Europ. J. Agronomy 81 (2016) 46–51

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Delayed permanent water rice production systems do not improve the recovery of ^{15}N-urea compared to continuously flooded systems

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ARTICLE INFO

Article history:
Received 16 August 2016
Accepted 22 August 2016
Available online 1 September 2016

Keywords:
Oryza sativa
Delayed flood
Nitrogen
Nitrogen use efficiency
Water management

ABSTRACT

Crop recovery of nitrogen (N) fertiliser in flooded rice systems is low relative to fertiliser N recoveries in aerobic crops, and the N losses have environmental consequences. Recent water shortages across the globe have seen a move towards alternative water management strategies such as delayed permanent water (DPW, also known as delayed flood). To investigate whether N fertiliser regimes used in DPW systems result in greater recovery of N fertiliser than traditional continuously flooded (CF) rice systems, we conducted a multi-N rate field trial using ^{15}N-labelled urea. Around 27% of the ^{15}N-labelled fertiliser was recovered in aboveground biomass at maturity, regardless of water regime or N fertiliser rate, and approximately 20% recovered in the soil to 300 mm depth. Plants in the CF system accumulated more total N at each rate of applied N fertiliser than plants in the DPW system due to greater exploitation of native soil N reserves, presumably because the earlier application of N fertiliser in the CF systems led to greater early growth and higher crop N demand. The greater crop biomass production as a result of higher N uptake in the CF system did not increase grain yields above those observed in the DPW system, likely due to cold weather damage. In the following season at the same site, a single N rate (150 kg N ha^{-1}) trial found no significant differences in crop N uptake, biomass yields, grain yields or ^{15}N-labelled urea recovery in DPW, CF and drill sown-CF (DS-CF) treatments. However, owing to higher ^{15}N fertiliser recovery in the 0–100 mm soil horizon, total plant + soil recovery of ^{15}N was significantly higher in the CF treatment (63%) than the DS-CF and DPW treatments (around 50% recoveries). The loss of 40–50% of the applied N (presumably as NH_3 or N_2) in both seasons regardless of watering regime suggests that new fertiliser N management strategies beyond optimising the rate and timing of urea application are needed, particularly in light of increasing N fertiliser prices.

1. Introduction

In rice (*Oryza sativa* L.) production systems, where over 70% of the world's crop is cultivated under lowland (flooded) conditions, the recovery of nitrogen (N) fertilisers is low. As little as 20–40% of the N applied is recovered by the crop due to losses via NH_3 volatilisation and nitrification–denitrification (Vlek and Byrnes, 1986). Volatilisation of NH_3 is an environmental concern due to potential eutrophication issues following re-deposition, and while losses of N_2 have no direct impact on the environment, there is an indirect environmental cost associated with the embodied energy associated with N fertiliser production. However, since the review by Vlek and Byrnes (1986), agronomic strategies for N applications have been improved, including application of N to the soil immediately prior to flooding since broadcasting N into floodwaters is particularly inefficient (Humphreys et al., 1987).

Flooding of soils traditionally occurs prior to or immediately after sowing in continuously flooded [CF] crops, and in high-input, high-yielding systems pre-germinated seed is typically broadcast into floodwaters using aircraft (LaHue et al., 2016). However, there has been a recent global push to improve the water use efficiency of rice production, which has resulted in the emergence of alternative watering strategies (Rejesus et al., 2011). These strategies include alternate wetting and drying (AWD) which involves allowing soils to briefly dry before re-flooding events (Rejesus et al., 2011) and delaying the permanent flooding of drill-sown crops until just prior to panicle initiation (PI), referred to as delayed permanent water (DPW; Dunn and Gaydon, 2011). In these drill-sown crops, the

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http://dx.doi.org/10.1016/j.eja.2016.08.009
1161-0301/

efficiency of N uptake is also improved by applying N to the soil immediately prior to flooding, with greater NH_3-N losses observed with greater delays between N fertiliser application and flooding (Norman et al., 2009).

In Australia's temperate rice growing region, best management practice (BMP) for N fertiliser application to aerially-sown CF rice involves banding urea 5–10 cm below the soil surface prior to the flooding of bays, while BMP for drill-sown crops or DPW crops involves broadcasting urea granules onto the soil surface immediately prior to flooding after the aerobic phase (Dunn et al., 2014). Fertiliser N recovery using ^{15}N isotope-labelled urea has been investigated in drill-sown rice systems (Humphreys et al., 1987, 1992), including DPW systems (Bollich et al., 1994), but no CF treatments were included for comparison so the relative effectiveness of each system for N fertiliser recovery remains unknown. We hypothesised that recovery of N fertiliser would be greater in DPW crops compared to CF crops because of the presence of actively growing rice roots combined with higher crop N demand at the time of N application. To test this hypothesis, we investigated the uptake of ^{15}N-labelled urea at multiple application rates in DPW and CF crops in the field, and in the following season at the same site, compared ^{15}N-labelled urea recovery (150 kg N ha^{-1}) of DPW and CF crops with that of drill sown-CF (DS-CF) crops where permanent floodwater is applied to fields around 8 weeks after drill sowing.

2. Materials and methods

Two field trials were conducted in consecutive seasons in adjacent areas of the same paddock to investigate the impact of watering regime on the recovery of ^{15}N-labelled urea. In the first season (2014-15), the impact of water regime (CF or DPW) on the recovery of ^{15}N-labelled urea at five N fertiliser rates (0, 50, 90, 130 and 190 kg N ha^{-1} as 5.1 atom% ^{15}N-urea) was investigated, while in the second season (2015-16), the impact of watering regime (CF, DPW or DS-CF) on the recovery of a single rate of ^{15}N-labelled urea (150 kg N ha^{-1} as 5.1 atom% ^{15}N-urea) was investigated. The DS-CF treatment is essentially the same as the DPW treatment, except that crops are permanently flooded around 8 weeks after sowing (DS-CF) as opposed to around three months after sowing (DPW).

2.1. Main plots

The field site was located at Rice Research Australia Pty Ltd, Jerilderie, NSW, Australia (35.3500° S, 145.7333° E) on a Sodosol (Isbell, 1996) with pH (1:5 $CaCl_2$) 4.88; EC (dS m^{-1}) 0.071; total C (%) 1.58; total N (%) 0.132; Bray ^{1} P (mg kg^{-1}) 10.3; and CEC (cmol^{+} kg^{-1}) 7.6, in the 0–100 mm horizon. In 2014–15, main plots (4.7 m wide × 40 m long) were established with a bund height of 600 mm with two water treatments (CF, DPW) laid out in a randomised block design (n = 3). In 2015–16, main plots (4.7 m wide × 40 m long) were established with a bund height of 600 mm with three water treatments (CF, DPW and DS-CF) laid out in an randomised block design (n = 4)

In the 2014–15 season, straw was burned on 28th October 2014. The following day, the site was rotary hoed and 125 kg ha^{-1} monoammonium-phosphate (MAP) was drilled at 100 mm depth in all main plots, except for the last 10 m of plots that contained microplots. In CF plots, 250 kg ha^{-1} urea was also drilled at 50–100 mm depth. On 30th October 2014 rice cv. Sherpa was direct-drilled at 150 kg seed ha^{-1} with a single disc Excel Stubble Warrior (200 mm disc spacing) in DPW plots. On 3rd November, rice cv. Sherpa was sown (pre-germinated) by hand at 150 kg seed ha^{-1} into floodwater in CF plots. Delayed permanent water plots were 'flushed' on 30th October, 6th November, 14th November and 1st December before permanent flooding occurred on 17th December. A 40 mm rainfall event on 24th November negated the need for a flush irrigation around this time. Nitrogen (250 kg ha^{-1} urea) was broadcast onto the dry soil surface of the DPW plots immediately prior to permanent flooding. Weeds were controlled by aerial application of 285 g L^{-1} cyhalofop butyl on 19th December 2014.

In the 2015–16 season, straw was burned on 14th September 2015 and the site was rotary hoed two days later. On 16th October 125 kg ha^{-1} MAP was drilled at 100 mm depth in all DS-CF and DPW main plots, except for the last 10 m of plots that contained microplots. On 23rd October 2015 DS-CF and DPW plots were direct drilled at 150 kg seed ha^{-1} (cv. YRM70) with a single disc Excel Stubble Warrior (200 mm disc spacing). On 12th November 2015, 125 kg ha^{-1} MAP and 250 kg ha^{-1} urea were drilled at 50–100 mm depth in CF plots, except for the last 10 m of plots that contained micro-plots. The following day, pre-germinated seeds of cv. YRM70 were sown by hand at 150 kg seed ha^{-1} into floodwater. Flush irrigation events occurred in the DS-CF and DPW on 2nd December 2015, 8th December 2015 and 17th December 2015 before the DS-CF plots were permanently flooded on 24th December 2015. The DPW plots received a further flush irrigation on 29th December 2015 before they were permanently flooded on the 4th of January 2016. Nitrogen (250 kg ha^{-1} urea) was broadcast onto the dry soil surface of the DS-CF and DPW plots immediately prior to permanent flooding.

2.2. Measurement in main plots

In the 2014–15 season, biomass cuts were taken immediately prior to permanent water on 17th December 2014, around 1 week after PI on (14th January 2015) and at maturity (7th May 2015) using a 0.2 m^{2} steel ring for CF plots and a 1 m length of row was cut in the DPW plots. Biomass cuts were only taken at maturity (27th April 2016) in the 2015–16 season. Following the hand cuts at maturity, a 15 m length from all plots was harvested using a Yanmar GC325 combine harvester with a comb width of 1m. All samples were oven-dried at 60 °C for 72 h and weighed before assessment of total N using Dumas combustion (LECO TruMAC CNS, Saint Joseph, MI, USA).

2.3. Micro-plots

In both seasons ^{15}N-urea trials were conducted in the 10-m lengths of the main plots that didn't receive basal MAP fertiliser. Steel rings (1-m-diameter, 300-mm-high) were inserted into the soil to a depth of 150 mm as per Humphreys et al. (1987). The rings contained 2-mm-diameter holes 25 mm above the soil surface facing away from the head ditch, to allow water to enter the rings. Immediately prior to flooding and sowing of the CF plots, ^{15}N-urea was manually banded at 70 mm depth at 200 mm band spacing in each of the five rings per plot (0, 50, 90, 130 and 190 kg N ha^{-1} as 5.1 atom% ^{15}N-urea) in the 2014–15 season, and in the single ring (150 kg N ha^{-1} as 5.1 atom% ^{15}N-urea) in the 2015–16 season. Phosphorus (P; as superphosphate) was broadcast onto the soil at 10 kg P ha^{-1} immediately prior to flooding (see dates in main plot section above). Fertiliser N rates were assigned randomly to the five rings within each plot in the 2014–15 trial.

For DPW plots in the 2014–15 season and DPW and DS-CF plots in the 2015–16 season, the rings were inserted immediately after the first flush (30th October 2014 in the 2014–15 season and 2nd December in the 2015–16 season), was broadcast onto the soil surface within all rings in both seasons. The ^{15}N-urea, and 10 kg ha^{-1} P, were broadcast onto the dry soil surface within the rings immediately prior to permanent flooding (see dates in main plot section above). Weed control and irrigation management were conducted as per the main plots.