0.01
Plantain	1.08	1.11	1.15	1.23	1.26	0.03
P. ryegrass	1.09	1.11	1.14	1.12	1.18	0.02

SEM = standard error of the mean.

Figure 1 Predicted (a) concentration of N in urine (g/L) and (b) total daily N excreted in urine (g/cow/day) from simulated cows grazing swards of chicory (○), lucerne (▲), plantain (■), and perennial ryegrass (●) fertilised with increasing rates of nitrogen.

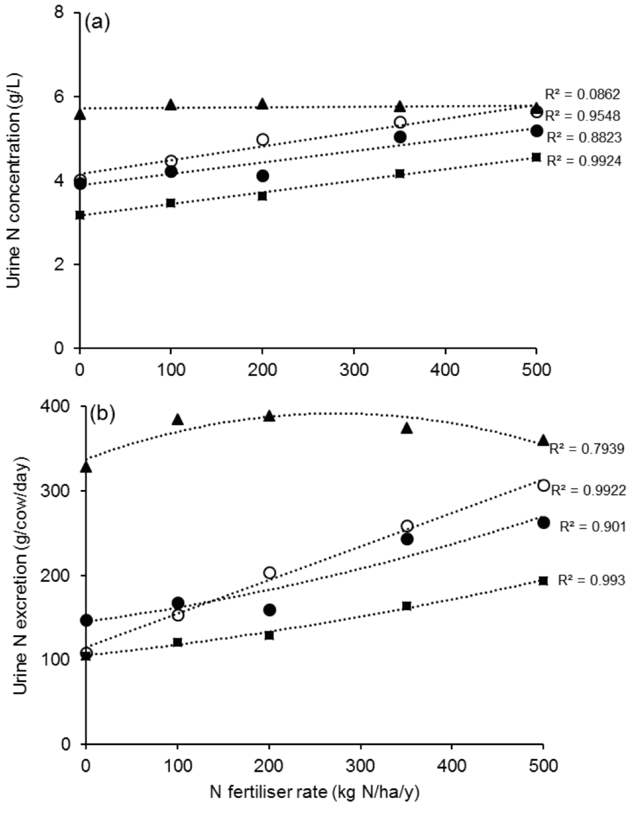

Table 3 The predicted effect of increasing N fertiliser rate applied to swards of chicory, lucerne, plantain, and perennial ryegrass on nitrogen intake, partitioning of dietary nitrogen, and the nitrogen use efficiency (NUE) of simulated dairy cows.

	N fertiliser rate (kg N/ha/y)					
	0	100	200	350	500	SEM
Nitrogen intake (g/cow/d)						
Chicory	247	343	425	478	540	51
Lucerne	726	772	758	740	726	9
Plantain	281	324	362	447	493	39
P. ryegrass	365	412	426	505	563	35
N partitioning, g/kg of N intake						
Milk N						
Chicory	237	189	163	145	133	18
Lucerne	120	112	112	115	116	2
Plantain	231	210	196	172	159	14
P. ryegrass	179	162	158	135	126	10
Urine N						
Chicory	445	451	479	541	568	25
Lucerne	454	499	513	507	496	10
Plantain	375	373	356	367	393	6
P. ryegrass	405	409	375	484	466	21
Faecal N						
Chicory	337	312	320	281	272	12
Lucerne	288	271	292	267	271	4
Plantain	419	423	421	400	359	12
P. ryegrass	396	375	363	318	317	16
Unaccounted N/N retained						
Chicory	-19	48	38	32	27	12
Lucerne	124	120	114	118	123	2
Plantain	-3	-1	3	6	9	2
P. ryegrass	20	54	105	63	90	15
Nitrogen use efficiency (g MS/ g N intake)						
Chicory	3.63	2.99	2.50	2.24	2.11	0.28
Lucerne	1.89	1.67	1.68	1.73	1.80	0.04
Plantain	3.83	3.42	3.19	2.76	2.55	0.23
P. ryegrass	2.98	2.69	2.67	2.23	2.09	0.16

SEM = standard error of the mean.

simulated cows grazing highly fertilised chicory (>200N), and fertilised lucerne, could be associated with the high rumen ammonia concentrations (>16 mmol/L) predicted by the model, which would reduce incentive for grazing (Gregorini et al. 2013). Whereas, high rumen ammonia concentrations were not commonly predicted when cows grazed ryegrass and plantain, likely owing to the lesser predicted N intake of cows fed plantain and ryegrass, with herbage containing lower soluble CP and higher rumen undegradable protein content compared with the that from chicory and lucerne diets. This modelling study, therefore, suggests that the DMI of dairy cows can be indirectly altered by N fertiliser application rates.

Milk production and NUE

Predicted MS yield increased when N fertiliser applied to chicory, plantain and ryegrass increased from 0-200N. At rates exceeding 200N, predicted MS yield continued to increase from cows grazing plantain, but the MS response from cows to rates exceeding 200N applied to chicory and ryegrass was marginal. Similarly, application of N to lucerne was not predicted to affect MS production. The absence of continued MS increases at higher rates of N fertiliser, or to fertilised lucerne, agrees with conclusion of Castillo et al. (2000), that the milk production response to increasing herbage N concentration is negligible when the diet contains a high proportion of degradable N, and where N intake was sufficient to meet cow requirements, as was predicted in the current study. Furthermore, the efficiency with which N is used for product and partitioning of N to milk were predicted to decline as N fertilisation increased. Therefore, this modelling study suggests that there is no benefit to increasing N fertiliser application rate beyond 200N to ryegrass and chicory for MS production, but rates greater than 200N could be applied to plantain swards to potentially improve MS production.

Nitrogen excretion

Predicted total urinary N excretion from cows increased by 90–199 g/cow/d as fertiliser N application increased to chicory, plantain and ryegrass (0–500N) (i.e., up to a 180% increase). The largest increases were predicted to occur in N application rates exceeding 200N in plantain and ryegrass diets, whereas predicted urine N excretion increased progressively with increasing N applied to chicory. The increase in N excretion was likely associated with increased N intake (Castillo et al. 2000), and greater partitioning of N to urine, due to both greater predicted DMI and N content of highly fertilised herbage. These results support the potential of strategic fertiliser N management to minimise urinary N excretion and concentration.

Plantain diets were predicted to result in lower rumen ammonia concentrations and concomitantly, lesser N excretion than the other forages modelled in this study. This is probably a consequence of the relatively low N concentration in plantain herbage, with a greater proportion of rumen undegradable N, compared with the other forages. The findings agree with studies that have demonstrated decreased urine N concentration where plantain comprised part of the diet of dairy cows (Box et al. 2016; Minneé et al. 2017) and highlight the opportunity provided by modelling to explore strategies for reducing N excretion through inclusion of plantain in the diet.

Conclusions

Adjusting the application rate of N fertiliser to chicory, plantain and ryegrass provides a means to reduce N losses to the environment. In the context of this study, predictions of MS production and N excretion by the MINDY model suggested application of 200 kg N/ha/y as the optimal compromise between MS production and N excretion. At this rate, predicted DMI and MS production from cows grazing chicory was maximised, and no further gains were achieved through additional N fertiliser. Predictions for plantain and ryegrass showed greater N application resulted in small increases in MS production, but the amount of N excreted increased exponentially. The simulations confirmed the negative production and environmental consequences from applying N fertiliser to lucerne swards.

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