Influence of urea fertiliser formulation, urease inhibitor and season on ammonia loss from ryegrass

Helen Suter^{a,c} • Humaira Sultana^a • Debra Turner^a • Rohan Davies^b • Charlie Walker^b • Deli Chen^{a,c}

^aDepartment of Agriculture and Food Systems, Melbourne School of Land and Environment, The University of Melbourne, Australia 3010.

^bIncitec Pivot Limited, PO Box 54, North Geelong, Victoria 3215, Australia

^cCorresponding author: E-mail: helencs@unimelb.edu.au; delichen@unimelb.edu.au

Abstract

This paper reports the results of experiments to determine whether ammonia (NH₃) loss can be reduced and nitrogen (N) use efficiency improved by using two relatively new commercial urea formulations rather than granular urea and urea ammonium nitrate. Four nitrogen treatments were applied at a rate of 40 kg N ha⁻¹: granular urea, “Green Urea 14™” [containing 45.8% nitrogen (N) as urea and “Agrotain®” (N-(n-butyl) thiophosphoric triamide) @ 5 L t⁻¹ of urea as a urease inhibitor], “Nhance”, a fine particle spray [containing 46% N as urea, “Agrotain” @ 1 L t⁻¹ of urea and gibberellic acid (applied at a rate of 10 g ha⁻¹)] and urea ammonium nitrate in solution (UAN) surface applied. Ammonia loss was determined in autumn and spring using a micrometeorological method. In autumn, use of the Green Urea and Nhance reduced NH₃ loss from the 30% of applied N lost from the granular urea to 9% and 23% respectively. Loss from all treatments in spring was very small (less than 2% of applied N), because 4 mm of rain fell within 24 hours of application onto an already wet site. The use of the Nhance and Green Urea instead of granular urea did not result in increased agronomic efficiency or recovery efficiency of the applied N, and this is most likely due to the presence of sufficient available N from both fertiliser application and the soil. A ¹⁵N study recovered 72.8% of the applied N in the plants and soil, and showed that 30% of the total N taken up by the plant was derived from the fertiliser, and 70% from the soil.

Keywords

Green Urea; N-(n-butyl) thiophosphoric triamide; Agrotain; fine particle spray; ammonia loss; pasture production

Introduction

Urea is the most common nitrogen (N) fertiliser used in Australia, because of cost and ease of transport and application. Consumption in 2009 was approximately 1.1 million tonnes (IFA 2011). However, considerable losses of N can occur if the urea is not incorporated into soil soon after application (Cai et al. 2002). The loss occurs by NH_3 volatilisation in acidic soils because of elevated pH around a hydrolysing urea granule when urea is surface applied (Sherlock et al. 1987). Broadcasting urea onto grass swards has resulted in large losses of NH_3 to the atmosphere by volatilisation (Harper et al. 1983; Jarvis et al. 1995; Prasertsak et al. 2001; Eckard et al. 2003; Vaio et al. 2008) because the plants and surface mat have high urease activity (Hoult and McGarity 1986; Watson and Miller 1996; Meyer et al. 1961). The level of NH_3 emission is highly influenced by climatic conditions, particularly temperature, wind speed and rainfall (Harper et al. 1983).

The lost nitrogen represents a serious economic loss to farmers, but it can also affect human health and contaminate the environment (Galloway et al. 2008). After deposition on land surfaces and water bodies NH_3 acts as a secondary source of nitrous oxide which contributes to global warming and ozone depletion (Mosier et al. 1998). Therefore it is important to limit NH_3 loss. Ammonia volatilisation from urea applications can be reduced through deep placement, washing the fertiliser into the soil, or reducing the high pH in the vicinity of urea granules caused by hydrolysis of the urea. One would expect that when urea is applied as fine particles (Quinfert 2011) rather than large granules the localised elevated pH effect would be less. Reducing the localised pH around the granule may also be achieved by slowing the release or hydrolysis of the urea using a controlled release fertiliser or a urease inhibitor (Chen et al. 2008; Sanz-Cobena et al. 2008; Zaman et al. 2008; Turner et al. 2010).

Use of N-(n-butyl) thiophosphoric triamide (NBPT) as a urease inhibitor has reduced NH_3 loss from urea applied to soil by 60-80% in laboratory studies (Watson et al. 2008), by 28-88% in field studies on a range of cropping soils in the Americas (Rawluk et al. 2001), and by 90% from an Australian wheat crop (Turner et al. 2010). The high levels of NH_3 loss from pastures and the reported reductions in loss with NBPT suggest that there may be a role for using urease inhibitors to reduce NH_3 loss from dairy pastures fertilised with urea.

This paper reports the results of a field trial conducted in south-western Victoria, Australia to compare efficiency of fertiliser N use and NH_3 loss from ryegrass fertilised with a fine particle spray ('Nhance'), 'Green Urea 14', urea and UAN.

Material and methods

Site

The experiment was conducted on a two year old ryegrass (*Lolium perenne* L) seed crop at Murroon in south-western Victoria, Australia (38°26'10.18" S 143°47'34.57"E). The ryegrass was sown in rows which meant that there was a greater amount of bare soil (20%) compared to a typical established pasture. The duplex soil at the site is classified as a Chromosol (Isbell 1996); the surface horizon (0-25 cm) is a silty loam with 22% clay, 38% silt and 40% sand, and had an initial pH_{CaCl2} of 4.6. Soil total N and C measured using a combustion technique (Hydra 20-20, SerCon) were 0.2% and 2.7% respectively and the soil C:N ratio was 13. The 0-5 cm soil layer contained 8.4 kg N ha⁻¹ as ammonium (NH₄⁺) and 0.5 kg N ha⁻¹ as nitrate (NO₃⁻) at the start of the experiment in autumn. The bulk density of the topsoil was 1.23 g cm⁻³ and the cation exchange capacity was 4.98 cmol (+) kg soil⁻¹. The urease activity measured using the technique of Douglas and Bremner (1971) was 97 mg urea-N kg soil⁻¹ hour⁻¹. The mean annual temperatures averaged for the closest Bureau of Meteorology stations at Colac (38.23°S, 143.79°E) and Cape Otway (38.86°S, 143.51°E), are 18°C (maximum) and 9°C (minimum). Climatic variables were measured on-site with a weather station (model WXT510; Vaisala, Helsinki, Finland). Soil moisture (0–5cm depth) was measured using ML2x theta probes (Delta-T Devices Ltd., Cambridge, UK). Soil temperature was measured at 10 cm depth using an Enviropro® unit with a mini MAIT logger and a hand held unit (MAIT™ Industries). The site ran east-west and the prevailing wind was from the southwest. The autumn trial commenced on 12th April 2010 and finished on 10th May 2010. The spring trial commenced on 27th September 2010 and finished on 21st October 2010.

Ammonia loss

Ammonia volatilization was studied in three treated circular plots of 25 m radius. The centres of the areas were 100 m apart and the areas were located so that a line joining the centres was perpendicular to the prevailing wind direction to ensure that NH₃ emissions from one area did not interfere with emissions from the others. The treatments applied in autumn were 'Nhance', a fine particle spray [containing 46% N as urea, Agrotain (N-(n-butyl) thiophosphorictriamide) as a urease inhibitor @ 1 L t⁻¹, and gibberillic acid (a plant growth promoter included in the commercial formulation) @ 10 mg ha⁻¹, hereafter referred to as Nhance], 'Green Urea™ 14' [containing 45.8% N as urea and Agrotain @ 5.0 L t⁻¹, hereafter referred to as Green Urea] and granular urea, surface applied. Nhance was applied using Quinfert's 'Fluidator' technology, which

converts conventional granular urea into a thick fluid of fine particles (Quinfert 2011). The application of Nhance was not repeated in spring due to unforeseen logistical issues related to a second application of the product to the site. The treatments in spring were surface applications of Green Urea, granular urea, and urea ammonium nitrate (21.5% N as urea, 10.5% N as ammonium, and 10.5% N as nitrate) as a solution in water (UAN). UAN applied in solution was used in spring as a means of investigating the potential for a different form of N to reduce NH_3 emissions compared to the conventionally used granular urea products. The fertilisers were applied at the rate of 40 kg N ha^{-1} . Green Urea 14 and UAN were supplied by Incitec Pivot Ltd, and Nhance was provided by Quinfert Pty Ltd.

Ammonia loss was determined with a simplified mass balance micrometeorological method (Turner et al. 2010; Wilson et al. 1967; Frenay et al. 1985) using the Leuning et al. (1985) NH_3 samplers. Duplicate samplers were used to measure horizontal flux density at 0.8m above the grass at the centre of the circular areas. Background measurements were made with samplers placed on masts located on the upwind side of the treated areas. Ammonia emission was determined from 12th April to 10th May 2010, and 27th September to 21st October 2010. Initially, measurements were made twice daily during the periods 0800–1700 h and 1700–0800 h (overnight), but when the emission rate declined measurements were made over a longer time. Ammonia captured in the Leuning samplers was eluted with 40 mL milliQ water and analysed using a SAN++ segmented flow analyser (Skalar Analytical).

Soil and biomass measurements

Urea, NH_4^+ and NO_3^- were determined in soil samples collected from within the circles and background areas. In autumn composite samples were collected by taking 60 soil cores (18 mm diameter) from two transects (perpendicular to each other) across each circle. In addition thirty cores were collected at random from the background area to make a composite sample. In spring, each circle was divided into 4 quarters and composite samples were made by taking 15 soil cores from each quarter (a total of 60 cores for each circle). Each composite of 15 cores was treated as one sample so that in spring there were 4 samples per circle. The soil (replicated subsamples of 20g oven dried equivalent) was placed in a 250 mL wide-mouth plastic bottle, and 100 mL of 2 M KCl solution containing 10 mgL^{-1} phenylmercuric acetate was added. The soil suspensions were shaken for 1 hour then filtered through Whatman No 42 filter papers. The filtrate was collected and kept in a freezer (-20°C) until analysed for urea, NH_4^+ , and NO_3^- using a SAN++ segmented flow analyser (Skalar Analytical).

Ryegrass biomass on the treated areas was determined by cutting the forage from a 0.84 m² area using a small rotary lawnmower one month after fertilisation. In addition monthly cuts were made from autumn to spring to assess the longevity of any fertiliser effect. Pasture cages, 2m x 1m used to protect the areas sampled from grazing by sheep, were left in the same position during the autumn and spring campaigns. The ryegrass samples were dried in the laboratory at 70°C for 2 hours. Nitrogen content of the biomass was determined by a Kjeldahl digestion method with colourimetric analysis by Lachat 8500 Flow Injection Analyser (Rayment and Lyons 2011).

A ¹⁵N microplot experiment was conducted at the same site just outside the circular areas during autumn. Four replicate microplots were established by inserting cylinders of PVC pipe (25 cm internal diameter) into the ground so that 16 cm was below the soil surface and 4 cm projected above the soil. ¹⁵N labelled granular urea (10.22 atom % ¹⁵N) was applied to the microplots on day 1 of the NH₃ experiment at a rate of 40 kg N ha⁻¹. On the last NH₃ measurement day for the autumn experiment, the microplots were removed and the entire soil sample collected. Additional soil (3 cores per plot) was collected from each of the 16-26 cm and 26-36 cm layers beneath the microplots using a 10 cm x 2.5 cm (ID) corer. All soil was dried at 40°C, mixed and sieved, and subsamples from all layers finely ground (< 0.2 mm mesh), and analysed for ¹⁵N on an isotope ratio mass spectrometer (Hydra 20-20, SerCon). Plant biomass was measured for aboveground plant material and roots for each microplot. Aboveground plant material was harvested, dried at 65°C, and ground for ¹⁵N analysis. Major roots were removed from the soil, dried at 65°C (without washing), and ground separately for ¹⁵N analysis. Plant biomass was also measured.

Statistical analysis

Analysis of variance was performed using the program R (Hornik 2009) to assess the effects of the added fertiliser on plant biomass production and N content.

Results

Weather and soil conditions

In autumn at the trial site, the soil temperature ranged from 10 to 20°C, and there was very little rainfall for the first few days after fertiliser application (Fig. 1). The maximum air temperature ranged from 13 to 26°C during the autumn experiment and from 10 to 22°C during the spring study (Fig.1). Over the first four days of each experiment air temperatures ranged from 7.3 to 22°C in autumn, and from 1.7 to 14°C in spring. Soil

temperature at 10 cm depth ranged from overnight lows of 8°C to daytime highs of 20°C (autumn) and from 11 to 22°C. Rain fell at regular intervals during the year (Fig.1) and the total rainfall for 2010 was 803 mm. In autumn, showers fell the day prior to fertiliser application but there was very little rainfall for the first few days after fertiliser application. Dew formed on the pasture every night. In spring 4 mm rain fell within 24 hour of fertiliser application. Soil moisture at the site was similar across all treatments and ranged from 24 to 50% WFPS during the autumn experiment and 45 to 89% WFPS during the spring study. Wind speed across the field site over the first five days of NH₃ measurement ranged from 1 to 32 km hr⁻¹ in autumn and from 1 to 39 km hr⁻¹ in spring.

Nitrogen transformations

Autumn

In the granular urea treatment urea disappeared rapidly and only 0.6 kg N ha⁻¹ of the urea applied remained in the soil after 3 days (Fig. 2a). In the Green Urea treatment the transformation was slowed slightly; after 3 days 1.4 kg N ha⁻¹ was present as urea. Urea disappeared at a similar rate to the granular urea in the Nhance with 0.7 kg N ha⁻¹ found in the pasture soil after 3 days (Fig. 2a).

Prior to fertiliser application the content of NH₄⁺ in the surface soil layer was 8.4 kg N ha⁻¹. In the granular urea treatment the NH₄⁺ level in the 0-5 cm layer increased to 45 kg N ha⁻¹ 3 days after fertilization (DAF) and then decreased gradually to 5.5 kg N ha⁻¹ over the next 19 days (Fig. 2b), reaching a similar level at 21 DAF to the non-fertilised plots (1 kg N ha⁻¹). In the Green Urea treatment the NH₄⁺ content increased initially to 56 kg N ha⁻¹ on 3 DAF and then decreased in a similar fashion to that in the granular urea treatment to 4 kg N ha⁻¹ on 21 DAF (Fig. 2b). In the Nhance treatment NH₄⁺ was produced and transformed in a similar fashion to that in the granular urea treatment with 37 kg N ha⁻¹ present on 3 DAF decreasing to 4.3 kg N ha⁻¹ at 21 DAF (Fig. 2b).

The NO₃⁻ content of the surface soil layer before fertiliser application was 0.5 kg N ha⁻¹. In the granular urea treatment the NO₃⁻ content increased slowly to 2.8 kg N ha⁻¹ on 9 DAF and then decreased quickly to 0.6 kg N ha⁻¹ probably as a result of a combination of plant uptake and leaching below 5 cm due to rainfall of 22 mm between 9 and 12 DAF. After application of Green Urea the NO₃⁻ content increased to 3.5 kg N ha⁻¹ on 9 DAF and then fluctuated in a similar fashion to NO₃⁻ in the granular urea treatment. In the Nhance treatment NO₃⁻ increased to 6.1 kg N ha⁻¹ on 9 DAF and then decreased between 9 and 12 DAF to

1.3 kg N ha⁻¹ (Fig. 2c). The concentration of urea plus NH₄⁺ and NO₃⁻ in the soil at the end of the experiment (day 28) is given in Table 1.

Spring

In spring the fertilisers were applied to wet soil after a period of substantial rainfall during August and September (Fig. 1). When granular urea and UAN were top dressed onto the pasture the rate of hydrolysis of urea was rapid; the majority of the granular urea was hydrolysed within 3 DAF and all of the urea in UAN was hydrolysed by 2 DAF (Fig. 3a). In the Green Urea treatment hydrolysis proceeded more slowly than it did in the urea treatments, but after 4 days only 3.6 kg N ha⁻¹ remained in the soil as urea (Fig. 3a). Ammonium levels were lower in the surface soil of the Green Urea treatment than the granular urea treatment initially (Fig. 3b), but there was no difference between treatments 5 DAF. In the UAN treatment the NH₄⁺ level in the surface soil increased initially to 18 kg N ha⁻¹ because of the addition of NH₄⁺ in the fertiliser (10 kg N ha⁻¹) and the hydrolysis of the added urea. Little NO₃⁻ was produced in the surface soil of the granular urea and Green Urea treatments and that added in the UAN treatment was lost within 7 DAF (Fig. 3c).

Ammonia loss

Autumn

The maximum vertical flux densities of NH₃ from the granular urea, Nhande, and Green Urea treatments were 5.1, 3.3 and 1.7 kg N ha⁻¹ day⁻¹, respectively (Fig. 4a). The cumulative NH₃ losses from the three treatments were 12, 9.1 and 3.7 kg N ha⁻¹ (30, 23 and 9% of applied N), respectively (Fig. 4b, Table 1). Most of the NH₃ was lost during the first 4 DAF (Fig. 4).

Spring

Both the rates and the total amounts of ammonia loss for the granular urea and Green Urea treatments were much lower in spring than they were in autumn. The maximum vertical flux densities of NH₃ from the granular urea, UAN and Green Urea treatments were 0.42, 0.40 and 0.35 kg N ha⁻¹ day⁻¹ (Fig. 5a). The cumulative NH₃ losses from the granular urea, UAN and Green Urea treatments were 0.82, 0.78 and 0.47 kg N ha⁻¹ (2, 2 and 1% of applied N), respectively (Fig. 5b, Table 1). The majority of the NH₃ was lost during the first 6 DAF (Fig. 5).

Biomass production

In autumn, biomass production from the control (no N applied) was 337 kg ha⁻¹. The biomass production was significantly increased ($P<0.05$) in the granular urea, Green Urea and Nhance treatments to 665, 599 and 551 kg ha⁻¹, respectively, one month after N application (Table 1). However, the agronomic efficiency (i.e. kg pasture increase per kg N applied) of granular urea (8.2) was not improved by using the Green Urea and Nhance treatments (6.6 and 5.4, respectively). In spring the surface applications of granular urea, Green Urea and UAN also significantly ($P<0.05$) increased biomass production one month after fertiliser application from 1341 (no fertiliser added), to 2041, 1991 and 2138 kg ha⁻¹, respectively. However, there was no significant difference in biomass production due to the different fertiliser treatments. The agronomic efficiencies of the granular urea, Green Urea and UAN applications were 18, 16 and 20 kg pasture increase per kg N applied.

Biomass production in the period May to September was determined from 4 pasture cuts taken in May, June, July and September. The cumulative biomass in the granular urea, Green Urea and Nhance treatments resulting from the applications on April 12th was 705, 671 and 779 kg respectively. The results were not significantly different ($P<0.05$).

Nitrogen uptake

Nitrogen uptake by ryegrass in the non-fertilised treatment in autumn (9.8 kg N ha⁻¹) was lower than that in spring (34.9 kg N ha⁻¹) (Table 1). Nitrogen uptake was significantly ($P<0.01$) increased by all fertiliser treatments and was linearly related to increased dry matter production ($R^2=0.77$). In the granulated urea and Green Urea treatments N uptake was significantly higher ($P<0.01$) in spring (65.3 and 59.7 kg N ha⁻¹, respectively) than in autumn (23.3 and 21.0 kg N ha⁻¹, respectively). Apparent fertiliser recoveries (RE_N) by the ryegrass in autumn were 33.8, 28.0 and 23.8% for the granular urea, Green Urea and Nhance treatments, respectively, and in spring the apparent recoveries for granular urea, Green Urea and UAN, respectively, were 76.1, 62.2 and 89.2% (Table 1).

¹⁵N balance

The labelled granular urea microplot study which ran for 1 month after the application in autumn showed that 29.1, 13.1 and 30.6% of the applied N was recovered in the shoot biomass, roots and soil, respectively. Twenty four per cent (24%) of the applied N was found in the top 6 cm of soil and 6.6 % was

found in the 6-16 cm soil layer. No fertiliser N was found in the soil below 16 cm. Total ^{15}N recovery in the plant and soil was 72.8 % indicating that 27.2 % of the applied N was lost from the plant-soil system. The ^{15}N study showed that of the total nitrogen measured in the plant roots and shoots (59 kg N ha^{-1}), 30% of this was derived from the applied fertiliser N ($17.7 \text{ kg N ha}^{-1}$), and 70% from indigenous soil N ($41.5 \text{ kg N ha}^{-1}$).

Discussion

In autumn heavy dew led to the rapid hydrolysis of the urea granules, promoted by the high urease activity ($97 \mu\text{g urea N g soil}^{-1} \text{ hr}^{-1}$) of the soil, and warm daytime temperatures (maximum 22°C over the first 4 days; Fig. 1) drove the high losses of NH_3 . In spring the rain (4 mm) which fell in the 24 hours following fertiliser application most likely dissolved the urea and washed it into the already moist soil (66% WFPS on 1 DAF). This combined with low temperatures after the fertiliser was applied (maximum 14°C over the first 4 days) resulted in very little ammonia loss compared to autumn. The additional moisture on site in spring assisted the dissolution because higher losses from urea would be expected with low inputs of water (Sanz-Cobena et al. 2011). The soil data shows that urea was rapidly hydrolysed in both season; some of the urea would have been hydrolyzed to NH_3 and some may have been taken up directly by the pasture (Stiegler et al. 2010). The NH_4^+ levels in the 0-5 cm soil layer in autumn were higher than those in spring. This may have been caused by the drier conditions in autumn and/or more rapid uptake of N in spring. The amounts of NH_3 lost from the granular urea treatment in autumn are somewhat higher than those reported elsewhere for pasture systems in Australia (Prasertsak et al. 2001; Eckard et al. 2003). This might be due to the low density of the pasture at our site compared to the previous studies and thus less reabsorption of volatilised NH_3 by the pasture shoots, a process discussed in the paper of Frank et al. (2004).

The main pathways for N loss from the plant-soil system are NH_3 volatilization, nitrification, denitrification, leaching and runoff (Chen et al. 2008). The autumn microplot study with ^{15}N labelled granular urea showed that the total loss from the plant soil system was 27.2% of the N applied. Since none of the applied N was found in the soil below 16 cm at the final sampling, it can be concluded that no N was leached below the root zone and no runoff could have occurred because the wall of the microplot extended to 4 cm above the soil surface. As the NH_3 loss in autumn (30% of the applied N) was essentially the same as total N lost from the microplot, the results indicate that loss of N by nitrification or denitrification of the granular urea was negligible.

Use of a urease inhibitor with urea (Green Urea) slowed the rate of urea hydrolysis compared to that of urea alone as shown by the amount of urea in soil, and resulted in reduced NH_3 loss from the ryegrass

pasture in autumn (Fig. 4). The reduction in NH_3 loss from the application of Green Urea was similar to those reported in other studies on pastures where the urea had been treated with NBPT (Watson et al. 1990), and greater than those reported in others (Zaman et al. 2008). The greatest reduction in NH_3 loss due to the addition of NBPT to the urea in this study occurred in autumn when conditions were optimal for NH_3 loss. In spring, the amounts of NH_3 lost from all treatments were so low it was difficult to discern a real benefit of using Green Urea. Seasonal variation on the effect of NBPT to reduce NH_3 volatilisation from applications of urea has been reported elsewhere (Rawluk et al. 2001; Grant et al. 1996; Koenig et al. 2007).

One would expect that when urea is applied as fine particles (Quin et al. 2005) rather than large granules the localised elevated pH effect due to hydrolysis of the urea (Sherlock et al. 1987) should be less, and in this acid soil (pH 4.6) may be negligible and as a result NH_3 loss should be low. However, it was found that NH_3 loss from the Nhance treatment (23% of the applied N) was only slightly less than that from granular urea (30%). Because the fluid used in the Nhance treatment contained Agrotain (NBPT) it is not possible to determine from our results whether the reduced loss was due to the NBPT or the method of application. Dawar et al. (2011) conducted experiments using fine particle sprays with and without NBPT and concluded that use of a fine particle spray did not reduce NH_3 loss compared to granular urea.

Biomass production was greater in spring than autumn, reflecting the different growth patterns expected in south-western Victoria for those times of year (DPIV 2011). The benefit of using N fertilisers for plant production lasted from April until September for all treatments. In autumn the Green Urea and Nhance treatments did not increase the production of biomass, N content or N uptake compared to granular urea. The reduction in NH_3 loss in autumn was not translated into increased biomass or improved N content of the plant. The reason we did not see a yield response in autumn might be because the amount of N applied or available was in excess of that required for the plant growth at that time of year even when a large percentage of this N was lost. The adequate N (not limiting) could be due to a combination of fertiliser N inputs and soil mineralisation in autumn, which is likely to have been stimulated by the addition of fertiliser N (Feyter et al. 1985). The data from the ^{15}N microplots showed that for the granular urea treatment at 40 kg N ha^{-1} , only 30% of the N taken up by the plant was derived from the fertilizer, with 70% of the N taken up by the plant coming from the indigenous N pool. Apart from the 8.9 kg N ha^{-1} available as NH_4^+ and NO_3^- at the start of the experiment, the additional 7.4 kg N ha^{-1} was derived from mineralisation. For the $23.3 \text{ kg N ha}^{-1}$ taken up by the plant in the granular urea treatment in autumn (Table 1) we estimate that 7 kg N ha^{-1} comes from the fertiliser (based on the ^{15}N microplot result) and $16.3 \text{ kg N ha}^{-1}$ from indigenous soil N. Therefore even with

a loss of 30% (or 12 kg N ha⁻¹) of the applied N in the granular urea treatment there is still sufficient fertiliser N (28 kg N ha⁻¹) to meet the plants' requirements. The productivity gain from using the Green Urea and Nhandance treatments would be only possible in situations where N, counting both N saved due to these treatments and supply of indigenous soil N, is limiting or at least not in surplus. This indicates lower N rates could be applied at this site in autumn when using Green Urea for environmentally and economically beneficial outcomes. However this approach must ensure N is balanced so that it is not being mined from the soil over time.

Conclusions

Up to 30 % of applied urea N can be lost through NH₃ volatilisation when surface applied to acidic pasture soil. However, this loss is negligible when excess water causes the urea to be dissolved and diffused into a much larger soil volume where it is buffered from the localised elevated pH caused by urea hydrolysis. When the potential of NH₃ loss was high the application of Green Urea (urea coated with NBPT) was effective in reducing NH₃ loss compared to granular urea from 30% to 9% of applied N, and to a lesser extent Nhandance was also effective in reducing NH₃ loss compared to granular urea (reduction to 23% of applied N). The reduction in NH₃ loss may not be reflected in the biomass production when the supply of N is not limiting, particularly when 70% of the pasture N uptake is derived from soil.

The potential of NH₃ volatilisation in this acidic soil is seasonally and climatically dependent, as is the effect of Green Urea. This makes the adoption of Green Urea and urease inhibitor treated products a challenge for management of N fertilisers in pastures.

Acknowledgements

The authors thank the Department of Agriculture, Fisheries and Forestry, the Grains Research and Development Corporation, Incitec Pivot Ltd and ARC for funding the project. Laboratory and field assistance was provided by Mr M. Mahoney, Dr X. Chen, Associate Professor R. Edis, Y. Liu, L. Chen and M. Benfell.

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Fig. 1 Daily rainfall (column) and maximum air temperature (line) at the experimental site during the study period. The arrows designate the starting times for the autumn and spring trials

Fig. 2 Urea (a), NH_4^+ (b) and NO_3^- (c) concentrations in the surface soil (0-5 cm) of the control (no fertiliser) ($\times$), top dressed granular urea ($\diamond$), Green Urea ($\blacklozenge$), and Nhance ($\triangle$) treatments in autumn.

Fig. 3 Urea (a), NH_4^+ (b) and NO_3^- (c) concentrations in the surface soil (0-5 cm) of the control (no fertiliser) ($\times$) top dressed granular urea ($\diamond$), Green Urea ($\blacklozenge$), and UAN ($\blacktriangle$) treatments in spring

Fig. 4 Daily (a) and Cumulative (b) ammonia loss from ryegrass in the top-dressed granular urea ($\diamond$), Green Urea ($\blacklozenge$) and Nhance ($\triangle$) treatments during autumn

Fig. 5 Daily (a) and Cumulative (b) ammonia loss from ryegrass in the top-dressed granular urea ($\diamond$), Green Urea ($\blacklozenge$) and urea ammonium nitrate ($\blacktriangle$) treatments during spring

Table 1. Effect of surface applications of granular urea, Green Urea, Nhance and urea ammonium nitrate (UAN) on ammonia loss, biomass production and nitrogen recovery in autumn and spring

Table 1. Effect of surface applications of granular urea, Green Urea, Nhance and urea ammonium nitrate (UAN) on ammonia loss, biomass production (kg of dry matter (DM) per hectare) and nitrogen recovery in autumn and spring

	Treatment				
	Control	Granular urea	Green urea	Nhance	UAN
Autumn					
Ammonia loss (kg N ha^{-1})	0	12.0	3.8	9.0	-
Ammonia loss (% of applied N)	-	30	9	23	-
Biomass production (kg DM ha^{-1})	337	665	599	551	-
Agronomic N efficiency ¹	-	8.2	6.6	5.4	-
Nitrogen uptake (kg N ha^{-1})	9.8	23.3	21.0	19.3	-
Apparent recovery efficiency ² (%)	-	33.8	28.0	23.8	-
Soil urea, ammonium and nitrate	7	17	20	14	-

(kg N ha⁻¹) at harvest

Spring

Ammonia loss (kg ha ⁻¹)	0	0.8	0.5	-	0.8
Ammonia loss (% of applied N)	-	2	1.3	-	2
Biomass production (kg DM ha ⁻¹)	1341	2041	1991	-	2138
Agronomic N efficiency	-	18	16	-	20
Nitrogen uptake (kg N ha ⁻¹)	34.9	65.3	59.7		70.6
Apparent recovery efficiency (%)	-	76.1	62.2	-	89.2
Soil urea, ammonium and nitrate (kg N ha ⁻¹) at harvest	2.0	3.1	3.4	-	3.1

422 ¹Agronomic efficiency of applied N [kg pasture increase per kg N applied], ²Apparent recovery
423 efficiency of applied N [net kg N taken up per kg N applied]

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Fig. 1 Daily rainfall (column) and maximum air temperature (line) at the experimental site during the study period. The arrows designate the starting times for the autumn and spring trials

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Fig. 3 Urea (a), NH_4^+ (b) and NO_3^- (c) concentrations in the surface soil (0-5 cm) of the control (no fertiliser) (×) top dressed granular urea (◇), Green Urea (◆), and UAN (▲) treatments in spring

Fig. 4 Daily (a) and Cumulative (b) NH_3 loss from ryegrass in the top-dressed granular urea (◇), Green Urea (◆) and Nhande (△) treatments during autumn

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447 **Fig. 5** Daily (a) and Cumulative (b) NH₃ loss from ryegrass in the top-dressed granular urea (◇), Green Urea
448 (◆) and urea ammonium nitrate (▲) treatments during spring

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