INITIAL EVALUATION OF THE EFFECTS OF DICYANDIAMIDE (DCD) ON NITROUS OXIDE EMISSIONS, NITRATE LEACHING AND DRY MATTER PRODUCTION FROM DAIRY PASTURES IN A RANGE OF LOCATIONS WITHIN NEW ZEALAND

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Abstract

Dairying is New Zealand's largest agricultural export industry (Statistics NZ). Cattle urinations deposit about 700-1000 kg N/ha at each site, and it is the fate of such urine that is subject to much research and industry scrutiny. Urine and dung deposited by grazing livestock are the single largest source of nitrous oxide (N_2O) emissions in New Zealand. N_2O emissions increased by 23% between 1990 and 2009, mainly due to a sharp increase in fertiliser-N use with intensification, largely on dairy farms, and a consequent increase in excretal-N. Urine leaching into soil can directly contribute nitrate, and indirectly contribute N_2O, to ground water systems that eventually lead to lakes or rivers. These environmental concerns have stimulated research into the effects of nitrification inhibitors (NI). The general theory of using these inhibitors is that they slow down N turnover by slowing the oxidation of N to nitrate, causing N to stay in the more immobile ammonium form. The longer residence time of N in the ammonium form may contribute to additional pasture growth.

One of the NI's that has been studied in New Zealand for several years is dicyandiamide (DCD). The application of DCD has been shown to reduce N_2O emissions and nitrate leaching, and, in results from Canterbury, has been shown to consistently stimulate additional pasture growth. Considering the implications of DCD use for both possible environmental and production benefits, a trial series was implemented to study DCD in a wider range of environments. This was a collaborative project funded by MAF, Fonterra, Dairy NZ and FMRA and managed by the Pastoral Greenhouse gas Research Consortium (PGgRc) utilising research staff from AgResearch, Landcare, and from Lincoln University.

A three year research programme, commencing in autumn 2009, was established in each of the Waikato (AgResearch Tokanui Research Farm), Manawatu (Massey University), Canterbury (Lincoln University) and South Otago (Telford Training Farm) regions. At each location there was a grazing trial to measure the effect of DCD treatment on pasture dry matter (DM) response, small plot trials to measure effects of DCD on pasture DM response, nitrous oxide emissions, and soil DCD movement beneath cattle urine (artificial) patches, and in years 2 and 3, measurement of the effects of DCD application on nitrate leaching.

Reductions in N_2O emissions were consistently recorded following DCD applications at all sites in the three year trial, without any clear differentiation between North and South Island sites, and averaging 49% reduction overall. This was associated with longer residency times for DCD in soil (0-10cm depth) in South Island (130 days average) than North Island (80 days average) sites. In 2009 and 2010 lysimeters at the Waikato and Canterbury sites, and grazed plots in Manawatu, showed that DCD application significantly reduced N leaching losses. Drained plots at the South Otago site showed no DCD effects on N leaching, no doubt partly due to the low late winter- early spring rainfalls recorded there in those years. Pasture dry matter production responses following DCD application to plots that had previously received urine were significant in winter- early spring in 7 of 12 site years, but consistent only at the South Otago site, and not at all at the Waikato site. During 2009 and 2010 these responses were reflected in annual responses on only 3 of 8 occasions (Full year for 2011-2012 not available). Pasture response results from DCD application to urine patches were not reflected in responses in grazed pasture. Significant responses in winter- early spring were measured in 4 of 12 site years with no responses recorded in South Otago. Only 3 of 8 site years showed full year growth responses in grazed pasture. These results are discussed and conclusions drawn.

Introduction

Dairying is New Zealand's second largest export industry (to Tourism; Statistics NZ) and continues to grow as dairy farming expands onto land areas previously used for sheep and beef farming or cropping. For example in Southland there was a 2.5-fold increase in the area in dairying (from 63,000 ha in 1998-99 to 155,000 ha in 2008-09, and cow numbers increased from 170,000 to 418,000 in the same period). This on-going expansion attracts attention because of environmental concerns, particularly from nitrate (NO_3^-) leaching to waterways and nitrous oxide (N_2O) emissions (a potent greenhouse gas). In grazed pastures, the main source of these nitrogen losses is from animal urine deposition (e.g. Ledgard 1999; de Klein et al. 2001). Cattle urinations deposit about 700-1000 kg nitrogen (N)/ha at each site, which is well in excess of plant requirements (Saggar 2004) and its fate is subject to much research and scrutiny.

Largely as a result of its low human population, relatively large domestic animal population, and dependence on primary production, New Zealand is unique amongst OECD countries with agricultural greenhouse gas (GHG) emissions contributing about 50% of total emissions. Although carbon dioxide (CO_2) is still the main GHG (47% of total emissions; MfE 2011), the relative contribution of methane (CH_4) and N_2O emissions is much larger (37% and 14%, respectively) than in other developed countries. N_2O emissions increased by 23% between 1990 and 2009, mainly due to a sharp increase in dairy farm expansions and intensification, and a consequent increase in excretal-N deposition and N fertilizer use. In comparison, N_2O production globally increased by 17% in the same period. It has been assumed that N_2O emissions from agricultural practices will increase by 35–60% until 2030 (IPCC 2007).

The problems associated with NO_3 leaching into NZ lakes and waterways have been well documented (Parliamentary Commissioner for the Environment Report 2004). In order to reduce these problems some Regional Councils have now imposed N limitations on farmers in sensitive catchments. Farmers therefore have to develop new management techniques in order to maintain productivity, or otherwise they may have to reduce stock numbers. Urine N leaching from soil can directly contribute NO_3, and indirectly contribute N_2O, to groundwater systems that eventually lead to lakes or rivers. These nutrient enriched waters can enhance aquatic algal and weed growth, and can pose health problems if used for drinking supplies (Anon. 2005).

These environmental concerns have stimulated research into the efficacy of nitrification inhibitors (NI) to reduce N losses. The general theory of using these inhibitors is that they slow down N turnover by slowing the oxidation of ammonium (NH_4^+) to nitrate, causing N to stay in the more immobile NH_4^+ form. NI's are used to minimise N_2O emissions and losses of NO_3 from soil. The longer residence time of N in the NH_4^+ form may contribute to additional pasture growth. It is considered that pasture response from DCD use is a major potential driver to increasing adoption of this technology and that better understanding of factors affecting response are required.

One of the NI's that has been studied in New Zealand for several years is dicyandiamide (DCD) (Di and Cameron 2002; Di and Cameron 2003). The application of DCD has been shown to reduce N_2O emissions (Di and Cameron 2006; Di et al. 2007, 2010; De Klein et al. 2011) and nitrate leaching (Di and Cameron 2005, and 2007; Sprosen et al 2009; Monaghan et al 2009) and in results from Canterbury has been shown to consistently stimulate additional pasture growth (e.g. Moir et al. 2007). This has been confirmed in some other locations but not in others (Monaghan et al 2009. The reasons for these differences are unclear. Considering the positive benefits of DCD use for both environmental and farming benefits, a trial series was implemented to study several of the soil N mechanisms affected by DCD application. MAF, Fonterra, Dairy NZ, and FMRA entered into a heads of agreement to conduct research into the application of NI's in the dairy industry. Its purpose was to support an expanded research programme to provide independent verification of the role of NI's as a cost effective tool for N_2O and NO_3 leaching reduction and pasture dry matter increases across dairying regions in New Zealand. The Pastoral Greenhouse Research Consortium Ltd (PGgRc) coordinated and managed the programme of work.

A three year research programme, commencing in autumn 2009, was established in each of the Waikato (Tokanui), Manawatu (Massey), Canterbury (Lincoln) and South Otago (Telford) regions. At each location there were:-

- Small plot trials to measure DCD movement in soil beneath cattle urine (artificial) patches, effects of DCD on soil mineral N changes, N_2O emissions and pasture dry matter (DM) production.
- In years 2 and 3 measurement of the effects of DCD application on NO_3 leaching.
- A grazing trial to measure the effect of DCD treatment on pasture DM responses.

Methods

In the full trials a range of treatments were applied in relation to measurements of DCD residency periods, N_2O emissions, pasture production from small plots, NO_3 leaching and pasture responses from grazed pasture. Only a selection of these treatments are presented here. The full trial details will be presented in subsequent science papers.

Small plot trials

There were two small plot trials at each location in an area fenced from the paddock used for the grazing trial, with one used for measurement of N_2O emissions and the other for pasture growth measurements.

Nitrous oxide emission measurement:
Plots were 0.55 m across by 5.0 m long with a 0.5m wide buffer area surrounding each plot.
2009: Treatments were cow urine or dung with or without a single DCD application. In all years, the timing of treatment application coincided with that for the mowing trial (see below).

2010 & 2011: Treatments were cow urine without or with DCD applied twice. Trials commenced in mid-April /early May 2010. DCD was applied twice (mid-April /early May and again in late-July).

In the Waikato, Canterbury and South Otago trials, treatments were applied within 500 mm diameter gas collection rings inserted into the soil. These gas rings had water-troughs to provide a gas tight seal for each gas chamber. Real cow urine (700 kg N/ha) and a DCD solution (10 kg/ha; in relevant treatments) were applied evenly within the rings. There were 6 replicates per treatment.

In the Manawatu, treatments were randomly allocated to a 0.5 m x 0.5 m subplot within a larger plot measuring 1.25 m x 3.0 m. Real cow urine (700 kg N/ha) and a DCD solution (10 kg/ha) were evenly spread over the whole sub-plot and a 0.5 m diameter chamber placed on the plot.

There were 6 replicates per treatment.

Measurements:
Nitrous oxide emissions were measured from plots twice a week for the first 6 weeks, then once a week for the following 3 to 4 months until no treatment effects were evident. Additional sampling followed if there was $\geq$10 mm rain.

Between midday and 2 pm of each sampling day, samples were taken at t= 0, t= 20/30 minutes and t= 40/60 minutes for the first 6 weeks, and (t= 0 and t= 30 or 40 minutes for weeks 6 onwards).

Pasture growth measurements:
2009: Treatments (applied in May) were synthetic urine with or without a single DCD application and a control. Each plot measured 1.25 m x 2.0 m, with a 0.5 m buffer between plots in rows and a 1.0 m buffer between plots between rows

2010: Treatments (applied in late-April/May) were urine, N fertiliser or a control all with or without DCD (applied in late-April/May and again in June/July). Plots were 0.5 m x 5 m with a 0.5 m wide buffer area surrounding each plot.

2011: Treatments were urine (applied in April) with different DCD applications (0, 1, 2, 4 or 6 times), N fertiliser (25 kg N/ha applied twice in June and August) with or without DCD applied twice (April and June in Waikato and Manawatu, or April and July in Canterbury and South Otago)

Plots were 0.5 m across by 5 m long with a 0.5 m wide buffer area surrounding each plot.
In all years urine was applied at 700 kg N/ha, DCD at 10 kg/ha per application. There were 17 replicates for each treatment in all years.

Measurements:

1. Soil DCD concentrations: 0-10 and 10-20 cm depths (weekly initially and extending to two week intervals after one month and stopping when background levels were reached).
2. Soil mineral-N (ammonium and nitrate) 0-10 and 10-20 cm depth (weekly initially and extending to two week intervals after one month as determined by DCD sampling timetable) and at the 20-40cm depth if required due to DCD movement through soil into this layer. (Results not presented)
3. Pasture growth

N leaching trials (years 2 and 3 only)

The effects of autumn applications of DCD on N leaching losses were measured at all sites. Because of differing soil types and drainage characteristics in each region different approaches were taken.

In Canterbury and Waikato lysimeters were used to measure the effects of timing of urine application and associated DCD applications (see Balvert et al. this proceedings for details on the Waikato lysimeter trial).

In the Waikato in 2010 urine and DCD were applied in March and followed by DCD applications in May and July (3xDCD), and in March, April and June (3xDCD) in 2011.

In Canterbury in 2010, urine and DCD were applied in April and followed by DCD applications in June and August (3xDCD), and in April, June and August (3xDCD)in 2011.
In Manawatu and South Otago, field trials were used to measure the effects of DCD application during autumn on nitrate leaching and pasture growth.

In the Manawatu_18 grazed, drained paddocks (~0.06ha) were used to measure nitrate leaching and pasture growth. There were two treatments. Control paddocks (9) were grazed and received urea fertilizer only. The other nine received DCD after grazing on1st March and in mid-April, and again in June (2011) or September (2010). Urea was applied in April, October and November.

Pasture growth was estimated from Pasture Plate measurements (60 per paddock) taken before and after each grazing. These continued until April the following year.

In South Otago, the leaching study was on 20 mown, drained plots. Plots were 2m wide x 10 m long downslope with a drain in the middle of each plot at 0.7 m depth and with plastic lining to 1 m depth around the outside of the plots. All drains and plot edges were dug by a chain trencher which created a very neat 10-12 cm wide slot, with minimal disturbance of the surrounding soil. When the adjacent grazing trial was grazed, pasture on all plots of the leachate trial was cut and DM production measured. Thereafter each plot received two simulated urine patches per ‘grazing’ (2L real cow urine applied to 50 cm diameter rings). All plots also received urea fertilizer at the same rate and the same time as the grazing trial.

There were two treatments: 1.Control (urine patches plus urea); 2. Control+DCD (urine patches plus urea plus DCD). Urine patches were applied in March, May and September in

2010 and in March, April, and July in 2011. This treatment received three DCD applications (at 10 kg/ha) in March, May and September 2010, and in March, April and July in 2011.

Nitrate leaching was measured from subsurface flow collected from the central drain in each plot.

Grazing trial

For years 2009 and 2010 the grazing trial had two treatments: 1. Control – No DCD; 2. DCD applied at 10kg/ha in autumn and again in late-winter/early spring.

A paddock was selected that was part of a routine grazing rotation. 70 plots (10m x10m each) were marked out (64 in Manawatu). Half of the plots were sprayed with DCD (10 kg DCD/ha equivalent) within 2 or 3 days following the autumn (April/May) grazing. The other plots were unsprayed. DCD was again applied following the winter (late-June to mid-September depending on site) grazing. Treatments were in a randomized, paired design.

For year 2011, the grazing plots were split by halving the size of the existing plots (new plots were at Lincoln) to accommodate 4 treatments instead of 2 treatments. Results from only the original two treatments will be reported here. Basal fertilisers were applied to ensure adequate fertility. N fertiliser was applied at 25 kg N/ha following the May grazing, and in some locations increased to 50 kg N/ha following subsequent grazings. Total N fertilizer application was no greater than170 kgN/ha/year.

Pasture was grazed when pasture mass reached about 2800kg DM/ha. Each plot was measured for pre- and post-grazing pasture mass by taking the average of 80 rising plate meter readings (40 plate readings per smaller plot in 2011).

Cow numbers and duration for each grazing were noted. Post-grazing pasture mass was aimed to be about 1450kgDM/ha. Any plots pugged by grazing, or other unusual conditions causing variability in growth were noted.

Measurements of air and soil temperatures and rainfall were made at all sites throughout each trial period.

Results

DCD residency time after application

The duration of the period that DCD persists in soil following application potentially determines its effectiveness in slowing soil nitrification. DCD was applied at the rate of 10 kg/ha yet the first sampling and analysis soon after application was not able to achieve 100% recovery. The recovery of DCD at this time ranged from about 7- 8 kg/ha in Waikato to 3-5 kg/ha in Manawatu, 7 kg/ha in Canterbury and 3-7 kg/ha n South Otago (results not presented). The incomplete DCD recovery could only partly be explained by DCD being intercepted and retained on the surface of pasture. The concentration of DCD in topsoil sometimes increased for a short period in subsequent samplings which could be explained by DCD being washed off the pasture plants. The concentration then usually declined exponentially towards zero. In the 2009 and 2011 mowing trials, this took less time in the North Island sites (average 83 days) than in the South Island sites (average 130 days) (See Table 1).

In the 2010 mowing trials, the DCD residency time was generally lower than in the other years (likely due to wet winter conditions). In Canterbury there was 150mm of rainfall in May 2010 which would no doubt have resulted in more leaching of both urine and DCD from the topsoil than in 2009 when there was only very low rainfall over the winter. Similarly, June 2010 was very wet in Waikato (236 mm rainfall). In contrast in Manawatu, soil conditions were very dry in autumn 2010 and only slowly wet up during winter so leaching should not have been a factor in the shorter DCD residency time in 2010 than 2009, although DCD had not reached zero concentration at the time of measurement in 2010 (due to a second application being made). Temperature was similar to the long term average.

In South Otago there was a period of heavy rain in late May 2010 which could have resulted in more DCD and urine leaching than in early winter 2009 therefore resulting in a lower DCD residency time than in the previous year.

DCD applied in mid-winter generally showed a longer residency time than that applied in late autumn.

DCD effects on soil nitrification (results not presented)

At all sites and in all years, soil ammonium levels typically were higher under urine patches that had received DCD (+DCD) than under those that had not (nil-DCD). In both treatments, the ammonium concentrations declined exponentially, with the concentrations in the nil-DCD treatment generally reaching zero before those in the +DCD treatment.

Conversely, soil nitrate levels increased sharply over the month following urine application (nil-DCD), but the increases were both slower and lower in the +DCD treatment.

DCD effects on nitrous oxide emissions from urine

The application of DCD consistently reduced the emission of N_2O from urine patches at all sites in all years (Table 2). The nitrous oxide reductions in 2009 were slightly higher in the South Island (60% average reduction) than in the North Island trials (43% average reduction).

However the relationship and pattern of N_2O reduction was less clear in years 2 and 3. This was probably related to the variability in persistence of DCD as discussed above. It also appeared to be related to differences in the magnitude of background emissions without DCD, with relatively high emissions recorded in some sites (e.g. Waikato and South Otago) in the third year which coincided with lower percent reductions in emissions.

The 3-year average values showed a reduction of 34, 55, 63 and 42% of N_2O emissions for the Waikato, Manawatu, Canterbury and South Otago sites, respectively indicating that there was no difference in effectiveness between the North and South Island trials. However, there was wide variation between years within sites (1.5-fold to 3.5-fold).

DCD effects on N leaching

There were a different number of treatments at sites using differing measurement techniques and only the key results are described below.

Lysimeters (Waikato and Canterbury)-
Urine was applied once only and followed by DCD applications.

In Waikato in 2010, urine applied in April and DCD applied three times (April June and August) leached 48% less ($P<0.05$) nitrate-N than the urine only treatment. In contrast, when urine was applied in April with only two subsequent DCD applications (DCDx2 ; April and July), there was no significant reduction in nitrate leached. In 2011 the urine (April-applied) + DCDx3 treatment leached 69% less compared to the treatment with April-applied urine-only (Table 3).

In Canterbury, in 2010, when urine was applied in April, and DCD applied three times (April, June and August), the NO_3 leaching loss from the urine applied in April was significantly ($P<0.001$) reduced by 67%; from 295 kg N/ha down to 95 kg N/ha. When DCD was applied twice (April and July) the NO_3 leaching loss was significantly reduced ($P<0.001$) by 50%; from 295 kg N/ha down to 145 kg N/ha.

In 2011, two applications of DCD reduced the NO_3 leaching loss from urine applied in April by 48%. When urine was applied in March 2011 two applications of DCD reduced the NO_3 leaching loss by 18%. Three DCD applications reduced NO_3 leaching by 24%.

Drained small plots (South Otago)
Drainage occurred from May to December 2010 and from May to September 2011. In both years the total drainage was low at about 150mm. In 2010, total N leaching losses from the simulated grazing plots were about 14 kg N/ha/year for both the No DCD and the +DCD plots. In 2011, 3 applications of DCD reduced average N leaching losses from 9.8 to 8.8 kg N/ha (10% reduction), although this was not a statistically significant reduction.

There was also no effect of DCD application on pasture DM production in 2010 or 2011.

Grazed plots (Manawatu)
In the Manawatu, drainage occurred from June to October in 2010 and from early May to October in 2011. DCD was applied in early March, late April and early October and there were 5 grazings through to the start of November in each year.

Nitrogen loss in 2010 was reduced by 21% ($P<0.05$) from 10.5kgN/ha to 8.3 kgN/ha by the application of DCD, and by 22% (1.52 kg N/ha) in 2011. In both years the N loss was predominately as NO_3.

There was no effect of DCD application on annual pasture growth in 2010 but in 2011 it produced 14.6 % (or 890 kg DM/ha) higher DM production than the Control treatment average of 6084 kg DM/ha.

DCD effects on pasture production

Mown pasture - There were variable pasture growth responses from DCD application to urine patches at all sites and the pattern of these responses varied between locations over the three year trial period (Table 4).

Winter-Spring growth – In the Waikato, DCD had no significant effect on pasture growth over the winter-spring in 2009, 2010 or 2011.

In Manawatu, DCD produced a significant ($P<0.001$) increase of 8.5% in winter-spring pasture growth in 2009. However, there was no significant response in the subsequent years (2010 or 2011).

In Canterbury, the winter-spring pasture growth response to a single DCD application was not significant in 2009, but there was a 17% increase in 2010 ($P<0.05$) and a 10% increase to two DCD applications in 2011 ($P<0.05$).

In South Otago, the winter-spring response to a single DCD application was 10% in 2009 ($P<0.05$) and12% ($P<0.05$) in 2010 and in 2011 the response was a 7% increase from two applications of DCD.

Total Annual growth- (available only for 2009 and 2010) In Waikato and Manawatu in 2009 and 2010, there was no significant difference in total annual pasture growth between the urine and urine+DCD treatments.

In Canterbury there was no annual pasture growth response to a single application of DCD in 2009, but a significant ($P<0.05$) increase in pasture growth was measured in 2010 (6.6%).
South Otago showed consistent annual pasture DM responses to DCD application of 4.8% and 5.0% respectively in 2009 and 2010.

Grazed pasture
Pasture production results from the total 2011-2012 year are not yet available.

Pasture production responses from DCD application to grazed pasture were not significant in either winter-spring, or annually, at Waikato or South Otago in any year of the trials (See Table 5).

In 2009-2010 significant pasture responses occurred at the Manawatu and Canterbury sites. In Canterbury, the winter/spring pasture response to DCD was 16.5% ($P<0.001$) and the annual response was 10.2% ($P<0.001$). In Manawatu, the winter/spring response was 8.8% ($P<0.05$) and the annual response was 6.9% ($P=0.11$). In 2010-2011 winter-spring and annual pasture responses to DCD application occurred only in Canterbury (Table 5).

Up to November 2011 DCD treatment at the Manawatu trial produced a pasture response of 7.0%. This was supported by a 14.6% pasture response in the nearby grazed drainage trial (with three applications of DCD).

Discussion
DCD persisted in soil for 40-150 days (depending on site and year) and was effective in delaying nitrification and reducing nitrate accumulation in soil at all sites. In 2009 and 2011 the average DCD persistence periods were 83 days for the North Island sites and 130 days for the South Island sites (Table 1). However this was not directly reflected in the reduction in N_2O emissions from urine patches measured at each site

The overall average N_2O emissions as similar in all years being 51% in 2009-2010, 50% in 2010-2011 and in 2011-2012 was 49%. The highest averages were in the Manawatu and Canterbury (55% and 63% respectively), the average reduction at South Otago was 42% and the lowest average reduction was at the Waikato site (40%).The reduction in N_2O emissions following DCD application in a wide range of other trials in Waikato, Manawatu, Canterbury and Otago averaged 55.4% (de Klein et al. 2011) which was similar to the mean in these studies.

The presence of DCD in soil obviously has a bearing on the associated effects in depressing N_2O emissions. However in general, the residency periods generally exceeded the major flux period for N_2O at each site. For example in the 2009-2010 year the major flux periods were 60, 70, 90 and 90 days respectively for the Waikato, Manawatu, Canterbury and South Otago sites (results not shown) whereas the DCD residency periods were 83, 84, 150 and 160 days respectively.

DCD residency time is influenced by both the biological degradation of the DCD (which is affected by temperature and soil conditions), and by leaching/runoff of the DCD (which is influenced by rainfall/drainage). Both temperature and rainfall varied between sites and also between years, which led to the range in DCD residency times in Table 1.

Little pasture growth occurs below soil temperatures of 5^0C (Whitehead 1995), and DCD degradation accelerates above 12^0C (Kelliher et al 2008). There is therefore a relatively narrow window of opportunity for DCD to persist and to reduce nitrification, and for pasture to utilise additional available N before leaching occurs. Winter temperatures in South Otago for example are below 5^0C until early September and reach 12^0 C in early November. By comparison at Waikato temperatures are above 5^0C all winter and above 12^0C from early November.

There is an absence of information defining the minimum concentration of DCD in different soils that is effective in reducing N_2O emissions, and also whether this effectiveness diminishes as that concentration is approached. Similarly there appears to have been little examination to date of the effect of different rates of DCD application on effectiveness in reducing N_2O emissions.

The effect of DCD on N leaching from urine patches was studied only in 2010, and 2011.The lysimeter technique used showed that DCD application, either 2 or 3 times,in Canterbury, and with three times of DCD application only in Waikato, was effective in significantly reducing N leaching losses from urine patches. The overall average reductions, from urine treated with three applications of DCD, were similar at both sites i.e. about 43-48%. However, leaching in grazed pasture systems also occurs from urine returned earlier (e.g. late-summer and autumn) and therefore the DCD effects on reducing annual N leaching from grazed pastures treated will be proportionately lower than that measured from late-autumn/winter urine.

In South Otago in 2010 and 2011 the drained plot technique was unable to detect any effect of 3 applications of DCD on N leaching losses from simulated urine patches. This was probably due to low total winter-spring rainfalls in each year (ie about 330 and 390mm in 2010 and 2011 respectively) which reduced the leaching potential.

In the Manawatu, results from drained, grazed pastures showed that DCD application (3 times) reduced N leaching by 21-22% in each year. This was associated with about 685 and 823 mm rainfall to the end of October in 2010 and 2011 respectively. This rainfall was much higher than recorded in South Otago over the same periods.

These Manawatu results are very significant as they represent one of the few measurements of N leaching under realistic grazing conditions. Although the leaching reduction represented only about 2 kg N/ha, most of this was accounted for as nitrate. Earlier results from grazed pasture plots in Southland (Monaghan et al. 2009) showed an average reduction in nitrate leaching loss of 41.5% which equated to 5.5kg nitrate-N/ha. This also was under higher rainfall than during the South Otago site in these studies.

Pasture growth responses to DCD application were measured in both grazed and mown plots in some site-years. The mown plots included treatments with and without urine, DCD and N fertiliser to test the various mechanisms proposed for the yield responses measured in grazing plots in some previous studies. Of particular interest were the inter-urine areas which represent the greater part of any grazed paddock at any time of year. Although significant pasture responses may be recorded following DCD application to urine patches the extrapolation of these effects to grazed paddocks must incorporate any effects that have also occurred in non-urine areas. In these trials DCD applied to inter-urine areas (Control Plots) with or without urea applied gave no significant response in 7 of 8 site-years. In one year the Lincoln site gave a 5% winter- early spring pasture response to DCD (results not presented).

It may be expected that the results of DCD application to grazed pasture would reflect a proportional contribution from the effects measured in mown plots from each of urine and inter-urine areas. DCD application to urine patches increased pasture production in mown plots in 8 of 12 site years. Significant pasture responses ranged from 2-17% increased growth in the winter-spring period. This effect was consistent in South Otago over 3 years (average 9.7% in winter-spring), occurred in Canterbury in two of three years (13.5% average over two years in winter-spring but nothing in the third year), and occurred in only one year in Waikato and Manawatu trials.

Previous work on the areas of pasture affected by urine deposition on grazing (Moir et al 2010) have shown less than 10% of the area affected at a single grazing. For example in Canterbury, urine was estimated to have covered 7.2 % of the pasture area after the first grazing. Similarly, in the Manawatu grazed drainage trial, urinations were estimated to cover 11.2% of the grazed area after four grazings. If the pasture responses from DCD on urine from the mown plots are extrapolated using these affected areas they would equate to pasture responses from the grazed area of only about 1-2% (assuming no effect on inter-urine areas). Clearly these responses are insufficient to explain all of the significant measured responses to DCD application in grazed pastures in one year in Manawatu, and in two years in Canterbury.

Other sources of pasture response in inter-urine areas may therefore be involved, such as greater pasture growth from the N inputs in DCD, the N saved from leaching and de-nitrification, the effect of DCD on N fertilizer applied, and indirect responses to DCD as the N retained in the urine patches is recycled through the rest of the pasture by grazing animals. In non-urine affected areas the saving from reduced gaseous and leaching losses will be small and if added to the N added in the DCD with two applications could equate to about 14-15 kg N/ha. At a pasture response of 15 kg DM/kg N this would equate to an extra 210-225 kg DM/ha or around 3-5% increase over the winter/spring period.

There was no obvious relationship between responses to DCD in plot trials and grazing trials, however this is not surprising given that few (if any) significant pasture growth responses in grazed pastures to DCD application would be expected based on the size of responses to DCD in the mowed plot trials. In addition the inherent variability of productivity in grazed pastures poses difficulty in measuring small responses. It should also be noted that site conditions will have resulted in variability in response potential between years. An indication of the variability in weather conditions from year to year and site to site are shown in Table 1.

These trials have not been able to replicate the large responses (20% or more) reported in some studies in either mown or grazed plots, despite concerted efforts to test the hypotheses that would underpin these large responses (e.g. significant edge effects in urine patches or interactions between DCD and N fertiliser in the inter-urine patch area). A more elaborate examination of results will be made in the science papers to follow.

Conclusions

- DCD applied in autumn persisted in the soil for periods of from 83-84 days in North Island trials, and from 40 -160 days in South Island trials.
- DCD was effective in delaying nitrification and reducing nitrate accumulation in soil at all sites.
- DCD application inhibited N_2O emission from urine patches at all sites in all years with an overall average of 50% reduction.
- DCD application (2 or 3 applications) reduced nitrate leaching from urine patches in lysimeters at the Waikato and Canterbury sites. This ranged from 18-69%. A reduction in nitrate leaching of 21-22% was measured from grazed plots in the Manawatu (3 applications). The effect of DCD was not significant (3 applications) in South Otago.
- DCD applications to non - urine treated areas in mown plots produced no significant pasture production response.
- DCD application to urine patches significantly increased winter-spring pasture production in mown plots consistently in South Otago over 3 years (average 9.7% in winter-spring), in Canterbury in 2 of 3 years (average 13.5%), occurred in only one year in Manawatu, but not at all in Waikato trials. Ie the effect of DCD on pasture growth diminished from south to north.
- DCD application to grazed pasture significantly increased winter-spring production in 2 out of 3 years in the Manawatu (7.9% average) and Canterbury (11.2% average), but not at all in the Waikato and South Otago trials. The DCD effect on annual pasture production was significant in two years in Canterbury (6.7% average), and in one year only in Manawatu. (Year 3 results not yet completed)

In conclusion, these trials have shown that in a range of locations within NZ, over a three year period, an application of DCD to dairy pasture will significantly reduce N_2O emissions and nitrate leaching from urine patches. The associated effects on pasture growth are less well understood. This will be explored in more detail in the science papers yet to be prepared.

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Tables

Table 1: DCD residence period (days until DCD was no longer detected) in soil (0-10cm depth) after application in autumn

	Waikato	**Manawatu**	**Canterbury**	**South Otago**
2009-2010	83 (mild, dry)	84 (cool/wet)	150 (dry,)	160 (wet/cool/ dry)
2010-2011	56* (mild,very wet)	42*(mild/dry,)	40 (wet)	90 (cool/ wet)
2011-2012	84(mild,wet)	84(mild/dry/wet)	120 (dry)	90 (mild/ dry)

*Not at zero due to reapplication of DCD

Table 2: The effect of DCD in reducing nitrous oxide emission from urine patches applied in autumn (% reduction)

	Waikato	**Manawatu**	**Canterbury**	**South Otago**
2009-2010	31	54	76	44
2010-2011	71	37	41	52
2011-2012	19 NS	75	71	31

Table 3: The effect of DCD application in reducing N leaching losses from simulated urine application in March or April* to either lysimeters or field plots, or from actual urination sites in grazed pasture. (% reduction).

	Waikato (Lysimeters)		**Manawatu (Grazed plots)**	**Canterbury (Lysimeters)**		**South Otago (Mown plots)**
2009-2010	Not measured					
	2xDCD (April, July 2011)	3xDCD (March, May, July 2010 *April,June,August, 2010; March, April, June 2011)	3xDCD (March, April, Sept 2010; March, April, June 2011)	2xDCD (April, July 2010; March, April 2011; April, July 2011*,)	3xDCD (April, June, August 2010; March, April, July 2011)	3xDCD (March, May, Sept 2010; March, April, July 2011)
2010-2011	(6)NS	26 48*	21	50*	67*	(8)NS
2011-2012		50 69*	22	24 48*	18	(11)NS

Table 4: Mown plots**:** The effect of DCD application on pasture dry matter production in urine patches (% increase)

	Waikato		**Manawatu**		**Canterbury**		**South Otago**	
	W-Spr	**Annual**	**W-Spr**	**Annual**	**W-Spr**	**Annual**	**W-Spr**	**Annual**
2009-2010*	(-0.4)NS	(-0.8)NS	8.5	(4.6)NS	(1.0)NS	(1.5)NS	10.0	4.8
2010-2011*	(1.6)NS	(-2.5)NS	(4.0)NS	(6.8)NS	17.0	6.6	12.0	5.0
2011-2012**	(-1.0)NS	na	(6.5)NS	na	10.0	na	7.0	na

*DCD applied once in May 2009, or in mid-April /early May 2010

**DCD applied twice- in April and June (Waikato and Manawatu), or April and July (Canterbury and South Otago)

Table 5: Grazed plots**:** The effect of DCD application on pasture dry matter production (% increase) -

	Waikato		**Manawatu**		**Canterbury**		**South Otago**	
	W-Spr	**Annual**	**W-Spr**	**Annual**	**W-Spr**	**Annual**	**W-Spr**	**Annual**
2009-2010	(1.7)NS	(1.3)NS	8.8	6.9	16.5	10.2	(0.6)NS	(1.1)NS
2010-2011	(2.4)NS	(1.4)NS	(4.0)NS	(5.4)NS	5.8	3.2	(1.7)NS	(1.3)NS
2011-2012	(0.7)NS	na	7.0 14.6*	na	(1.4)NS	na	(-1.0)NS	na

*From grazed drainage trial

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