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The fate of urea nitrogen applied in a foliar spray to wheat at heading

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Abstract

Nitrogen losses from irrigated wheat (cv. Matong) grown on a heavy clay in the Goulburn-Murray Irrigation Region following foliar applications of urea at heading were investigated. Ammonia (NH_3) volatilization was determined by a micrometeorological method and total nitrogen (N) loss was determined by a ^{15}N balance technique. The effects of the foliar application on grain N concentration and grain yield were determined also.

Little nitrogen was lost by NH_3 volatilization following the foliar application. The rate of NH_3 loss increased briefly from <11 g N ha^{-1} hr^{-1} to >19 g N $ha^{-1}hr^{-1}$ following rainfalls of 3 and 2 mm which washed 34% of the applied N from the plant onto the soil and increased the pH of the surface soil. The pH effect was short lived and total NH_3 loss amounted to only 2.13 kg N ha^{-1} or 4.3% of the applied N.

The ^{15}N balance study also showed that little N was lost from the plant-soil system until rain had washed the fertilizer from the plant onto the soil. In the period 152 to 206 DAS, the soil component of the applied N decreased from 34% to 9%. This fraction then increased slightly to 12% of the applied N at harvest. At that time, 69% of the applied N was recovered in the plants indicating that 19% of the applied N had been lost from the plant-soil system. As there was no evidence for leaching of N, the difference between total N loss as measured by ^{15}N balance (19%) and NH_3 loss (4%) is considered to be loss by denitrification (15%).

The fertilizer N assimilated by the plant was efficiently remobilised from the leaves and stems to the head; 78% of the fertilizer N assimilated by the plant tops had been translocated to the head by the time of harvest. Grain N concentration responded to the foliar N application. The fitted response function had significant linear (P = 0.004) and quadratic (P = 0.10) trends to N rate, whereas there was no significant effect on grain yield.

Introduction

Grain with protein content below 9.5% (grain N content 1.67%) is frequently produced in the Goulburn-Murray Irrigation Region and the more reliable rainfall areas in north-eastern Victoria. The application of fertilizer N to wheat in southern Australia is not common because legume dominated pastures are considered to provide adequate N for the wheat crop [9]. However, these low grain protein levels suggest that legume-based pastures do not contribute sufficient N for the subsequent wheat crop. The protein content of non-fertilized but well-watered crops may be low if the available N supplies decline prior to grain formation and the crop continues to accumulate dry matter which in-turn dilutes N in the grain [7, 11, 24]. These findings serve to highlight the need for supplementary applications of N fertilizer to cereals in this region.

Fertilizer N applications at flowering are effective in increasing both grain protein [4, 11, 15, 18, 22, 23] and the baking quality of the flour produced from the grain [4, 15, 16]. Greater increases in grain protein were obtained when the applications were made close to flowering. Nitrogen applications at earlier stages of development have promotive effects on yield which dilute the increases in grain protein [11, 21]. The net response is complex and depends on N uptake, N redistribution to the grain, yield and the N balance of the soil-plant system.

Little is known of the fate or the use efficiency of fertilizer N applied to wheat close to flowering. In one study [18], granular urea was spread on the soil surface at heading and washed into the soil with an irrigation immediately following application. Neither biomass nor grain yield was significantly increased by that treatment, but grain N concentration was increased from 2.03 to 2.46%. In the same study a ^{15}N balance showed that, at harvest, 50% of the applied N had been assimilated by the crop, 30% remained in the soil and the remainder had been lost by denitrification.

An alternative method of applying N at heading is to spray the crop with a urea solution. Finney et al. [4] and Strong [22] showed that grain N concentration may be increased by this method of application, and they assessed the efficiency of the technique by measuring N uptake and grain yield. No data is available on the loss of fertilizer N applied in this way or the recovery of fertilizer N in the crop. Knowledge of the recovery by the crop and losses from the plant-soil system is required so that fertilizer management practices can be developed to maximize grain yield and quality. The aims of the field experiment reported here were to determine the fate of foliar N applied to wheat at heading and to ascertain the effect of such an application on grain yield and grain N concentration.

Material and methods

The trial was located at Undera, 18 km north of the Institute for Irrigation and Salinity Research (145°14′ E, 36°24′ S), in the Goulburn-Murray Irrigation Region. The soil at the site was a red-brown earth (classification: Dr. 2.33 [13]; Typic Haplustalf [20]). The area was cropped with lupins in the winter of 1987; yield was about 1 t ha^{-1} and the stubble was grazed.

A semi-dwarf wheat (cv. Matong) was direct drilled into the stubble at 105 kg ha^{-1} on April 29, 1988, in drill rows spaced at 0.17 m. Diammonium phosphate (70 kg ha^{-1}; 24% P and 21% N) was direct drilled with the seed. 'Tilt' was applied to the crop on September 29, 153 days after sowing (i.e. 153 DAS) to prevent the spread of stripe rust. The application of 'Tilt' was effective and the crop was otherwise free of disease.

The crop was watered by flood irrigation with the entire area being totally inundated for approximately 12 hours. Irrigation commenced on September 19 (143 DAS), 16 days before anthesis. Subsequent irrigations were scheduled when the cumulative evaporation minus rainfall deficit was 60 mm (Fig. 1c).

A circular area (radius 25 m) within the wheat crop was defined for the study of NH_3 volatilization following the foliar application of urea. The centre of the circle was approximately 50 m from the southern edge of the cropped area and was surrounded on all sides by unfertilized wheat. Urea (50 kg N ha^{-1}) was applied as a solution (24% w/w) with a wetting agent (Nufarm surfactant; 0.1 L/100 L of solution) on September 22 (146 DAS). The application coincided with head emergence (Z.55 [25]). The urea solution was sprayed on the plants with a hand held boom. Plants were 0.9 m tall and the LAI was 4.9 ± 0.8 at this stage.

Rainfall, temperature, and Class A pan evaporation were measured at the weather station at the Institute for Irrigation and Salinity Research (I.I.S.R.), approximately 18 km from the trial site. Rainfall was also recorded at the Undera site during the period when NH_3 volatilization was measured.

Plant measurements

Plant tops were harvested from five separate 1.0 m sections of a row, selected at random from each of the fertilized and unfertilized areas on 11 occasions viz. 144, 147, 148, 149, 150, 151, 153, 154, 158, 168, and 180 DAS. The plant samples were washed with 2 L of distilled water containing 15 μM phenyl-mercuric acetate immediately after harvest using the procedure outlined below for the plant material from the ^{15}N microplots. Approximately 0.1 L of the washing solution was saved for urea and ammoniacal (ammonia plus ammonium) N analyses. Leaf area was measured with an electronic planimeter.

Soil measurements

Soil samples were collected from the 0–0.05 m depth daily for an 8 day period after urea application and then at irregular intervals until harvest (Fig. 4). At each sampling 5 cores were taken from within the fertilized circular area and 5 from the unfertilized area. Moist soil (equivalent to 10 g dry weight) was extracted immediately with 0.05 L of 2 M KCl containing 15 μM phenylmercuric acetate. The pH of the soil surface was measured directly during the period 153–158 DAS with a flat tip glass electrode and millivolt meter. Gravimetric soil moisture was determined by drying a sample (18–22 g wet weight) for 20 minutes in a microwave oven [5]. Bulk density, determined by the core method using cylinders with an internal diameter of 73 mm [1] was 1320 and 1520 kg m^{-3} in the 0.02–0.08 m and 0.12–0.18 m soil layers, respectively.

Ammonia volatilization

The vertical flux density of NH_3 from the fertilized circular area was determined by the procedure described by Smith et al. [17] using NH_3 samplers developed by Leuning et al. [8]. Samplers were placed on a mast at the centre of the circular area, 0.1, 0.2, 0.4, 0.8 and 1.2 m above the top of the canopy. Sampling times for each run varied depending on the rate of emission and the time of day (see Fig. 6). Background measurements were made with samplers placed on a mast located on the upwind side of the treated area.

^{15}N balance study

Microplots, each 1 × 1 m and spaced at 2 m intervals, were established outside the circular area and spanned 6 wheat rows. Treatments (6 sampling times) were randomised in 6 replicates. Urea (50 kg N ha^{-1}), containing 4.104 atom % ^{15}N, was applied in aqueous solution (18% w/w) with a wetting agent (Nufarm surfactant) to the plants by a hand-held spray on 145 DAS. Each microplot was enclosed with plastic sheeting before spraying to ensure that the labelled urea was applied to the plants in the microplot only.

Six microplots were destructively sampled 4 hours after the urea application (145 DAS), and at 152, 159, 179, 206 and 230 DAS (maturity). Sampling consisted of cutting the plants at ground level from 0.5 m lengths of the 2 adjacent rows in the centre of each microplot. The plant material was placed in a clean plastic bag, the cut ends protruding, and 2 L of distilled water, containing 15 μM phenylmercuric acetate, was added. The plant material was washed by shaking for 30 seconds, and 1 L of washing solution was retained for inorganic N, urea and ^{15}N analysis. The plant material was washed in clean water, placed in a clean bag, and returned to the laboratory where a sub-sample of 25 stems was separated into components, cut into 0.01 m pieces and oven dried at 70°C. The dried plant material was weighed and ground to pass through a 0.42 mm sieve, and total N and ^{15}N were determined in each component. The washing procedure was not undertaken on the final two sampling dates (206 and 230 DAS) because analyses had shown that no fertilizer N was present on the exterior of the plants after 180 DAS.

Soil samples were taken by removing the entire 0–0.15 m soil layer from a 0.30 by 0.30 m area within the harvested area of each microplot. The soil samples, including plant crowns and coarse roots, were air dried and ground to less than 2 mm. Plant crowns and coarse root material, separated from the soil during grinding, was ground to pass through a 0.42 mm screen. The soil, plant crowns and roots were then well mixed and bulk sub-samples finely ground (<250 μm) for total N and ^{15}N analyses.

Nitrogen fertilizer trial

In a parallel experiment on the same crop, nitrogen at 0, 12.5, 25, 50 and 75 kg N ha^{-1} was applied to the crop by spraying with urea solution (24% w/w) containing 'Nufarm Surfactant' on 146 DAS. Plots were 5 m by 20 m and were located approximately 50 m to the west of the fertilized circular area. Treatments were arranged in a 5 by 5 latin square. Plants in this experiment were sampled at harvest only. Tops were harvested from a 1.36 m^2 area (2 drill rows by 4 m) to measure total biomass, spike number and individual grain weight. The number of spikelets per spike was counted on a sub-sample of 50 spikes prior to threshing. Kernel number per spikelet was calculated from the hand harvest yield, spikes m^{-2}, spikelets $spike^{-1}$ and individual grain weight. Sub-samples of straw and head material were retained for total N analysis. Grain was harvested with a plot header from an area 26.25 m^2 (1.75 m by 15 m) and sub-samples (5 kg) were retained for N analysis. Yield, biomass and individual grain weight are on an oven dry basis.

Chemical analyses

Ammonium in soil and plant samples was determined by an indophenol blue method [6], urea by a modified diacetyl monoxime method [12], and NO_2^- and NO_3^- were measured using an Auto Analyzer fitted with a copperized cadmium column by a modified Griess-Ilosvay method [6]. Total N concentration in plant material was determined on an Auto Analyser after micro-Kjeldahl digestion [14]. Total N and ^{15}N enrichment of the plant and soil samples from the ^{15}N labelled microplots were determined by an automated flow method in which Dumas combustion was linked to a mass spectrometer.

Weather

The lowest air temperatures were measured in the winter approximately 50 days after sowing (Fig. 1). The mean minimum temperature ranged from 2 to 16°C whereas the mean maximum ranged from 12°C during the winter months to 28°C at crop maturity. Class A pan evaporation increased from 8 mm per week at 80 DAS, to 42 mm per week at 203 DAS with proportionate increases in cumulative water deficits. Irrigation commenced on 144 DAS; approximately 95 mm was applied at the first irrigation. Additional water was applied on 168, 184 and 200 DAS. Rainfall of 3 mm and 2 mm was recorded on 152 and 153 DAS at the experimental site.

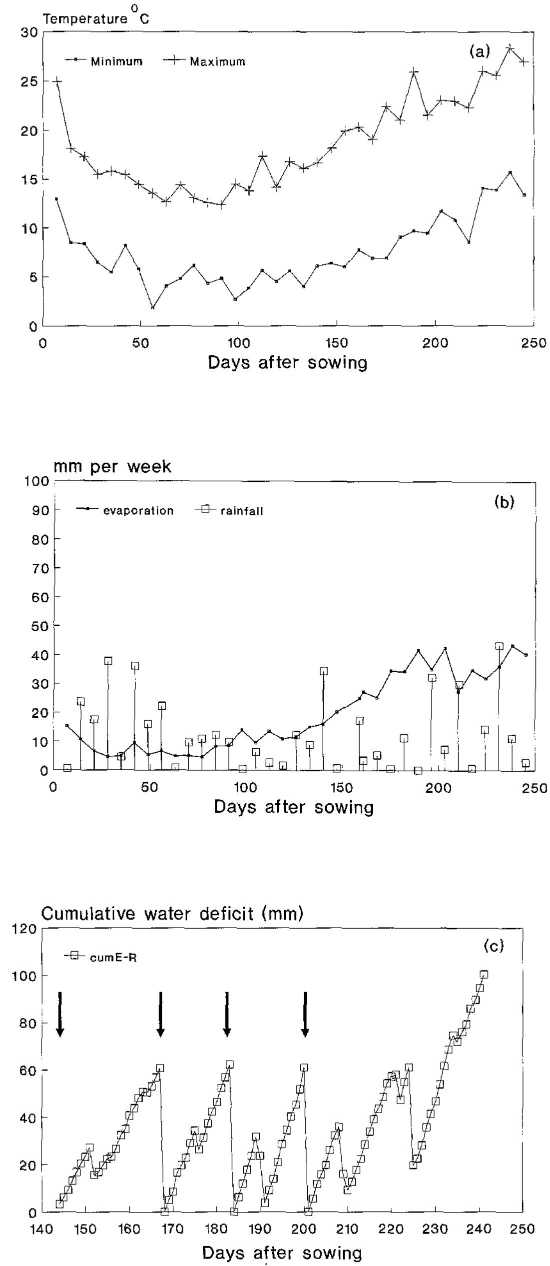

Fig. 1. Air temperature (a), evaporation and rainfall at the Institute for Irrigation and Salinity Research Station (b) and cumulative E_p–R and times of irrigation (denoted by the arrows) at the Undera site (c).

Results

Plant nitrogen

Regular harvests of plants from the fertilized circular area and unfertilized areas for urea and ammoniacal N analyses showed that appreciable urea and little ammoniacal N could be removed from the fertilized wheat, in the 10 day period after fertilization, by a quick washing with distilled water (Fig. 2). It is assumed that the N removed in this way was located on the exterior of the plants and that the remaining N had been absorbed by the wheat. Four hours after foliar application of urea to the plants in the circular area only 18% of the N remained on the exterior of the wheat (Fig. 2a). The amount of urea in the washing solution remained high for four days and then decreased following rain on 152 DAS (Fig. 2a). No urea was detected on the exterior of the plants in the unfertilized areas.

A small amount of ammoniacal N was produced on the surface of the wheat by urea hydrolysis immediately after urea application, but the maximum value of 0.016 g N m^{-2} (0.32% of the applied N) was not reached until four days after the spray was applied (Fig. 2b). The ammoniacal N on the exterior of the plants from the unfertilized areas remained at a low value throughout the experiment (Fig. 2b).

The study with ^{15}N labelled urea in microplots showed a similar pattern of residual N on the surface of the wheat plants with time, but the results are less detailed because of infrequent sampling (Fig. 3). These results show that 30% of the applied N was removed by the washing shortly after urea application, and that 68% of the applied N had been absorbed into the wheat plants. Both N fractions decreased after the rainfall on 152 DAS and little applied N was present on the plants' surface by 159 DAS (Fig. 3).

Soil nitrogen

The ammonium content of the surface soil in the circular area increased from 0.8 g N m^{-2} before urea application to a maximum of 1.8 g N m^{-2} on 150 DAS, whereas the ammonium content of the unfertilized area remained at about 1 g N m^{-2} during this period (Fig. 4a). No rain fell at the experimental site between the time of urea application (146 DAS) and 152 DAS to wash urea from the exterior of the plants onto the soil surface, and thus it appears that some of the urea spray had reached the soil surface and was hydrolysed to NH_3. After rain had fallen on 152 and 153 DAS, the difference in ammonium content of the surface soil between the circular area and the unfertilized area was maintained for 10 days, but at a lower value than previously (Fig. 4a). There was little difference between the two areas after 180 DAS.

The nitrate content of the soil within the fertilized, circular area was not significantly different from that of the unfertilized soil until rain fell on 152 DAS (Fig. 4b). After the rainfall, the nitrate content in the soil of the circular area increased rapidly to a maximum on 160 DAS and then fell.

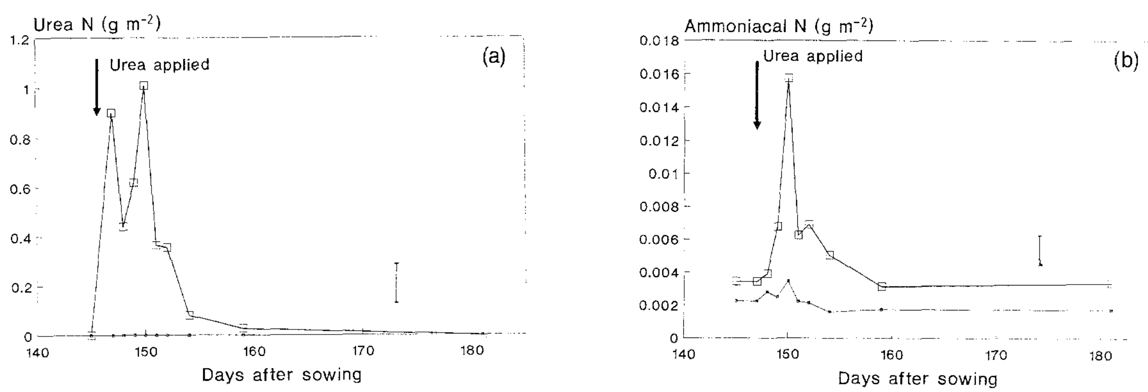

Fig. 2. Urea (a) and ammoniacal nitrogen (b) removed from wheat leaves, following foliar application of urea (50 kg N ha^{-1} at head emergence), by washing with distilled water. Unfertilized (■) and fertilized (□). Vertical bars represent L.S.D.'s (P = 0.05) appropriate to comparisons between time.

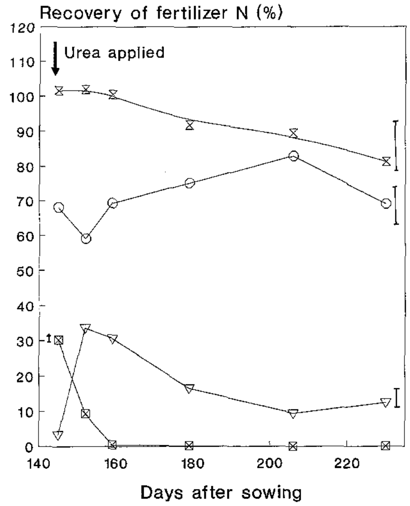

Fig. 3. Fertilizer nitrogen remaining on plant surfaces, incorporated into plant shoots and recovered in the 0–0.15 m soil layer at various times after a foliar application of labelled urea to wheat. Total (⧖), plant (○), washing (☒) and soil (▽). Vertical bars represent L.S.D.'s (P = 0.05) appropriate to comparisons between time.

Rain washed urea from the exterior of the plants to the soil where it was nitrified. There was no significant difference in soil nitrate content between the fertilized and unfertilized areas after 170 DAS (Fig. 4b).

The nitrite content of the surface 0.05 m soil was not significantly increased by the foliar application ($P < 0.05$); the maximum content was less than 0.014 g N m^{-2} (data not presented).

The pH of the surface soil in the fertilized circular area, as determined *in situ* with a flat surface pH electrode, was significantly higher than that of the unfertilized area immediately following the rain on 152 and 153 DAS (Fig. 5). (No measurements had been made before that time because of the unavailability of the electrode). Soil pH increased due to the enzymatic hydrolysis of urea to NH_3, and subsequently decreased because of the oxidation of ammonium by Nitrosomonas to nitrate [10]. Therefore, the higher surface soil pH in the circular area shows that urea had been transported to the soil surface (Fig. 5). The surface soil pH in the circular area remained above 7 until 156 DAS and then declined, so that there was little difference in pH of the surface soil between the fertilized and unfertilized areas after 158 DAS.

The microplot study with ^{15}N labelled urea also showed that some of the spray had penetrated the plant canopy and reached the soil surface. Figure 3 shows that 3% of the applied N was present in the 0–0.15 m soil layer immediately after the foliar application. The amount in the soil increased to 34% of the applied N following the rainfall on 152 DAS. Thereafter, the labelled N in the soil decreased to a minimum of 9% on 206 DAS. Part of this decrease was due to plant uptake (Fig. 3), and part was due to N loss to the atmosphere (see later). Between 206 DAS and the final harvest, the labelled N incorporated in the soil rose to 12%, presumably as a result of translocation from the plant (Fig. 3).

Nitrogen loss

Little NH_3 was emitted from the fertilized circular area during the first few days after the foliar

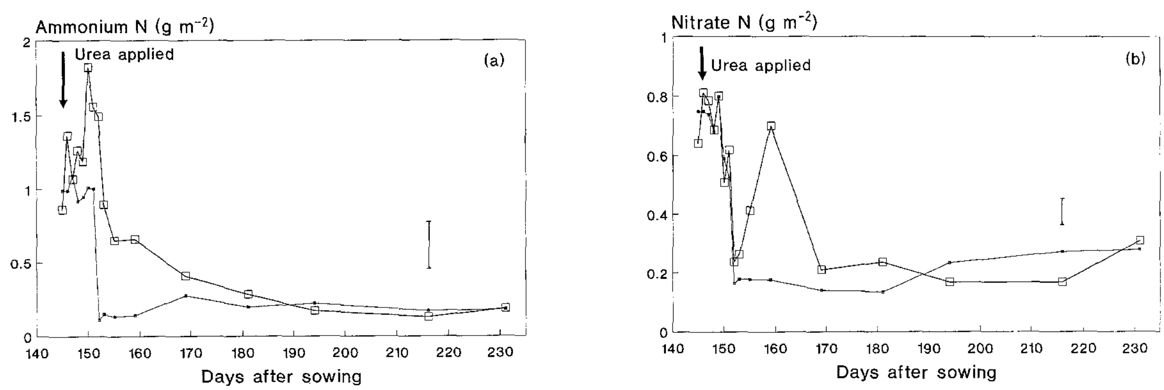

Fig. 4. Extractable mineral nitrogen in the 0–0.05 m layers of the unfertilized (■) and fertilized (□) soils after a foliar application of urea (a) ammonium; (b) nitrate. Vertical bars represent L.S.D.'s (P = 0.05) appropriate to comparisons between time.

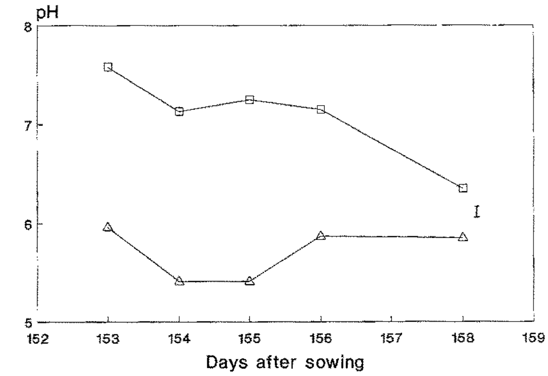

Fig. 5. pH of the surface soil in the unfertilized (△) and fertilized (□) areas after foliar application of urea. Vertical bars represent L.S.D.'s (P = 0.05) appropriate to comparisons between time.

application (Fig. 6). High rates of emission were measured following the rainfall on the sixth and seventh days after urea application when the soil pH was high (Fig. 5). The greatest NH_3 flux density measured was 22.5 g N ha^{-1} hr^{-1} on 152 DAS. After 153 DAS the rates of NH_3 emission declined and were negligible after 158 DAS by which time the pH of the surface soil inside the circular area had fallen to less than 7 (Fig. 5). Loss by NH_3 volatilization during the period of study amounted to 2.13 kg N ha^{-1} or 4.3% of the nitrogen applied (Fig. 6).

The ^{15}N balance study in microplots showed that little N was lost from the plant-soil system between the time of application and the rainfall on 152 DAS (Fig. 3). From that time until the final harvest 19% of the applied N was lost from the plant-soil system. At the time of the final harvest 81% of the applied N was recovered in

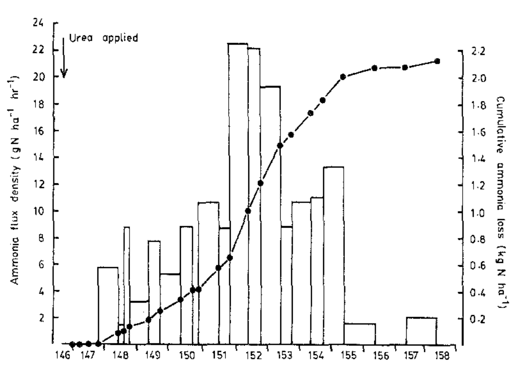

Fig. 6. Ammonia flux density and cumulative ammonia loss following a foliar application of urea to wheat at head emergence.

the plant-soil system; 12% of the applied N had been immobilized in the soil (roots, plant crowns, and soil organic N) and 69% of the applied N was recovered in plants. We therefore conclude that 19% of the applied N had been lost to the atmosphere.

Assimilation of nitrogen by plants

Uptake of the foliar applied N by the wheat plants was rapid. Within four hours of the application of urea, 68% of the applied ^{15}N had been incorporated into the plants (Fig. 3). At that time 53% of the applied N was recovered in the green leaves, 13% was present in the stems and 2% was found in the senescent leaves (Fig. 7). The amount assimilated into the wheat plants decreased to 60% following rain on 152 DAS (Figs. 3 and 7). Between 159 and 206 DAS a further 14% of the applied N was assimilated by the wheat plants (Fig. 3). The slow rate of assimilation of N during this period was probably due to the fact that the main source of supply was the urea N that had been washed onto the soil. Little (0.5%) of the foliar N remained on the exterior of the plants at 159 DAS (Fig. 3).

Assimilation of the applied N into wheat tops reached a maximum of 83% on 206 DAS; this had fallen to 69% at the time of the final harvest (Fig. 3). The amount of applied N recovered in green leaves fell continuously from just after application, to zero at the time of the final harvest (Fig. 7). Less than 10% of the applied N was recovered in senescent leaves. Uptake of the applied N into stems increased to a maximum of 32% on 179 DAS and then decreased to 7% at maturity. Translocation of the applied N into the heads increased steadily until 206 DAS; there was no further assimilation into the heads between 206 DAS and harvest on 230 DAS (Fig. 7). At harvest 54% of the applied N had been incorporated into the heads (Fig. 7). This meant that 78% of the N assimilated by wheat tops had been translocated to the heads by the time of the final harvest.

Effects of foliar application on grain

No increase in plant biomass or grain yield was obtained following foliar applications of 12.5, 25,

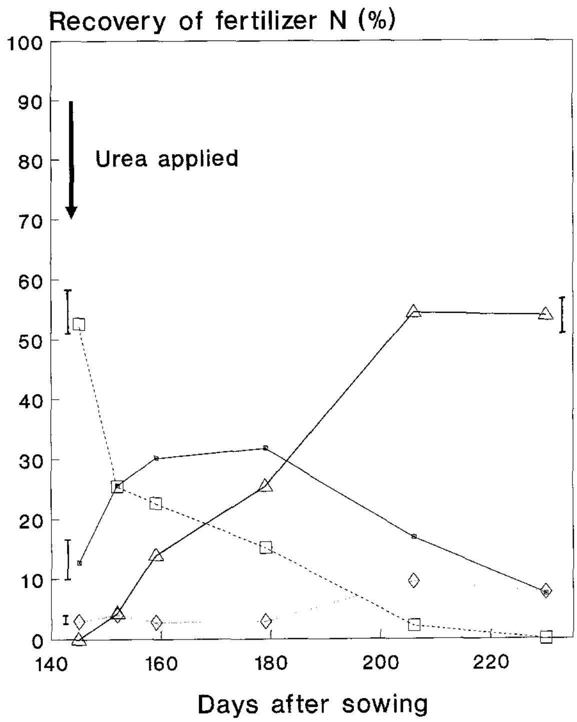

Fig. 7. Distribution of labelled nitrogen, applied as a foliar spray to wheat at head emergence, in stem (■), green leaves (□), senescent leaves (◇) and heads (△).

50 or 75 kg N ha^{-1}, whether measured by hand harvest from a small area (1.36 m^2) or by a plot header from a large area of 26.25 m^2 (Table 1).

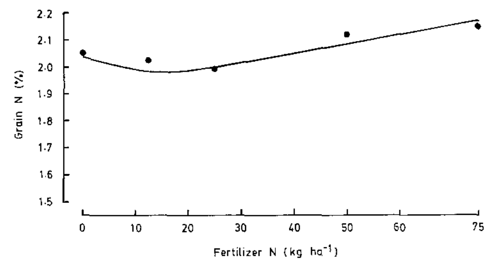

Fig. 8. Effect of foliar applications of urea on grain N concentration. The fitted response function has significant linear (P = 0.004) and quadratic (P = 0.10) trends to N rate.

This is in line with the lack of an effect of the urea applications on the number of spikes m^{-2}, number of spikelets spike^{-1}, kernels spikelet^{-1}, individual kernel weight and harvest index. It is also in agreement with the results of other studies [7, 18, 22] which showed no response to N applied close to anthesis. Grain N concentration responded to the foliar N application (Fig. 8). The fitted response function had significant linear (P = 0.004) and quadratic (P = 0.10) trends to N rate. Nitrogen application increased total N in the biomass and grain at harvest. Both biomass N and grain N (g N m^{-2}) had significant linear responses (P = 0.008 and 0.02 for biomass N and grain N, respectively), suggesting approximately 66% of the N applied at head emergence was assimilated and retained by the crop.

Table 1. Effect of foliar applications of nitrogen on yield, components of yield and nitrogen accumulation and distribution in the crop

Nitrogen rate (kg N ha^{-1})	0	12.5	25	50	75	L.S.D. (P = 0.05)
Header harvest						
Grain yield (t ha^{-1})	5.6	6.2	6.2	6.4	6.3	0.80
Hand harvest						
Biomass (g m^{-2})	1770	1740	1690	1780	1770	374
Grain (g m^{-2})	580	610	600	680	690	140
Harvest index	0.33	0.36	0.33	0.36	0.36	0.07
Spikes m^{-2}	440	470	440	470	460	90
Spikelets spike^{-1}	20.0	21.4	20.1	20.2	20.3	1.60
Kernels spikelet^{-1}	1.96	1.82	1.89	1.92	2.06	0.15
Kernel weight (mg)	33.3	33.6	33.6	33.9	33.3	3.2
Biomass N (g m^{-2})	19.8	20.7	20.2	23.5	24.4	3.6*
Grain N (g m^{-2})	11.7	12.4	12.0	14.5	14.9	3.0*
N harvest index	0.60	0.60	0.60	0.61	0.61	0.06

*: P < 0.05.

Discussion

When the urea solutions were sprayed onto the wheat plants at heading the bulk of the urea was retained by the plants and, judging from the results of the plant washing with distilled water, most of that N (68% of the applied) was rapidly assimilated. It is assumed that the N removed by the distilled water washing (30% of that applied) was not assimilated, but on the exterior of the plants. As plant material has a high urease activity there was the possibility for NH_3 to be lost from the exterior of the wheat plants during the period when appreciable urea was on the exterior of the wheat. Enzymatic hydrolysis of the urea to NH_3 and a concomitant rise in pH could have led to NH_3 loss. However, there was no evidence for appreciable NH_3 loss from the plants during this period (146–150 DAS).

It is apparent from the results that, despite our efforts to spray the urea solution only onto the wheat plants, some of the spray had penetrated the plant canopy and reached the soil surface (Figs. 3 and 4). In addition, the surface soil pH measurements and the labelled N study showed that additional N was washed onto the soil by the rain which fell on 152 and 153 DAS. The low urea and ammoniacal N levels on the plant surfaces, and the higher pH and ammonium levels in the soil of the fertilized area after rain suggest that the NH_3 lost to the atmosphere came from the soil rather than the plants.

The emission of NH_3 following the foliar application of urea was greater than that measured when granular urea was broadcast onto dry soil and washed in by sprinkler irrigation (22 mm) and rainfall (11 mm) [18]. In that experiment, the bulk of the urea was washed below the soil surface before hydrolysis occurred and the pH of the 0–0.15 m layer remained below 7.2; this ensured that any NH_3 formed was effectively retained by the soil [2, 3].

Once the N had been sprayed or washed onto the soil it was subject to the same loss processes as N applied directly to the soil. Results from this study and previous work [17, 18] show that N is not leached from the soil and thus it is concluded that all losses are gaseous, either by NH_3 volatilization or denitrification. The results of this study showed that 19% of the foliar applied N had been lost to the atmosphere (Fig. 3). As NH_3 loss amounted to 4% of the applied N (Fig. 6), we conclude that 15% of the applied N was lost by denitrification. A previous study indicated that 16% of the urea N applied to soil at heading was lost by denitrification [18].

The foliar-applied N seems to have been utilized better than N applied directly to the soil. In the current study, 69% of the applied N had been incorporated by the crop, whereas when the N was applied to the soil only 50% of the applied N had been assimilated by the crop by the time of the final harvest [18]. Assimilation of the N from post sowing applications at or near heading was greater than when all of the fertilizer N was applied at sowing. Only 40% of the N applied at sowing was recovered by wheat [19].

Foliar applications of urea can be used effectively to increase the protein content of wheat grain. However, the increase in grain protein from the foliar application of urea was less than the response measured when the equivalent amount of granular urea was applied to the soil and washed in by sprinkler irrigation and rainfall [18]. The lower grain protein response in the current study may be caused by a slightly different time of application. Finney et al. [4], Pushman and Bingham [15] and Spiertz and Ellen [21] reported differential effects on grain yield and grain protein depending on whether N was applied prior to or at anthesis.

The results of the experiment show that the farmer has an additional management practice for increasing grain protein in irrigated wheat. They also show that it is important to keep the foliar application off the soil surface otherwise the N will be lost in the same manner and to the same extent as soil applied N.

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