

Nitrification and Urease Inhibitors

A Review of the National and International Literature on their Effects on Nitrate Leaching, Greenhouse Gas Emissions and Ammonia Volatilisation from Temperate Legume-Based Pastoral Systems

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Table of Contents

Executive Summary	vii
1 Introduction	1
The size of the problem	1
Some Theory	2
2 Products	3
2.1 Nitrification Inhibitors	3
2.2 Urease Inhibitors	4
3 International Research	4
3.1 Nitrification Inhibitors	4
3.2 Urease Inhibitors	5
4 New Zealand Research	5
5 New Zealand Research In Progress	6
6 Questions And Issues	7
6.1 Soil and water quality	7
6.2 Plant toxicity	7
6.3 Size and duration of benefits	7
6.4 Nitrification and Urease Inhibitors: Magic bullets?	8
7 Conclusions	9
Acknowledgments	iii
References	11
Appendix Current New Zealand Research On Nitrification Inhibitors	17
Summit-Quinphos Ltd	17
Ravensdown Fertiliser Cooperative Ltd.	17
Ballance AgriNutrients Ltd	17

Figure

Figure 1: Some key biochemical reactions relevant to the use of nitrification and urease inhibitors	16
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Tables

Table 1: Summary of results measuring losses of nitrogen from legume-based temperate pastures (from Ledgard 2001)	1
Table 2: Inputs and losses of nitrogen from an average Waikato dairy farm and sheep & beef farm (Input data used to generate these scenarios are from Meat and Wool Innovation Sheep and Beef Surveys and Dexcel Economic Survey of New Zealand Dairy Farms. Output d	2

Executive Summary

1. The combined losses of N (leaching of nitrate, gaseous losses of ammonia, nitrogen and nitrous oxide) to the environment are large (about 30-40% of the N entering the pastoral system via clover N fixation and fertiliser N). They represent a significant loss in economic efficiency (N-use efficiency) and have important impacts on groundwater quality and greenhouse gas emissions.
2. Nitrification inhibitors restrict the microbial conversion of ammonium (NH_4^+) to nitrate (NO_3^-) and hence to the gases, nitrogen (N_2) and nitrous oxide (N_2O) (a greenhouse gas) in soil. Urease inhibitors restrict the conversion of urea and urine to ammonium, and hence to nitrate, in soils. Nitrate, but no ammonium, is mobile in soils and can therefore be leached. Thus, nitrification and urease inhibitors have potential to reduce nitrate leaching, reduce emissions of ammonium and the greenhouse gas, nitrous oxide.
3. The most common nitrification inhibitor is dicyandiamide (DCD). It is available in New Zealand in three proprietary products: Eco-N (Ravensdown Fertiliser Co-operative Ltd), N-Care (Ballance AgriNutrients Ltd) and Taurine (Summit-Quinphos Ltd). Agrotain is the most common urease inhibitor and is available in New Zealand as Sustain (Summit-Quinphos Ltd).
4. There is a large body of research internationally on nitrification and urease inhibitors. Most of this research is from the Northern Hemisphere and consequently examines their effectiveness when used in conjunction with high inputs of fertiliser nitrogen or animal manures. While some very large beneficial effects (on reducing N losses and hence increasing plant production) have been reported the results are variable. There are examples where no effects or negative effects have been measured. There is limited evidence of plant toxicity and nutrient imbalance.
5. New Zealand's legume-based pastoral system is unique. Clover N is the primary source of N and animals graze *in situ*. The urine patch is the primary source for N losses, not fertiliser N.
6. The research to-date in New Zealand is limited. Most of the research is with lysimeters or on small field plots, treated with high rates of either urine, fertiliser N or dairy shed effluent. While some very large beneficial effects have been reported, subsequent results have been smaller, although significant. There are no trials which have examined the effectiveness of these chemicals on a large scale and on paddocks covered with a mosaic of urine patches of variable distribution and age.
7. It is reasonable to conclude from the national and international literature that nitrification inhibitors (in particular DCD) and urease inhibitors (in particular Agrotain) are potentially useful tools for managing nitrate leaching losses and gaseous losses of N from pastures. In this sense, 'proof of concept' has been achieved.
8. Further research is essential to quantify the costs and benefits of these products across the whole range of soil and climatic factors which influence their effectiveness and in which the products are likely to be recommended.
9. Future research must be long-term (3 years) and quantify at a realistic scale (ie large plots covered with a mosaic of urine patches or variable distribution and age) the effects of these chemicals on pasture production, nitrate leaching losses and ammonia and nitrous oxide emissions.

10. Available, but limited, research indicates that these chemicals are benign, but further research is required to confirm that they have no effect on soil and water quality and are not detrimental to animal and human health.

1 Introduction

One of the most pressing environmental issues confronting pastoral agriculture in New Zealand is the loss of soil N, derived from either fertiliser N or symbiotic N fixation by legumes, to the atmosphere as gases (ammonia (NH₃), nitrogen (N₂) and nitrous oxide (N₂O), the latter being a potent greenhouse gas) or to groundwater via leaching as nitrate (NO₃⁻). These losses of N not only decrease N-use efficiency, and hence have economic implications, but just as importantly, impact on groundwater quality and contribute to greenhouse gas emissions.

To safeguard public health, New Zealand has adopted the WHO standard for drinking water, limiting the nitrate N concentration to 11.3 ppm and various industry-driven voluntary codes have been developed (eg the Market Focused Accord developed by Fonterra and the Fertiliser Code of Practice initiated by the Fertiliser Industry) to encourage land users to adopt appropriate management practices to limit nitrate leaching. Additionally, the New Zealand government has signed and ratified the Kyoto Protocol which will limit greenhouse gas emissions to 1990 levels.

Losses of N via leaching and gaseous emissions generally increase with farming intensity (Ledgard 2001) and so unless effective controls can be found to minimise these losses, they could put a limit on the productivity of New Zealand pastoral soils.

This report examines the potential role of nitrification and urease inhibitors as tools to manage these losses. First, the potential size of the problem is assessed and some theory explaining the function of nitrification and urease inhibitors is discussed. The international and national literature is then reviewed and finally some unresolved issues and problems are discussed.

2 The size of the problem

Ledgard (2001) has recently reviewed and condensed much of the international and national research quantifying the amounts of N lost via denitrification, ammonia volatilisation and nitrate leaching in temperate, legume-based pastoral systems (Table 1).

Table 1: Summary of results measuring losses of nitrogen from legume-based temperate pastures (from Ledgard 2001)

Mechanism of loss	Mean and range (kg N/ha/yr)
N ₂ O emissions	2 (0.5-5)
Total denitrification	6 (4-17) ¹
Ammonia volatilisation	7 (1-17)
Leaching	23 (12-100) ²

1. includes emissions of N₂, N₂O, and NO.

2. at a total N input (legume plus fertiliser N) of 100 kg N/ha/yr.

As indicated by the range in these measurements, these losses are extremely variable, depending as they do on a host of interacting factors including: soil (type and texture, pH, moisture content, organic matter content, CEC), climate (rainfall intensity and frequency, temperature, wind) and fertiliser type (urea, ammonia, nitrate) (see Ryden 1986, Harrison and Webb 2001, Ledgard 2001 for recent reviews). Much of the information relevant to New Zealand has now been integrated into OVERSEER 5 (Ledgard 2001) and Table 2 gives the N inputs and losses from a typical Waikato dairy farm and sheep & beef property.

Table 2: Inputs and losses of nitrogen from an average Waikato dairy farm and sheep & beef farm (Input data used to generate these scenarios are from Meat and Wool Innovation Sheep and Beef Surveys and Dexcel Economic Survey of New Zealand Dairy Farms. Output data is from OVERSEER 5)

	Average dairy farm	Average sheep & beef farm
N Inputs		
Fertiliser	122	10
Clover	101	65
N Outputs		
Product	69 (31) ¹	11 (15)
Atmosphere	56 (25)	18 (24)
Leaching	37 (17)	10 (13)
Immobilisation ²	61 (27)	35 (46)

Note 1. figure in brackets is the loss expressed as a percentage of total N input
 2. incorporated into the soil organic matter

These data indicate that the combined losses of N to the environment are about 30-40% of the total N entering pastoral systems. At the individual farm level these losses represent about \$77/ha (based on the current cost of N at \$0.83/kg N) for the average dairy farm (\$6900 per average farm of 90 ha) and \$23/ha on the average sheep & beef farm (\$6800 per average farm of 296 ha).

It is estimated that there are 567,447 ha under dairying in the Waikato Region and a further 804,784 ha under sheep and beef (Charles, B pers. comm.). Applying this information to the figures above, the value of N lost at a regional level by leaching is about \$22m and to the atmosphere about \$37 m. Clearly there are strong economic reasons to find ways to reduce these losses.

It is estimated that the average New Zealand dairy farm and sheep & beef farm produces 2200-2700 and 400-1400 respectively kg CO₂ equivalents/ha of N₂O (Ledgard et al. 2003, OVERSEER 5). Extrapolating these figures across the Waikato region suggests that greenhouse gas emissions of N are about 0.3-1.1 m tonnes CO₂ - equivalents from the sheep & beef sector and 1.2-1.5 m tonnes from dairying. Together these sources contribute about 2m tonnes of CO₂ equivalents of N₂O similar to the carbon dioxide emitted annually from Waikato peat soils (Edmeades 1998).

3 Some Theory

Soil ammonium (NH₄⁺) is derived from several sources: directly from the **mineralisation** of organic matter and the addition of ammonium-containing fertilisers, and, indirectly, as the result of the **hydrolysis** of applied urine and fertiliser urea (figure 1). The hydrolysis of urine and urea to ammonia is usually rapid (several days) and is facilitated by a ubiquitous soil microbial enzyme, **urease** (figure 1). Volatilisation of ammonia to the atmosphere only occurs at high pH (pH > 7.0). Thus it can occur on all alkaline soils (such soils are rare in New Zealand) and on all soils where urea or urine is applied because the process of hydrolysis produces alkaline conditions in the immediate vicinity of contact with soil.

Under typical conditions ammonium is **oxidised** first to nitrite (NO₂⁻) by a specific bacteria (*Nitrosomonas*) and then to nitrate (NO₃⁻) by the bacteria (*Nitrobacter*) (figure 1). The relative speed of these reactions is such under normal soil conditions ammonia

and nitrate concentrations in soils are low, relative to nitrate. However, plants can utilise both ammonium and nitrate.

Nitrate is soluble and negatively charged and is not held to any extent by the soil. It is therefore subject to leaching under the appropriate conditions. In contrast, ammonium is positively charged and retained as a cation by the soil cation exchange capacity (CEC). Furthermore, under anaerobic conditions nitrate N can be reduced by denitrifying bacteria to the gases nitrous oxide (N₂O) and nitrogen (N₂) - **denitrification**. These gases can also be produced from ammonia and nitrite under aerobic conditions by chemical reactions - **chemodenitrification**.

For these reasons, controlling the processes of **nitrification** and/or **urease hydrolysis** are, theoretically at least, potential tools to restrict N leaching, greenhouse gas emissions and ammonia volatilisation from soils. [It is noted that inhibition of these processes will have no effect on other mechanisms by which N enters water bodies such as by direct application and runoff]. As a consequence the N cycle should be more efficient and N use efficiency increased. It is for this reason that much research has been undertaken internationally to a) identifying potential nitrification and urease inhibitors and b) measuring their effects on nitrate leaching, gas emissions and plant growth.

Most of this research has been undertaken in the Northern Hemisphere where arable farming is the major land use. It has focussed therefore on the use of nitrification inhibitors in conjunction with fertiliser N and animal wastes, and urease inhibitors applied with urea-based fertiliser - these are the major sources of N into predominantly arable systems.

New Zealand agriculture is unique in this context. Pastoral agriculture is the dominant land use and animals are grazed *in situ* all year round. Ball et al. (1979) were first to show that the major source of N losses in these systems was the urine patch. This has subsequently been substantiated by other researchers (Ryden et al. 1984, Field et al. 1985, Fraser et al. 1994, Silva et al. 1999, Di and Cameron 2002). Reinforcing this, Ledgard et al. (1996) showed unequivocally that fertiliser N (urea) contributed only a minor proportion of total leached N (approx 1% at 200 kg N/ha/yr) under intense grazing. It is for these reasons that much of the current New Zealand research on managing N losses is focussed on the urine patch.

4 Products

4.1 Nitrification Inhibitors

There is a large body of research on the development and effects of nitrification inhibitors (Stelly 1980, Prasad and Power 1995) Three nitrification inhibitors have emerged from this research on a commercial basis: Nitrapyrin (chemical name, 2-chloro-6 (trichloromethyl) pyridine; trade name N Serve), dicyandiamide (DCD) (chemical name, dicyandiamide; international trade names: Alzon, Didin and Ensan) and more recently DMPP (chemical name, 3,4 dimethylpyrazole-phosphate) (Zerulla et al. 2000).

Three different formulations of DCD are currently available in New Zealand: N-Care (from Ballance AgriNutrients Ltd) is a granulated urea-based product which contains DCD and is applied as a normal fertiliser. Eco-N (Ravensdown Fertiliser Co-operative Ltd) is a suspension preparation which is sprayed onto soils. A third company (Summit-Quinphos Ltd) has announced its own formulation (Taurine) which uses a special animal-mounted mechanism to deliver liquid DCD directly onto the urine patch. This product is not yet on the market.

4.2 Urease Inhibitors

There are several reviews on the development of urease inhibitors in the international literature (Gould et al. 1986, Watson 2000) and while many chemicals have been tested, only one has been developed through to registration - nBTPT (chemical name, N-(n-butyl) thiophosphoric triamide; trade name Agrotain). Agrotain is available in New Zealand as an active ingredient in the Summit-Quinphos Ltd product Sustain - a urea-based fertiliser treated with Agrotain.

5 International Research

5.1 Nitrification Inhibitors

The majority of the research indicates that nitrification inhibitors, when applied to soils in conjunction with N fertilisers or animal wastes, have beneficial effects on reducing nitrate leaching and nitrous oxide emissions, and, as a result increase plant growth (ie increase N use efficiency) (Stelly 1980, McTaggart et al. 1994, Prasad and Power 1995, Klein et al. 1996, McTaggart et al. 1997, Velthof et al. 1997, Williamson et al. 1998, Merino et al. 2002) However, this is not always the case. There are reports of nil or variable effects of nitrification inhibitors on N losses and plant yields (Cremer 1986, Malzer et al. 1989, Fox and Bandel 1989, Frye et al. 1989, Waddington et al. 1989, Schwarz et al. 1994, Davies and Williams 1995, Prasad and Power 1995, Merino et al. 2001). Several studies reported that DCD increased ammonia volatilisation by increasing soil ammonium concentrations and hence emissions (Davies and Williams 1995, Nastri et al. 2000, Gioacchini et al. 2002), Extending this, Gioacchini et al. (2002) suggested that DCD may have a priming effect on net mineralisation of soil organic N resulting in greater N losses in the long term. Furthermore, there are some reports suggesting that some nitrification inhibitors, including DCD, may have a toxicity effect on some plants (Reeves and Touchton 1986, Prasad and Power 1995, Macadam et al. 2003).

The variable nature of these results should not be a surprise. The effectiveness of nitrification inhibitors decreases with time after application to soils, dependant particularly on soil temperature, soil moisture, soil pH and organic matter content (see discussion latter).

However, in the field, the effects of nitrification inhibitors are far more difficult to predict. Their effects are most likely to be greater on soils which are N rich and where the N losses due to leaching and denitrification are large. The expression of these effects through to plant growth will depend on the soil N status; limiting N losses on soils which are N rich may have little effect on plant production. Thus, soil N status, and all the soil factors (texture, temperature, moisture content, organic matter content, pH) and climatic factors (temperature, rainfall intensity and frequency) which determine the size of these losses, will impact on the observed effectiveness of nitrification inhibitors (see Meisinger et al. 1980, van der Meer et al. 1986, Harrison and Webb 2001, Di and Cameron 2002 for reviews and the following for specific studies: Rodgers et al. 1985, Prasad and Power 1995, Puttanna et al. 1999, Irigoyen et al. 2003, Di and Cameron 2004).

Put simply, large beneficial effects of nitrification inhibitors on nitrate leaching are more likely on friable free-draining soils under high rainfall. Whether a yield benefit occurs will depend on the soil N status - if soil N levels are high, conserving N may have little effect on plant yield. Conversely, nitrification inhibitors may have little effect on N leaching from heavy clay soils with impeded drainage. However in this latter situation they may increase ammonia volatilisation, given appropriate conditions, by increasing the soil ammonium concentration.

5.2 Urease Inhibitors

There is considerable evidence showing that fertiliser urea can be less efficient (ie lower plant yield per unit N applied) than nitrate-type fertilisers (Watson et al. 1990, Harrison and Webb 2001). The major reason for this is that the soil pH in the vicinity of urea granules increases as a result of hydrolysis (see figure 1), facilitating the volatilisation of ammonia to the atmosphere. Typical losses range from 5-20% of the total N applied, but the results are extremely variable and can be up to 50% in extreme conditions (Ryden 1986, Watson et al. 1990, Harrison and Webb 2001). Similar results have been reported for the proportional loss of N from urine affected pastures (Ledgard 2001). These reviewers provide detailed accounts of the factors determining ammonia volatilisation, the most important of which are soil pH, temperature, moisture and rainfall. In brief, ammonia volatilisation, from either urea or urine, is greater under conditions of high soil pH, coupled with warm, moist soils under windy conditions.

Not surprisingly, the measured benefits of treating urea (and by inference urine patches) with urease inhibitors (most of the research has been done with nBPT) are also variable, depending on the same variables that control ammonia volatilisation. Furthermore, it cannot be assumed that a reduction in ammonium volatilisation will translate into an increase in crop yield (Hendrickson 1992, Watson et al. 1998).

Urea can damage seedlings and inhibit germination (because of the accumulation of high concentrations of NH_4^+ (Watson 2000). By slowing the rate of hydrolysis, nBPT can reduce this effect (Wang et al. 1995, Malhi et al. 2003). There is also evidence of phytotoxicity associated with the use of nBPT (Krogmeier et al. 1989, Bremner 1995, Watson 2000). This is caused by the uptake of urea by plants, which causes leaf-tip scorch. It is not known whether this is a direct toxicity of urea or an indirect effect, however, it is transitory and occur in situations where high rates of urea and the inhibitor are used.

6 New Zealand Research

Thirteen (13) studies examining the effects of the nitrification inhibitor, DCD, have been reported. Only 6 of these have been completed and published. The balance are either unpublished or not completed. Seven are lysimeter studies, one is a laboratory incubation study and 5 are small-plot field trials. All but 3 studies were conducted in Canterbury. Twelve studies examined the effects of DCD on pasture treated with either large inputs of urea and urine or, in one case dairy shed effluent. One study examined the effect of DCD in combination with fallow duration in an arable system. It must be noted that there are currently no published studies with the proprietary products (Ballance's 'Ncare' and Summit-Quinphos's 'Taurine') and no studies examining the effects of DCDs in the 'normal' farm situation (ie on pasture covered with a mosaic of urine patches of variable age).

The first reported work in New Zealand (Francis et al. 1995) examined the effect of length of fallow (ploughing in March or May) and DCD applications on nitrate leaching and the subsequent growth of wheat over 2 years. Cumulative leaching losses in each year were about 100 kg N/ha and shortening the fallow period reduced leaching by an average of 70 kg N/ha. DCD was effective at reducing nitrate leaching by about 30-45%. Thus they concluded that the most reliable method to reduce nitrate losses was to delay ploughing as long as possible. The various treatments had little effect on subsequent wheat yields.

Williamson et al. (1998) reported that DCD reduced nitrate losses from lysimeters treated with a heavy loading of dairy shed effluent (1100 kgN/ha) from about 600 to about 500 kg N/ha and increased plant (ryegrass) yield from 14 to 17 t/ha. [Note that in many of the reports the results are presented graphically which require interpolation - hence the terms 'about' and 'approximately' in this report]. Cookson and Cornforth

(2002) reported that in a field trial DCD (10 & 25 kg/ha) applied with urine (750 kg N/ha equivalent) decreased peak soil nitrate concentrations from 140 to 60 and 35 ppm respectively, from which they inferred that nitrate leaching could be reduced by 54-73%. In their trial pasture yield was not significantly affected by DCD.

Di and Cameron (2002b, 2003, 2004a,b and Ravensdown Fertiliser Co-operative Ltd unpublished) have conducted many experiments (10) most of which have been in lysimeters (6). Most of their experiments have measured the effects of DCD and more lately eco-N (Ravensdown's proprietary formulation) in combinations with high inputs of urine (1000 kg N/ha) often together with high inputs of urea (200 kg N/ha) (see Table 3). Their initial results (Di and Cameron 2002) suggested large effects of DCD on reducing N leaching (76%) and increasing pasture production (33%). They extrapolated this data to suggest that in the field (ie assuming that urine patches covered 25% of the pasture) DCD may reduce leaching losses from 118 to 46 kg N/ha/yr (61%) and increase pasture production from 11 to 15 t/ha (36%). However, in this experiment, DCD was applied on 8 occasions during the experiment. Qualitatively similar results have been obtained in lysimeters with 2 applications of eco-N. Where experiments have been conducted in small scale lysimeters in the other regions (eg Taupo) or in the field (West Coast, Canterbury North block and South block), smaller, but significant effects have been measured.

In three experiments DCD reduced N₂O and/or ammonia emissions from urea/urine applications and a laboratory incubation study confirmed that the effectiveness of DCD is soil temperature dependant. In particular it was found that the half life of DCD was reduced from about 114 days to about 20 days by increasing the temperature from 8°C to 20°C. From their field trial results, Cookson and Cornforth inferred a half-life for DCD of about 50 days at an average soil temperature of 13 °C.

There is only one study in New Zealand on the effects of the urease inhibitor Agrotain (Summit Quinphos Ltd, unpublished) - a 3 month field trial in the Waikato comparing urea and Sustain (urea treated with Agrotain) applied at a single high rate of N (150 kg N/ha) in spring. The results suggest large beneficial effects of Agrotain on leaching losses (reduced by 53%), ammonia volatilisation (reduced by 69%) and pasture response to N (increased 69%). However, this high rate of N input for a single application makes it difficult to extrapolate these results to the typical farm situation where N is applied at much smaller rates (eg 20-40 kg N/ha per application). Further work under more typical conditions is required to confirm these results.

It seems reasonable to conclude from the available research in New Zealand and overseas that DCD and Agrotain are potentially useful tools for managing nitrate leaching losses and gaseous losses of N from pastures. In this sense, 'proof of concept' has been achieved to the extent that further research is justified to quantify the costs and benefits of these products across the whole range of soil and climatic factors which influence their effectiveness and in which the products are likely to be recommended.

7 New Zealand Research In Progress

Attached in Appendix 1 is a list of research in-progress funded by the three major New Zealand fertiliser companies. Of particular note, given the comments below under the Section Question and Issues are the Ravensdown trials in progress at Dexcel and Massey University examining the effects of econ-N in realistic on-farm situations.

It is likely that some of the questions raised below will be answered by this research-in-progress. Nevertheless, it is necessary to make explicit the issues and questions arising solely from the research available in the public domain.

8 Questions And Issues

8.1 Soil and water quality

DCD is not a biocide (Amberger 1989) and has no effect on soil microbial biomass (Di and Cameron 2004a). It acts specifically on an enzyme (ammonia monooxygenase) contained in *Nitrosomonas*, by blocking the site where ammonium is converted to nitrite. It is also water soluble and biodegradable (Amberger 1989, McCarty and Bremner 1989) to carbon dioxide, water and ammonia. As noted earlier, its rate of degradation and hence its effectiveness decreases with time after application to soils: increasing the soil temperature, soil pH, soil moisture and soil organic matter content decrease its effectiveness. (Rodger et al. 1985, Prasad and Power 1995, Puttanna et al. 1999, Irigoyen et al. 2003, Di and Cameron 2004a).

Cavanagh and O'Halloran (2003) have reviewed the available literature on potential environmental and human health issues related to the use of DCD (Ravensdown 2003). They noted that DCD was highly soluble and therefore likely to be highly mobile in soils, but concluded that ... "it is unlikely that detrimental effects would be observed from any contamination of potable groundwater," and that there is "limited data on the toxic properties [of DCD] although that available indicates that DCD is generally non-toxic."

Watson (2000), quoting from company information, states that nBPT (Agrotain) has "successfully passed extensive toxicological and environmental tests" and degrades into its constituent elements (N, P, S carbon and hydrogen). It has no effect on the size and activity of soil biomass (Banerjee et al. 1999, Kucharski 1992) and acts by blocking the active site of the urease enzyme (Watson 2000).

The available evidence suggests therefore that both these products (DCD and Agrotain) are environmentally benign. It is also likely that the international research on this issue is generic and can be transferred to New Zealand soils. Notwithstanding this, caution requires that the appropriate research be undertaken in New Zealand to ensure that sustained and or indiscriminate use of these chemicals will have no long-term effects on soil and water quality, and human and animal health.

8.2 Plant toxicity

There is evidence that both DCD and Agrotain can be toxic or cause toxicity to plants in some circumstances. Most of this research is on crops and not pasture plants. The exception is the work reported by Macadam et al. (2003). They reported that DCD caused necrosis in white clover. It is possible that this effect is due to a nutrient imbalance inducing potassium deficiency, and it could be an artefact of the experiment rather than a real effect likely to occur in the field. Nevertheless, research is required to demonstrate that neither DCD nor Agrotain are toxic to, or cause nutrient imbalance in, New Zealand pasture species. Indeed such effects have not been reported in the New Zealand research to date.

8.3 Size and duration of benefits

The New Zealand research on the effects of DCD on legume-based pastures is limited: most of the research is short term (12 months or less), limited to two geographical regions, and is restricted to the impacts of DCD on urine applied with or without urea, or in one case, dairy shed effluent. Furthermore, the trial designs are limited to either lysimeter studies of small-plot field trials. There is no current research information on the proprietary products Ncare and Tuarine (Table 3).

For these reasons it is extremely difficult to extrapolate from the current published New Zealand research to general statements or predictions of the effects of the various

DCD and agrotain-based formulations on nitrate leaching, gaseous emissions and pasture production, on-farm, where pastures are overlain with a mosaic of urine patches to various extents and of varying ages.

The challenge for the future is to quantify the effects of DCD and Agrotain on N leaching losses and gaseous N emissions across the whole range of soil and climatic conditions existing in New Zealand. This research should be long-term (at least 3 years) to define the duration of their effects and quantify the impact of likely season-to-season and year-to-year fluctuations in climatic conditions on their efficacy. Present New Zealand estimates of the half life of DCD range from 50 to 100 days but this data is restricted to one soil group. Similarly, this research must also examine the effects of these chemicals on soil quality, in particular soil biomass and activity. Until such information is available it is not possible to objectively assess the potential role of these chemicals as tools to manage soil, water and air quality.

In addition, it is important that future field work include measurements of pasture production. This is essential to provide land-users with practical, robust information on the costs and benefits of these products, which it is anticipated will be a major driver for their use.

8.4 Nitrification and Urease Inhibitors: Magic bullets?

Is it possible that the widespread use of nitrification and urease inhibitors in pastoral agriculture will be such that New Zealand will need no other forms of remediation to minimise nitrate leaching and gaseous emissions?

Research has already shown that there are many management practices that can be adopted to minimise nitrate leaching, ammonia volatilisation and denitrification: These are already included in many Best Management Practices (eg Market Focussed, Fertiliser Code of Practice) and include:

1. Fertiliser N use - form, rate, timing and placement. Not applying fertiliser N to waterlogged soils or to over-limed soils
2. Effluent use - applying effluents at appropriate rates relative to pasture and crop requirements
3. Winter stock management - feed pads, removal of animals from sensitive catchments
4. Soil drainage - avoiding anaerobic soil conditions and pugging.
5. Pasture type - using deep rooted pasture species.
6. Landscape modifications - riparian planting
7. Cropping - no-tillage systems, timing of cultivation and length of fallow.

Other, more futuristic ideas are being investigated (Ledgard 2001). These include: better synchronisation of plant N requirements and N inputs, increasing N utilisation in plant and animals and manipulating through diet the distribution of N in animal excreta.

There is evidence (Tveitnes and Haland 1989, Francis et al. 1995, McTaggart et al. 1997, Velthof et al. 1997, Rozas et al. 1999) suggesting that the benefits of DCD may be no better than those which can already be achieved by adopting Best Management Practices (in these examples applying the appropriate rate and form of fertiliser N at the appropriate time, or cultivating at the correct time and not 'over-fallowing'). Similarly, in his review of the effects of nBPT in corn production, Hendrickson (1992) concluded that urease inhibitors would be of limited value where Best Management Practices were followed - in this case, soil incorporation of urea or the use of urea - ammonium nitrate mixtures. Based on this, it is perhaps more realistic to regard the use of nitrification and urease inhibitors as simply another tool in the BMP tool box, rather than a magic bullet.

In respect to the management of the agricultural land around Lake Taupo and the Rotorua lakes, much more research would be required to specifically quantify the costs and benefits of these chemicals in these specific regions before land-users can be confident of using these new technologies. However it must be said that the soils in these regions are generally friable and free-draining. The proportion of nitrate leaching from urine patches on these soils is likely to be higher than on other less well drained soils. Countering this, these soils are generally colder (higher elevation) and have higher organic matter contents, factors which may limit the usefulness of nitrification and urease inhibitors.

One final point of concern must be raised. If nitrification and urease inhibitors are effective and result is a more efficient N cycle, then less N inputs (either fertiliser N or clover N) will be required to achieve a given level of production. It is likely, however, that farmers will simply use this technology to increase productivity - ie increase production per unit area - the consequences of which are a greater return of N to the soil (as decaying plant material, urine and to a lesser extent dung). What are the possible consequences of this?

Soils can accumulate large amounts of N as organic matter but this biological process reaches a steady-state defined by the climate and soil group (Jackman 1964). If the soil can no longer 'absorb' (incorporate) more N in the organic form, more ammonium N is likely to accumulate. Will this mean greater volatilisation losses as ammonia, as has been shown in some trials (Davies and Williams 1995, Nastri et al. 2000) or generate a priming effect as suggested by Gioacchini et al. (2002). Will this require increasingly greater DCD inputs to prevent nitrification? What is the limit of DCD inputs and what then happens to a soil, primed in this condition, if DCD can no longer be applied? These are important issues which must be explored and answered in long-term research trials.

9 Conclusions

The available research nationally and internationally allows the following conclusions with respect to the use of nitrification and urease inhibitors to control losses of N from pastoral agricultural systems via nitrate leaching and gaseous emissions:

1. The chemicals DCD (a nitrification inhibitor) and Agrotain (a urease inhibitor) are environmentally benign and their use in agriculture is unlikely to have adverse effects on soil and water quality and human health.
2. Some large beneficial effects of DCD and Agrotain on reducing nitrate leaching and gaseous emissions from soils and hence improved N-use efficiency and plant growth, have been reported but the results are variable. In some cases negative effects on gaseous losses and plant production have been observed.
3. This variability can be attributed to a) the many soil factors that control the effectiveness of these chemicals in soils, b) the many soil and climate factors that control the soil processes of nitrate leaching, ammonia volatilisation and denitrification and c) the soil N status.

However, the currently available research is limited in its application to the typical New Zealand legume-based pastoral situation, where urine is the major source of N loss, and pastures are, at any given time, covered with a mosaic of urine patches of differing age and varying spatial distribution.

Most of the international literature has focussed on the use of these chemicals to control N losses from N inputs from fertiliser or animal wastes, when spread evenly and at high N inputs, as is the practice in arable farming. Furthermore, most of the New Zealand research to date has been focussed largely on the use of DCDs for controlling N losses from whole urine patches (ie not the mosaic of urine patches). It is also limited

in design (lysimeters and small field plots) and geographically (predominantly 2 regions).

Nevertheless, it is reasonable to suggest that DCD and Agrotain (and possibly other chemicals to be developed) have potential to decrease nitrate leaching, reduce greenhouse gas (N₂O) and ammonia emissions and otherwise increase the efficiency of the N cycle under New Zealand's legume-based, grazed pasture systems. As such they are potentially additional tools to assist New Zealand agriculture achieve its economic and environmental goals.

Considerably more research is required therefore to move this emerging technology from the current 'proof of concept' situation to a practical, cost-effective technology, on the farm. In particular, full scale field trials are required, particularly with DCD, to measure its effects under the realistic on-farm situation where pasture are covered with a mosaic of urine patches of varying age and special distribution. Long-term trials of this type are required which will:

1. quantify the size of their effects (N leaching, gaseous emissions and pasture production) across the whole range of soil x climate variables where the products are intended for use.
2. quantify the duration of the effects (in other words determine the rates x frequency matrix) across the whole range of soil x climate variables where the products are intended for use.
3. quantify the likely within and between year effects of climate x soil interactions
4. quantify the effects (both short and long term) of these chemicals, and their repeated use, on soil and water quality, and human and animal health.

Some research to these ends is in progress. Of particular relevance to Environment Waikato and Bay of Plenty, is the large scale trial at Dexcel (Hamilton) and the small scale lysimeter work in the Taupo region (see Appendix One). Additional trials will, however, be required, covering the full range of climatic and soil conditions in these regions, to provide quantitative information such that land-users and planning authorities can be confident that these chemicals are a reliable, cost-effective tool to manage nitrate leaching and gaseous losses.

Finally it is suggested that this technology should not be seen as a magic bullet. It is more likely than not that once all the trial results are 'in' that nitrification and urease inhibitors will simply become another tool in the tool kit of Best Management Practices.

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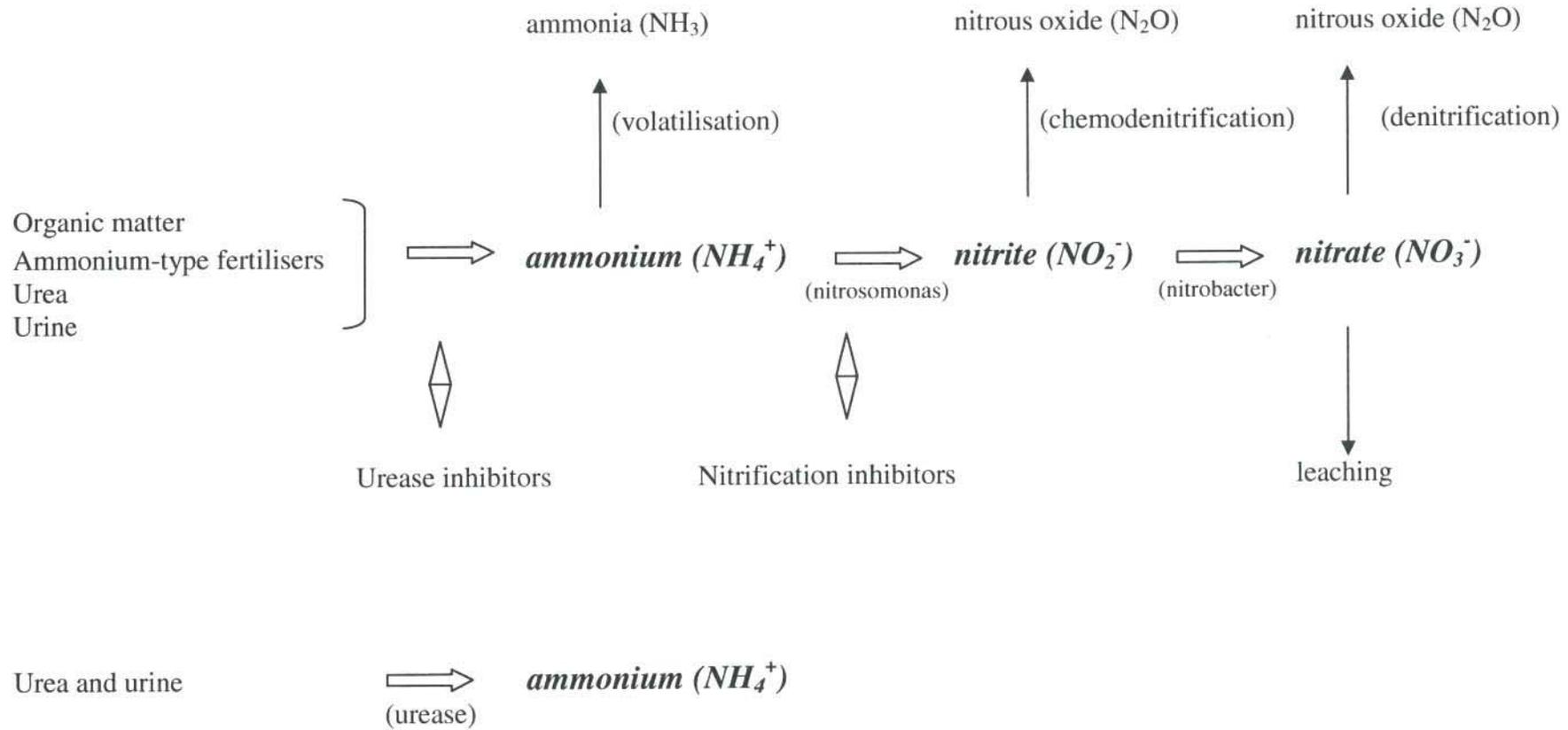
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Figure 1: Some key biochemical reactions relevant to the use of nitrification and urease inhibitors



Appendix Current New Zealand Research On Nitrification Inhibitors

Summit-Quinphos Ltd

1. **Post Doctorate Research with NIWA, Hamilton under Dr. L. Nguyen.**
This work compares pasture yield, pasture N uptake, nitrate leaching and ammonia and nitrous oxide loss with urea treated with different inhibitors. A preliminary report on this work will be available shortly.
2. **PhD Study at Massey University, Palmerston North under D N Bolan**
This study is looking at the effect of inhibitors on nitrogen losses from both urea fertilizer and cow urine.
3. **The University of Western Sydney, under Prof. M Wilson**
Studies of the nature of the bond between elemental S and urea, and with and without urease inhibitor.
4. **NIWA, Christchurch, under Dr C Howard-Williams**
Development of the Taurine Device.
5. **AgAssociates, Auckland under Dr A. Braithwaite**
Laboratory manufacturing and leaching studies with various inhibitor-treated urea products.
6. **Internal Summit-Quinphos Research, under Dr B Quin**
Wider examination of the role of inhibitors in New Zealand agriculture.

Ravensdown Fertiliser Cooperative Ltd.

1. Eight replicated trials throughout New Zealand measuring pasture yield, nitrate leaching and nitrous oxide emissions.

Ballance AgriNutrients Ltd

(in association with AgResearch Ltd)

1. Replicated trials throughout New Zealand covering a range of climates examining the effects of rates and timing of a number of formulations of DCD on pasture production and leaching losses.