Diurnal changes in the nutritive composition of four forage species at high and low N fertiliser

L.A. BOX, G.R. EDWARDS and R.H. BRYANT
Agriculture and Life Sciences Faculty, Lincoln University, Lincoln, New Zealand
lisa.box@lincolnuni.ac.nz

Abstract
Chicory and plantain have been suggested as alternative grazed forages to perennial ryegrass for New Zealand dairy systems. While diurnal changes in plant chemical composition have been described for ryegrass there is currently little information for herbs. This experiment aimed to compare the effect of nitrogen inputs (low and high) and harvesting time (am versus pm) on the chemical composition of four forages (ryegrass, plantain, chicory and white clover). The effect of harvest time was greater than N fertiliser inputs on chemical composition for all forages. Ryegrass showed the greatest increase in water soluble carbohydrate diurnally, at the expense of neutral detergent fibre and to a lesser extent crude protein. This suggests afternoon allocation of ryegrass may be beneficial to improve the nutritive value of pasture on offer; allocation timing is less important for white clover, chicory and plantain.

Keywords: chicory, clover, crude protein, plantain, ryegrass, water soluble carbohydrate

Introduction
The composition of nutrients available to grazing animals in ryegrass pastures varies widely due to seasonal and diurnal changes. A ryegrass-based pasture can have low crude protein (CP) and high fibre concentrations in summer, which may restrict feed intake so that animal nutrient requirements are often not met (Waghorn 2002). At other times of the year ryegrass-based pastures can have a high concentration and solubility of CP (Bryant *et al.* 2012a) resulting in a low utilisation efficiency and a large proportion of dietary N being excreted in the urine (Tamminga 1992). Urinary N losses are an environmental concern and mitigation strategies are sought to meet new regulations. A positive relationship between CP intake and urinary N losses has been well established (Tas *et al.* 2006). Management strategies or pasture species which improve the nutritive value of pasture and reduce the N content may be valuable to pastoral grazing systems. One potential mitigation strategy may be to allocate pasture in the afternoon to reduce the proportion of N in the pasture and thus the supply to the animal (Moorby *et al.* 2006; Bryant *et al.* 2014).

Ryegrass shows a diurnal change in water soluble carbohydrate (WSC) concentration increasing from morning to night (Miller *et al.* 2001). This is offset by a decline in CP and fibre. In a previous experiment when an elevated WSC concentration was achieved in high sugar ryegrass by harvesting in the afternoon, urinary N output was reduced by 28.7 g/cow/day compared with a non-selected ryegrass harvested in the morning (Miller *et al.* 2001). Another mitigation option may be to use alternative plant species. Pastures which include herbs (plantain and chicory) have been identified as a means of reducing urinary N concentration compared with a ryegrass-white clover pasture, while maintaining or improving milk production (Bryant *et al.* 2012b; Totty *et al.* 2013; Edwards *et al.* 2015; Box *et al.* 2016). However, the mechanisms contributing to this effect are unclear.

While diurnal changes in the chemical composition of ryegrass have been well studied, less information is available for alternative herb and legume species (e.g. plantain, chicory, red and white clover). The purpose of this study was to compare the effect of N inputs and harvest time on herbage nutritive value of conventional and alternative pasture forages.

Materials and methods
Experimental site and design
The experiment was conducted from 8 October 2014 to 18 May 2015 at the Lincoln University Research Dairy Farm, Canterbury New Zealand (43º64'S, 172º46'E). A split-split plot design was used with three replicates. Treatments were forage type (4 species), N rate (two levels) and harvest time (am and pm). The four forage types were; diploid perennial ryegrass, plantain, chicory, and white clover (Table 1). N fertiliser was applied following each defoliation as calcium ammonium nitrate (27 : 0 : 0 : 0; N : P : K : S), with the total annual N application rate split evenly throughout the year. Before the experiment began, the planned N fertiliser treatments were 200 and 500 kg N/ha/year. It was estimated that nine harvests for legumes and ten harvests for grasses and herbs would occur. However, due to best practice methods, legumes were harvested seven times and grasses and herbs harvested nine times. This resulted in lower levels of N applied than proposed and differences in rates of N fertiliser applied between legumes and grasses and herbs. The final two fertiliser rates were low N inputs of 180 kg N/ha/year for grasses and herbs and 156 kg N/ha/year for legumes or high N

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inputs of 450 kg N/ha/year for grasses and herbs and 389 kg N/ha/year for legumes.

Management

All species were sown as monocultures in March 2014 using a Flexiseeder 14 row plot drill (2.1 m width) following cultivation. Plots (6.3 m^2) were managed as described by Martin *et al.* (2017). All species were grown under the same climatic and edaphic conditions with soils and nutrient (excluding nitrogen) being non-limiting to growth. The site was irrigated with a travelling irrigator between October and March, with ~20-30 mm water applied per week. Plots were fertilised with 12.8 kg P/ha, 20 kg K/ha and 32.8 kg S/ha in March and October 2014. Lime was applied in October 2014 at a rate of 2 t/ha.

Plots were managed by mowing with a Walker MC GHS ride-on rotary lawnmower, with mower height set to 4 cm for all species under a cut and carry regime. The timing of harvests was determined by best practices for maximising herbage growth and persistence of the three different functional groups: grasses, legumes and herbs (Moot *et al.* 2003; Lee *et al*. 2011). Grasses and herbs were defoliated at 32, 26 and 30 day intervals in spring, summer and autumn, respectively. Legumes were harvested at 41, 35 and 41 day intervals in spring, summer and autumn, respectively. Due to low soil temperatures and slow growth rates, no plots were harvested in winter.

Table 1 Forage species sown and their scientific name, cultivar and sowing rate.

Forage	Scientific name	Cultivar	Sowing rate (kg/ha)
Perennial ryegrass	*Lolium perenne*	One50 AR37	20
Chicory	*Cichorium intybus*	Choice	8
Plantain	*Plantago lanceolata*	Tonic	10
White clover	*Trifolium repens*	Kopu II	5

Table 2 Mean herbage crude protein (CP) concentration (g/kg DM) of forages cut between 9 October and 30 October 2014 (spring), 24 November 2014 and 10 February 2015 (summer) or 10 March and 18 May 2015 (autumn) in the morning (AM) or afternoon (PM) at low and high N fertiliser inputs.

N inputs	Harvest Time	Forage	Spring	Summer	Autumn
Low	AM	Ryegrass	158	124	182
		Chicory	167	180	217
		Plantain	157	142	198
		White Clover	257	260	294
	PM	Ryegrass	143	115	166
		Chicory	166	162	193
		Plantain	145	131	179
		White Clover	246	246	277
High	AM	Ryegrass	210	158	220
		Chicory	188	223	246
		Plantain	186	163	204
		White Clover	274	250	295
	PM	Ryegrass	175	155	205
		Chicory	189	195	221
		Plantain	164	152	191
		White Clover	239	245	288
	SEM		2.8	2.2	2.4
Probabilities		Forage	<0.001	<0.001	<0.001
		N rate	<0.001	<0.001	<0.001
		Forage*N rate	0.070	0.002	0.017
		Time	<0.001	<0.001	<0.001
		Forage*Time	0.005	0.022	0.120
		N rate*Time	0.012	0.832	0.220
		Forage*time*Nrate	0.145	0.290	0.700

Herbage measurements

At each harvest samples were taken from each plot at 0700 and 1600 hours. A 1 m strip was cut at grazing height (4 cm) using electric hand-shears. Each sample was frozen and freeze-dried before being ground through a 1 mm sieve using a M200 rotor mill (Retsch Inc. Newtown, Pennsylvania, USA). Ground samples were scanned by near infra-red reflectance spectrophotometer (NIRS, NIRSystems 5000, Foss, Maryland, USA) to determine crude protein (CP), water soluble carbohydrates (WSC), fibre (NDF) and digestibility (DOMD). NIRS calibrations were created using samples from this experiment and from Martin *et al.* (2017). However, when samples were outside the calibration spectrum, wet chemistry was conducted. Data for each plot were averaged seasonally. Harvests in spring occurred between 9 October 2014 and 30 October 2014. Summer harvests occurred between 24 November 2014 and 10 February 2015 and autumn harvests between 10 March 2014 and 18 May 2015.

Statistical analysis

Data were averaged for each treatment seasonally. Data were analysed by spilt-split plot ANOVA using Genstat (VSN International LTD. 2102) with forage type as the whole plot, N rate as the split-plot and time of day as the split-split plot. Differences were considered significant at P<0.05.

Results

Crude protein

The CP concentration of white clover (average 264 g/kg DM) was the highest of all species and was unaffected by N fertiliser. Increasing N fertiliser inputs increased (P<0.001) the CP concentration of ryegrass, chicory and plantain by an average of 29 g/kg DM across all seasons (Table 2). The increase in CP with increasing fertiliser inputs for ryegrass, chicory and plantain was lower in spring (+ 13 g CP/kg DM) than summer (+ 30 g CP/kg DM) or autumn (+ 26 g CP/kg DM). Herbs had greater (P<0.001) CP concentration (average 184 g/kg DM) than ryegrass (average 166 g/kg DM) in autumn

Table 3 Mean herbage water soluble carbohydrate (WSC) concentration (g/kg DM) of forages cut between 9 October and 30 October 2014 (spring), 24 November 2014 and 10 February 2015 (summer) or 10 March and 18 May 2015 (autumn) in the morning (AM) or afternoon (PM) at low and high N fertiliser inputs.

N inputs	Harvest Time	Forage	Spring	Summer	Autumn
Low	AM	Ryegrass	230	274	161
		Chicory	190	152	143
		Plantain	210	179	164
		White Clover	194	132	156
	PM	Ryegrass	295	333	234
		Chicory	241	189	202
		Plantain	227	202	214
		White Clover	225	163	193
High	AM	Ryegrass	192	222	142
		Chicory	186	151	151
		Plantain	202	176	177
		White Clover	175	149	165
	PM	Ryegrass	255	259	189
		Chicory	228	204	204
		Plantain	227	208	203
		White Clover	225	166	181
	SEM		4.2	3.2	2.6
Probabilities		Forage	0.033	<0.001	0.013
		N rate	0.021	0.021	0.019
		Forage*N rate	0.138	0.001	0.003
		Time	<0.001	<0.001	<0.001
		Forage*Time	<0.001	0.002	0.004
		N rate*Time	0.727	0.524	0.005
		Forage*time*Nrate	0.418	0.020	0.688

and summer. Across all seasons the CP concentration of grasses and herbs was reduced on average by 16 g CP/kg DM by harvesting in the afternoon regardless of N fertiliser rate. Chicory tended to have a greater CP concentration than plantain and a greater concentration of CP at the higher N rate in summer.

Water soluble carbohydrates

Increasing N inputs reduced (P=0.030) the WSC concentration of grasses by 39 g/kg in spring, 30 g/kg DM summer and 63 g/kg in autumn (Table 3). There was no N input effect on WSC concentration for herbs or legumes. White clover, chicory and plantain tended to have a lower WSC concentration than ryegrass across all seasons and treatments. Across all seasons, there was an increase in the WSC concentration from morning to afternoon for all species which was not affected by N rate. The effect of time of day on WSC concentration was different for each species. Ryegrass showed the greatest increase in WSC concentration diurnally. In autumn and spring, the increase in WSC concentration from morning to afternoon was close to twice that as the increase for herbs and about three times that in white clover. In spring and summer the increase in WSC concentration from morning to afternoon was greater (P=0.038) for chicory than plantain.

Fibre

The average concentration of NDF was two times greater for ryegrass than plantain, chicory or white clover across all seasons regardless of N rate (Table 4). The effect of time of day and N fertiliser on fibre concentration was inconsistent across forage types and seasons. In autumn and spring the diurnal reduction in NDF concentration of ryegrass was the greatest (P<0.001) of all forage types (average -26 g NDF/kg DM). There was no time of day effect on the NDF concentration of plantain in autumn or spring. The effect of harvest time on NDF concentration in summer was similar (P=0.082) for all forages. There was no effect on N fertiliser on the NDF concentration for all forages in in autumn and summer. In spring there was a small (>10 g NDF/kg DM) but significant (P=0.004) reduction in NDF with increasing N inputs for all forages.

Digestibility

There was no influence of N fertiliser rate on DOMD for all species across all seasons (Table 5). Across all seasons chicory and white clover had the highest (P=0.002) DOMD regardless of harvest time. There was no diurnal influence on the DOMD of chicory and plantain in spring. In autumn the diurnal increase in DOMD was greatest for ryegrass (+ 29 g/kg DM), intermediate for chicory (+ 24 g/kg DM) and lowest for plantain and white clover (+ 14 and 11 g/kg DM, respectively). The diurnal increase in DOMD was similar for chicory and plantain (+ 16 and 10 g/kg DM, respectively) in summer. This was lower than the diurnal increase in DOMD ryegrass (+ 29 g/kg DM) and white clover (+ 25 g/kg DM) in summer.

WSC:CP ratio

The ratio of WSC to CP for all pasture species had a large seasonal variation (Table 6). White clover consistently had the lowest WSC:CP which was typically less than half that of the WSC:CP of ryegrass. For all seasons and pasture species, the WSC:CP ratio was increased by harvesting in the afternoon. Across all seasons and management treatments ryegrass had the highest WSC:CP which only fell below 1.0 for samples harvested in the morning during autumn.

Discussion

The aim of this study was to investigate the effects of time of day and N fertiliser inputs on chemical composition of four different forage species. Nitrogen inputs had little effects on the chemical composition of the forages. Increasing N fertiliser inputs did not improve DOMD and WSC nor reduce NDF concentration of any of the forages. Unsurprisingly, and similar to previous research (Elgersma & Hassink 1997; Martin *et al.* 2017) there was an increase in CP for ryegrass, chicory and plantain when N fertiliser inputs were increased and no effect of N fertiliser on the CP of

Table 4 Mean herbage neutral detergent fibre (NDF) concentration (g/kg DM) of forages cut between 9 October and 30 October 2014 (spring), 24 November 2014 and 10 February 2015 (summer) or 10 March and 18 May 2015 (autumn) in the morning (AM) or afternoon (PM) at low and high N fertiliser inputs.

N inputs	Harvest Time	Forage	Spring	Summer	Autumn
Low	AM	Ryegrass	424	466	455
		Chicory	183	231	186
		Plantain	248	302	237
		White Clover	222	270	231
	PM	Ryegrass	391	434	431
		Chicory	158	227	185
		Plantain	221	303	233
		White Clover	215	254	218
High	AM	Ryegrass	403	467	443
		Chicory	176	227	202
		Plantain	228	297	236
		White Clover	216	263	225
	PM	Ryegrass	401	442	426
		Chicory	144	225	186
		Plantain	198	291	240
		White Clover	212	259	223
	SEM		6.0	4.4	5.1
Probabilities		Forage	<0.001	<0.001	<0.001
		N rate	0.004	0.537	0.767
		Forage*N rate	0.207	0.608	0.065
		Time	<0.001	0.002	<0.001
		Forage*Time	0.082	0.008	0.007
		N rate*Time	0.205	0.486	0.419
		Forage*time*Nrate	0.083	0.761	0.060

Table 5 Mean herbage digestibility of organic matter (DOMD) concentration (g/kg DM) of forages cut between 9 October and 30 October 2014 (spring), 24 November 2014 and 10 February 2015 (summer) or 10 March and 18 May 2015 (autumn) in the morning (AM) or afternoon (PM) at low and high N fertiliser inputs.

N inputs	Harvest Time	Forage	Spring	Summer	Autumn
Low	AM	Ryegrass	781	753	757
		Chicory	808	770	812
		Plantain	774	728	775
		White Clover	807	753	806
	PM	Ryegrass	808	785	790
		Chicory	807	783	833
		Plantain	773	733	795
		White Clover	822	787	820
High	AM	Ryegrass	787	742	758
		Chicory	809	775	812
		Plantain	792	740	783
		White Clover	816	761	814
	PM	Ryegrass	796	769	783
		Chicory	817	794	839
		Plantain	788	753	792
		White Clover	823	777	823
	SEM		2.0	4.4	5.1
Probabilities		Forage	0.002	0.002	<0.001
		N rate	0.11	0.574	0.161
		Forage*N rate	0.277	0.146	0.197
		Time	0.002	<0.001	<0.001
		Forage*Time	0.007	0.032	0.006
		N rate*Time	0.208	0.749	0.231
		Forage*time*Nrate	0.099	0.329	0.286

white clover. This suggests altering N fertiliser inputs is not a beneficial management practice to improve forage quality (DOMD and WSC). The effect of harvest time on WSC, NDF and DOMD of all forages was greater than the effect of N fertiliser.

Diurnal changes in chemical composition of ryegrass have been previously used to create an increase in the concentration of WSC at the expense of CP with a goal of increasing the utilisation efficiency of dietary N (Miller *et al.* 2001; Moorby *et al.* 2006). The reduction in both CP and NDF as WSC increases would be favourable to animals grazing pastures in New Zealand in most circumstances. Experiments which utilised diurnal changes in plant chemical composition have inconsistently shown reductions in urinary N concentrations (Miller *et al.* 2001; Bryant *et al.* 2014). In the current experiment, forage types showed differences in their concentration of WSC and their diurnal accumulation of WSC. While harvesting in the afternoon increased the WSC concentrations of all species, ryegrass had the greatest accumulation of sugars diurnally. This did not always translate to larger reductions in CP compared with the other forages. For ryegrass, chicory and plantain, the average diurnal change in CP was small (<16 g CP/kg DM), however, when combined with the diurnal increase in WSC the WSC:CP ratio was altered.

Edwards *et al.* (2007) suggested a WSC:CP ratio above *c.* 0.7 can lead to a direct reduction in the proportion of N intake excreted in urine. This occurred for grasses and herbs in spring and summer, however, the WSC:CP ratio of legumes was typically below 0.7 across all seasons. There was a strong effect of harvesting in the afternoon on the WSC:CP ratio in autumn which was consistent across all species although greatest for ryegrass. This higher WSC:CP ratio in the afternoon may increase microbial protein synthesis efficiency and nitrogen-use efficiency of dairy cows (Vibart *et al.* 2012), as herbage provides more rapidly fermentable carbohydrates (Hristov *et al.* 2005) and produces less ammonia in the rumen (Tamminga 1996). The larger diurnal accumulation of WSC for ryegrass suggests that afternoon allocation was more important for ryegrass than chicory or plantain.

Table 6 Mean herbage WSC:CP ratio of forages cut between 9 October and 30 October 2014 (spring), 24 November 2014 and 10 February 2015 (summer) or 10 March and 18 May 2015 (autumn) in the morning (AM) or afternoon (PM) at low and high N fertiliser inputs.

N inputs	Harvest Time	Forage	Spring	Summer	Autumn
Low	AM	Ryegrass	1.5	2.3	0.9
		Chicory	1.2	0.9	0.7
		Plantain	1.3	1.3	0.8
		White Clover	0.8	0.5	0.5
	PM	Ryegrass	0.9	1.5	0.6
		Chicory	1.0	0.7	0.6
		Plantain	1.1	1.1	0.9
		White Clover	0.6	0.6	0.6
High	AM	Ryegrass	2.1	3.0	1.4
		Chicory	1.5	1.2	1.1
		Plantain	1.6	1.6	1.2
		White Clover	0.9	0.7	0.7
	PM	Ryegrass	1.5	1.8	0.9
		Chicory	1.2	1.1	0.9
		Plantain	1.4	1.4	1.1
		White Clover	0.9	0.7	0.6
	SEM		0.55	0.50	0.23
Probabilities		Forage	0.001	<0.001	<0.001
		N rate	<0.001	<0.001	<0.001
		Forage*N rate	0.006	<0.001	0.006
		Time	<0.001	<0.001	<0.001
		Forage*Time	<0.001	<0.001	0.002
		N rate*Time	0.907	0.004	0.006
		Forage*time*Nrate	0.247	0.003	0.532

Under summer irrigation, grasses grown in Canterbury may not meet the CP requirements of high producing cows. In summer ryegrass at the lower N rate had an average CP concentration of 119 g CP/kg DM which is below the CP requirement for a high producing dairy cow (CSIRO 2007). At this time, increasing N inputs from 180 kg N/ha/year to 450 kg N/ha/year increased the CP concentration of ryegrass, chicory and plantain by an average of 3.2 g CP/kg DM. Chicory and plantain at low N inputs in summer had a higher average CP concentration (153 g CP/kg DM) than ryegrass (119 g CP/kg DM), which is consistent with the results of previous studies (Sanderson *et al.* 2003; Belesky *et al.* 2004). Where N fertiliser use is limited herbs may provide a suitable alternative to meet CP requirements. Chicory had the highest CP concentration regardless of N fertiliser rate or harvest time. This is consistent with findings of Martin *et al.* (2017) who showed chicory had a greater N concentration than plantain or ryegrass across fertiliser inputs ranging from 0 to 450 kg N/ha/year. This may lead to higher N intakes from chicory per unit of DM consumed compared with ryegrass or plantain. Despite this increased CP concentration, grazing experiments which include chicory in the diet of dairy cows have consistently shown a reduction in urinary N concentration (Totty *et al.* 2013; Bryant *et al.* 2017; Minneé *et al.* 2017) which suggests factors other than CP intake may drive lower N excretion in livestock grazing pasture containing chicory.

Fibre content for all pasture species increased over the summer. This was particularly prevalent in the grass species. For all forage types the proportion of NDF could be reduced by harvesting in the afternoon but could not be altered by N fertiliser. The diurnal reduction in NDF (average 13 g/kg DM) was typically larger than the average reduction in CP (10 g/kg DM). This diurnal reduction in NDF was generally greatest for ryegrass. The reduction in NDF, combined with a reduction in CP offset the diurnal increase in WSC. This contrasts with the findings of Cosgrove *et al.* (2009), who reported that a diurnal increase in WSC in three ryegrass cultivars was largely offset by reduction in CP and to a lesser extent NDF. Despite the differences both experiments show the potential of increased WSC concentration to enhance the nutritional value of forages, in particular ryegrass. For chicory, plantain and white clover the proportion of NDF was always below the recommended 35% for adequate rumen function (CSIRO 2007). The lower NDF of chicory and plantain has been recorded before in dairy grazing experiments (Totty *et al.* 2013; Box *et al.* 2016) where milk production was similar or greater, indicating that the low NDF of herbs or mixed swards was not negatively affecting milk production.

Conclusions

The diurnal effect on chemical composition was greater than the effects of N fertiliser inputs. Ryegrass showed the greatest diurnal accumulation of WSC concentration. However, this did not always translate to the largest reduction in CP from morning to afternoon as NDF reduction were typically greater than reductions in CP. In autumn, there was a strong effect of harvesting forages in the afternoon on WSC:CP, particularly for ryegrass. Afternoon allocation of ryegrass may offer a strategy to enhance the nutritive value of forages. Allocation timing appears to be less important for chicory and plantain.

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Variable and differential application of nutrients to a hill country farm

J.D. MORTON and A.G. GILLINGHAM
MortonAg, 27 Waimakariri Drive, Napier 4110, New Zealand
Research Consultant, 92 Waicola Drive, Palmerston North, New Zealand
mortonag@vodafone.co.nz

Abstract

Traditionally fertiliser has been aerially applied at a uniform rate to hill country, but the technology now exists to apply nutrients at a variable rate (VR) and each nutrient differentially, depending on the production potential and pasture composition of each part of the hill. A hypothetical case study of a sheep farm was modelled to show the economic benefits of VR application of phosphorus (P) and sulphur (S) and differential application of nitrogen (N), compared with application of a uniform rate of P and S. The financial analysis demonstrates that the VR strategy of less P and S to steeper slopes where there is low legume and more on easier slopes where there is more legume, costs less than the application of P and S at a uniform rate over all slopes. The cost saving could be used to apply N to steep land on both sunny and shady aspects and easy land on sunny aspects. This differential N application in late winter/early spring ensures better pasture cover for lactating ewes to improve ewe condition at weaning. When this gain in condition was maintained through to mating, lambing percentage increased in the following spring. The benefit from this increased lamb production was an increase in financial returns of $63/ha/year. A qualitative sensitivity analysis indicated that this value remains stable in response to changes in the proportion of each slope class, soil Olsen P level, the relative cost of fertiliser P and N and sheep to cattle ratio.

Keywords: differential application, hill country, lamb production, nitrogen, phosphorus, aerial topdressing, variable rate

Terminology

Variable rate (VR) fertiliser application occurs when the same nutrients, normally P and S, are flown onto an area at different rates according to the production potential and stocking rate of each slope class. The slope ranges of the area were identified using a Digital Elevation Map, and quadrats (normally representing not less than 0.5 ha) are allocated one slope class in a prescription map, if they have the largest proportion of the area within that class (Morton *et al*. 2016).

Differential nutrient application occurs when one fertiliser nutrient, usually N, is applied to certain parts of the farm, usually steep slopes or sunny aspects where the pasture production response is greatest (Gillingham *et al*. 1998).

Introduction

Fertiliser is a discretionary cost in a sheep and beef farm budget and is frequently reduced in years where income is limited by poor returns or adverse climatic events. With the prospect of no consistent inflation-adjusted increase in meat and wool prices, the only way of ensuring that adequate fertiliser is applied is to improve the efficiency of nutrient use. While fertiliser has been traditionally spread at a uniform rate, the aircraft technology now exists to apply nutrients both at a variable rate and differentially to different parts of a hill country farm, depending on production potential and pasture composition (Murray & Yule 2007; Morton *et al*. 2016; White *et al*. 2017).

Nearly all hill country requires P and S to sustain legume and pasture growth. A uniform application rate of P and S results in a mis-match between the variable requirement of the pasture, depending on production potential that determines stocking rate, and the uniform rates traditionally applied in fertiliser (Gillingham *et al*. 1998). Variable rate application allows fertiliser P and S rates to be adjusted, usually on the basis of slope, which is the main determinant of pasture production (Lambert *et al*. 1983); flatter areas with better legume growth receiving more than steeper areas with poorer legume growth.

Several trials have shown a high efficiency of response in pasture production to fertiliser N in hill country, especially on steeper slopes with less soil N (Morton *et al*. 2016).

This paper investigates the economic benefits of VR and differential nutrient application, by applying them optimally to a case study hill sheep farm in a modelling exercise.

Methodology

The case study farm had a total area of 600 ha - 200 ha of flat within the hill landscape, 200 ha of easy hill (12-25 degree slope) comprising 100 ha each of sunny (north and west aspects) and shady (south and east aspects), and 200 ha of steep hill (>26 degrees slope) comprising 100 ha each of sunny and shady aspect, all on sedimentary soils with adequate soil potassium.