Temporary immobilisation promotes nitrogen use efficiency of irrigated rice

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Abstract
Nitrogen use efficiency (NUE) of flooded rice is notoriously low compared to upland crops. An exception is irrigated rice growing in the semi-arid, temperate Riverina region of south-eastern Australia where NUE is high and the time of fertiliser application is unusual by international standards. In this region, N fertiliser applied at the permanent flood (PF) stage leads to larger yield responses than when topdressed at panicle initiation (PI). In many other regions topdressing at PI is more efficient. In the field experiment described here, application of 200 kg N ha^{-1} as urea immediately before PF increased yield of medium-grain rice from 7.3 to 13.6 t ha^{-1}, representing an apparent recovery of 76% of the applied N, compared with a yield of 11.4 t ha^{-1} and apparent recovery of 39% for same amount of N topdressed at PI. Sequential sampling showed that soil ammonium fell to low concentrations soon after urea application at both PF and PI and remained at background levels similar to the zero-N control for the rest of the growing season. Meanwhile above-ground N content of the crop increased steadily until maturity, suggesting that 38 kg N ha^{-1} of the fertiliser N had been temporarily immobilised before re-mineralisation and uptake by the crop. The higher efficiency of the PF application was because urea was washed into the soil with the irrigation water, while the urea topdressed at PI was initially held in the water column and at the soil-water interface before crop uptake, temporary immobilisation and loss, presumably via denitrification or ammonia volatilisation.

Key Words
Nitrogen fertiliser, net mineralisation, immobilisation, re-mineralisation

Introduction
Australian rice crops are mostly grown in the Riverina region of south-eastern Australia in a semi-arid environment between latitudes 33-36°S. Crops are sown by aircraft into flooded field or dry-sown and then irrigated at approximately weekly intervals until the crop is about 0.15 m tall. The field is then permanently flooded for 5 months. Nitrogen (N) management of rice in this regions is unusual, if not globally unique, because the largest yield responses are from fertiliser applied to dry soil prior to flooding. In contrast, greatest N responses in other environments occur when N application is split, with most applied mid-season. In the Riverina, the apparent recovery of fertiliser N at crop maturity is typically >60% of the amount applied on farms where the average yield for medium-grain rice is 11 t ha^{-1} (Russell et al. 2008). In experiments, where yield can be >14 t ha^{-1}, the apparent N recovery is often >70% (Horie et al. 1997; Dunn et al. 2014). In other regions where N fertiliser is topdressed or applied in split applications, the apparent N recovery is typically <40% (Cassman et al. 1998). This study investigated the reasons for the high NUE and the greater responsiveness of rice to early N application in southern Australia.

Materials and methods
A field experiment crop was conducted at the Yanco Agricultural Institute in south-eastern Australia. The soil was a Birganbigil clay loam (red-brown earth, Typic Paleustalf) with a total N concentration of 1.0 g kg^{-1} in the top 10 cm. The cultivar Amaroo, a medium grain semi-dwarf was dry seeded at a rate of 140 kg ha^{-1} on 10 October 1990 using a disc seeder at a depth of about 5mm. The experiment was a randomised block design with four replicates. The plot size was 25m x 2.1m with a row width of 15cm. The field was flood irrigated (flushed) 3, 10 and 24 days after sowing (DAS), followed by permanent flood (PF) to a depth of 10 cm 33 DAS. The flood water was retained until late March, after which the soil was allowed to dry until crop maturity. The supply of nutrients other than N were sufficient for a target yield of 15 t ha^{-1}, weeds were controlled with recommended herbicides and there were no insect pests. The experimental treatments tested rates and timing of N fertiliser applied as granular urea. The treatments reported here were the zero-N control (0N) and applications of 200 kg N ha^{-1} broadcast onto the soil surface immediately before PF (200PF) or at panicle initiation (PI) 85 DAS (200PI). Soil mineral N was measured at 2-week intervals from PF until maturity on all plots. Eight cores of 42mm diameter were collected to a depth of 10cm from each plot and mixed thoroughly. The samples were kept at temperatures below 4ºC until analysis, when 80g of wet soil

was added to 200ml of 2M KCl plus 5µg g^{-1} phenyl mercuric acetate. Ammonium concentration was measured with methods described by Bacon et al. (1986). There was negligible nitrate or nitrite and we report only ammonium. Net soil N mineralisation in the top 10 cm was measured for the period of rice growth by sequential sampling using an *in situ* method, using samples bulked from 10 capped tubes (Khanna and Raison 2013). Above-ground parts of the plants were sampled on the same days that soils were sampled in quadrats of 6 adjacent rows of 1m. After drying at 70°C the N concentration was measured by a micro-Kjeldahl method (Bacon et al. 1986).

Results

Crop yields and N-related properties were typical of experimental and well-managed commercial rice crops in the region (Table 1). Rice yields in the Riverina are relatively high because of full irrigation, intense solar radiation and low incidence of pests and diseases in this semi-arid environment. The yield, N uptake, apparent N-fertiliser recovery and agronomic efficiency were greater for N-fertiliser application at PF than at PI, reflecting results from previous studies (Bacon et al. 1994; Russell et al. 2006; Dunn et al. 2014).

Table 1. Yield, biomass and N-related properties of rice in relation to N fertiliser (kg N ha^{-1}) applied as urea, pre-flood (PF) or at panicle initiation (PI).

	0N	200PF	200PI	$LSD_{0.05}$
Grain yield (t ha^{-1} at 14% moisture)	7.28	13.59	11.37	1.13
Biomass (t ha^{-1})	11.61	24.21	17.95	2.38
Grain protein (%)	5.17	7.50	6.34	0.63
Crop N uptake (kg ha^{-1})	80.3	230.9	159.8	15.7
Apparent fertiliser-N recovery (%)		76.3	39.0	15.5
N-use efficiency (kg grain kg N^{-1})		31.4	17.8	6.9

Soil and plant N

In the control crops, the amount of soil NH_4^+ at PF was 15 kg N ha^{-1} and decreased to about 5 kg N ha^{-1} by maturity (Fig. 1a). Net mineralisation of N, estimated as the sum of sequential *in situ* incubations, was 153 kg N ha^{-1}. The seasonal rates of net mineralisation was similar to the measurements and models of Angus et al. (1994) who found that the rate in spring was limited by low temperature, and reached a maximum of 1.4 kg N ha^{-1} d^{-1} when daily mean screen temperature was 25°C in midsummer. N uptake by the control crop was 80 kg ha^{-1}, little over half of the mineralized soil N.

Of the 200 kg N ha^{-1} applied at PF, about three-quarters was detected as soil NH_4^+-N at a sampling 5 days later and the amount in the soil fell to the background level by the time of PI, 56 days later (Fig. 1b). For the period when soil NH_4^+ was above the background level crop N uptake increased by 142 kgN/ha. After that, when soil NH_4^+ remained at the background level, the rice accumulated an additional 89 kg N ha^{-1}. At the same time N-uptake by the control crop was 51 kg N ha^{-1} despite the similar levels of soil NH_4^+.

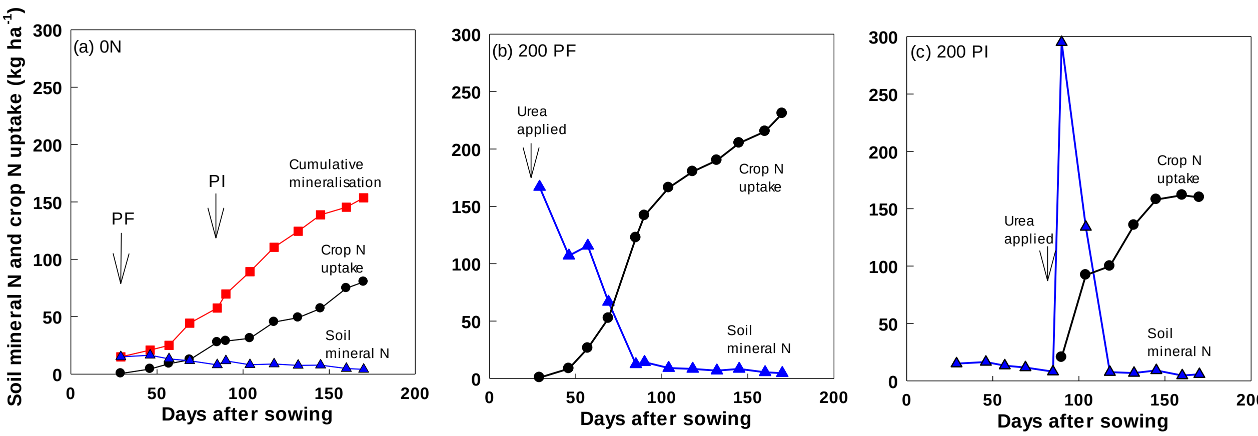

Fig 1. Soil mineral N in the top 10 cm and above-ground crop uptake for (a) 0N control, (b) 200 kg N ha^{-1} broadcast before permanent flood, (c) 200 kg N ha^{-1} broadcast at panicle initiation. Cumulative soil N-mineralisation in the 0N crop was measured by sequential sampling of *in-situ* tubes.

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The amount of soil NH_4^+-N measured 5 days after the PI application of 200 kg N ha^{-1} PI exceeded the amount of N applied, presumably because of sampling errors, but soil NH_4^+ decreased to the background level within 28 days (Fig. 1c). Crop-N uptake during this period was 79 kg N ha^{-1}, but while soil NH_4^+ remained at the background level there was a further crop uptake of 60 kg N ha^{-1}, which was little different from the 51 kg N ha^{-1} taken up by the 0N control (Table 2).

Table 2. Summary of N fluxes in soil and crop (kg ha^{-1}).

	0N control	200PF	200PI
Net N mineralization	153		
Apparent fertiliser-N loss		49	122
Crop N uptake before PI	29	142	29
Crop N uptake after PI	51	89	139

Discussion

A background level of 5-15 kg N ha^{-1} of soil NH_4^+ persisted through the growing season of the 0N control crop. Soil NH_4^+ rose briefly after urea application and crop N-uptake increased in response for the two fertilised crops. In the case of 200PI crop, N uptake returned almost to the rate of the 0N control crop, indicating that little or none of the applied N persisted in the soil.

However in the case of the 200PF crop, rapid N uptake persisted even after soil NH_4^+ had returned to the background level. Our hypothesis is the source of at least 38 kg N ha^{-1} (89-51: the excess of N uptake after PI for 200PF over the 0N control in Table 2) was remineralised N following immobilisation of NH_4^+ that had been hydrolysed from urea applied as 200PF. The time between the start of immobilisation and finish of remineralisation for 200PF was about 140 days. Temporary immobilisation of fertiliser N may represent a form of delayed N release. It has not been discussed in the literature but may be a significant component of the N-cycle in the warm and wet conditions of flooded rice soil.

The reason for the high apparent recovery of the fertiliser N applied at PF was partly because urea was dissolved in the irrigation water and carried into the relatively dry topsoil where it was largely protected from losses from ammonia volatilisation and denitrification. It is unlikely that the urea was leached deeper than 10 cm in this clay soil, based on ^{15}N measurements by Humphreys et al. (1987). It is possible that not all the urea had hydrolysed within the 5 days from application until sampling (Humphreys et al. 1987). The low apparent recovery of the N applied at PI is consistent with many reports of denitrification and ammonia volatilisation of urea broadcast into the water column of flooded rice (e.g. Humphreys et al. 1987; Cassman et al. 1998)

Crop-N uptake was about half of the N mineralisation for the 0N control but it is unclear what happened to the other half. It is possible that there was an artefact in the *in-situ* incubation test or that some of the soil NH_4^+ was immobilised before uptake. There is competition for soil mineral N between roots and immobilising microbes, irrespective of whether the N arises from mineralisation or fertiliser.

Temporary immobilisation followed by re-mineralisation within the growing season does not represent a loss, as is the case with ammonia volatilisation, denitrification or leaching. It may even be of benefit if the immobilised N is protected from these losses. There is need for research on the amount and nature of soil organic matter and crop residues in relation to the duration of N-immobilisation and the extent of re-mineralisation. Retention of large amounts of rice stubble may result low NUE because of prolonged immobilisation of fertiliser N (Li et al. 2016). Conversely low levels of soil organic matter and little retained stubble may result in much of the fertiliser N remaining in the mineral form, which is at risk of loss. The optimum level of soil organic matter, at least as far as immobilization and re-mineralization are concerned, may depend on how long fertiliser N is immobilized in the soil organic matter. If the environmental conditions favour re-mineralization during crop growth, then high organic matter may be optimum. If they do not, relatively low levels of soil organic matter may enable re-mineralization instead of long-term tie up of fertiliser N.

The rapid N turnover in the flooded rice system may provide insights for other systems. If fertiliser N is immobilised in drier and cooler environments, it may not be available for the current crop, and re-mineralisation may be delayed until after harvest (Pilbeam 1995). If re-mineralisation is delayed for several years the financial effect may be similar to N losses from the soil-plant system. It may be possible to reduce immobilization of fertiliser N by spatially separating the fertiliser, as much as possible, from most of the immobilising microbes, for example by banding or deep placement of the fertiliser.

Conclusions

Efficiency of N fertiliser use for irrigated rice grown in southern Australia is greater for urea applied at PF than for N fertiliser in other rice-growing systems. Part of the reason for the high NUE in this region was that urea was washed into dry topsoil by irrigation. This process minimized losses from ammonia volatilisation and denitrification and the apparent N recovery of 76% is high by international standards. An additional contributor to the high NUE may have been temporary immobilisation of fertiliser N, followed by re-mineralisation later in the growing season.

References

Angus JF, Ohnishi M, Horie, T and Williams RL (1994). A preliminary study to predict net nitrogen mineralisation in flooded rice soil using anaerobic incubation. Australian Journal of Experimental Agriculture 34, 995-999.

Bacon PE, McGarrity JW, Hoult EH and Alter D (1986). Soil mineral nitrogen concentration within cycles of flood irrigation: effect of rice stubble and fertilization management. Soil Biology and Biochemistry 18, 173-178

Bacon PE, Reinke RF, Angus JF and Lewin LG (1994). Crop growth, soil mineralisation and uptake in rice fields. In: 'Temperate rice – achievements and potential' Eds Humphreys E, Murray EA, Clampett, WS and Lewin LG) pp. 503-513 (NSW Agriculture, Griffith)

Buresh RJ, Reddy KR and van Kessel C (2008). Nitrogen transformations in submerged soils. pp. 401-436 In: Nitrogen in agricultural systems Agronomy Monograph 49 (American Society of Agronomy, Madison WI)

Cassman KG, Peng S, Olk DC, Ladha JK, Reichardt W, Dobermann, A and Singh U (1998). Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Research 56, 7-39.

DeDatta SK (1981). Principles and practices of rice production. Wiley, Singapore

Dunn BW, Dunn TS and Beecher HG (2014). Nitrogen timing and rate effects on growth and yield of delayed permanent water rice in south-eastern Australia. Crop and Pasture Science 65, 878-887.

Horie T, Ohnishi M, Angus JF, Lewin LG, Tsukaguchi T and Matano T (1997). Physiological characteristics of high yielding rice inferred from cross-location experiments. Field Crops Research 52, 55-68.

Humphries E, Chalk PM, Muirhead WA, Melhuish FM and White RJG (1987). Effects of time of urea application on combine-sown Calrose rice in south-eastern Australia. III Fertiliser nitrogen recovery, efficiency of fertiliser and soil nitrogen supply. Australian Journal of Agricultural Research 38, 129-138.

Khanna PK and Raison RJ (2013) *In situ* core methods for estimating soil mineral-N fluxes: Re-evaluation based on 25 years of application and experience. Soil Biology and Biochemistry 64, 203-210.

Li Y, Wu J , Shen J, Liu S, Wang C, Chen D, Huang T and Zhang J (2016). Soil microbial C:N ratio is a robust indicator of soil productivity for paddy fields. Scientific Reports (in press).

Pilbeam CJ (1995). Effect of climate on the recovery in crop and soil of ^{15}N-labelled fertilizer applied to wheat. Fertilizer Research 3, 209-215.

Russell CA, Dunn BW, Batten GD, Williams RL and Angus JF (2006) Soil tests to predict optimum fertilizer nitrogen rate for rice. Field Crops Research 97, 286-301.