Effectiveness of policy options to reduce nitrous oxide emissions and nitrate leaching from arable and annual horticultural land uses

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A report prepared for the
Ministry of Agriculture and Forestry

Copy 1 of 10

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1 Executive summary

This report was commissioned by the Ministry of Agriculture and Forestry to provide information on the effectiveness of two key policy instruments (an incentive to use a nitrification inhibitor and a charge on nitrogen (N) fertiliser) for reducing nitrous oxide and nitrate leaching from arable and annual horticultural land uses. This information was provided through a literature review and by using existing Crop & Food Research crop models to estimate the effect of reducing N fertiliser application rates on potential yield, nitrate leaching losses and nitrous oxide emissions. The main findings from this work are:

- reducing N fertiliser application rate is unlikely to have a significant effect on reducing nitrate leaching losses or indirect nitrous oxide emissions from **wheat crops**;
- reducing N fertiliser application rate may have a significant effect on reducing nitrate leaching losses and indirect nitrous oxide emissions from **potato crops**;
- a small reduction in N fertiliser application rates is unlikely to reduce wheat or potato yield. However, the impact of any reduction in fertiliser rate on crop quality needs to be assessed;
- other crop and soil management practices (e.g. timing of cultivation and fertiliser application, use of cover crops) may have a larger effect on nitrate leaching losses than the amount of applied N fertiliser;
- nitrification inhibitors are unlikely to be effective tools for significantly reducing nitrous oxide emissions from New Zealand cropping soils;
- nitrification inhibitors are unlikely to be an effective policy tool for reducing nitrate leaching from cropping soils;
- nitrification inhibitors may be one of the tools that growers can use to improve N use efficiency depending on the environment and crop;
- more data is needed on the effects of nitrification inhibitors in New Zealand cropping systems as only one trial has been reported in the scientific literature.

2 Introduction

This report was commissioned by the Ministry of Agriculture and Forestry to provide information on the effectiveness of two key policy instruments (an incentive to use a nitrification inhibitor (NI) and a charge on nitrogen (N) fertiliser) for reducing nitrous oxide (N_2O) and nitrate (NO_3^-) leaching from arable and annual horticultural land uses. This report contains information from two activities:

1. a review of relevant national and international literature on the effectiveness of NI on reducing N_2O emissions and NO_3^- leaching from key arable and annual horticultural crops, as it applies to New Zealand circumstances;
2. the use of existing Crop & Food Research models to estimate the effect of reducing N fertiliser application rates on potential yield, NO_3^- leaching losses and N_2O emissions from one key arable (wheat) and one key horticultural crop (potatoes) for two soil types in four regions.

3 Literature review

The contribution of cropping soils to New Zealand's total N_2O emissions is small since this land use accounts for less than 5% of New Zealand's agricultural area. Most of the N_2O emissions in New Zealand come from excretal inputs from pastoral soils (82%), with the contribution of fertiliser N to total N_2O emissions from pastoral soils considered to be relatively small (approx. 14%) (de Klein & Ledgard 2005).

Overseas work has shown that N_2O emissions from crops are influenced by tillage management, climate variability, soil factors and fertiliser additions. In addition, the emissions estimates are affected both by measurement frequency and length of measurement period. There is only very limited information on N_2O emissions from cropped soils in New Zealand, and this is insufficient to establish the typical annual N_2O emissions for our range of crops and soils.

Average annual emissions from fertilised maize paddocks in the Manawatu were estimated to be about 2.4 to 3.4 kg N_2O-N/ha/year (Choudhary et al. 2001), but were based on low frequency measurements. Nitrous oxide emissions measured from fertilised and unfertilised spring-planted potatoes in Canterbury were about 1 kg N_2O-N/ha over a four-month period (Thomas et al. 2004). Nitrous oxide emissions from fertilised onions established following ploughing of a clover pasture were 3.8 kg N_2O–N/ha over an 8.5-month period (van der Weerden et al. 2000). Emissions from onions grown organically over the same period and established following ploughing of a herb ley were 1.6 kg N_2O-N/ha (van der Weerden et al. 2000).

While there is more data for NO_3^- leaching than for N_2O emissions from New Zealand cropping soils, there have still only been a few studies published. Most of these have been short-term studies over winter, as this is when most of the annual drainage is expected to occur. The size of these winter NO_3^- leaching losses depend on the amount of drainage and the amount of NO_3^- in the soil when drainage occurs. In Canterbury winter NO_3^- losses can range from 0 to about 150 kg N/ha (Francis 1995). Recent studies have shown that leaching losses from cropped soils from spring to autumn are very small, unless excessive amounts of irrigation are applied during this time (Francis et al. 2007).

Leaching losses from cropping soils in New Zealand are expected to be greater than from pastoral soils, mainly due to fallow periods between successive crops (Thomas et al. 2005).

3.1 *Nitrate leaching sources from New Zealand cropping soils*

In New Zealand cropped soils, most leaching occurs over the winter when most of the annual drainage occurs. In New Zealand arable systems, fertiliser N is not the main source for N leaching. A study with winter wheat showed that only 5% of the applied fertiliser (urea at 200 kg N/ha) remained in the soil at harvest, whereas 25% of the fertiliser had been incorporated into soil organic matter (Haynes 1999). The extent of NO_3^- leaching depends greatly on the amount of soil organic matter that is mineralised between harvest and the start of winter, the length of the fallow period and the amount of N uptake by the following crop. Consequently, potential leaching losses are greatest when high N fertility soils (e.g. as found under leguminous pastures) are cultivated in late summer and left fallow over the winter (Francis et al. 1992). In contrast, the contribution of soil mineralisation to leaching is likely to be much lower for soils that have been intensively cropped for many years.

Most of the NO_3^- that is present in cropped soil at the start of winter is produced in the months following harvest when soil is moist and warm. As explained later, NI will not persist long in these conditions and are expected to have little effect in reducing the accumulation of NO_3^- in the soil before winter. Application of NI to cropped soils in winter will have no effect on reducing losses as large amounts of NO_3^- are already present in the soil.

3.2 *Timing of fertiliser applications to arable crops*

In New Zealand, autumn-sown arable crops do not generally require N fertiliser before spring as there is sufficient mineral N in the soil over winter from the mineralisation of soil organic matter. Consequently, fertiliser is normally applied to arable crops in spring when drainage from the soil is low and crop demand for N is increasing.

3.3 *Timing of fertiliser applications to vegetable crops*

Most vegetable crops in New Zealand are planted in spring, when drainage has ceased. Consequently, fertiliser applied to these crops is not directly at risk of leaching. However, vegetable crops that are planted in autumn or winter will often receive fertiliser applications during the autumn and winter as they have sparse root systems and are inefficient at recovering mineral N that is present in the soil. For such crops the recommended practice is to split fertiliser applications to match crop demand and subsequently minimise leaching losses.

3.4 *Mode of action of nitrification inhibitors*

Nitrification is the biochemical process of oxidation of ammonium (NH_4^+) to NO_3^-. Autotrophic bacteria (*Nitrosomonas* spp.) convert NH_4^+ to nitrite (NO_2^-), *Nitrobacter* spp. bacteria then convert NO_2^- to NO_3^-.

Denitrification is the biochemical process whereby NO_3^- is reduced to di-nitrogen (N_2), with N_2O an intermediary product. Most N_2O evolved from soil under aerobic or semi-aerobic conditions will come from nitrification, whereas N_2O emitted from wet soils is produced by denitrification (Bremner 1997).

Nitrification inhibitors are chemical compounds that delay the oxidation of NH_4^+ to NO_2^- by depressing the activities of the *Nitrosomonas* spp. nitrifying bacteria in the soil.

Nitrification inhibitors have been primarily used in agriculture to improve N use efficiency. This is achieved by reducing gaseous and leaching losses of N, which often enhances crop N uptake.

Nitrification inhibitors affect N_2O losses directly by reducing the rate of nitrification (and thus the amount of N_2O produced during nitrification) and indirectly by reducing the amount of NO_3^- in the soil that can be denitrified. Leaching losses can also be reduced by maintaining fertiliser and soil mineral N in the NH_4^+ form as it is much less mobile than NO_3^-.

In some cases NI applied with urea may enhance volatilisation of NH_3 when there is NH_4^+ and the pH is high. This might occur if the urea and inhibitor are broadcast on the soil surface. During hydrolysis of the urea to NH_4^+ the pH increases. At pH values above about 8, volatilisation of NH_3^+ occurs. Inhibition of nitrification will maintain a high pH; the pH reduces following nitrification. It is normally recommended that urea be incorporated into the soil soon after application or applied before irrigation or rain. In these cases the risk of volatilisation is low because soil buffering prevents large pH increases.

Nitrification inhibitors can also directly or indirectly influence the N cycle in a number of ways that include NH_4^+ fixation and release and mineralisation and immobilisation (Subbarao et al. 2006).

3.5 *Forms of nitrification inhibitors used in agricultural systems*

Worldwide hundreds of NI are known (Slangen & Kerkhoff 1984; Prasad & Power 1995). However, only a few compounds have been evaluated in the field and of these only a few have been used commercially (Table 1). Overseas two NI have been widely used. These are DCD, which is used mainly in Europe, and nitrapyrin, which is used to a lesser extent and only in the US (Zerulla et al. 2001). Recently a newly developed commercial product (DMPP) has been extensively tested in the field (Weiske et al. 2001) and is available commercially overseas (Subbarao et al. 2006). DCD is the main NI currently used in New Zealand, and it is only used in pastoral systems.

This review only considers NI. It is worth mentioning, however, that urease inhibitors can be used to inhibit the hydrolysis of urea to NH_3. Such inhibitors can prevent significant N losses from surface-applied urea fertiliser or from urine. The mostly widely urease inhibitor is nBPT (N-(n-butyl) thiophosphoric triamide), which is sold in New Zealand under the tradename Agrotain.

Table 1: Commonly used nitrification inhibitors used in agriculture.

Name	Trade names (available overseas)	Mode of application
2-chloro-6-(trichloromeythl) pyridine (Nitrapyrin)	(N-Serve)	Requires injection into the soil to > 5 to 10 cm Not suited to blending with solid fertilisers
Dicyandiamide (DCD)	Eco-N, N-care (Alzon, Didin, Ensan, Basammon)	Blending with solid N fertilisers or as a suspension sprayed on pasture
3,4-Dimethylpyrazol-phospphate (DMPP)	(ENTEC)	Blending with solid N fertilisers

3.6 Application of nitrification inhibitors to crops

Overseas, NI are applied at the time of fertilisation, often as coatings on fertilisers (with either DCD or DMPP) or applied with manures. To provide effective inhibition of nitrification the NI has to be present at the sites where nitrification occurs within the soil. The application rates vary between the different NI compounds. For example, DMPP (Table 1) is effective at less than one-tenth of the DCD application rate (Zerulla et al. 2001).

3.7 Factors that affect nitrification inhibitor performance

The response of nitrification to NI is variable at the field scale and is affected by soil temperature, pH, organic matter, moisture and texture. Many of the inhibition responses reported in the literature are based on laboratory experiments, and not field trials.

3.7.1 Soil temperature

Soil temperature has a strong effect on the persistence of NI. Reported half-values (when 50% of the compound has disappeared) of nitrapyrin and DCD are shown in Table 2. Some literature suggests that DMPP is likely to degrade more slowly than DCD (Weiske et al. 2001). The commonly used NI are most effective at low soil temperatures, i.e. ≤ 5°C, and their effectiveness reduces with increasing temperature, whereas nitrification tends to increase with soil temperature. Above 30°C, DCD and DMPP may only be effective for a week (Irigoyen et al. 2003).

Table 2: Effect of soil temperature on half-lives of nitrapyrin and DCD.

NI	Temperature (°C)	Half-life (days)	Reference
Nitrapyrin	20	9 to 16	Slangen & Kerkhoff 1984
	10	43 to 77	Slangen & Kerkhoff 1984
DCD	22	15	Bronson et al. 1989
	20	18-25	Di & Cameron 2004
	8	53	Bronson et al. 1989
		111-16	Di & Cameron 2004

3.7.2 *Soil pH*

The effectiveness of NI decreases with increasing pH (Puttanna et al. 1999) although some NI compounds will be unstable below pH values of 4 (Subbarao et al. 2006). Nitrification is likely to be enhanced at neutral pHs (Slangen & Kerkhoff 1984).

3.7.3 *Soil organic matter (SOM)*

Nitrification inhibitors tend to be most effective in soils with low SOM, when they are more mobile and bioactive. In contrast NI tend to be less effective in soils with high levels of SOM. Heterotrophic organisms may utilise the NI substrate or it may be adsorbed by SOM, reducing the mobility, volatility and bioactivity of the NI.

To overcome the increased rates of NI degradation in soils of high pH and SOM, the amount of NI compound required needs to be increased (Subbarao et al. 2006).

3.7.4 *Soil moisture*

Nitrification inhibitors tend to be ineffective when soils are saturated. Some NI, such as DCD, are highly soluble in water and may be more at risk of leaching (Puttanna et al. 1999; Subbarao et al. 2006). Where NH_4^+ fertilisers and DCD are applied to soils that leach, DCD is likely to be parted from less mobile NH_4^+. DMPP is less mobile than DCD and is less likely to move away from the sites where NH_4^+ has been applied (Barth et al. 2001). We have not found any evidence that DCD leaching occurs in the field, although one pot study has suggested a loss of DCD up to 15% that was attributed to leaching (Slangen & Kerkhoff 1984). Relatively high soil moisture conditions may also be conducive to the degradation of the NI by soil micro-organisms.

3.7.5 *Soil texture*

In general, NI are most effective in light-textured soils where NO_3^- is more likely to leach rapidly and are least effective in heavy-textured soils.

3.8 *Overseas use of nitrification inhibitors*

Use of NI in cropping systems is low worldwide. In the late 1990s approximately 1.16% of the cropped area (1.8 M ha) in the US was treated with either nitrapyrin or DCD. In Western Europe about 0.29% of the total land under cultivation (200 000 ha) had DCD-containing fertilisers applied (Subbarao et al. 2006). Nitrification inhibitors have not been more widely used as they are costly and have not provided economic benefit for the majority of cropping systems (Subbarao et al. 2006).

3.9 *Effectiveness of nitrification inhibitors in reducing nitrous oxide emission from arable and vegetable cropping systems*

Nitrous oxide is produced from two key processes in the soil – denitrification and nitrification. It has been established that nitrification is a major contributor to N_2O emissions from well-aerated soils that have received NH_4^+ and NH_4^+-based fertilisers (Bremner 1997; Smith et al. 1997). The relative contribution of nitrification and denitrification to N_2O emissions varies greatly in response to a wide range of soil and other environmental conditions and can change during a growing season (Skiba et al. 1993). Nitrification inhibitors do not directly inhibit N_2O emissions from denitrification. However, NI may indirectly reduce denitrification by inhibiting the production of NO_3^-.

There have been a number of studies that have looked at N_2O emissions from fertilised soils and there is a great range in the size of N_2O losses from these fertilised systems (Eichner 1990). The key factors affecting fertiliser-derived emissions are shown in Table 3. In most cases the N_2O emissions associated with the applied fertiliser occur within the growing season and often occur shortly after fertilisation. However, few studies have made measurements for annual or longer time periods (Eichner 1990).

Table 3: Key factors affecting fertiliser-derived N_2O emissions, from Eichner (1990).

Management practices	Environmental factors
Fertiliser type	Temperature
Application rate	Precipitation
Application technique	Soil moisture content
Timing of application	Organic C content
Tillage practices	Oxygen availability
Use of other chemicals	Porosity
Crop type	pH
Irrigation	Freeze and thaw cycle
Residual N and C from crops and fertiliser	Micro-organisms

3.9.1 New Zealand literature

We are aware of no published (or unpublished) New Zealand studies where N_2O emissions have been measured from crops that have had NI applied. There have been a small number of experiments where N_2O emissions (without a NI) have been measured from field crops (van der Weerden et al. 2000; Choudhary et al. 2001, 2002; Thomas et al. 2004).

In New Zealand, conditions that favour the production of N_2O through denitrification are most likely to occur during winter (i.e. when soil is very wet). The NO_3^- that is present in cropped soil at this time has primarily resulted from the mineralisation of soil organic matter since harvest and is often distributed throughout the topsoil. Nitrification inhibitors applied to the soil surface in the winter are unlikely to have major impacts on reducing N_2O emissions due to poor contact between the nitrate and the inhibitor.

3.9.2 International literature – fertiliser effects

Based on a number of overseas studies, N_2O emissions are likely to be reduced when a NI is applied with an NH_4^+ and NH_4^+-based fertiliser. The reported range of this emission reduction is large, between approximately 0 and 80%. However, many of these studies where N_2O emissions were reduced were short term and laboratory-based or focused on the growing season of a crop. Some studies only covered the period following the application of fertiliser. When a NI is applied with fertiliser, the reduction in N_2O emissions is often only short term (weeks) (Linzmeier et al. 2001). Consequently, the effect of the application of the NI on an annual basis may be small.

Based on field data only, the effectiveness of NI in reducing N_2O emissions from applied fertiliser is highly variable (Table 4). The reduction due to a NI can range from 0 to 65%. However, only one of these field studies measured emissions over 12 months, so the actual effect of the inhibitor on reducing annual N_2O emissions is likely to be less than this.

The overall effect of the NI on the annual N_2O emission needs to be considered; factors involved include the persistence of the NI (Section 3.7.1), fertiliser type, and the range of environmental and management factors that drive the N_2O emissions. When fertiliser was applied as ammonium sulfate nitrate to winter wheat in spring there was no overall reduction in N_2O emissions (Linzmeier et al. 2001).

The effectiveness of NI applied with fertilisers is strongly dependent on the form and timing of the fertiliser application. The amount of NO_3^- contained in the fertiliser is a key factor that affects the amount of N_2O emitted from a wheat crop. Linzmeier et al. (2001) found that an early application of a NI (DMPP) with an NH_4^+-based fertiliser resulted in much smaller N_2O emissions than when a NO_3^--based fertiliser was applied later in the growing season. In some studies there was no effect of NI on N_2O emissions from NH_4^+-NO_3^- fertilised crops compared with NI applied with urea and other NH_4^+-based fertilisers (McTaggart et al. 1997, 2001). Consequently, it is recommended that NI are applied with NH_4^+-based fertilisers. Bronson et al. (1992) found that the reduction of N_2O emissions by a NI applied in the soil of surface-irrigated maize crops was due to the indirect effect of the NI reducing the amount of NO_3^- produced from nitrification in the soil.

3.9.3 *Soil organic matter effects*

While NI may be effective at reducing the N_2O emissions from an NH_4^+-based fertiliser, much of the N_2O emission comes from nitrification and denitrification of soil mineral N, and not fertiliser N. For example, the greatest N_2O emissions from a potato paddock in New Zealand came from non-fertilised furrows that had been compacted by tractor traffic (Thomas et al. 2004). The emissions from the potato ridges resulting from the nitrification of the NH_4^+-based fertiliser were less than 10% of the emissions from the unfertilised, compacted furrows (Thomas et al. 2004). In this case, addition of a NI with fertiliser may have reduced the emissions from the NH_4^+-based fertiliser that was only applied to the ridges, but would have had little effect on emissions from the unfertilised furrows where most of the N_2O was produced.

Linzmeier et al. (2001), using ^{15}N-labelled N fertiliser, found that only 10–40% of the N_2O emission from a winter wheat crop came directly from the N fertiliser. The remainder was assumed to come from the soil.

Nitrification inhibitors can also be responsible for immobilisation of fertiliser N that can be mineralised by subsequent crops (Bronson et al. 1991). In their study of two successive winter wheat crops they found that about 20% of the urea fertiliser N applied to the first crop had been immobilised by the soil and then taken up by the following wheat crop.

Table 4: Effect of nitrification inhibitors on nitrous oxide emissions from fertilised crops.

Location	Crop	Soil type	NI	N fertiliser form	N application rate kg N/ha	N_2O emission reduction	Measurement period	Reference
Colorado, United States	Furrow irrigated, spring sown maize	Clay loam, mesic Aridic Argiustoll	Nitrapyrin at 15 cm applied in summer	Urea	218	41 to 65%	97 days	Bronson et al. 1992
Giessen, Germany	Summer barley, maize, winter wheat	Clayey loam, Fluvisol	DCD and DMPP applied with fertiliser in spring	ASN	90, 160, 180 (per year)	26 to 49%	3 years	Weiske et al. 2001
Edinburgh, Scotland	Spring barley	Alluvial sandy loam	Single application of DCD applied with fertiliser in spring (12.5 kg/ha)	AN, urea Two spring applications	120	40% from urea No effect from ammonium nitrate	56 days	McTaggart et al. 1997
Bavaria, Germany	Winter wheat	Silty loam, brown earth	DCD and DMPP applied with fertiliser at spring	ASN and CAN	160	50% from ASN, but **no effect** over whole period	3.5 months	Linzmeier et al. 2001
India	Irrigated wheat	Sandy loam, inceptisol	DCD	Urea	120	49%	95 days	Deepanjan et al. 2002

AN – ammonium nitrate, ASN - ammonium sulfate nitrate, CAN – calcium ammonium nitrate

3.10 Effectiveness of nitrification inhibitors in reducing nitrate leaching from arable and vegetable cropping systems

Soil NO_3^- leaches more readily than NH_4^+; nitrification inhibitors may reduce NO_3^- leaching by conserving N as NH_4^+ instead of as NO_3^-. The risk of NO_3^- leaching is further reduced if soil N is retained in the upper soil layers.

3.10.1 New Zealand literature

There is very little relevant New Zealand data for the effects of NI on NO_3^- leaching from crops. In their field study in Canterbury (Francis et al. 1995) found that DCD applied at the time of autumn ploughing of a ryegrass/white clover pasture reduced NO_3^- leaching losses of the fallow soil by between 25 and 50%. However, they found that delaying cultivation was more effective at reducing NO_3^- leaching than the application of the DCD (Francis et al. 1995). A review of different management practices for minimising NO_3^- leaching in Canterbury conditions concluded that delaying ploughing of pasture as late as possible in autumn and winter was the most effective way of reducing NO_3^- leaching losses (Francis 1995). However, in cases where earlier cultivation was required using a NI would reduce NO_3^- leaching more than an autumn-sown cover crop (Francis 1995).

3.10.2 International literature

A larger number of studies have measured NO_3^- leaching from fertilised crops where NI has been applied. The NO_3^- leaching results are far more variable than the effects on N_2O emissions with the effects ranging from reduced to increased leaching.

In a number of studies leaching from cropped soil was not affected by the use of a NI applied in autumn and summer (Davies & Williams 1995; Beckwith et al. 1998; Fernandez-Escobar et al. 2004; Molina Roco & Ortega Blu 2006) and in some cases NO_3^- leaching was found to be enhanced (Gioacchini et al. 2002; Chaves et al. 2006).

In a study where a NI (DCD) was incorporated with cauliflower residues in simulated autumn and winter conditions, NO_3^- leaching was increased (Chaves et al. 2006). The authors concluded that DCD increased soil mineral N by a priming effect that increased soil immobilisation of NH_4^+ and enhanced the subsequent mineralisation to NO_3^-. In contrast, DMPP used in the same study with the same treatment conditions did not have a priming affect (Chaves et al. 2006). The authors of this study and the study of Gioacchini et al. (2002) have not been able to explain how this priming process occurs with DCD. Ammonium is the preferred form of N for many soil micro-organisms so increasing the persistence of NH_4^+ in soils may enhance soil immobilisation.

In a lysimeter experiment using ^{15}N-labelled urea applied in spring, NO_3^- leaching was stimulated in soil treated with DCD. More NO_3^- was leached from the +DCD treatment than urea only (Gioacchini et al. 2002). Furthermore, most of the leached NO_3^- from the NI-treated soil had come from the soil N pool (i.e. not the labelled urea).

In a study comparing a range of traditional fertilisers with a NI (DCD) applied with fertiliser and slow release fertilisers in summer using olive nursery plants in Spain, Fernandez-Escobar et al. (2004) found that the DCD fertiliser did not reduce NO_3^- leaching compared with the traditional fertilisers, whereas the slow release fertilisers did effectively reduce the amount of NO_3^- leached.

Wolt (2004) reported that in 75% of cases NO_3^- leaching was reduced by the addition of NI to maize crops in mid-Western USA (autumn and spring applications of nitrapyrin) and that overall NI might reduce leaching by about 16%.

3.10.3 *Effects of timing of nitrification inhibitors and fertiliser application*

In a three-year lysimeter study of leaching from urea-fertilised, irrigated maize on a sandy loam soil, NI (nitrapyrin) influenced the timing of N loss but did not affect the total amount of NO_3^- leached (Walters & Malzer 1990).

In an eight-year field study of maize and soybean rotations in the USA a range of fertiliser treatments was applied, including an autumn-applied NH_4^+ fertiliser with NI (nitrapyrin). The results from the study showed that the application of the NI decreased NO_3^- leaching by about 17%. However, this had the same effect as applying the fertiliser without the NI in spring (Randall et al. 2003). High residual amounts of soil mineral N from unused fertiliser N and mineralised organic N in the soil in autumn were responsible for the high NO_3^- leaching losses during the winter period. Applying N fertiliser in autumn would not normally be recommended for New Zealand crops.

Bronson et al. (1991) used ^{15}N-labelled urea to show that DCD applied with urea reduced the amount of autumn-applied fertiliser that was leached compared with the urea only. However, the amount leached from the NI-applied plots was not different from plots that had split applications of the urea fertiliser.

Arregui & Quemada (2006) measured NO_3^- leaching from autumn-sown wheat-barley-rapeseed rotations in Spain when fertilisers and NI were applied in the spring, which would be typical of similar New Zealand cropping rotations. They found that the soil mineral N content at planting and the drainage were the key drivers of NO_3^- leaching. There was no effect of either split fertiliser application or NI applied with fertilisers in the spring as most of the drainage had occurred by this stage.

3.11 *Improving nutrient use efficiency in crops*

Nitrification inhibitors have the potential to increase nutrient use efficiency in cropping situations. This is largely achieved by directly or indirectly reducing gaseous N losses (N_2O, nitric oxide and N_2) and NO_3^- leaching.

The beneficial effects of NI may include:

- better synchronicity of soil and fertiliser N supply with crop N demand,
- more flexible timing of fertiliser applications,
- reduced total N fertiliser application rate and fewer applications of fertiliser,

- maximising plant uptake of N and yield, although often there may be no yield response,
- improving produce quality. In some leafy, fast-growing vegetable crops NI have reduced the NO_3^- concentrations in the leaves (Prasad & Power 1995; Zerulla et al. 2001).

4 Model estimates of reducing nitrogen fertiliser application rates on potential yield, nitrate leaching and nitrous oxide emissions

The basis of the modelling in this section is the assumption that imposing a charge on N fertiliser will reduce the amount of fertiliser that is applied.

4.1 Model information

We used existing Crop & Food Research soil and plant models (Armour et al. 2002, 2004; Jamieson et al. 1998, 2003, 2006) to estimate the effect of reducing N fertiliser application rates on potential yield, NO_3^- leaching losses below 1.0 m depth and N_2O emissions (direct and indirect) from one key arable (wheat) and one key horticultural crop (potatoes). These are daily time-step, mechanistic models that are responsive to daily weather variables and have been calibrated to New Zealand conditions. Estimates using these models were made for two soil types (one fast and one slow draining) in each of four regions (Canterbury, Hawke's Bay, Manawatu and Waikato). In the Waikato, estimates were only made for potatoes as wheat is not commonly grown in this region.

Model simulations for each combination of crop, soil type and location were run for 10 years of real weather data (1995–2004) at five different N fertiliser rates. Weather data from Lincoln, Lawn Road (near Havelock North), Palmerston North and Ruakura (near Hamilton) were used for Canterbury, Hawke's Bay, Manawatu and Waikato respectively. The five N fertiliser rates were 1.0, 0.9, 0.6, 0.3 and 0.0 times the standard rate for each crop. Initial soil conditions were assumed to be the same for both crops with 60, 30 and 10 kg N/ha in the soil at 0–30, 30–60 and 60–100 cm depths respectively. The initial soil moisture deficit was assumed to be zero.

Model estimates of NO_3^- leaching were compared with the IPCC estimate of NO_3^- leaching, which is calculated from the fertiliser application rate and the proportion of applied fertiliser that is assumed to be lost by leaching (or $Frac_{LEACH}$):

IPCC leaching estimate = Applied N fertiliser (kg N/ha) * $Frac_{LEACH}$

For New Zealand, the value of $Frac_{LEACH}$ is 0.07 (Ministry for the Environment 2006).

Direct N_2O emissions due to the application of N fertiliser were calculated from the amount of applied fertiliser and the IPCC emission factor EF_1:

Direct N_2O emissions = Applied N fertiliser (kg N/ha) * EF_1

For New Zealand, the value of EF_1 is 0.01 (Ministry for the Environment 2006).

Indirect N_2O emissions were calculated as the product of the IPCC emission factor EF_5 (0.025) and the amount of leached N that was estimated either from (a) the model estimates or (b) the IPCC value of $FRAC_{LEACH}$:

(a) Model indirect emission estimate = Model leaching loss (kg N/ha) * 0.025

(b) IPCC indirect emission estimate = Fertiliser application rate (kg N/ha) * 0.07 * 0.025

The estimates of direct and indirect emissions of N_2O were used to assess the effectiveness of varying N fertiliser application rates on reducing N_2O emissions from fertiliser applied to these crops.

Estimates of national leaching losses from wheat and potato crops were calculated using both the model and IPCC method estimates of NO_3^- leaching and the total area under these crops in New Zealand (42 000 ha and 12 000 ha for wheat and potatoes respectively). National direct and indirect N_2O emissions from fertiliser applications were calculated similarly using these cropping areas.

4.1.1 *Wheat simulations*

In each year, wheat was sown on 20 April, with N fertiliser applied in three equal applications on 8 October, 23 October and 20 November. Based on our knowledge of current farming practices, we used 180 kg N/ha as the standard N fertiliser rate for wheat. Simulations were also run for fertiliser (as urea) application rates of 162, 108, 54 and 0 kg N/ha. Irrigation was applied in optimal amounts and at optimal timings to the wheat grown in Canterbury and Hawke's Bay. No irrigation was applied to the wheat crop grown in the Manawatu. In each year wheat was harvested in February and the soil then remained fallow over the following winter. Leaching losses have been estimated for two periods: during the growing season (April to February) and in the winter following harvest (March to August). Consequently, leaching losses for each wheat crop cover a 16-month period. We have done this so that the effect of a crop on losses over the following winter can be measured. Yields are expressed in t/ha at 14% moisture. We have not taken into account the effect that varying fertiliser application rate has on wheat quality, although there is scientific evidence for this (e.g. Matre et al. 2006; Triboi et al. 2006).

4.1.2 *Potato simulations*

In each year, potatoes were planted on 16 October, with N fertiliser applied in three equal applications on 16 October, 3 November and 1 December. Based on our knowledge of current farming practices, we used 300 kg N/ha as urea as the standard N fertiliser rate for potatoes. Simulations were also run for fertiliser application rates of 270, 180, 90 and 0 kg N/ha. Irrigation was applied in optimal amounts and at optimal timings to the potatoes grown in

Canterbury and Hawke's Bay. No irrigation was applied to the potato crop grown in the Manawatu or Waikato. In each year potatoes were harvested in March and the soil then remained fallow over the following winter. Leaching losses have been estimated for two periods: during the growing season (October to March) and in the winter following harvest (April to August). Consequently, leaching losses for each potato crop cover a 12-month period. Yields are expressed in t/ha fresh weight. No account has been taken of the effect of varying fertiliser application rates on potato quality. Our models show that potatoes do uptake luxury amounts of N when there is a plentiful supply.

There is very limited information currently available on the influence of fertiliser N on potato quality. Searle et al. (2005) found that the quality of Ilam Hardy potatoes grown in Canterbury was affected by N fertiliser application rates. However, the effect of N rate on quality depended on the end use of potato. Nitrogen rates greater than 200 kg/ha reduced French fry quality, whereas high rates of N (c. 300 kg/ha) were required for desired textural qualities of table potatoes (Searle et al. 2005). This is an aspect that needs further investigation.

4.2 *Model estimates*

4.2.1 *Wheat yield estimates*

Estimated mean potential wheat harvest yields (1995–2004) are shown in Table 5 and Figure 1. The results show that the maximum yields were obtained at fertiliser application rates of 162 and 180 kg N/ha. Below 162 kg N/ha, yields were reduced, with the lowest yields predicted where no fertiliser was applied. At low fertiliser rates, yields were higher for the slow draining than fast draining soils. Similar yield patterns were apparent for all three regions.

It needs to be emphasised that these results do not provide any information on wheat quality. Although maximum yields were obtained at a fertiliser rate of 162 kg N/ha, higher quality wheat (and therefore the economic return to the grower) may have been obtained at the higher fertiliser rate.

Our models show that potatoes do uptake luxury amounts of N when there is a plentiful supply.

There is very limited information currently available on the influence of fertiliser N on potato quality. Searle et al. (2005) found that the quality of Ilam Hardy potatoes grown in Canterbury were affected by N fertiliser application rates, however the effect of N rate on quality depended on the end use of potato. N rates greater than 200 kgN/ha reduced French fry quality, whereas high rates of N (c. 300 kgN/ha) were required for desired textural qualities of table potatoes (Searle et al. 2005). This is an aspect that needs further investigation.

Table 5: Estimated mean wheat harvest yields (1995–2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

Region	Drainage class	Mean wheat harvest yield (t/ha @ 14% moisture) at different fertiliser rates (kg N/ha)				
		0	54	102	162	180
Canterbury	Fast	8.6	11.7	13.4	13.9	14.2
	Slow	13.0	14.2	14.6	14.8	14.8
	Mean	10.8	12.9	14.0	14.3	14.5
Hawke's Bay	Fast	9.0	11.9	14.0	14.2	14.2
	Slow	13.1	14.2	14.4	14.5	14.5
	Mean	11.0	13.0	14.2	14.4	14.4
Manawatu	Fast	9.0	11.8	13.4	13.5	13.5
	Slow	12.5	13.3	13.6	13.6	13.6
	Mean	10.7	12.6	13.5	13.6	13.6

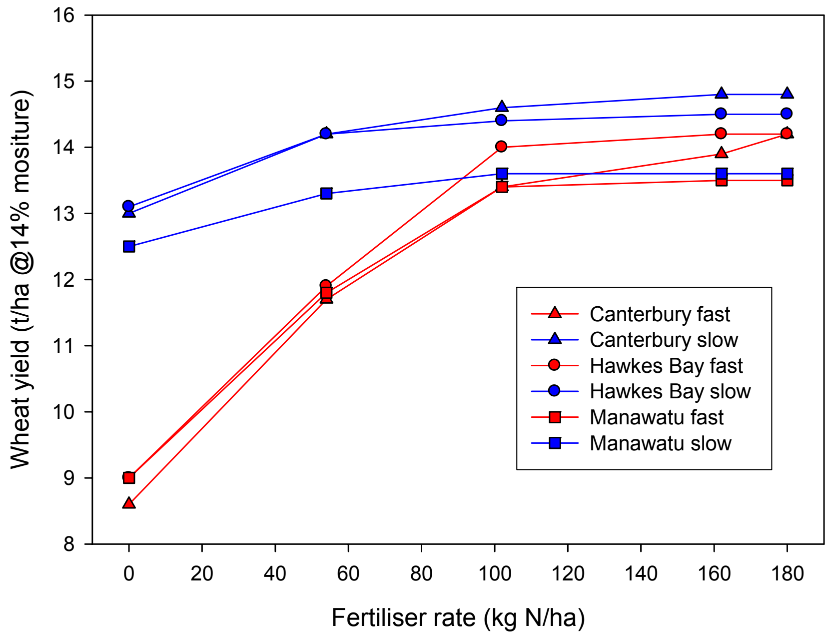

Figure 1: Estimated mean wheat harvest yields (1995–2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

4.2.2 Potato yield estimates

Estimated mean potential potato harvest yields (1995–2004) are shown in Table 6 and Figure 2. The results show that the maximum yields were obtained at fertiliser application rates of 180 kg N/ha. Above this rate luxury uptake of N occurred, which did not increase yield but may have affected crop quality. Below 180 kg N/ha, yields were reduced, with the lowest yields predicted where no fertiliser was applied. At low fertiliser rates yields were higher for the slow draining than fast draining soils. Similar yield patterns were apparent for all three regions.

These results do not provide any information on potato quality. Although maximum yields were obtained at a fertiliser rate of 180 kg N/ha, higher quality potatoes (and therefore the economic return to the grower) may have been obtained at the higher fertiliser rates.

Table 6: Estimated mean potato harvest yields (1995–2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

Region	Drainage class	Mean potato harvest yield (t/ha fresh weight) at different fertiliser rates (kg N/ha)				
		0	90	180	270	300
Canterbury	Fast	62	76	80	80	80
	Slow	70	77	78	78	78
	Mean	67	76	79	79	79
Hawke's Bay	Fast	69	86	93	93	93
	Slow	80	88	90	90	90
	Mean	74	87	92	92	92
Manawatu	Fast	48	61	67	67	67
	Slow	53	59	60	60	60
	Mean	51	60	63	63	63
Waikato	Fast	54	68	73	73	73
	Slow	62	67	68	68	68
	Mean	58	68	70	70	70

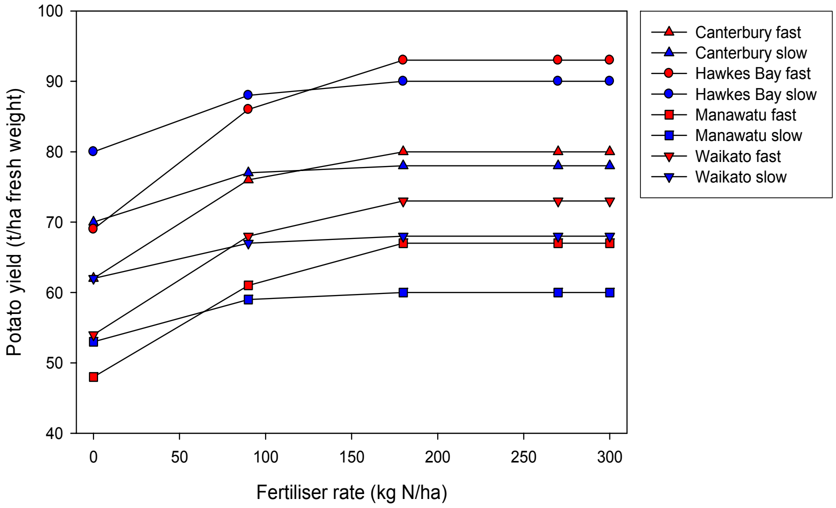

Figure 2: Estimated mean potato harvest yields (1995–2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

4.2.3 Nitrate leaching loss estimates from wheat crops

Estimated mean NO_3^- leaching losses (1995-2004) are presented in Table 7 and Figure 3. The losses are presented for both the growing season and the following winter, and cover a total period of 16 months. Losses for Canterbury fast draining soils during the growing season tended to be greater than losses during the following winter. For both Hawke's Bay and the Manawatu, losses were greater during the winter than during the growing season. In all regions, estimated losses over 16 months are greater from fast than slow draining soils.

Increasing the fertiliser rate resulted in only a small increase in the estimated NO_3^- leaching loss over 16 months. This increase was greater for the slow than fast draining soils. When averaged across all regions and both soil types, leaching losses over 16 months were estimated to increase from 21.6 to 24.8 kg N/ha (a difference of 3.2 kg N/ha or 15%) as fertiliser application rate increased from 0 to 180 kg N/ha. In contrast, leaching losses based on the IPCC method increased from 0 to 12.6 kg N/ha as the fertiliser application rate increased from 0 to 180 kg N/ha.

Table 7: Estimated mean nitrate leaching losses over 16 months from wheat crops (1995-2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

			Mean nitrate leaching loss (kg N/ha) at different fertiliser rates (kg N/ha)				
Region	Drainage class	Period	0	54	102	162	180
Canterbury	Fast	Growing season	9.3	9.3	8.3	9.5	9.7
		Winter	5.2	5.0	5.0	5.0	5.1
		Total	14.5	14.3	13.3	14.4	14.7
	Slow	Growing season	4.7	4.8	4.8	5.2	5.5
		Winter	3.9	3.9	4.0	5.2	5.8
		Total	8.7	8.7	8.8	10.5	11.2
Hawke's Bay	Fast	Growing season	9.8	9.8	9.8	9.7	10.0
		Winter	12.9	12.3	12.3	14.0	14.5
		Total	22.7	22.1	22.1	23.7	24.5
	Slow	Growing season	5.4	5.5	5.5	5.7	5.8
		Winter	10.0	9.9	11.1	13.8	15.2
		Total	15.4	15.4	16.6	19.5	21.0
Manawatu	Fast	Growing season	14.8	14.8	14.9	15.0	15.0
		Winter	24.6	24.8	24.8	26.4	24.7
		Total	39.4	39.6	39.7	41.3	39.8
	Slow	Growing season	9.3	9.4	9.4	9.6	9.8
		Winter	20.9	22.4	22.3	28.0	27.7
		Total	30.2	31.8	31.7	37.6	37.6
Mean		Model estimate	21.6	21.9	22.0	24.6	24.8
		IPCC $Frac_{LEACH}$	0.0	3.8	7.6	11.3	12.6

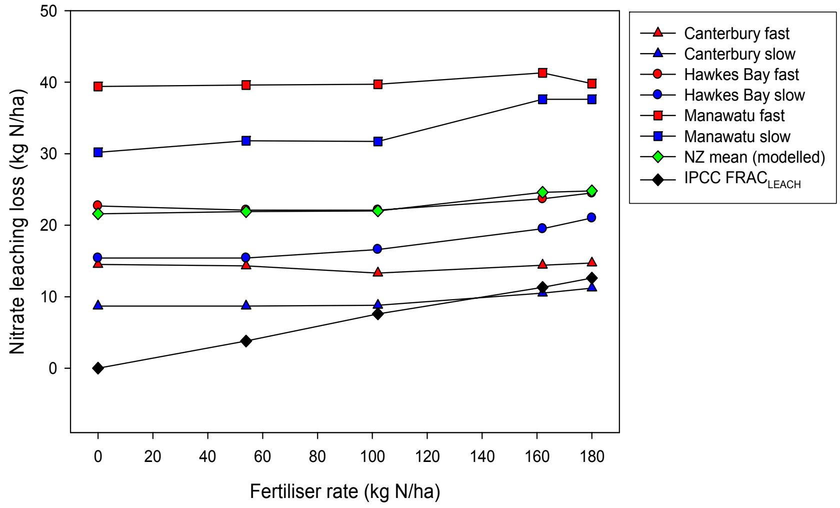

Figure 3: Estimated mean nitrate leaching losses over 16 months from wheat crops (1995-2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

4.2.4 *Nitrate leaching loss estimates from potato crops*

Estimated mean NO_3^- leaching losses (1995–2004) are presented in Table 8 and Figure 4. The losses are presented for both the growing season and the following winter, and cover a total period of 12 months. For all regions, losses were greater from fast draining than from slow draining soils and were much greater during the winter than during the growing season.

Increasing the fertiliser rate resulted in an increase in the estimated leaching loss over 12 months, with the size of the increase least for Canterbury and greatest for Waikato. When averaged across all regions and both soil types, leaching losses over 12 months were estimated to increase from 10.8 to 25.7 kg N/ha (a difference of 14.9 kg N/ha or 238%) as fertiliser application rate increased from 0 to 300 kg N/ha. Leaching losses based on the IPCC method increased from 0 to 21.0 kg N/ha as the fertiliser application rate increased from 0 to 300 kg N/ha.

Table 8: Estimated mean nitrate leaching losses over 12 months from potato crops (1995–2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

Region	Drainage class	Period	Mean nitrate leaching loss (kg N/ha) at different fertiliser rates (kg N/ha)				
			0	90	180	270	300
Canterbury	Fast	Growing season	0.6	0.7	0.8	1.1	1.2
		Winter	2.5	2.3	2.2	3.7	4.2
		Total	3.2	3.0	3.0	4.8	5.4
	Slow	Growing season	0.2	0.3	0.4	0.5	0.6
		Winter	1.6	1.1	1.4	1.8	1.9
		Total	1.8	1.4	1.8	2.3	2.5
Hawke's Bay	Fast	Growing season	1.1	1.0	1.2	1.7	2.0
		Winter	7.9	7.2	7.8	15.9	20.2
		Total	9.0	8.2	9.1	17.6	22.1
	Slow	Growing season	0.3	0.3	0.5	0.7	0.8
		Winter	5.9	5.9	8.6	13.5	15.1
		Total	6.2	6.2	9.0	14.3	15.9
Manawatu	Fast	Growing season	2.7	2.9	3.2	2.0	3.7
		Winter	10.3	10.7	13.8	24.1	26.7
		Total	13.0	13.6	17.0	26.1	30.4
	Slow	Growing season	1.4	1.5	1.2	1.3	1.9
		Winter	8.5	9.7	14.2	18.6	19.9
		Total	9.9	11.2	15.4	19.9	21.8
Waikato	Fast	Growing season	1.7	2.6	5.4	8.5	9.5
		Winter	18.7	19.3	21.7	37.4	43.2
		Total	20.4	22.0	27.1	45.8	52.7
	Slow	Growing season	0.6	1.3	2.6	3.9	4.3
		Winter	15.8	16.9	22.0	29.8	32.2
		Total	16.4	18.2	24.6	33.7	36.6
Mean		Model estimate	10.8	11.5	14.7	22.7	25.7
		IPCC $Frac_{LEACH}$	0.0	6.3	12.6	18.9	21.0

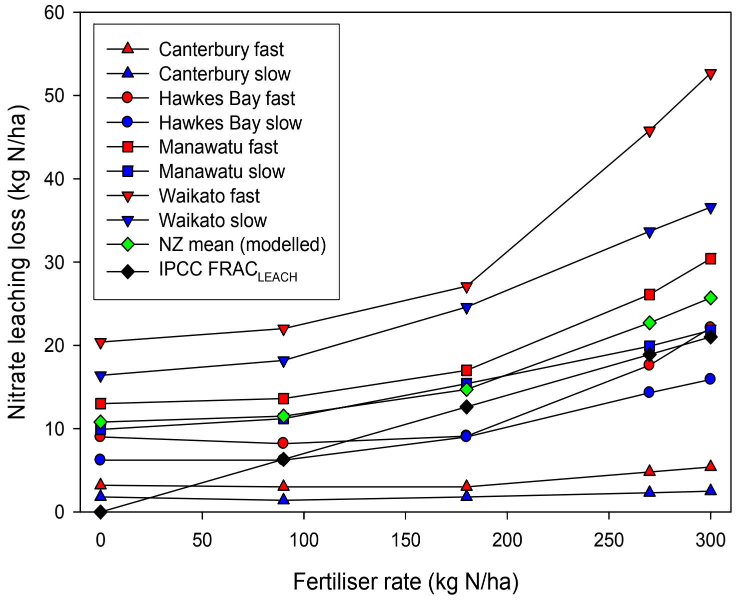

Figure 4: Estimated mean nitrate leaching losses over 12 months from potato crops (1995–2004) at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate.

4.2.5 *Nitrous oxide emission estimates from wheat crops*

Estimated mean indirect N_2O emissions (1995–2004) from fertiliser applied to wheat crops are presented in Table 9 and Figure 5. The emissions are presented for both the growing season and the following winter, and cover a total period of 16 months. These results show the same patterns as for the NO_3^- leaching results (see Section 4.2.3).

Increasing the fertiliser rate resulted in only a small increase in the model-estimated indirect N_2O emissions from fertiliser over 16 months. When averaged across all regions and both soil types, indirect emissions from fertiliser over 16 months were estimated to increase by 0.08 kg N_2O-N/ha (or 15%) as fertiliser application rate increased from 0 to 180 kg N/ha. In contrast, indirect emissions from fertiliser based on the IPCC method increased from 0 to 0.32 kg N_2O-N/ha as the fertiliser application rate increased from 0 to 180 kg N/ha. Indirect emissions calculated from the model estimates of NO_3^- leaching were much greater than those calculated from the IPCC estimate of NO_3^- leaching, particularly at low N fertiliser application rates.

Estimates of direct emissions of N_2O increased with increasing fertiliser application rate and were much larger than the indirect emission estimates when fertiliser was applied. Using the IPPC calculations, direct emissions are about 6 times larger than indirect emissions.

Table 9: Estimated indirect and direct nitrous oxide emissions over 16 months from fertiliser applied to wheat crops at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate. Indirect emissions are calculated from using either the mean estimated leaching losses from model simulations (1995–2004) or the New Zealand value for $Frac_{LEACH}$ (0.07).

Region	Drainage class	Mean nitrous oxide emissions (kg N_2O-N/ha) at different fertiliser rates (kg N/ha)				
		0	54	102	162	180
Indirect emissions						
Canterbury	Fast	0.36	0.36	0.33	0.36	0.37
	Slow	0.22	0.22	0.22	0.26	0.28
Hawke's Bay	Fast	0.57	0.55	0.55	0.59	0.61
	Slow	0.39	0.38	0.41	0.49	0.52
Manawatu	Fast	0.99	0.99	0.99	1.03	0.99
	Slow	0.76	0.79	0.79	0.94	0.94
Mean	Model estimate	0.54	0.55	0.55	0.62	0.62
	IPCC $Frac_{LEACH}$	0.00	0.09	0.19	0.28	0.32
Direct emissions						
		0.00	0.54	1.02	1.62	1.8
Total emissions						
	Model estimate	0.54	1.09	1.57	2.14	2.42
	IPCC	0.00	0.63	1.21	1.90	2.12

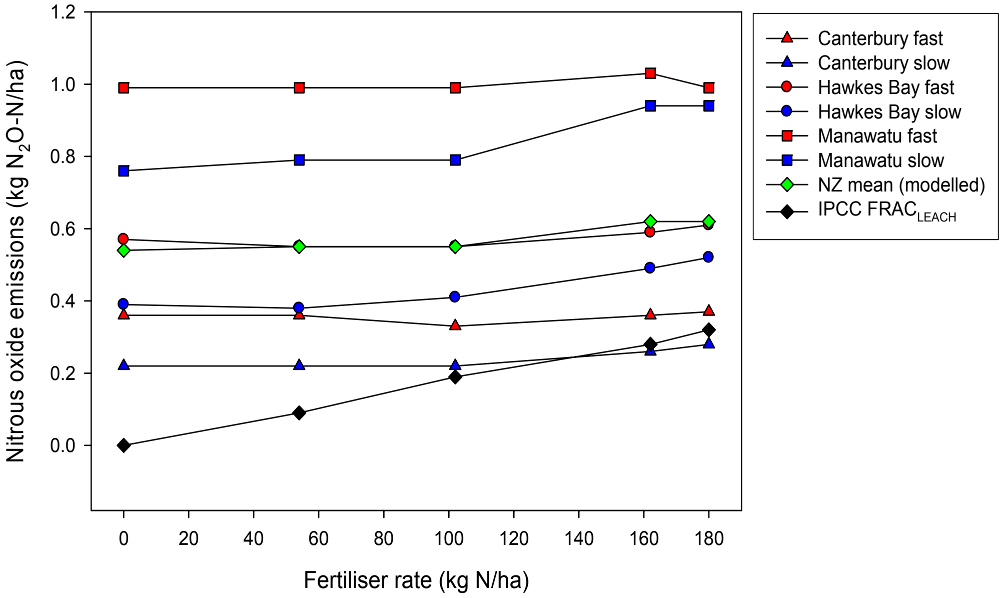

Figure 5: Estimated indirect nitrous oxide emissions over 16 months from fertiliser applied to wheat crops at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate. Indirect emissions are calculated from using either the mean estimated leaching losses from model simulations (1995–2004) or the New Zealand value for Frac$_{LEACH}$ (0.07).

4.2.6 *Nitrous oxide emission estimates from potato crops*

Estimated mean indirect N_2O emissions (1995–2004) from fertiliser applied to potato crops are presented in Table 10 and Figure 6. The emissions are presented for both the growing season and the following winter, and cover a total period of 12 months. These results show the same patterns as the NO_3^- leaching results (see Section 4.2.3).

Increasing the fertiliser rate resulted in a small increase in the model-estimated indirect N_2O emissions from fertiliser over 12 months. When averaged across all regions and both soil types, indirect emissions from fertiliser over 12 months were estimated to increase from 0.27 to 0.64 kg N_2O-N/ha (by 0.37 kg N_2O-N/ha or 237%) as fertiliser application rate increased from 0 to 180 kg N/ha. In contrast, indirect emissions from fertiliser based on the IPCC method increased from 0 to 0.53 kg N_2O-N/ha as the fertiliser application rate increased from 0 to 300 kg N/ha. Indirect emissions calculated from the model estimates of NO_3^- leaching were greater than those calculated from the IPCC estimate of NO_3^- leaching at all N fertiliser application rates.

Estimates of direct emissions of N_2O increased with increasing fertiliser application rate and were much larger than the indirect emission estimates when fertiliser was applied.

Table 10: Estimated indirect and direct nitrous oxide emissions over 12 months from fertiliser applied to potato crops at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate. Indirect emissions are calculated from using either the mean estimated leaching losses from model simulations (1995-2004) or the New Zealand value for $Frac_{LEACH}$ (0.07).

		Mean nitrous oxide emission (kg N_2O-N/ha) at different fertiliser rates (kg N/ha)				
Region	Drainage class	0	90	180	270	300
Indirect emissions						
Canterbury	Fast	0.08	0.07	0.08	0.12	0.14
	Slow	0.05	0.03	0.04	0.06	0.06
Hawke's Bay	Fast	0.23	0.20	0.23	0.44	0.55
	Slow	0.16	0.15	0.23	0.36	0.40
Manawatu	Fast	0.33	0.34	0.43	0.65	0.76
	Slow	0.25	0.28	0.38	0.50	0.55
Waikato	Fast	0.51	0.55	0.68	1.15	1.32
	Slow	0.41	0.46	0.62	0.84	0.91
Mean	Model estimate	0.27	0.29	0.37	0.57	0.64
	IPCC $Frac_{LEACH}$	0.00	0.16	0.32	0.47	0.53
Direct emissions						
		0.00	1.13	2.23	3.38	3.75
Total emissions						
	Model estimate	0.27	1.42	2.60	3.95	4.39
	IPCC	0.00	1.29	2.55	3.85	4.28

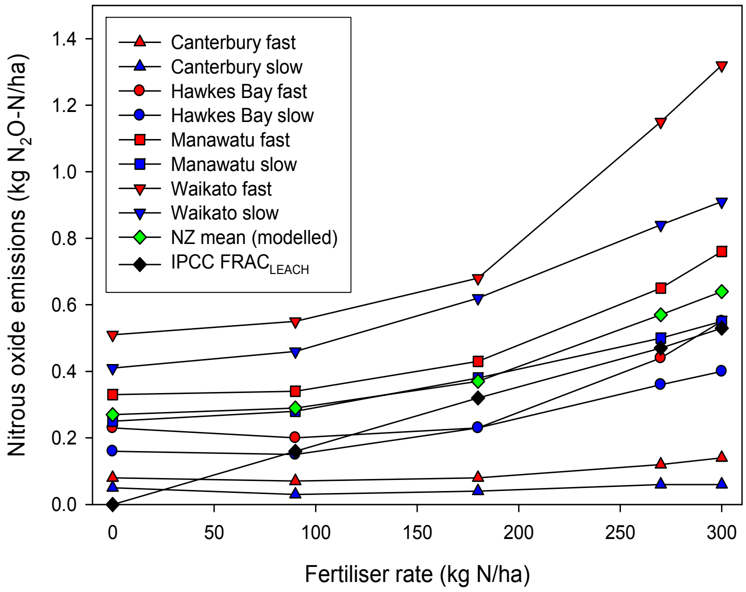

Figure 6: Estimated indirect nitrous oxide emissions over 12 months from fertiliser applied to potato crops at 0.0, 0.3, 0.6, 0.9 and 1.0 times the standard N fertiliser application rate. Indirect emissions are calculated from using either the mean estimated leaching losses from model simulations (1995-2004) or the New Zealand value for $Frac_{LEACH}$ (0.07).

4.2.7 National nitrous oxide emission estimates

Direct emissions of N_2O have a linear relationship with the rate of applied N fertiliser. For the national potato crop, the direct emission estimates are much greater than the indirect emission estimates (as calculated by either method) at all rates of fertiliser. For the national wheat crop, the direct emission estimates are much greater than the indirect emission estimates, except as calculated by the model at low rates of fertiliser (Table 11).

Table 11: Estimated national indirect and direct nitrous oxide emissions from fertiliser applied to wheat and potato crops. Indirect emissions are calculated from using either the mean estimated leaching losses (1995–2004) from model simulations or the New Zealand value for $Frac_{LEACH}$ (0.07).

Leaching estimation method	Crop	Mean national nitrous oxide emission (kg N_2O-N) at different fertiliser rates (as % of standard rate)				
		0	30	60	90	100
Indirect emissions						
IPCC $Frac_{LEACH}$	Wheat	0	3969	7938	11907	13230
Model simulation		22729	23037	23106	25881	26086
IPCC $Frac_{LEACH}$	Potato	0	1890	3780	5670	6300
Model simulation		3523	3437	4410	6808	7725
Direct emissions						
	Wheat	0	28500	56700	85050	94500
	Potato	0	13500	27000	40500	45000
Total emissions						
Model	Wheat	22,729	51,537	79,806	110,930	120,586
IPCC		0	32,469	64,638	96,957	107,730
Model	Potato	3,523	16,937	31,410	47,308	52,725
IPCC		0	15,390	30,780	46,170	51,300

5 Potential effect of using nitrification inhibitors in New Zealand cropping situations

5.1 Crop yields

- Model estimates for wheat suggest there may be no yield penalty when N fertiliser rates are reduced to 90% of the common current application rate of 180 kg N/ha.
- Model estimates for potatoes suggest there may be no yield penalty when N fertiliser rates are reduced to 60% of common current application rates.
- For both these crops, however, there may be significant reductions in crop quality when fertiliser rates are reduced. This aspect was outside the scope of this work, but needs to be considered before setting policy.

5.2 Nitrate leaching

- There is only one relevant published New Zealand study on the effect of a NI on reducing NO_3^- leaching losses from cropped soils.
- Nitrification inhibitors are much less likely to reduce NO_3^- leaching than reduce N_2O emissions.
- There will be little or no benefit of using a NI with applied fertiliser over the period when there is low risk of leaching, i.e. spring to autum (includes most spring-sown crops).
- There is likely to be little benefit of applying a NI to cropped soils in winter as NO_3^- has already been mineralised from the soil organic matter by this time.
- Mineralisation of SOM is the main source of leached NO_3^- over winter from arable soils.
- Nitrification inhibitors are most likely to be effective in intensively cropped vegetable soils that have low levels of SOM as these soils will have lower rates of mineralisation of SOM. However, there is no New Zealand data to support this.
- Nitrification inhibitors are most likely to be effective in free draining soils where the leaching risk is greatest.
- Other management practices (e.g. delaying cultivation in autumn and winter, reducing the length of the fallow period) are likely to be as or more effective at reducing NO_3^- leaching than using NI.
- Model estimates for wheat suggest that reducing N fertiliser rate will have very little effect on NO_3^- leaching losses, either during the growing season of the crop or during the subsequent winter.
- Model estimates for potatoes suggest that reducing N fertiliser rate will result in a reduced leaching loss, particularly over the following winter.
- In the model estimates, soil was left fallow over the winter following crop harvest. Growing a cover crop over the winter period would reduce winter leaching losses. Further model estimates should be made to compare the effectiveness of growing cover crops with the use of NI or a combination of both. Cover crops that are grazed by animals will have added N inputs through dung and urine.

5.3 Nitrous oxide emissions

- There is no New Zealand data on the effectiveness of NI on reducing N_2O emissions from crops. Based on overseas data, N_2O emissions may be reduced by more than 20% when applied with NH_4^+ or NH_4^+-based (urea) fertilisers for at least the period of crop growth, but this effect may be much smaller on an annual basis. The effect of a NI may be small if the fertiliser contains NO_3^- and conditions are conducive for denitrification.

- There is no New Zealand data to determine the importance of fertiliser-based emissions compared to N_2O emissions from mineralisation of SOM. Hence the overall effect of NI on annual N_2O emissions is unclear.
- The effectiveness of a NI is likely to vary widely based on the range of climate (temperature and rainfall) and soil factors (e.g. texture and SOM). Nitirification inhibitors will be least effective in soils with high amounts of SOM (e.g. peat soils) and high pH conditions.
- The effectiveness of the NI will also vary temporally and is likely to be much less effective for spring-sown than autumn-sown crops due to its temperature-dependent nature.
- Other soil and crop management practices may have a greater impact on reducing overall paddock N_2O emissions than a NI.
- In some cases NI applied with urea may enhance gaseous emissions of NH_3. This could occur if the urea fertiliser is not incorporated into the soil and inhibition of nitrification maintains a high pH. This could enhance indirect N_2O emissions.
- Direct emissions of N_2O are usually much greater than indirect emissions of N_2O by up to a factor of 6.
- Our literature review suggests that the assumed relationship between N fertiliser rate and direct emissions of N_2O is simplistic and overlooks many other important considerations.
- New Zealand model estimates of indirect emissions are often different to estimates produced using the IPCC methodology incorporating $Frac_{LEACH}$.
- Model estimates for wheat suggest that indirect N_2O emissions are largely unaffected by N fertiliser rate.
- Model estimates for potato suggest that indirect N_2O emissions increase with increasing N fertiliser rate.

5.4 *Fertiliser use efficiency*

Based on current practices, strategies that increase the efficiency (product output per unit of N input) of N fertiliser use will reduce N_2O emissions and **may** reduce NO_3^- leaching.

Relevant, alternative strategies to improve N fertiliser efficiency include (Freney 1997):

- adjusting rates of fertiliser application
- application method
- matching N supply with demand
- supplying fertiliser in irrigation water
- applying fertiliser to plant rather than soil
- use of slow release fertilisers.

6 Conclusions

- Nitrification inhibitors are unlikely to be effective tools for reducing N_2O emissions from New Zealand cropping soils.
- Nitrification inhibitors are unlikely to be an effective policy tool for reducing NO_3^- leaching from cropping soils. Using NI may be one of the tools that growers can use to improve N use efficiency depending on the climatic and soil environment and crop type.
- More data is needed on the effects of NI in New Zealand cropping systems.
- Reducing N fertiliser application rates is unlikely to have a significant effect on reducing NO_3^- leaching losses or indirect N_2O emissions from wheat crops.
- Reducing N fertiliser application rates may have a significant effect on reducing NO_3^- leaching losses and indirect N_2O emissions from potato crops.

7 References

Armour T, Jamieson PD, Zyskowski RF 2002. Testing the Sirius Wheat Calculator. Agronomy NZ 32: 1–6.

Armour T, Jamieson P, Zyskowski R 2004. Using the Sirius Wheat Calculator to manage wheat quality – the Canterbury experience. Agronomy NZ 34: 171–176.

Arregui LM, Quemada M 2006. Drainage and nitrate leaching in a crop rotation under different N-fertilizer strategies: application of capacitance probes. Plant and Soil 288(1/2): 57-69.

Barth G, von Tucher S, Schmidhalter U 2001. Influence of soil parameters on the effect of 3,4-dimethylpyrazole-phosphate as a nitrification inhibitor. Biology and Fertility of Soils 34(2): 98-102.

Beckwith CP, Cooper J, Smith KA, Shepherd MA 1998. Nitrate leaching loss following application of organic manures to sandy soils in arable cropping. I. Effects of application time, manure type, overwinter crop cover and nitrification inhibition. Soil Use and Management 14(3): 123-130.

Bremner JM 1997. Sources of nitrous oxide in soils. Nutrient Cycling in Agroecosystems 49(1-3): 7-16.

Bronson KF, Mosier AR, Bishnoi SR 1992. Nitrous oxide emissions in irrigated corn as affected by nitrification inhibitors. Soil Science Society of America Journal 56(1): 161-165.

Bronson KF, Touchton JT, Hauck RD, Kelley KR 1991. Nitrogen-15 recovery in winter wheat as affected by application timing and dicyandiamide. Soil Science Society of America Journal 55(1): 130-135.

Chaves B, Opoku A, de Neve S, Boeckx P, van Cleemput O, Hofman G 2006. Influence of DCD and DMPP on soil N dynamics after incorporation of vegetable crop residues. Biology and Fertility of Soils 43(1): 62-68.

Choudhary MA, Akramkhanov A, Saggar S 2001. Nitrous oxide emissions in soils cropped with maize under long-term tillage and under permanent pasture in New Zealand. Soil & Tillage Research 62(1/2): 61-71.

Choudhary MA, Akramkhanov A, Saggar S 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agriculture Ecosystems & Environment 93(1-3): 33-43.

Davies DM, Williams PJ 1995. The effect of the nitrification inhibitor dicyandiamide on nitrate leaching and ammonia volatilization: a U.K. nitrate sensitive areas perspective. Journal of Environmental Management 45(3): 263-272.

de Klein CAM, Ledgard SF 2005. Nitrous oxide emissions from New Zealand agriculture - key sources and mitigation strategies. Nutrient Cycling in Agroecosystems 72(1): 77-85.

Deepanjan M, Himanshu P, Sushil K, Jain MC 2002. Nitrous oxide emission from a sandy loam Inceptisol under irrigated wheat in India as influenced by different nitrification inhibitors. Agriculture, Ecosystems & Environment 91(1/3): 283-293.

Di HJ, Cameron KC 2004. Effects of temperature and application rate of a nitrification inhibitor, dicyandiamide (DCD), on nitrification rate and microbial biomass in a grazed pasture soil. Australian Journal of Soil Research 42(8): 927-932.

Eichner MJ 1990. Nitrous-Oxide Emissions from Fertilized Soils - Summary of Available Data. Journal of Environmental Quality 19(2): 272-280.

Fernandez-Escobar R, Benlloch M, Herrera E, Garcia-Novelo JM 2004. Effect of traditional and slow-release N fertilizers on growth of olive nursery plants and N losses by leaching. Scientia Horticulturae 101(1/2): 39-49.

Francis GS 1995. Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. Journal of Contaminant Hydrology 20(3-4): 313-327.

Francis GS, Haynes RJ, Sparling GP, Ross DJ, Williams PH 1992. Nitrogen mineralization, nitrate leaching and crop growth following cultivation of a temporary leguminous pasture in autumn and winter. Fertilizer Research 33: 59-70.

Francis GS, Haynes RJ, Speir TW, Williams PH 1995. The effects of a nitrification inhibitor on leaching losses and recovery of mineralized nitrogen by a wheat crop after ploughing-in temporary leguminous pastures. Fertilizer Research 41(1): 33-39.

Francis GS, Thomas SM, Barlow HE, Tabley FJ, Gillespie RN 2007. Management strategies to minimise nitrate leaching losses from arable soils. Designing Sustainable Farms – Critical Aspects of Soil and Water Management. 20th Annual Workshop of the Fertiliser and Lime Research Centre. In press.

Freney JR 1997. Strategies to reduce gaseous emissions of nitrogen from irrigated agriculture. Nutrient Cycling in Agroecosystems 48(1/2): 155-160.

Gioacchini P, Nastri A, Marzadori C, Giovannini C, Antisari LV, Gessa C 2002. Influence of urease and nitrification inhibitors on N losses from soils fertilized with urea. Biology and Fertility of Soils 36(2): 129-135.

Haynes RJ 1999. Fate and recovery of 15N-labelled fertilizer urea applied to winter wheat in spring in the Canterbury region of New Zealand. Journal of Agricultural Science, Cambridge 133: 125-130.

Jamieson PD, Semenov MA, Brooking IR, Francis GS 1998. *Sirius*: a mechanistic model of wheat response to environmental variation. European Journal of Agronomy 8: 161–179.

Jamieson PD, Stone PJ, Zyskowski RF, Sinton S 2003. Implementation and testing of the Potato Calculator, a decision support system for nitrogen and irrigation management. Chapter 6. In: Haverkort AJ, Mackerron DKL ed. Decision support systems in potato production: bringing models to practice. Wageningen Academic Publishers. Pp. 85–99.

Jamieson PD, Zyskowski RF, Sinton SM, Brown HE, Butler RC 2006. The Potato Calculator: a tool for scheduling nitrogen fertilizer applications. Agronomy NZ 36, (In press).

Linzmeier W, Gutser R, Schmidhalter U 2001. Nitrous oxide emission from soil and from a nitrogen-15-labelled fertilizer with the new nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP). Biology and Fertility of Soils 34(2): 103-108.

Martre P, Jamieson PD, Semenov MA, Zyskowski RF, Porter JR, Triboi E 2006. Modelling protein content and composition in relation to crop nitrogen dynamics for wheat. European Journal of Agronomy 25(2): 138-154.

McTaggart IP, Clayton H, Parker J, Swan L, Smith KA 1997. Nitrous oxide emissions from grassland and spring barley, following N fertiliser application with and without nitrification inhibitors. Biology and Fertility of Soils, 25(3): 261-268.

Ministry for the Environment 2006. New Zealand's greenhouse gas inventory 1990–2004. The National Inventory Report and Common Reporting Format. April 2006. Wellington, Ministry for the Environment. 184 p.

Molina Roco M, Ortega Blu R 2006. Evaluation of the nitrification inhibitor 3,4-dimethylpyrazole phosphate in two Chilean soils. Journal of Plant Nutrition 29(3): 521-534.

Prasad R, Power JF 1995. Nitrification inhibitors for agriculture, health, and the environment. Advances in Agronomy 54: 233-281.

Puttanna K, Gowda NMN, Rao EVSP 1999. Effect of concentration, temperature, moisture, liming and organic matter on the efficacy of the nitrification inhibitors benzotriazole, o-nitrophenol, m-nitroaniline and dicyandiamide. Nutrient Cycling in Agroecosystems 54(3): 251-257.

Randall GW, Vetsch JA, Huffman JR 2003. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin. Journal of Environmental Quality 32(5): 1764-1772.

Searle BP, Jarvis P, Lucas RJ 2005. Managing potato crops for culinary quality. Proceedings of the First International Symposium on Root and Tuber Crops Food Down Under'. February 9-12 2004. Palmerston North, Acta Horticulturae 670: 107-120.

Skiba U, Smith KA, Fowler D 1993. Nitrification and denitrification as sources of nitric-oxide and nitrous-oxide in a sandy loam soil. Soil Biology & Biochemistry 25(11): 1527-1536.

Slangen JHG, Kerkhoff P 1984. Nitrification inhibitors in agriculture and horticulture: a literature review. Fertilizer Research 5(1): 1-76.

Smith KA, McTaggart IP, Tsuruta H 1997. Emissions of N_2O and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation. Soil Use and Management 13(4): 296-304.

Subbarao GV, Ito O, Sahrawat KL, Berry WL, Nakahara K, Ishikawa T, Watanabe T, Suenaga K, Rondon M, Rao IM 2006. Scope and strategies for regulation of nitrification in agricultural systems-challenges and opportunities. Critical Reviews in Plant Sciences 25(4): 303-335.

Thomas SM, Barlow HE, Francis GS, Hedderley DI 2004. Emissions of nitrous oxide from fertilised potatoes. In: Supersoil 2004: Proceedings of the 3rd Australian New Zealand Soils Conference, University of Sydney, Australia, 5 – 9 December 2004. www.regional.org.au/au/asssi/supersoil2004

Thomas SM, Ledgard SF, Francis GS 2005. Improving estimates of nitrate leaching for quantifying New Zealand's indirect nitrous oxide emissions. Nutrient Cycling in Agroecosystems 73: 213–226.

Triboi E, Martre P, Girousse C, Ravel C, Triboi-Blondel M 2006. Unravelling environmental and genetic relationships between grain yield and nitrogen concentration for wheat. European Journal of Agronomy 25(2): 108-118.

van der Weerden TJ, Sherlock RR, Williams PH, Cameron KC 2000. Effect of three contrasting onion (*Allium cepa* L.) production systems on nitrous oxide emissions from soil. Biology and Fertility of Soils 31(3-4): 334-342.

Walters DT, Malzer GL 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 urea: II. Nitrogen leaching and balance. Soil Science Society of America Journal 54(1): 122-130.

Weiske A, Benckiser G, Ottow JCG 2001. Effect of the new nitrification inhibitor DMPP in comparison to DCD on nitrous oxide (N_2O) emissions and methane (CH_4) oxidation during 3 years of repeated applications in field experiments. Nutrient Cycling in Agroecosystems 60(1/3): 57-64.

Weiske A, Benckiser G, Herbert T, Ottow JCG 2001. Influence of the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) in comparison to dicyandiamide (DCD) on nitrous oxide emissions, carbon dioxide fluxes and methane oxidation during 3 years of repeated application in field experiments. Biology and Fertility of Soils 34(2): 109-117.

Wolt JD 2004. A meta-evaluation of nitrapyrin agronomic and environmental effectiveness with emphasis on corn production in the Midwestern USA. Nutrient Cycling in Agroecosystems 69(1): 23-41.

Zerulla W, Barth T, Dressel J, Erhardt K, von Locquenghien KH, Pasda G, Radle M, Wissemeier AH 2001. 3,4-Dimethylpyrazole phosphate (DMPP) – a new nitrification inhibitor for agriculture and horticulture. An introduction. Biology and Fertility of Soils 34(2): 79-84.