

EFFECT OF URINE, POTASSIUM AND DICYANDIAMIDE (DCD) APPLICATION ON PASTURE PRODUCTION FROM A FREE- DRAINING CANTERBURY DAIRY PASTURE SOIL

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Abstract

A cut-and-carry trial was conducted on a low Quick-test-potassium (QTK ≤ 4) Lismore soil during 2012-13 in Springston, Canterbury to test the responsiveness of a dairy pasture to urine, dicyandiamide (DCD) and potassium (K) applications. Over the full year the applications of urine-only, urine+K, urine+DCD, and urine+DCD+K increased pasture production significantly over the non-urine control treatment by 23%, 29%, 36% and 42%, respectively. Applications of K, DCD and DCD+K increased production over the urine-only treatments by 5%, 10% and 15%, respectively, for both spring and full-year totals. There were no significant increases to K or DCD applications for non-urine treatments.

The pasture responses to K and DCD applications were attributed to maintaining better balanced plant nutrition, rather than to soil K deficiency per se, as urine application maintained QTK levels to recommended values (QTK ~ 6) for the duration of the trial. However, K deficiency may still have occurred at times of high demand where K uptake was restricted by the shallow soil depth. Whilst these differences were considered to have their roots, at least partly, in K nutrition, it may also reflect differences that are particular to cut-and-carry trial management and measurement. Continual harvesting of DM reduces K availability quickly in some soils even after large initial K applications in urine (>800 kg K/ha). The findings of this cut-and-carry trial show that regular K application can increase pasture DM responses both to applied urine-N and the use of a nitrification inhibitor, and not just when soil K levels are low.

Keywords

Nitrogen uptake, nutrient interaction, nitrification inhibitor, dry-matter response, potassium uptake

Introduction

The benefits of applying nitrification inhibitors such as dicyandiamide (DCD) to grazed pastures to reduce nitrous oxide emissions and nitrate leaching from animal urine spots has been well documented over the last ten years (Di & Cameron 2002; Di & Cameron 2005; Di et al. 2007). However, pasture dry-matter (DM) responses to DCD application have been somewhat more varied, ranging from 0-20% (Cookson & Cornforth 2002; Moir et al. 2007; Menneer et al. 2008; Carey et al. 2012). Explanations for these differences vary, ranging from the regional effects of temperature, moisture and timing of DCD application on inhibitor persistence, to the effect of differing measurement protocols (Menneer et al. 2008; Snow et al. 2011). Recently two papers have been published reporting quite different DM responses to DCD-application, one summarising results from on-farm field-scale grazing measurements

(Carey et al. 2012), and the other from a series of small-plot cut-and-carry trials (Gillingham et al. 2012). Whilst Carey et al. (2012) reported DM increases of 19%, overall, for DCD-treated paddocks (132 individual paddocks), Gillingham et al. (2012) reported non-significant differences for the majority of the small-plot trials.

One theory for the different DM responses to DCD applications might be the interaction of potassium (K) with the nitrogen (N) retained by DCD application, especially in frequently cut pastures that are K-limited or deficient. Dry-matter responses to K application in New Zealand have been shown to occur through a combination of factors including N x K interactions, low exchangeable-K (QTK \leq 6) and/or low reserve-K (\leq 1 cmol/kg soil), restricted soil depth, and K removal in cut and carry systems (e.g. under mown pasture trials) (Williams et al. 1986; Morton et al. 1999; Morton et al. 2001; Carey & Metherell 2003a; Carey et al. 2011). Over 50 years ago During and McNaught (1961) in a cut-and-carry trial, showed that urine application, containing the equivalent of ~600 kg K/ha, protected the pasture from K deficiency symptoms for little more than a year, despite only modest levels of production (~7 tonnes DM/ha). In cut-and-carry trials, large amounts of K are removed in herbage and if these are not adequately replaced then exchangeable-K can be run down quickly (Carey & Metherell 2003a). In typical dairy-urine application trials, around 700 and 800 kg of N and K per ha are applied, respectively, and this has probably been thought sufficient to counteract any prospect of K deficiency. In most field leaching experiments, however, urine application is often timed to coincide with maximum drainage, rather than maximum pasture growth, so opportunities for losses of K through leaching and/or fixation are potentially high (During & McNaught 1961). If pasture is being continually removed (~350 kg K; ~14,000 kg DM x 2.5% K), K leaching losses significant and side-dressings of K are inadequate, then a DM response could occur.

In a glasshouse experiment using 15 cm soil cores, Williams et al. (1989) found large losses of urinary K and N (~48% of total applied) in collected leachate with only 41% and 52% of the K and N applied, respectively, recovered in herbage. Pasture uptake of K was approximately equivalent to the difference in the initial exchangeable-K increase after urine deposition, and exchangeable-K at season's end (similar to initial), but the remainder was assumed largely lost through leaching. Similarly, During and McNaught (1961) indirectly showed that leaching losses of K were potentially large with little more than 20% of applied K found in pasture. However, these reports appear to be at odds with other New Zealand studies where there is evidence showing relatively low-to-modest leaching losses of K under urine spots for intensive grazing studies (Hogg 1981; Steele et al. 1984; Close & Woods 1986; Williams & Roberts 1988; Early et al. 1998). In fact, this difference may depend on interpretation of "loss" and whether the K retained within the soil profile remains available for plant uptake. In a field study of 11 dairy soils, Monaghan et al. (1999) found that whilst significant losses of K of up to 68% (average 17%) could occur through preferential leaching below 20 cm, it was not necessarily lost to plant uptake, although this was very much predicated on K uptake occurring from the old root channels where leachate and new roots intersected. The objective of this study was, therefore, to test the hypothesis that the lack of pasture response to DCD treatments in some cut and carry plot trials is due to a K limitation relative to N supply.

Materials and Methods

Site and soil characteristics

The trial site was situated on a long-standing Canterbury dairy farm near Springston (43.38° 20' S, 172.21° 58' E), 17 km south-west of Christchurch with a mixed perennial ryegrass/white clover pasture on a free-draining, moderately shallow Lismore soil (Pallic Firm Brown). The site was chosen principally for its low quick-test K value (~4) and potential responsiveness to K application. Key chemical properties of the soil pre-trial are shown in Table 1. Lismore soils are generally shallow silt loams and droughty without irrigation (Cutler 1968). The site was relatively stone-free to about 20 cm but increasingly stony below. Annual rainfall is approximately 650 mm but irrigation (~500 mm annually) is applied approximately fortnightly over the main growth season using a 'roto-rainer' irrigator (45 mm per irrigation).

Table 1. Key soil chemical test results for the trial site Lismore soil (0-7.5 cm).

^a pH	6.1
Olsen-P	28 mg/L
Quicktest -Ca	8
Quicktest-Mg	29
Quicktest -K	4
Quicktest-Na	11
CEC	16 cmol/kg
Reserve-K	3.6 cmol/kg
Sulphate-S	14 mg/kg
Organic-S	5 mg/kg
Base saturation	65%

^a Soil test methods according to Blakemore (1987) except reserve-K test (Carey & Metherell 2003b).

The site was fenced off from grazing, mowed and pegged out in early April 2012 and treatments were applied in late May 2012. Because of the large volume required, a synthetic urine solution was prepared as outlined by Clough et al. (1998) containing a dissolved mixture of urea, glycine (90:10 N content), potassium -bicarbonate, -chloride and -sulphate. Individual plots were 2.5 m² in area (5 m x 0.5 m; 0.5 m buffer between) and treatments were replicated 17 times in a randomised block design consisting of a 2x2x2 factorial; ±urine (1x 700 kg N/ha; 1x 860 kg K/ha), ±DCD (2x 10 kg Al/ha) and ±K (7x 40 kg K/ha as potassium chloride). The large degree of replication was intended to overcome any effects due to previous grazing although this was not particularly apparent as cows had not grazed the area for approximately three months prior to treatment application. Urine was applied at the rate of 10 L/m² by watering can whilst DCD was sprayed as a fully dissolved solution a day after urine application and again, separately, in late July. The potassium chloride treatments were applied after each of the first three harvests but then every second harvest (7x 40 kg/ha) once quick-test-K levels reached 9-10. Fertiliser urea was applied after every harvest (8x 20 kg N/ha) to every plot to simulate typical South Island dairy farm practice. The treatments are shown in Table 2.

Table 2. Summary of trial treatments

	<i>Urine</i> (kg N,K/ha)	<i>DCD</i> (kg AI/ha)	<i>KCl</i> kg K/ha
1. Control	0/0	0	0
2. Control+DCD	0/0	20	0
3. Control+K	0/0	0	280
4. Control+DCD+K	0/0	20	280
5. Urine	700/860	0	0
6. Urine+DCD	700/860	20	0
7. Urine+K	700/860	0	280
8. Urine+DCD+K	700/860	20	280

Pasture and soil measurements

Harvests were conducted approximately monthly once the main growing season began and consisted of a single 5 m long mown strip, approximately 0.5 wide, that was weighed, and a subsample taken for DM content and chemical analysis. Two qualitative clover surveys were conducted in October 2012 and March 2013 measuring clover proportion by cover using one 0.2 m² quadrat per plot placed 0.5 m in from start of each plot. Total-N and organic-C were measured in the dried pasture samples using an Elementar Vario-Max CN Elemental Analyser whilst pasture-K was determined after a nitric-acid/hydrogen peroxide microwave digestion (CEM MARS Xpress) using a Varian 720 ICP-OES (Inductively coupled plasma optical emission spectrophotometer). Pasture production and uptake of K and N were calculated from these measurements. Soil sampling (0-10 & 10-20 cm) of 6 of the 17 blocks was undertaken at the completion of the experiment and samples sent for reserve-K (Carey & Metherell 2003b) and exchangeable-K analysis (Blakemore et al. 1987). Standard soil tests were also performed on bulked treatment replicates in July and at the end of the trial. Statistics used analysis of variance for all individual harvests and cumulative totals using the Genstat (9th ed., version 9.1.0.150) statistical program (GenStat Committee 2009). Duncan's multiple range test was also used for detecting individual treatment differences. Means and least significant differences (LSD) are reported at the main and interaction level.

Results and discussion*Dry-matter production*

Unsurprisingly, application of urine significantly increased ($P < 0.001$) total and spring DM production but DCD and potassium chloride application also increased production ($P < 0.01$ - 0.001) as main effects (Figure 2 & Table 3). There were individual urine+DCD, DCD+K and urine+K interactions in some harvests but only the urine+DCD interaction was significant for the full season ($P < 0.001$). Multiple range comparisons for individual treatment totals using Duncan's test showed that the effect of K application on DM production was greatest for the urine treatments ($P < 0.05$) with effects between individual non-urine treatments not significant (Table 3). Generally, there were few significant effects between non-urine treatments for totals or individual harvests. Over the spring growth period (cuts 1-5), pasture production was 32% greater in the urine-only treatment compared to the non-urine treatment. Over the same period pasture production was 39%, 45% and 51% higher for the urine plus K, DCD and DCD+K treatments, respectively, compared to the control non-urine treatment. Over the full

year the increase in pasture production in the urine-only treatment over non-urine was 23%, and 29%, 36% and 42%, for urine plus K, DCD and DCD+K treatments, respectively (Table 3). Applications of K, DCD and DCD+K increased production over the urine-only treatment by 5%, 10% and 15%, respectively, for both spring and full-year totals (Table 3) although by cut 7 the DM production for urine and non-urine treatments was largely similar.

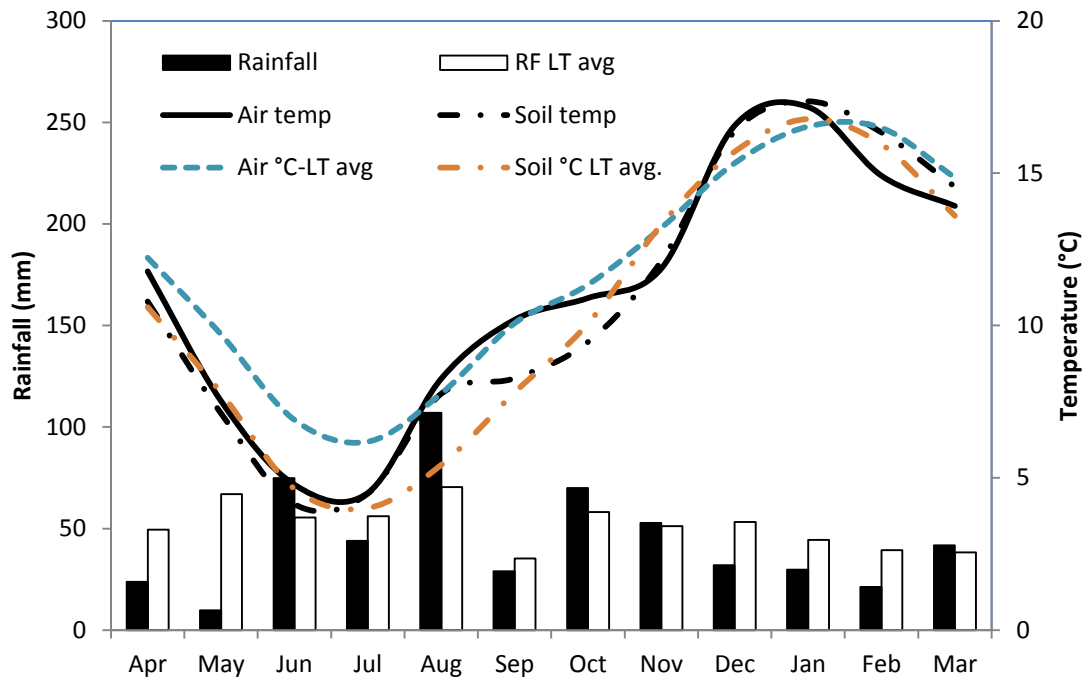


Figure 1. Monthly rainfall and mean air and soil temperatures (10 cm) for trial period compared with Lincoln long-term (LT) 30 year averages (1981-2010).

Dry-matter responses to K might seem surprising given that the urine-treated pasture received over 800 kg K/ha in a single application but K depletion in a cut-and-carry regime under similar conditions has been reported before (During & McNaught 1961). Without urine application there was no significant effect of DCD and/or K application on DM production and although urea was applied after every harvest it seems this was insufficient to provide much by way of an additional DM response to applied K. Ledgard et al. (1982) also found on a Waikato dairy pasture that at low N application rates, and less than optimal QTK values, K application did not significantly affect DM yields. Significant interactions for DM production were only observed in harvest 3 for urine-x-K, and in harvests 5 and 6 for DCD-x-K, although these represented about 20% and 24%, respectively, of total DM production. The former represents a time of likely maximum N availability and rapid pasture growth whilst the latter denotes a time when DCD would be expected have its biggest impact (Nov-Jan) having prolonged N availability (Sprosen et al. 2009). Unfortunately, it was also at this time that DM production declined abruptly obscuring any further DCD-x-K responses. Whilst DCD application has been shown to be particularly effective in reducing nitrous oxide gaseous losses and nitrate leaching under urine patches (Di & Cameron 2002, 2007) evidence to show that DCD use increases pasture production has also grown (Di & Cameron 2007; Moir et al. 2007; Carey et al. 2012).

Dry-matter production overall for the trial for the non-urine treatments at around 10 tonnes/ha was considerably lower than the norms indicated for the Canterbury region (~14-17 tonnes/ha) even allowing for the trial running less than a full year (11 months) and lower N application (160 kg N/ha) than the 200 kg N/ha used for the reference values (DairyNZ 2013). Although the trial was irrigated, the 2012-13 growing season fluctuated from the long-term means with a cooler than average winter and spring but a hotter summer, with rainfall over the main summer months only 60% of normal (Figure 1). Whilst total irrigation of 585 mm was applied, each application (~45 mm) was only sufficient to wet the upper 15-20 cm of the profile to field capacity. The presence of gravels below 20 cm meant upper soil layers dried out considerably between irrigations over the main summer period. Another possible reason was reduced N fixation from low clover coverage, and then nothing by way of animal excreta returns for almost 12 months creates other deficiencies or nutrient imbalances that reduce DM production and go towards explaining the anecdotal reports that cut-and-carry trials are less productive than equivalent grazing trials. The clover fraction remained low at below 2% for most treatments and did not change appreciably over the trial's duration. Consequently, it was not possible to conduct any robust statistical tests on treatment effects on clover composition. The benefits of good white clover coverage to DM production in New Zealand through improved pasture-N nutrition are well known (Brock & Hay 2001) and although K application might have expected to increase the clover presence, especially in deficient soils (Mosquera-Losada et al. 2004; Edmeades et al. 2010), it seems that the clover was too fragmented, and tillers too few, to bounce back within 10 months. Whether there were other contributing factors to the general absence of white clover such as clover weevil are unknown.

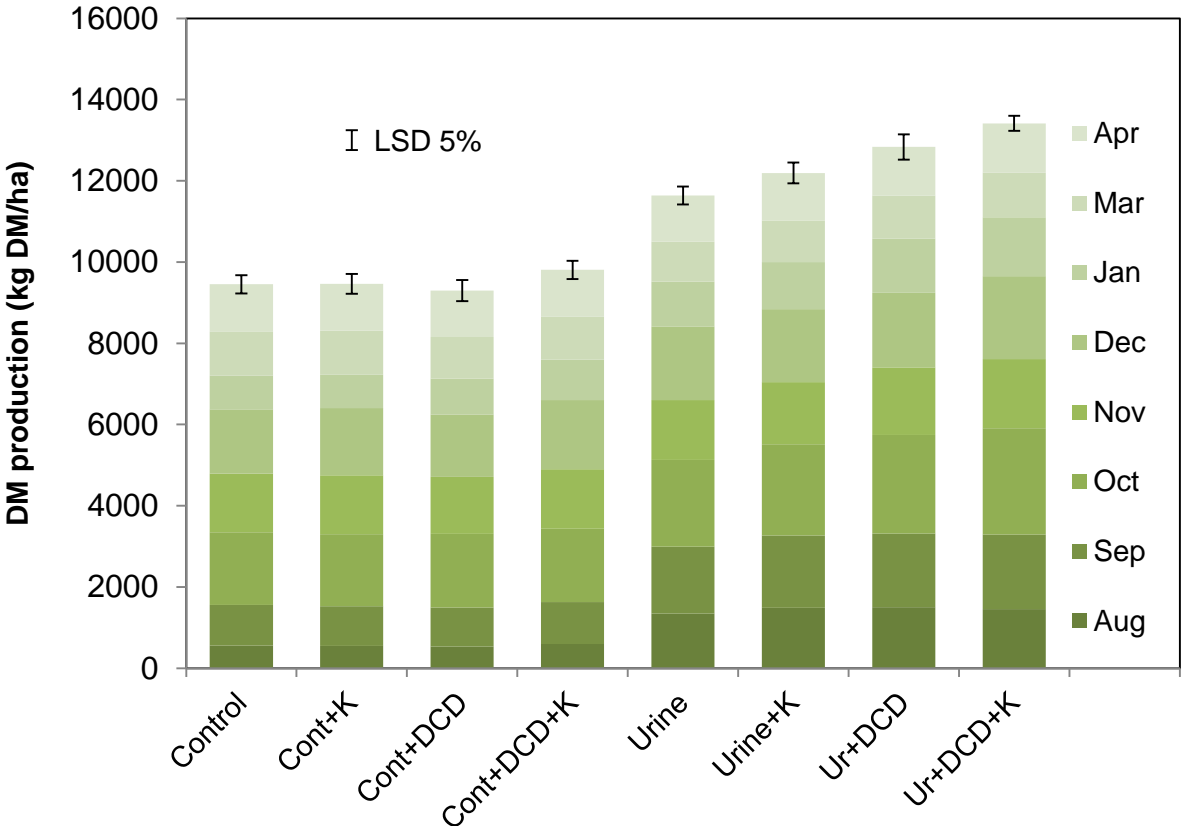


Figure 2. Total and individual DM harvest production for all trial treatments. Standard error and LSD (5%) bars for totals shown.

Table 3. Individual and total harvest DM means, relative yield (RY-Spring and Total) and total-K and -N uptake for all trial treatments and means of qualitative clover fraction survey. Statistical significance shown for main factors and interactions (LSD 5% at highest interaction level). Values followed by a differing letter are significantly different (P<0.05) using Duncan's multiple range test.

<i>Treatments</i>	<i>Cut 1</i>	<i>Cut 2</i>	<i>Cut 3</i>	<i>Cut 4</i>	<i>Cut 5</i>	<i>Cut 6</i>	<i>Cut 7</i>	<i>Cut 8</i>	<i>Spring</i>	<i>RY</i>	<i>Total</i>	<i>RY</i>	<i>K uptake</i>	<i>N uptake</i>	<i>Oct-12</i>	<i>Mar-13</i>	<i>Final QTK</i>
	kg/ha								kg/ha	%	kg/ha	%	kg/ha		Clover %		
Control	559	998	1786	1446	1586	823	1083	1171	6375	1.00	9452 a	1.00	152	286	1.3	1.9	4
Cont+K	551	979	1774	1451	1651	823	1083	1154	6404	1.00	9463 a	1.00	190	281	0.9	2.2	10
Cont+DCD	533	959	1818	1396	1543	879	1028	1140	6250	0.98	9297 a	0.98	145	282	0.9	1.3	4
Cont+DCD+K	599	1032	1800	1466	1702	998	1056	1154	6599	1.04	9807 a	1.04	190	295	2.1	1.5	7
Urine	1345	1650	2133	1471	1819	1102	980	1138	8418	1.32	11638 b	1.23	268	373	1.5	0.6	6
Uri+K	1487	1779	2249	1527	1798	1156	1031	1167	8839	1.39	12193 c	1.29	316	400	2.2	0.3	11
Uri+DCD	1503	1814	2428	1662	1834	1334	1060	1198	9241	1.45	12833 d	1.36	311	441	0.6	0.4	6
Uri+DCD+K	1451	1841	2619	1699	2040	1456	1065	1215	9650	1.51	13416 e	1.42	328	459	0.6	0.9	9
Urine	***	***	***	***	***	***	ns	ns	***	***	***	***	***	***	-	-	-
DCD	ns	ns	***	**	ns	***	ns	ns	***	**	***	***	*	***	-	-	-
K	ns	ns	*	ns	**	**	ns	ns	**	**	**	**	***	*	-	-	-
Urine*DCD	ns	ns	***	**	*	**	*	ns	***	***	***	***	ns	***	-	-	-
DCD*K	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	-	-	-
Urine*K	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	-	-	-
LSD (5%)	156	142	144	124	153	98	92	84	466	0.07	510	0.05	27	26	-	-	-

Nitrogen and potassium uptake and soil K measurements

Urine treatments received in excess of 800 kg N/ha from both urine and fertiliser-N application but only about half was recovered in pasture N uptake (Table 3). Whilst N uptake was up to 100% greater for urine over non-urine plots over the first three harvests (not shown), it slowly declined and by trial's end N uptake was only ~50% greater overall (~290 vs. ~420 kg N/ha). Strong statistical differences for urine, DCD and urine+DCD ($p < 0.001$) treatments were all recorded for N uptake whilst K application also enhanced N uptake ($p < 0.05$). Strong differences also occurred overall for K uptake for urine ($p < 0.001$) and fertiliser K application ($p < 0.001$), and to a lesser extent, DCD application ($p < 0.05$) with around 300 kg K/ha or ~80% more K (range 72%-114%) recovered in urine treatments than non-urine (~160 kg K/ha) by trial's end (Table 3). Potassium uptake on urine treatments was initially 2-3 times greater than non-urine treatments for the first 3 harvests but declined abruptly after (not shown). Final QTK measurements showed similar values to initial values for non-K treatments but urine treatment QTK values were ≥ 6 at the final harvest (Table 3).

Response mechanisms

By definition, K availability may have been at sufficiency levels (Roberts et al. 2009) but the overall size of this pool may still be limited by the reduced soil depth and a contributing factor to the DM response. In general, where there is high N availability, a near equivalent amount of K must also be present to maximise crop or pasture production and indeed this maxim has been at the forefront of balanced nutrition fertiliser studies studying crop N-x-K interactions (Gething 1993). Although K has been shown as important for a number of physiological functions in plants, a simple explanation for an increased DM response is that K^+ ions act as an accompanying cation carrier for NO_3^- ions from the roots to plant tissues (Bar-Tal 2011). Sinclair et al. (1996) and Morton et al. (1998) both showed for New Zealand mixed pastures that obtaining maximum DM response requires balanced nutrition. This implies that even where soil K levels might be considered adequate, if mineral-N is present in a disproportionately larger amount then production will be less than maximal. A second factor and obvious characteristic of any cut-and-carry trial is the continual removal of large quantities of nutrients in pasture herbage with K one of the largest. Under such regimes, rapid decreases in soil-K levels are likely to follow, especially if the soils are relatively shallow and of modest cation storage capacities. Studies showing pasture K uptake from depths well below the standard soil sampling zone demonstrate that this can be a significant contributor to total-K uptake (During & Campkin 1980; Carey & Metherell 2003a).

Conclusions

Potassium and DCD application both increased DM yield as main effects on urine-treated plots ($p < 0.01$ and 0.001 , respectively) in a cut-and-carry dairy pasture trial but not on non-urine treated plots. There was a DCD-x-K interaction pasture DM response in two harvests (5 & 6) but a large decrease in DM production following these two harvests meant no further significant responses were recorded and the interaction was not significant overall. This occurred at a time when the benefit of applying DCD might be expected to be greatest. Lack of vigour in later harvests of cut-and-carry trials after a year without grazing is not uncommon despite basal fertiliser application and may be a contributing factor to the lower responses reported for DCD application in a series of cut-and-carry trials summarised by Gillingham et al. (2012). Grazing trials such as those described by Carey et al. (2012) do not have to contend with the large scale removal of nutrients as in cut-and-carry trials since nutrients are re-deposited, albeit patchily, across the paddock, largely maintaining the nutrient status quo. Cut-and-carry trials, by their nature, do not have this nutrient re-cycling aspect. When used in conjunction with DCD application, there is evidence to show that K application in cut-and-carry trials can be crucial to fully evaluate the DM response effect of DCD treatments, whether to prevent K deficiency or to be in balance with N uptake.

References

- Bar-Tal A 2011. The Effects of Nitrogen Form on Interactions with Potassium. Nitrogen and Potassium Interactions. Switzerland, International Potash Institute. Pp. 9
<http://www.ipipotash.org/en/eifc/2011/29/3/english> (Accessed 27/1/2014)
- Blakemore LC, Searle PL, Daly BK 1987. Methods for Chemical Analysis of Soils. NZ Soil Bureau Report no. 80. 103 p. Lower Hutt.
- Brock JL, Hay MJM 2001. White clover performance in sown pastures: A biological/ecological perspective. Proceedings of the New Zealand Grasslands Association 63: 73-83.
- Carey PL, Metherell AK 2003a. Monitoring long-term changes in reserve potassium in some New Zealand soils using a modified sodium tetraphenyl-boron method. New Zealand Journal of Agricultural Research 46: 199-213.
- Carey PL, Metherell AK 2003b. Rates of release of non-exchangeable potassium in New Zealand soils using a modified sodium tetraphenyl-boron method. New Zealand Journal of Agricultural Research 46: 185-197.
- Carey PL, Curtin D, Scott CL 2011. An improved procedure for routine determination of reserve-K in pastoral soils. Plant and Soil 341: 461-472.
- Carey PL, Jiang S, Roberts AH 2012. Pasture dry matter responses to the use of a nitrification inhibitor: a national series of New Zealand farm trials. New Zealand Journal of Agricultural Research: 1-10.
- Close ME, Woods PH 1986. Leaching losses from irrigated pasture: Waiau-irrigation scheme, North Canterbury. New Zealand journal of agricultural research 29: 339-349.
- Clough TJ, Ledgard SF, Sprosen MS, Kear MJ 1998. Fate of ¹⁵N labelled urine on four soil types. Plant and Soil 199 (2): 195-203.
- Cookson WR, Cornforth IS 2002. Dicyandiamide slows nitrification in dairy cattle urine patches: effects on soil solution composition, soil pH and pasture yield. Soil Biology and Biochemistry 34 (10): 1461-1465.
- Cutler EJB 1968. Soils. In: Dixon JK ed. General Survey of Soils of the South Island, New Zealand. Wellington, Government Printer. Pp. 17-74.
- DairyNZ 2013. South Island. DairyNZ. Average Pasture Growth Data by Region (kg DM/ha/day). Accessed: 19/4/2013.
http://www.dairynz.co.nz/page/pageid/2145861167/Pasture_Growth_Data
- Di HJ, Cameron KC 2002. The use of a nitrification inhibitor, dicyandiamide (DCD), to reduce nitrate leaching from cow urine patches in a grazed dairy pasture under irrigation. Soil Use and Management 18: 395-403.
- Di HJ, Cameron KC 2005. Reducing environmental impacts of agriculture by using a fine particle suspension nitrification inhibitor to decrease nitrate leaching from grazed pastures. Agriculture, Ecosystems & Environment 109 (3-4): 202-212.
- Di HJ, Cameron KC 2007. Nitrate leaching losses and pasture yields as affected by different rates of animal urine nitrogen returns and application of a nitrification inhibitor—a lysimeter study. Nutrient Cycling in Agroecosystems 79: 281-290.
- Di HJ, Cameron KC, Sherlock R 2007. Comparison of the effectiveness of a nitrification inhibitor, dicyandiamide, in reducing nitrous oxide emissions in four different soils under different climatic and management conditions. Soil Use and Management 23: 1-9.

- During C, McNaught KJ 1961. Effects of cow urine on growth of pasture and uptake of nutrients. *New Zealand Journal of Agricultural Research* 4: 591-605.
- During C, Campkin R 1980. Sources of potassium taken up by ryegrass from some soils of the North Island. *New Zealand Journal of Agricultural Research* 23 (1): 85-91.
- Early MSB, Cameron KC, Fraser PM 1998. The fate of potassium, calcium, and magnesium in simulated urine patches on irrigated dairy pasture soil. *New Zealand Journal of Agricultural Research* 41 (1): 117-124.
- Edmeades DC, Morton JD, Waller JE, Metherell AK, Roberts AHC, Carey PL 2010. The diagnosis and correction of potassium deficiency in New Zealand pastoral soils: a review. *New Zealand Journal of Agricultural Research* 53 (2): 151-173.
- GenStat Committee 2009. *The Guide to GenStat Release12 - Parts 1-3*. VSN International. Oxford, UK.
- Gething PA 1993. *Improving Returns From Nitrogen Fertiliser- The Potassium-Nitrogen Partnership*. IPI Research Topics No. 13. 2nd revised ed^{ns}. Basel, Switzerland, International Potash Institute. Pp. 51.
- Gillingham AG, Ledgard SF, Saggart S, Cameron KC, Di HJ, de Klein CAM, Aspin MD 2012. Initial evaluation of the effects of dicyandiamide (DCD) on nitrous oxide emissions, nitrate leaching and dry matter production from dairy pastures. In: Currie LD, Christensen CL eds. *Advanced Nutrient Management: Gains from the Past - Goals for the Future*, Occasional Report No. 25: 1-16. <http://flrc.massey.ac.nz/publications.html>
- Hogg DE 1981. A lysimeter study of nutrient losses from urine and dung applications on pasture. *New Zealand Journal of Experimental Agriculture* 9 (1): 39-46.
- Ledgard SF, Saunders WMH 1982. Effects of nitrogen fertiliser and urine on pasture performance and the influence of soil phosphorus and potassium status. *New Zealand Journal of Agricultural Research* 25 (4): 541-547.
- Menner JC, Sprosen MS, Ledgard SF 2008. Effect of timing and formulation of dicyandiamide (DCD) application on nitrate leaching and pasture production in a Bay of Plenty pastoral soil. *New Zealand Journal of Agricultural Research* 51: 377-385.
- Moir JL, Cameron KC, Di HJ 2007. Effects of the nitrification inhibitor dicyandiamide on soil mineral N, pasture yield, nutrient uptake and pasture quality in a grazed pasture system. *Soil Use and Management* 23: 111-120.
- Monaghan RM, Carey P, Metherell AK, Singleton PL, Drewry J, Addison B 1999. Depth distribution of simulated urine in a range of soils soon after deposition. *New Zealand Journal of Agricultural Research* 42 (4): 501-511.
- Morton JD, Smith LC, Morrison JD 1998. Clover nutrient ratios to monitor pasture yield responses to fertiliser nutrients. *Proceedings of the New Zealand Grassland Association* 60: 141-148.
- Morton JD, Smith LC, Metherell AK 1999. Pasture yield responses to phosphorus, sulphur, and potassium applications on North Otago soils, New Zealand. *New Zealand Journal of Agricultural Research* 42 (2): 133-146.
- Morton JD, Smith LC, Dodds KG, Catto WD 2001. Balanced and adequate potassium and phosphorus nutrition of pasture. *New Zealand Journal of Agricultural Research* 44 (4): 269-277.
- Mosquera-Losada MR, Gonzalez-Rodriguez A, Rigueiro-Rodriguez A 2004. Fertilization with nitrogen and potassium on pastures in temperate areas. *Journal of Range Management* 57 (3): 280-290.

- Roberts AHC, Morton J, Edmeades DC (eds). 2009. Fertiliser Use on New Zealand Dairy Farms. Revised 2009 edn. Hamilton, Fert Research. 52 p.
- Sinclair AG, Smith LC, Morrison JD, Dodds KG 1996. Effects and interactions of phosphorus and sulphur on a mown white clover/ryegrass sward 1. Herbage dry matter production and balanced nutrition. *New Zealand Journal of Agricultural Research* (39): 421-433.
- Snow VO, Shepherd MA, Cichota R, Vogeler I 2011. Urine timing: Are the 2009 Waikato results relevant to other years, soils and regions? In: Currie LD, Christensen CL eds. Adding to the knowledge base for the nutrient manager, Occasional Report No. 24: 1-14. <http://flrc.massey.ac.nz/publications.html>
- Sprosen MS, Ledgard SF, Lindsey SB 2009. Effect of rate and form of dicyandiamide application on nitrate leaching and pasture production from a volcanic ash soil in the Waikato. *New Zealand Journal of Agricultural Research* 52 (1): 47-55.
- Steele KW, Judd MJ, Shannon PW 1984. Leaching of nitrate and other nutrients from grazed pasture. *New Zealand Journal of Agricultural Research* 27: 5-11.
- Williams PH, Roberts AHC 1988. Estimation of potassium losses from a grazed dairy farm in Taranaki. *New Zealand Journal of Experimental Agriculture* 16 (1): 23-27.
- Williams PH, Morton JD, Jackson BLJ 1986. Chemical soil test prediction of pasture responses to potassium on recent soils of the South Island west coast. *New Zealand Journal of Experimental Agriculture* 14 (4): 411-415.
- Williams PH, Hedley MJ, Gregg PEH 1989. Uptake of potassium and nitrogen by pasture from urine-affected soil. *New Zealand Journal of Agricultural Research* 32 (3): 415-421.