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Urea applied as a foliar spray or in granular form to subtropical dairy pastures of kikuyu (*Cenchrus clandestinus*) and Italian ryegrass (*Lolium multiflorum*) in eastern Australia

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Abstract. The nitrogen-use efficiency (NUE) of a fertiliser has implications for pasture growth and the environment. This study aimed to compare application of urea as a foliar spray or in granular form, to kikuyu (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) and short-rotation ryegrass (Italian ryegrass, *Lolium multiflorum* Lam.) pastures in the subtropical dairy region of eastern Australia. The first experiment was a replicated grazing study on a site with a high plant-available soil N (75 mg nitrate-N/kg). The granular rate of urea was 46 kg N/ha.month equivalent, and the foliar spray rate was 40% of the granular rate. Pasture growth rate (51 DM/ha.day with foliar spray vs 45 kg DM/ha.day with granules) and pasture consumed (4942 vs 4382 kg DM/ha) were not significantly different between treatments. However, over the 8 months of the study, soil nitrate-N levels fell from 75 to 22 mg/kg on the foliar plots but only fell to 60 mg/kg on the granular plots. The second experiment was a replicated plot-cut experiment on a site with a low plant-available soil N (8.7 mg nitrate-N/kg). The NUE for kikuyu grass was similar for all treatments with a mean of 14.8 kg DM/kg N for the four foliar treatments (high and low, with and without wetting agent) and 17.4 kg DM/kg N for the granular treatment. The NUE for the ryegrass was also similar for all treatments, with a mean of 13.2 kg DM/kg N for the foliar treatments and 15.8 kg DM/ha for the granular treatment. A third experiment, evaluating absorption of foliar-sprayed urea over time, found that >80% of the urea applied to kikuyu was absorbed by 7 h; for ryegrass, the amount absorbed was only ~45% but increased to ~75% if wetting agent was included. We suggest that the lack of benefit in NUE achieved by applying urea as a foliar spray, which contrasts with results from studies in temperate dairy farm systems, is primarily associated with the substantially lower tiller density and hence the smaller canopy area for absorption of the foliar spray by the new regrowth shoots post-grazing.

Keywords: dairy pasture, nitrogen-use efficiency, subtropical, urea absorption.

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Introduction

Nitrogen (N) fertilisers, particularly urea, are widely used by dairy farmers in Australia, with the proportion increasing from 58% in 1990 to 76% in 2012; the rate of application has also increased from 21 to 76 kg N/ha per annum (Stott and Gourley 2016). In New Zealand, the recommendation is that N-fertiliser application should not exceed 150 kg N/ha per annum in order to minimise the adverse impact of N-based fertilisers on the environment, primarily by minimising movement of nitrate (NO_3^-) into the groundwater. Similarly, in Europe, a limit of 107 kg N/ha per annum has been imposed, applied as fertiliser or manure (EEC 1991).

In the subtropical dairy region of Australia, dairy farmers commonly have a summer grass-based pasture comprising kikuyu (*Cenchrus pennisetiumclandestinus* (Hochst. ex Chiov.) Morrone) and other summer grasses, which is oversown in early autumn with a tetraploid short-rotation ryegrass (Italian ryegrass, *Lolium multiflorum* Lam.) to provide winter–spring feed. This system relies on relatively high rates of N-fertiliser input, with 46–60 kg N/ha.month recommended (Lowe *et al*. 2005; Christie *et al*. 2018) or 1.6 kg N/ha.day to cater for variation in grazing interval (Staines *et al*. 2017). Hence, there is a need to ensure that the applied N fertiliser is used efficiently, in terms of both farm economics and the environment. To this end, there is growing interest in the application of N-based (and other) fertilisers to pastures as a foliar spray, which is potentially more efficient than application in granular form (Dawar *et al*. 2012).

On contact with moist soil, the N in urea is converted to ammonium (NH_4^+) by the soil enzyme urease. Most of the NH_4^+ is attached to soil particles but some is converted to ammonia (NH_3) and volatilised into the air (annual mean loss of 11%, Eckard *et al*. 2003). The remaining NH_4^+ is loosely bound to the cation-exchange complex but can then be

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converted to NO_3^-, the form of N most used by plants. Unlike NH_4^+, NO_3^- is not bound and is therefore liable to leaching below the root-zone, or to denitrification to the greenhouse gas nitrous oxide (N_2O) when the soil is fully water-saturated. Loss as N_2O was found to account for ~3.8% of total N applied on dairy pastures in south-eastern Australia (Eckard *et al*. 2003).

Application of fertilisers in foliar sprays has been used in horticulture for many years, primarily for micro-minerals but also for macro-minerals, with the benefits of the nutrients being absorbed by the leaves, and hence bypassing the soil, where most of the losses to the environment occur, as outlined. There is experimental evidence that pasture plants can absorb urea through their leaves and that this urea-N can be metabolised within the plant (Morton *et al*. 2019). Furthermore, Franke (1967) found that application of urea to the leaf increased the permeability of the leaf cuticle and hence improved its diffusion into the leaf. Dawar *et al*. (2012) showed that dissolved urea was ~21% more efficient in promoting ryegrass growth when applied as a foliar spray than in granular form. This is in line with the previous research of Middleton and Smith (1979), who found that less energy is required to synthesise protein from NH_4^+ when it is directly absorbed from the leaf rather than after it is converted to NO_3^- and then absorbed by the roots of the plant.

In view of these studies, farmers are now applying urea and other N-based fertilisers as foliar sprays onto dairy pastures. This has led to development of specialist spray units that have constant agitation, thus allowing other soil nutrients, herbicides and insecticides, and even lime or pasture seed to be applied at the same time as the dissolved urea.

The present study considered N-fertilisation of a subtropical kikuyu–Italian ryegrass pasture. The aims were three-fold: (*i*) to compare the efficacy of urea applied as a foliar spray with that of the granular form in terms of pasture growth response while defining the contribution of plant-available soil N; (*ii*) to determine uptake over time of foliar-applied urea (absorption) by pasture plants, a critical factor in deciding when to apply the foliar spray on-farm in relation to forecast rain; and (*iii*) to compare the concentration of N in grass leaves at grazing after both methods of application in relation to adequacy of N availability to the plant, potential impact on cow health, and loss to the environment through volatilisation and leaching of N.

Materials and methods

Three experiments were conducted at two sites on the Far North Coast of New South Wales (NSW), Australia, separated by 30 km.

Experiment 1: study on a site with high plant-available soil N

Experiment 1 was a paddock-scale, replicated grazing trial with two fertiliser-application treatments on a soil with high plant-available N (75 mg NO_3^--N/kg) over an 8-month period, including 18 August–15 October 2015 for the ryegrass phase and 15 October 2015–30 March 2016 for the kikuyu phase. The site was near Lismore, NSW (29°S, 153°E; elevation 12 m a.m.s.l.). Figure 1 presents maximum and minimum temperatures and relative humidity over the experimental period (Fig. 1*a*) and daily rainfall (Fig. 1*b*).

The pasture was predominantly kikuyu-based with some paspalum (*Paspalum dilatatum* Poir.). As is common practice, the kikuyu-based pasture was oversown in autumn with 35 kg/ha of short-rotation Italian ryegrass cv. Tetila to provide pasture from late autumn to midspring. The pasture was irrigated if rainfall was inadequate as part of normal irrigation-management practice. Initial soil nutrient status and pH (Table 1) were more than adequate for pasture growth.

The experimental design comprised the two fertiliser application treatments randomly allocated over replicates:

- Treatment 1 (granular application) with three replications. Urea was broadcast in granular form at 100 kg/ha.month on a pro rata basis grazing interval , 2 days after pasture had been grazed by milking cows over a 24-h period. The broadcast timing represented the typical on-farm delay in applying urea (R Eckard, pers. comm.)
- Treatment 2 (foliar application) with seven replications. Urea was applied as a foliar spray through a boom-spray at a rate of 40% of the granular application. Urea was applied ~5 days after each grazing, to obtain enough regrowth to receive the spray, and in the late afternoon to minimise leaf burn. The ratio of urea to water was 1 : 3, and a non-ionic wetting agent was added at 37 mL/100 L water.

There were seven replicates of the foliar treatment, each plot being 9 m wide (the boom-spray width) and 55 m long, and three replicates of the granular treatment, each plot being 21 m wide (a spreader width) and 55 m long. Pre- and post-grazing pasture mass was estimated by an electronic rising-plate meter (Fulkerson and Slack 1993) at each grazing event, calibrated for the two grass species, to determine growth rate and pasture consumption by the milking cows. The N content of each grass species were determined from pluck samples to grazing height immediately before the last grazing.

Experiment 2: study on a site with low plant-available soil N

Experiment 2 was a replicated plot-cutting experiment with six fertiliser-application treatments on a soil with low plant-available soil N (8.7 mg NO_3^--N/kg) site over 11 months from 2 November 2018 to 10 October 2019. Phase 1 (kikuyu) was from 11 November 2018 to 3 April 2019 and Phase 2 (ryegrass) was from14 April to 10 October 2019. The site was at Wollongbar Agricultural Institute on the Far North Coast of NSW (28°S, 150°E; elevation 150 m a.m.s.l.), with a subtropical climate and a mean long-term annual rainfall of 1180 mm. Figure 2 presents maximum and minimum temperatures, relative humidity and times of urea application (arrows) during the experimental period (Fig. 2*a*), and the daily rainfall (Fig. 2*b*).

Irrigation was provided when rainfall was inadequate, based on daily evaporation and the crop factor of 0.7.

Soil analysis and sampling

The soil is a Red Krasnozem (Stace *et al*. 1968) of basaltic origin, with a base pasture of well-established kikuyu grass, and contained adequate levels of key macronutrients (Colwell phosphorus (P), 87 mg/kg, exchangeable potassium (K)

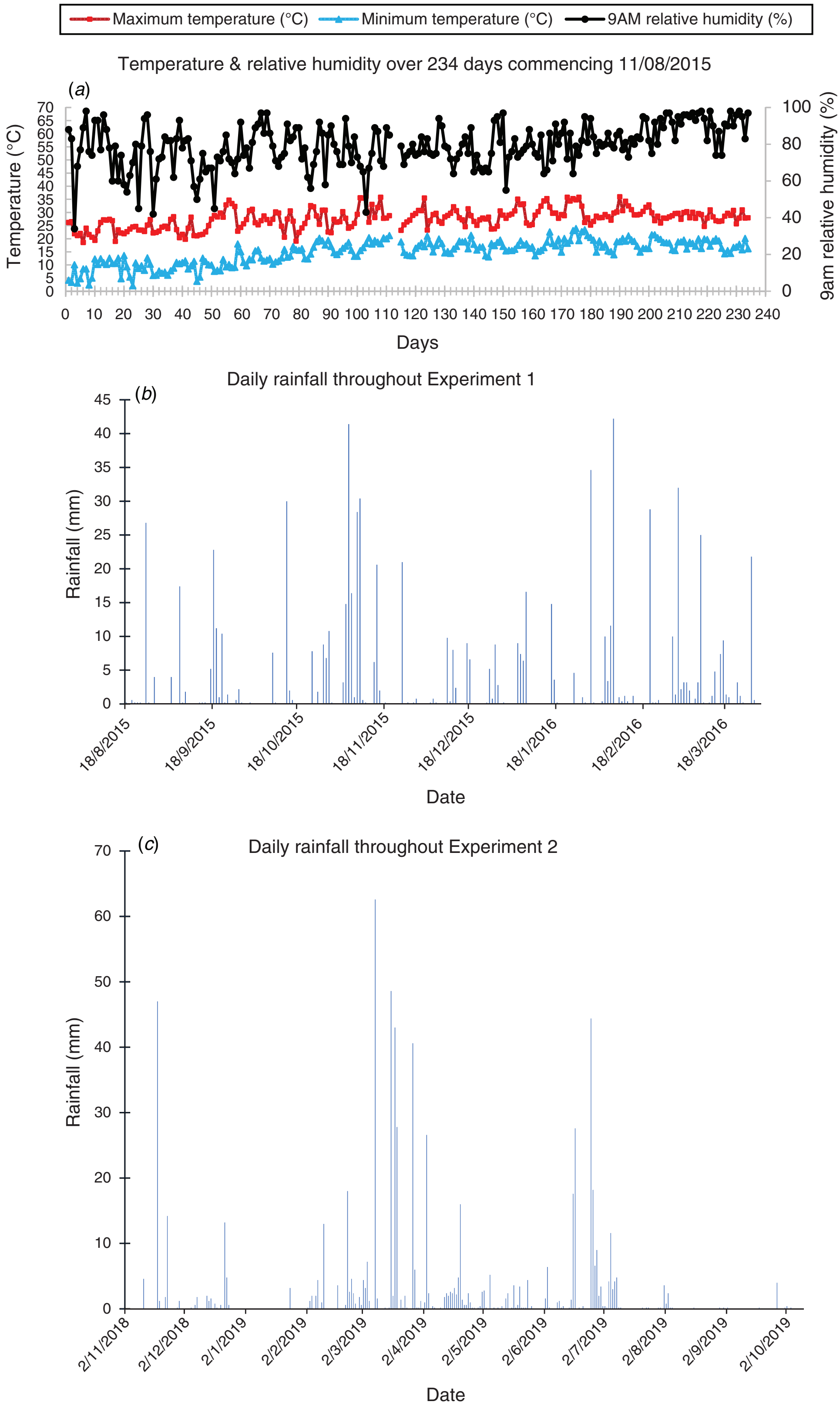

Fig. 1. (*a*) Daily maximum and minimum temperature and relative humidity; (*b*) daily rainfall during Experiment 1 (8 months); and (*c*) daily rainfall during Experiment 2 (11 months).

363 mg/kg, sulfur 38 mg/kg, and organic carbon (C) 5.5%). The pH($CaCl_2$) of 4.9 was not adjusted because raising it would increase mineralisation and, hence, plant-available soil N.

The mean soil NO_3^- on 26 March 2018, over the total plot area was 8.7 mg/kg, indicating little plant-available soil N (mean value for dairy pastures ($n = 421$) in this region is 23 mg NO_3^--N mg/kg; WJ Fulkerson unpublished data).

Deep soil core samples were taken from replicate 3 only, before the start of Phase 1 (2 November 2018) and at the end of Phase 2 (10 October 2019) to 50 cm depth, in 10-cm segments, and analysed for NO_3^- and NH_4^+ content. Soil samples to 10 cm were also taken at the beginning (10 April 2019) and end of Phase 2 for individual analysis of all treatments for NO_3^- and NH_4^+ content.

The mean NO_3^- and NH_4^+ of soil samples taken to 10 cm depth and pooled over all plots taken at the start of Phase 1 on 2 November 2018 and at the end of Phase 2 on10 October 2019, was 1.7 mg/kg and 15.6 mg/kg, respectively.

Ryegrass establishment

The kikuyu pasture was oversown with 40 kg Italian ryegrass cv. Tetila seed/ha on 3 April 2019. After seedling emergence, on 10 April and again on 5 May, 50 kg urea/ha was applied in granular form to all plots to assist establishment, before treatments commenced on 14 May.

Table 1. Soil analysis at the start of Expt 1 on 8 August 2015, pooled over all plots, and the end on 30 March 2016, for samples pooled over the foliar-spray and granular treatment plots

	8 August 2015	30 March 2016	
		Foliar	Granular
Colwell phosphorus (mg/kg)	171	114	167
Colwell potassium (mg/kg)	309	247	309
Sulfur (mg/kg)	48	28	35
Organic carbon (%)	5.1	4.8	5.0
pH($CaCl_2$)	5.1	5.0	4.9
NO_3^--N (mg/kg)	75	22	60
NH_4^+-N (mg/kg)	9	11	11

Experimental design

The experiment was a completely randomised plot design with six treatments and three replications and a plot size of 4 m by 1.5 m. Plots were harvested to a stubble height of 6 cm with a hand-push mower (Masport, Melbourne, Vic.). There was a 1.5-m kikuyu buffer between each treatment and a 2.5-m buffer between the replicates.

Phase 1: *kikuyu phase*. The target monthly application rates of urea for the six treatments in Phase 1 were as follows: nil, control; GH, 100 kg granular urea/ha; FH, 100 kg foliar urea/ha; FL, 50 kg foliar urea/ha; FHW, 100 kg foliar urea/ha plus non-ionic wetting agent; FLW, 50 kg foliar urea/ha plus non-ionic wetting agent.

Phase 2: *ryegrass phase*. The treatments were the same as in Phase 1, but the target application rates differed as follows: GH, 100 kg urea/ha; FH, 70 kg urea/ha; FL, 40 kg urea/ha; and wetting agent as required. The actual rate of application of urea was based on the defoliation interval, calculated as 3.3 kg urea/day (Staines *et al.*2017).

Application of foliar spray

The urea solution for the foliar spray was made by dissolving 1 kg urea in 2–3 L water (depending on treatment requirements). Where required, 30 mL non-ionic wetting agent/100 L water was added. The spray was applied via a quad-bike-mounted spray unit (SprayRider; C-Dax, Palmerston North, NZ), calibrated (with pressure and urea dilution rate adjusted) to give the target urea application rate per ha while the bike speed was kept constant at 2 km/h. The foliar spray was applied about one-third of the way through the anticipated interval between defoliations, estimated from Eqn 1 (Fulkerson *et al.* 1997), which is based on mean daily temperature over the previous inter-defoliation interval:

$$\text{3-Leaf appearance interval} = 3 \times (20 - 5.5 \times \text{mean daily temperature}) \quad (1)$$

with the mean time from defoliation to spray being (± s.d.) 7.8 ± 1.2 days for ryegrass and 5.3 ± 1.3 days for kikuyu. The actual mean inter-defoliation interval was 26.7 ± 6.1 days for

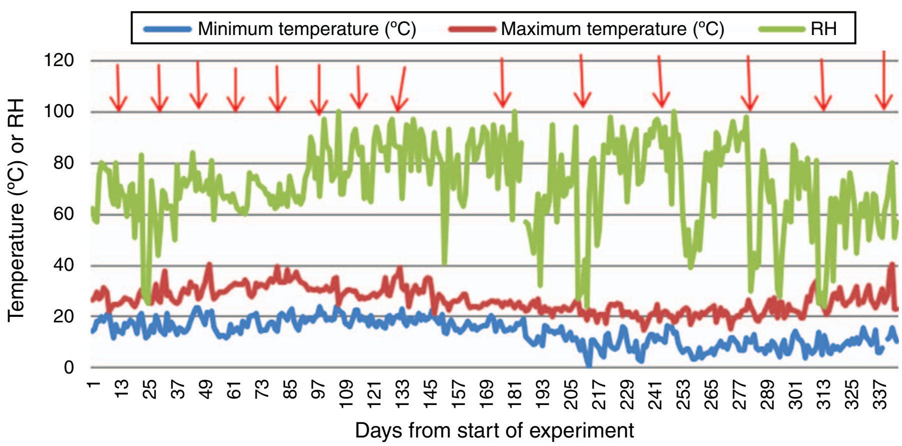

Fig. 2. Daily maximum and minimum temperature, relative humidity (RH) and the times of applying urea (indicated by arrows).

ryegrass and 16.0 ± 1.5 days for kikuyu. The recommendation is to apply urea as foliar spray 4–5 days after grazing. However, a decision on when to apply it is a compromise between earlier spraying, thereby providing more time for the plant to 'use' the N but with a smaller canopy cover to receive the urea, and later spraying, losing more absorbed N at grazing, with possible negative impacts on animal health due to higher pasture NO_3^- levels.

Foliar application was made when there was minimal wind. If there was a slight breeze, a wind shield (1 m by 2 m) was used to minimise spray drift. Although the spray unit was calibrated to apply the target application rate, the amount of urea actually applied to the plots may have varied depending on the speed of the quad bike and wind. In order to verify the amount of urea actually applied to the pasture canopy, a plastic tray (0.016 m^2 by 2 cm deep) was inserted into the sward, flush with the top of the grass canopy, immediately external to the plot but where the spray continued to be applied. In Phase 1, the verification process was applied only to foliar treatments in the third replicate. In Phase 2, the process was applied to all foliar treatments pooled over each replicate. Distilled water (100 mL) was then added, and the container was sealed and shaken for 30 s to dissolve the N; a 20-mL aliquot was analysed for N, in order to calculate the amount of urea applied (kg/ha). This value was used in all calculations and replaced the target values, which specify each treatment, in terms of kg urea per ha actually received by the pasture sward.

Sample collection and analyses

At each defoliation the green mass of each plot and a green subsample were weighed. The subsample was then dried in a force-draft oven set at 60°C for 48 h, and reweighed to calculate percentage DM and then DM (g) per plot. Where required, these dried pasture samples were analysed for percentage N and NO_3^- and NH_4^+ (mg/kg) at the Environmental Analysis Laboratory (EAL) (National Association of Testing Authorities approved) at Southern Cross University, Lismore, NSW.

Soil samples were similarly analysed but within 24 h of collection to minimise mineralisation of the disturbed soil.

Tiller density was recorded after the second last defoliation of ryegrass by counting the tillers within a 0.09-m^2 quadrat on each plot.

Experiment 3: determination of absorption of foliar-sprayed urea over time

This experiment evaluated the absorption of foliar-sprayed urea on kikuyu and ryegrass pastures over time at the site used for Expt 2.

The rate of absorption of foliar-sprayed urea was determined by washing the N off the leaves at specified times after foliar application, using a modification of the method outlined by Bowman and Paul (1989). Details of the procedure are as follows.

A foliar spray at a rate of 50 kg urea/ha with and without wetting agent was applied to separate plots (1.5 by 4 m) adjacent to the test plots and of similar pasture, approximately halfway through the normal interval between defoliations (7–15 days). A 0.09-m^2 quadrat of grass was cut to a stubble height of 6 cm at 0, 1, 3, 7 and 21 h after spraying. The cut grass was placed into a new aluminium tray and then immediately washed for 30 s in 1 L deionised water. After allowing the herbage sample to drain, a 20-mL subsample of the washings was sent to the EAL for analysis of total N. The drained forage sample was dried at 60°C for 48 h to determine dry weight of the initial sample in order to express N recovered as mg N per g DM.

Statistical analyses

Analysis of variance for pasture growth rate and pasture consumed in Expt 1 were performed with an unbalanced linear model that included effects of application types and residual errors. Pasture yields in Expt 2 were subjected to analysis of variance and the means were compared using Fisher's least significant difference test. The N absorption data were subject to quadratic regression analysis (Minitab 18; Minitab, State College, PA, USA).

Results

Experiment 1: high plant-available soil N

The pasture growth rate (kg DM/ha.day) and the total pasture consumption (kg DM/ha) over the 8 months of the experiment are shown in Table 2. The difference between the two treatments in pasture growth rate and pasture consumption was not significant ($P > 0.05$).

With regard to mean N status of pasture leaf (Table 3), the total N, NO_3^- and NH_4^+ contents in ryegrass and kikuyu were similar, irrespective of the mode of application of urea. However, there was a marked difference between the two grass species for all N measures, being substantially higher for ryegrass than kikuyu despite the same rate of urea being applied per month. However, the soil NO_3^--N concentration in the foliar-applied plots had dropped markedly from 75 mg/kg at the start of the experiment to 22 mg/kg at the end, whereas the NO_3^--N in the granular-applied plots had declined only slightly to 60 mg/kg (see Table 1).

Experiment 2: low plant-available soil N

Changes in soil NO_3^--N and NH_4^+-N levels over the experimental period:

The mean soil NO_3^--N and NH_4^+-N levels sampled to 0–10 cm depth, pooled over treatments and replicates were low at the beginning of the kikuyu phase (1.7 mg/kg and 15.6 mg/kg, respectively) and rose during the kikuyu phase (Table 4). The NO_3^--N levels then fell again whereas the

Table 2. Pasture growth rate and pasture consumed by milking cows when urea was applied as a foliar spray or granular form in Expt 1
Values are means ± standard error; n.s., not significant ($P > 0.05$)

Treatment	Grass growth (kg DM/ha.day)	Grass consumed (kg DM/ha)
Foliar	51.0 ± 1.4	4942 ± 165
Granular	45.0 ± 6.1	4382 ± 588
Significance	n.s.	n.s.

Table 3. Nitrogen contents in ryegrass leaf on 3 September 2015, and in kikuyu leaf on 29 March 2016, immediately pre-grazing when urea was applied as a foliar spray or in granular form in Expt 1

	Treatment	Total N (%)	NO_3^- (mg/kg)	NH_4^+ (mg/kg)
Ryegrass	Foliar	4.4	1047	439
	Granular	4.6	1904	502
Kikuyu	Foliar	3.2	24	354
	Granular	3.5	23	597

Table 4. Mean soil NO_3^--N and NH_4^+-N contents (mg/kg) to 10 cm depth for all six treatments at the end of kikuyu phase–beginning of ryegrass phase on 10 April 2019 and the end of ryegrass phase on 10 October 2019 in Expt 2

Treatments (with target monthly application of urea): FL, 50 kg foliar urea/ha; FH, 100 kg foliar urea/ha; FLW, 50 kg foliar urea/ha plus non-ionic wetting agent; FHW, 100 kg foliar urea/ha plus non-ionic wetting agent; GH, 100 kg granular urea/ha

Treatment	10 April 2019		10 October 2019	
	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N
Nil	11.6	25	3.3	26
FL	14.8	18.3	2.7	46
FLW	11.7	17.0	5.0	38
FH	9.6	20	3.8	34
FHW	12.5	19.7	4.0	25
GH	13.1	17.7	3.5	31
Mean ± s.d.	12.2 ± 1.7	19.5 ± 3	3.7 ± 0.8	33.3 ± 7.9

NH_4^+-N rose during ryegrass phase, but there was no significant difference between treatments.

The NO_3^-- N and NH_4^+- N of the deep soil core samples, taken before and after the experiment, are shown in Fig. 3. The sum of the NO_3^-- N contents of the 4 soil segments from 10–50 cm (subsoil) were the same at 1.2 mg/kg and although the NH_4^+- N contents did increase, from 9.6 to 13.5 mg/kg, this was not significant. These data indicate that there was no difference between methods of urea application with respect to loss of N down the soil profile.

Dry matter yields, N-use efficiency and cost of extra yield

Responses to application of urea, costed at $600/t, are presented for kikuyu (Table 5), and ryegrass (Table 6). The total DM yield of ryegrass was similar to kikuyu with a good overall response to urea application, but unlike kikuyu, there appeared to be a benefit of adding a non-ionic wetting agent to the foliar spray, and this is in line with the more rapid uptake of the dissolved urea in the absorption study (Expt 3, see below).

Nitrogen in ryegrass leaf

The amount of N recovered over the period and the percentage N in ryegrass leaves was significantly correlated with urea application rate as follows: N (kg) = 116.8 + 0.114 kg urea/ha (r^2 = 29%, P = 0.002, n = 6); and N (%) = 2.17 + 0.0003 kg urea/ha.day (r^2 = 19.5%, P = 0.001, n = 6). A linear relationship was the best fit over the range of values.

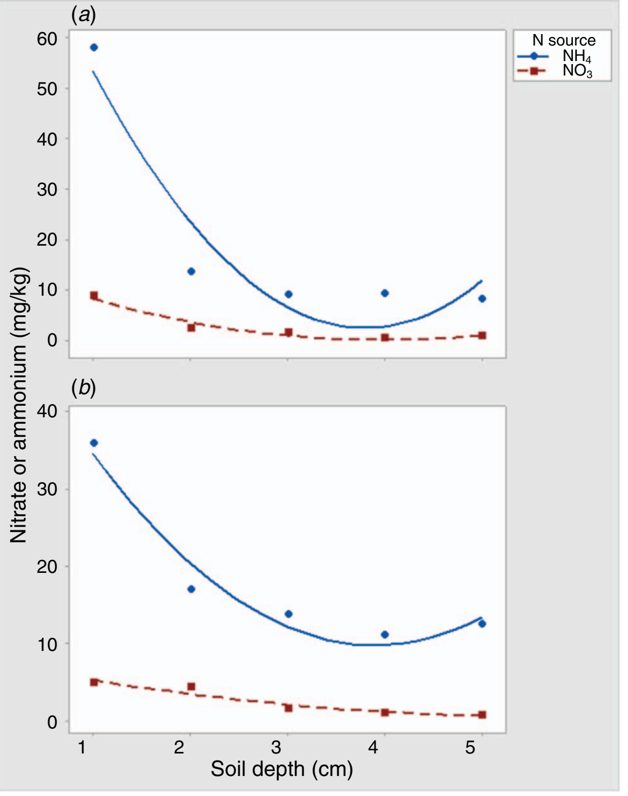

Fig. 3. Mean NO_3^-- N and NH_4^+- N (mg/kg) for soil samples from replicate 3 taken to 0.5 m depth in 10- cm segments (where 1 is the 0–10 cm section and 5 is 40–50 cm) taken (*a*) before commencement of the kikuyu phase and (*b*) at the conclusion of Experiment 2.

Table 5. Mean kikuyu dry matter (DM) yield, and extra DM yield, N-use efficiency (NUE) and cost of producing the extra DM over the nil control for urea applied as a foliar spray (F) and with or without wetting agent (W) or in granular form (G) at low (L) or high (H) rate

For total DM, means followed by the same letter are not significantly different at P = 0.05

Treatment (actual amount of urea applied per month)	Total DM (kg/ha)	Extra DM (kg/ha)	NUE (kg DM/kg N)	Cost of extra feed (cents/kg DM)
Nil	3088c	–	–	–
FL (49 kg/ha)	5190ab	2102	22	6
FLW (47 kg/ha)	4241bc	1153	12.8	10.3
FH (88 kg/ha)	4891b	1803	10.6	12.5
FHW (81 kg/ha)	5292ab	2202	14.1	9.4
GH (84 kg/ha)	6269a	3181	17.6	7.5

Tiller density

Mean ryegrass tiller density was 560 ± 76 tillers/m^2 and there was no significant difference (P > 0.05) among treatments.

Experiment 3: absorption of foliar applied urea by the grass over time

The N remaining on regrowth leaves (mg N/kg DM) at various times after applying urea as a foliar spray, as a percentage of

Table 6. Mean ryegrass yield (DM), and extra DM yield, N-use efficiency (NUE) and cost of producing the extra DM over the nil control for urea applied as a foliar spray (F) and with or without wetting agent (W) or applied in granular form (G) at low (L) or high (H) rate

Treatment (actual amount of urea applied per month)	Total DM (kg/ha)	Extra DM (kg/ha)	NUE (kg DM/kg N)	Cost of extra feed (cents/kg DM)
Nil	3956 (d)			
FL (44 kg/ha)	4950 (cd)	994	9.2	14.1
FLW (47 kg/ha)	6096(bc)	2140	18.3	7.1
FH (67 kg/ha)	5746 (bc)	1790	10.7	12.1
FHW (77 kg/ha)	6578 (ab)	2622	13.9	9.4
GH (99 kg/ha)	7789 (a)	3833	15.8	8.2

the N recovered immediately after applying the foliar spray, was determined for kikuyu and ryegrass (Fig. 4). The results show that >80% of the urea applied to kikuyu was 'absorbed' by 7 h; however, for ryegrass the amount absorbed was only ~45% but increased to ~75% if non-ionic wetting agent was included in the spray.

Discussion

At a site with high plant-available soil N (Expt 1), the pasture yield response was not significantly different from the granular treatment when urea was applied as a foliar spray at 40% of the granular rate. However, after 8 months of urea application, the soil NO_3^--N levels fell from 75 to 22 mg/kg when urea was applied as a foliar spray, but only fell to 60 mg/kg when applied in granular form. This indicated that the pasture drew on the soil N pool to allow it to achieve the same growth rate and pasture consumption for foliar (51 DM/ha.day and 4942 kg DM/ha) and granular (45 kg DM/ha.day and 4382 kg DM/ha) treatments. In confirmation of this, the mean plant N concentration pre-grazing for granular and foliar application, respectively, was 4.4% and 4.6% for ryegrass and 3.2% and 3.5% for kikuyu. These levels of N in ryegrass are well above the point at which NO_3^- is in excess of requirements for plant protein synthesis and starts to accumulate (3.8% N) but at about the point for commencement of accumulation in kikuyu pasture (3.4% N) (WJ Fulkerson and D Rowlings, unpublished data).

Research by Zaman and Blennerhassett (2009) and, more recently, Dawar *et al*. (2012), in a glasshouse study, found that N-use efficiency was 31% greater when urea was applied directly to the leaf as a foliar spray than when broadcast on the soil in granular form. That study was with perennial ryegrass (*Lolium perenne* L.) and the rate of N application in urea (25 kg N/ha) was similar to the present study.

The site of the low plant-available soil N (Expt 2) allowed for pasture growth response to N fertiliser application to be directly attributable to the fertiliser input, with little or no contribution from the soil N pool. In this case, there was no difference in N-use efficiency when urea was applied as a foliar spray or in granular form under conditions typical of dairy pasture systems in the subtropical region of Australia with kikuyu–short-rotation ryegrass pastures.

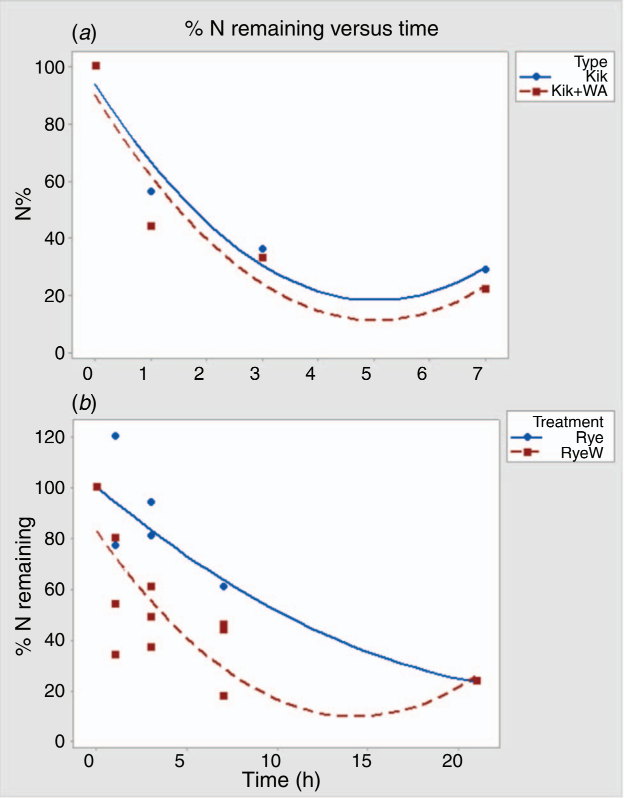

Fig. 4. Percentage N remaining over time on (*a*) kikuyu leaves and (*b*) ryegrass leaves, when urea was applied alone (Kik, Rye) or with a non-ionic wetting agent (KikW, RyeW).

This finding contrasts with some positive results obtained in temperate dairy regions. In the present study (Expt 1), the N content of pasture pre-grazing was similar whether urea was applied in a foliar spray or in granular form. However, the soil NO_3^--N levels fell substantially more in the foliar plots than the granular plots. This indicates that the pasture plant will make up the N deficiency by using soil N, which has implications for the interpretation of short-term trials associated with long-term effects of applying suboptimal levels of urea, on depletion of the soil N pool. However, it is likely that the response to foliar application of urea would be greater under the pasture systems used in the temperate dairy regions than in this study, as discussed below.

First, the lack of benefit of foliar versus granular application of urea in our subtropical environment is, we suggest, in part associated with the sward dynamics. The effectiveness of foliar spray obviously depends on the extent of canopy cover to receive and absorb the spray, with regrowth shoots being far more efficient at absorption than the older leaves at the base of the sward (Klein and Weinbaum 1984; Bowman and Paul 1992). The canopy cover will, in turn, depend on tiller density. In this regard, the tiller density of the short-rotation Italian ryegrass in our experiment was 560 tillers m^2, whereas the tiller density in this region averages 1317–1886 tillers/m^2 (Sinclair and Beale 2010), although the average seeding rates are also higher at ~50 kg/ha, compared with the present rate of

40 kg/ha. In contrast to our experiment, the tiller density of a typical monoculture of perennial ryegrass pasture in New Zealand is >2500 tillers/m^2 in winter and >5500 tillers/m^2 in spring (Chapman *et al*. 1983). Korte (1986) found similar plant densities. Ryegrass ploidy also influences tiller density, with Tozer *et al*. (2017) reporting 15.9–19 tillers/plant for diploid and 8.4–12.7 tillers/plant for tetraploid perennial ryegrass in New Zealand pastures.

Second, the lack of benefit of applying urea as a foliar spray may have been due, in part, to the proportion of N actually absorbed. In our study, <25% of urea applied remained on the leaves 7 h after foliar spray was applied to kikuyu and to ryegrass if wetting agent was also applied. Henning *et al*. (2013) reported similar results when the rate of urea absorption by bentgrass (*Agrostis stolonifera* L., also a C_4 summer grass) was estimated via a similar washing method to that used in this study. Those authors found that 75–80% of applied urea was absorbed in the first 2 h. On the other hand, Stiegler *et al*. (2013), using ^{15}N methodology, found 30–56% uptake after 8 h with a total uptake of 64%, also by bentgrass. Bowman and Paul (1992), using the ^{15}N method, also reported a lower absorption rate of 35% by *Poa pratensis* L. after 48 h. The ^{15}N method is considered to measure more accurately the N actually absorbed by the plant, and the results indicate that the washing method overestimates absorption.

Third, the difference between the two methods may be due, in part, to losses from volatilisation, because both grass species synthesise the urease enzyme, and potentially to the urea being 'washed' off the leaves by dew. In our study, the dew factor can be discounted; the sample at 7 h was collected before nightfall, and there is no indication that dew was involved in the sampling at 21 h because the percentage N remaining on the leaves did not change much between 7 and 21 h. Volatilisation could explain the difference in absorption between the two methods. However, when foliar-spraying urea on-farm, both dew and volatilisation would be involved.

The higher rate of absorption of urea by kikuyu grass (without wetting agent) probably relates to the climatic conditions during the summer growth season, with higher temperatures and humidity (Impley and Jones 1960; Henning *et al*. 2013) meaning that the stomata remain open for longer and the rate of absorption through the leaf dermis layer is be expected to be higher (Franke 1967). Other factors believed to have maximised opportunity for spray treatments in the present study are the low water volume in the spray (200–250 L/ha), small droplet size, and, for ryegrass but not kikuyu, the addition of non-ionic wetting agent to the spray.

The low soil N availability in Expt 2 is reflected in a lower leaf N content, varying from 2.4% for the nil treatment to 3% for the high granular urea (GH) treatment, and this was a significantly linear relationship, albeit at a lower tiller density than is typical for pastures in this region (Sinclair and Beale 2010). Despite this, the quantity of pasture harvested over the 11 months of this study was 13 044 kg DM/ha, well above the average pasture utilised in the region of 6.7 t DM/ha.year (n = 14; WJ Fulkerson, unpublished data).

Thus, the results of this research, and previous studies, indicate that most of the urea applied as a foliar spray can be absorbed by the regrowth leaves of both C_4 and C_3 grasses. The results of Expts 1 and 2 in this study indicate that there is no real benefit obtained from applying urea as a foliar spray over granular application under conditions typical of dairy farm systems in the subtropical dairy region of Australia. Several sward and climatic factors partly explain the lack of benefit, primarily associated with the amount of canopy area available to receive the spray, and this, in turn, depends on tiller density, ryegrass ploidy and climate.

There are practical benefits associated with applying urea as a foliar spray, including the ability of apply other fertilisers, herbicide, insecticides, and even lime or seed if constant agitation in the spray units is available in the one pass.

Conflict of interest

The authors declare no conflict of interest.

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