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Crop performance, nitrogen and water use in flooded and aerobic rice

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Abstract

Irrigated 'aerobic rice' is a new system being developed for lowland areas with water shortage and for favorable upland areas with access to supplementary irrigation. It entails the cultivation of nutrient-responsive cultivars in nonsaturated soil with sufficient external inputs to reach yields of 70–80% of high-input flooded rice. To obtain insights into crop performance, water use, and N use of aerobic rice, a field experiment was conducted in the dry seasons of 2002 and 2003 in the Philippines. Cultivar Apo was grown under flooded and aerobic conditions at 0 and at 150 kg fertilizer N ha^{-1}. The aerobic fields were flush irrigated when the soil water potential at 15-cm depth reached −30 kPa. A ^{15}N isotope study was carried out in microplots within the 150-N plots to determine the fate of applied N. The yield under aerobic conditions with 150 kg N ha^{-1} was 6.3 t ha^{-1} in 2002 and 4.2 t ha^{-1} in 2003, and the irrigation water input was 778 mm in 2002 and 826 mm in 2003. Compared with flooded conditions, the yield was 15 and 39% lower, and the irrigation water use 36 and 41% lower in aerobic plots in 2002 and 2003, respectively. N content at 150 kg N ha^{-1} in leaves and total plant was nearly the same for aerobic and flooded conditions, indicating that crop growth under aerobic conditions was limited by water deficit and not by N deficit. Under aerobic conditions, average fertilizer N recovery was 22% in both the main field and the microplot, whereas under flooded conditions, it was 49% in the main field and 36% in the microplot. Under both flooded and aerobic conditions, the fraction of ^{15}N that was determined in the soil after the growing season was 23%. Since nitrate contents in leachate water were negligible, we hypothesized that the N unaccounted for were gaseous losses. The N unaccounted for was higher under aerobic conditions than under flooded conditions. For aerobic rice, trials are suggested for optimizing dose and timing of N fertilizer. Also further improvements in water regime should be made to reduce crop water stress.

Introduction

Asia's food security depends largely on irrigated lowland rice fields, which produce three-quarters of all rice harvested (Maclean et al., 2002). However, the increasing scarcity of fresh water threatens the sustainability of the irrigated rice ecosystem (Guerra et al., 1998; Tuong and Bouman, 2003). Irrigated lowland rice in Asia usually has standing water for most of the growing season. Field techniques to actively save irrigation water were explored over the years and include direct (dry) seeding, keeping fields at soil saturation, and keeping fields alternately submerged–nonsubmerged. In an overview of these techniques, Bouman and Tuong (2001) concluded that, compared with flooded rice, small yield reductions of 0–6% occurred under saturated conditions, and larger yield reductions of 10–40% occurred under alternate

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submergence-nonsubmergence, when soil water potentials during the nonsubmerged phase reached values between −10 and −40 kPa.

A new development in water-saving technologies is the concept of "aerobic" rice (Bouman, 2001; Bouman et al., 2004). In aerobic rice systems, fields remain unsaturated throughout the season. Rice has been grown under nonflooded, aerobic soil conditions in uplands for centuries, but yields are on average only 1–2 t ha^{-1} because of adverse environmental conditions (poor soils, little rainfall, weeds), low use of external inputs, and low yield potential of upland rice cultivars (Maclean et al., 2002). The new concept of aerobic rice entails the use of nutrient-responsive cultivars that are adapted to aerobic soils (Bouman, 2001; Lafitte et al., 2002), aiming at yields of 70–80% of high-input flooded rice. The target environments are irrigated lowlands where water is insufficient to keep lowland (rainfed or irrigated) paddy fields flooded and favorable uplands with access to supplementary irrigation. Irrigation can be by surface irrigation (e.g., flush irrigation, furrow irrigation) or by sprinklers, and aims at keeping the soil "wet" but not flooded or saturated. In practice, irrigation will be applied to bring the soil water content up to field capacity once a lower threshold has been reached. For upland crops such as wheat or maize, this threshold is usually the soil water content halfway between field capacity and wilting point (Doorenbos and Pruit, 1984), but, for aerobic rice, the optimum threshold for re-irrigation still needs to be determined.

In Asia, special aerobic, nutrient-responsive rice cultivars have been developed already in northern China with a temperate climate (Wang et al., 2002) and research is under way to establish crop-water response functions (Yang et al., 2002). In tropical Asia, the International Rice Research Institute (IRRI) recently identified some existing improved upland and lowland cultivars that do well under aerobic conditions (George et al., 2002; Lafitte et al., 2002), but a quantification of water use and yield under well-documented aerobic conditions is still lacking.

Since the concept of aerobic rice is new, relatively few insights exist into nitrogen (N) dynamics and fertilizer N use. In flooded rice with saturated anaerobe soils, ammonium is the dominant form of available N. Most of the losses of fertilizer N occur immediately after application into the floodwater through ammonia volatilization (Vlek and Craswell, 1981). Some of the ammonia is nitrified in oxidized soil zones and in the floodwater (De Datta, 1981). This nitrate moves into reduced layers, where it denitrifies and is subsequently lost to the atmosphere as N_2 and N_2O (De Datta, 1981). Since nitrate is barely present in flooded rice soils, very little nitrate-N is leached to the groundwater (Bouman et al., 2002). In aerobic systems, on the other hand, the dominant form of N is nitrate and relatively little ammonia volatilization can be expected after fertilizer-N application. The application of irrigation water will create soil moisture conditions close to saturation immediately following irrigation and below field capacity a few days later. These alternate moist-dry soil conditions may stimulate nitrification-denitrification processes, resulting in a loss of nitrogen through N_2 and N_2O. In addition, nitrate is prone to leaching. The differences in soil N dynamics and pathway of N losses between flooded and aerobic systems may result in different fertilizer-N recoveries.

Cassman et al. (2002) compared the apparent N recovery (ANR) of maize grown in the USA and flooded rice in Asia and found on average a higher value for maize (0.37 ± 0.30) than for flooded rice (0.31 ± 0.18). Although obtained in different climatic regions with different crops, this suggests that upland systems can have equal or higher values of N recovery than flooded systems. However, field experiments are needed to compare fertilizer-N uptake and recovery between flooded and aerobic rice systems.

Recently, a study began at IRRI to compare crop growth, yield, water use, and N use of rice under flooded and aerobic conditions in the tropics. In this paper, we report on the crop performance and N use under flooded and aerobic conditions in two seasons using a nutrient-responsive upland cultivar. The analysis includes a comparison of the fate of fertilizer N in the two rice ecosystems.

Materials and methods

Treatments and design

The study was done in the dry seasons (January–May) of 2002 and 2003, and was embedded in a long-term experiment comparing rice under flooded and aerobic conditions since 2001 at IRRI, Los Baños, the Philippines (14°18′ N, 121°25′ E) (Bouman et al., 2004). The choice for the dry season was based on the local rainfall pattern. In the years 1979–2003, the rainfall from January to May was 290 ± 31 mm while rainfall in the wet season from June until October was 1333 ± 55 mm. Since in the wet season, true aerobic conditions were hard to impose, we decided to use only the dry season in our study. The soil of the experiment was a typic Tropaqualf, with 59% clay, 32% silt, and 9% sand, a total C content of 19.8 g kg^{-1}, and pH of 6.7.

Flooded fields always had standing water from transplanting until about 1 week before physiological maturity, with water depths increasing from 2 cm at transplanting to 10 cm at panicle initiation. Aerobic fields were kept saturated the first week after transplanting and then re-irrigated when the soil water potential at 15 cm depth reached −30 kPa. This threshold for soil water potential was based on results from research in alternately submerged–nonsubmerged systems (Belder et al., 2004; Bouman and Tuong, 2001; O'Toole and Baldia 1982; Wopereis et al., 1996). Around flowering, the threshold for irrigation was reduced to −10 kPa (field capacity) to avoid spikelet sterility (O'Toole and Garrity, 1984). Irrigations in 2002 were based on average soil water potential values over all four replicates, whereas in 2003, irrigations were based on soil water potential values of individual main plots. This change was based on observed heterogeneity between the replicates. Land preparation in the flooded fields consisted of wet tillage and harrowing (puddling), whereas in aerobic fields, dry tillage and harrowing were practiced. Drains of 0.4 m deep surrounded each field and plastic sheets were installed to 0.4 m depth in the bunds to separate the fields hydrologically. Flooded and aerobic fields were divided into one subplot receiving no fertilizer-N (0-N plot) and another subplot receiving 150 kg urea-N ha^{-1} (150-N plot) in three splits: 50 kg N ha^{-1} basal, 50 kg N ha^{-1} at 25 days after transplanting (DAT), and 50 kg N ha^{-1} at 45 DAT. Subplot size was 86 m^2 and all treatments were replicated four times. P, K, and Zn fertilizers were incorporated in each subplot 1 day before transplanting at a rate of 60, 40, and 5 kg ha^{-1}, respectively. Seedlings were transplanted at a spacing of 10 × 25 cm, with two seedlings per hill. Seedling age at transplanting was 20 days in 2002 and 24 days in 2003, and transplanting dates were 24 January in 2002 and 4 February in 2003. The cultivar that was used during both seasons was the improved upland cultivar Apo (IR55423–01). The choice for this cultivar was based on good performance under aerobic conditions and the responsiveness to nutrients (George et al., 2001). In the long-term experiment, several other cultivars were tested (Bouman et al., 2004).

Intensive pest and weed management was applied using a combination of pesticides, herbicides, and manual weed control. Weed pressure was much higher in aerobic than in flooded plots and weeds were manually removed several times before the canopy of the rice crop was closed.

Microplots of 0.8 × 1.0 m containing 32 hills were established in the flooded and aerobic 150-N plots. Each microplot was surrounded by metal plates that were 30 cm high and were inserted 15 cm deep in the soil before the basal fertilizer application. The microplot study was designed as a split plot with water regime as the main factor and N timing as the sub factor. The two water regimes were aerobic and flooded. N timing followed the splits in the 150-N plots so that ^{15}N labeled urea was applied either basal, 25 DAT or 45 DAT. Unlabelled "normal" urea was applied at the other two splits. The application method followed that in the main plot. Weak seedlings were replaced within the first 2 weeks after transplanting. Microplots had the same water regime as the main plots, but received irrigation water separately using buckets to avoid exchange of N. Any weeds were uprooted and put on top of the soil.

In between the two dry seasons of our experiments, both the flooded and aerobic fields were cropped with flooded rice (cultivar Apo) in the wet seasons (June–October). The 0-N plots again received 0 kg N ha^{-1} and the 150-N plots received 70 kg N ha^{-1}.

Measurements and calculations

Weather data were collected from a weather station at the site, and included daily rainfall, air temperature, and radiation. Seasonal means and sums are reported for the treatment with the longest growth duration. Growth duration was measured from transplanting until physiological maturity. Vapor pressure deficit was calculated as the difference between the saturated vapor pressure at the average day temperature of the air and the early morning vapor pressure.

Irrigation water was supplied to each field through 6-in. PVC pipes that spilled water into 90° boxed-weirs (V-notch type). The amount of water applied was monitored at each irrigation by measuring the depth of water over the V-notch. The groundwater table depth was measured daily in fully perforated PVC pipes installed down to 1.75 m in bunds separating subplots. Tensiometers were installed at 15 and 35 cm depth in the aerobic fields for daily measurement of the soil water potential. Water-filled pore space was computed from the soil water potential values and the soil water retention characteristics, which were determined from undisturbed soil samples taken from the same site.

In 2002, nitrate concentrations were measured from soil water samples collected at 30 and 60 cm depth in 150-N aerobic plots, and from samples collected in the groundwater tubes in aerobic and flooded 150-N plots. In 2003, nitrate concentration was determined from soil solution at 60 and 150 cm depth in both aerobic (0-N and 150-N) and flooded plots (0-N and 150-N). Water samples were stored at 4 °C and filtrated before analysis. Nitrate was determined colorimetrically, using the Technicon autoanalyzer method (Technicon Bulletin, 1986).

Crop samples were taken seven times in 2002 and eight times in 2003 at regular intervals of 10–15 days to determine aboveground biomass, leaf area index (LAI), and total plant N during the season. At each sampling, two areas of 0.25 m^2, comprising 10 hills each, were harvested from opposite sides in the plot. Plants were divided into green leaf blade, stem plus leaf sheath, dead leaf (if any), and panicle (if any). LAI was measured using a Licor LI3100 area meter. Biomass was determined after drying the samples at 70 °C for 3 days. Tissue N content was determined using the Kjeldahl method (Bergersen, 1980) and is reported for green leaf as "leaf-N content" and for total aboveground plant material as "total plant-N content". Grain yield was determined at maturity as the mean of two 5-m^2 samples per plot and is reported at 14% moisture content.

Water productivity was calculated as kg grain m^{-3} total water input (rainfall and the sum of all irrigations, including land preparation). ANR was calculated with the difference method using the total plant N at physiological maturity

$$\mathrm{ANR} = \frac{N_{\mathrm{tot,f}} - N_{\mathrm{tot,uf}}}{N_{\mathrm{applied}}} \quad (\mathrm{kg\ kg^{-1}}), \qquad (1)$$

where $N_{tot,f}$ and $N_{tot,uf}$ are total amounts of plant N in fertilized and unfertilized plots (kg ha^{-1}), respectively, and $N_{applied}$ is the amount of fertilizer-N applied (kg ha^{-1}).

In the microplots, all plants were cut at ground level at maturity and oven dried at 70 °C for 3 days. Plants of the four central hills were separated into grain and straw. Immediately after the plants were harvested, two soil samples per microplot were taken, comprising two of the four central hills. Each sample covered a surface area of 10 × 25 cm, was 30 cm deep, and included the roots of the plants. The soil samples were sectioned into three layers: 0–5 cm, 5–15 cm, and 15–30 cm. Roots were separated from the soil and rinsed with de-ionized water before oven drying. Water content of each soil layer was determined by drying other subsamples for 48 h at 105 °C. Other soil subsamples from each soil layer were dried at 40 °C for 3 weeks prior to N and ^{15}N analysis. All plant and soil samples were fine-ground to < 0.15 mm prior to N content analyses. N-total and atom% ^{15}N analyses were done with an automated C–N analyzer-mass spectrometer (ANCA-MS) similar to that described by Bronson et al. (2000).

Analysis of variance was based on a split-plot design with water as the main factor and N level as the sub factor. In the microplot study, water was the main factor and ^{15}N timing was the sub factor. Pair-wise comparisons between the aerobic and flooded treatment at 0-N and 150-N were carried out for the crop parameters grain yield, total plant N, and N content of leaves and total plant. Pair-wise comparisons between the aerobic and flooded treatment at 150-N were carried out for ANR and for N contents in the three soil layers.

Results

Weather

Average air temperature from transplanting to harvest was 26.9 ± 1.6 °C in 2002 and 27.5 ± 1.7 °C in 2003. Radiation sums were almost identical, with 2352 MJ m^{-2} $season^{-1}$ in 2002 and 2359 MJ m^{-2} $season^{-1}$ in 2003, and seasonal rainfall was 58 mm in 2002 and 92 mm in 2003. Average daily vapor pressure deficit was identical in the 2 years at 0.80 ± 0.17 kPa.

Main plots

Water

Total irrigation water input in flooded plots, including that for land preparation, was 1214 mm in 2002 and 1398 mm in 2003. Total irrigation water input in aerobic plots was 778 mm in 2002 and 826 mm in 2003, resulting in water savings of 436 and 572 mm $season^{-1}$ compared with flooded plots. The irrigation water inputs for flooded plots were comparable with those observed in heavy soils by Tabbal et al. (2002), and Bouman and Tuong (2001). The average seepage and percolation rate in flooded plots was 3.5 mm d^{-1} in 2002 and 5.0 mm d^{-1} in 2003 and in aerobic plots 2.5 mm d^{-1} in 2002 and 3.6 mm d^{-1} in 2003. A complete water balance is presented by Bouman et al. (2004). Groundwater table depth and soil water potential at 15 cm depth in aerobic plots in 2002 and 2003 are given in Figure 1. Consecutive irrigations caused the groundwater table to rise to the soil surface, and, subsequently, values of soil water potential came close to 0 kPa. The seasonal-average soil water potential in aerobic plots at 15 cm depth was −10 kPa (± 8 kPa) in 2002 and −7 kPa (± 9 kPa) kPa in 2003. The average soil water potential at 35 cm depth was −5 kPa (± 3 kPa) in 2002 and −9 kPa (± 7 kPa) in 2003. Groundwater table depth in flooded plots was mostly within 30 cm of the soil surface until about 1 week before physiological maturity. Shallow groundwater tables of < 30 cm depth under flooded rice fields were also observed by Belder et al. (2004). The frequency distribution of the daily water-filled pore space in aerobic plots at 15 cm depth is given in Figure 2. In both 2002 and 2003, the soil was close to saturation most of the time, with a minimum water-filled pore space of 82% in 2002.

Nitrate in groundwater and soil solution

Nitrate concentrations in groundwater tubes (2002) and at 150 cm depth (2003) were below 2 mg l^{-1} in both flooded and aerobic plots (Figure 3). These low values indicate very low leaching losses in both flooded and aerobic fields. Maximum nitrate concentrations in soil solution (30 and 60 cm depth, in 2002) in aerobic plots reached values of 7.5 m L^{-1} and reflected temporal patterns of fertilizer-N applications. Sampling the soil solution in 2003 at 60 and 150 cm showed no differences in nitrate concentrations between flooded and aerobic plots, between 0-N and 150-N plots, and between the two sampling depths (Figure 3c–d).

Crop growth and development, yield, and water productivity

In the 150-N plots, the temporal curves of LAI, biomass, and total plant N were all lower under aerobic conditions than under flooded conditions in both years (Figure 4). Maximum LAI in flooded plots was 6.3–6.5, while maximum LAI in aerobic plots was 4.6 in 2002 and 3.3 in 2003. The low LAI values in aerobic plots in 2003 were associated with reduced total biomass and grain yield at the end of the growing season (Table 1). With 150 kg N ha^{-1}, the yield under aerobic conditions was 15% lower than under flooded conditions in 2002, and 39% lower than under flooded conditions in 2003. In a pair-wise comparison, these differences were statistically significant at $P < 0.03$ in 2002 and $P < 0.001$ in 2003. Many plants in flooded 150-N plots lodged shortly before maturity. In the 0-N plots, the temporal curves of LAI, biomass, and total plant N were comparable between the aerobic and the flooded plots. The yield in aerobic 0-N plots was only 9–13% lower than in flooded plots, and the differences were not significant ($P < 0.05$).

The factors water and N both affected crop growth duration (Table 1). Crop duration was shortest in the flooded plots with 150-N in both years. In 2002, the aerobic 150-N plots matured 8 days earlier than the 0-N plots under both flooded and aerobic conditions, while in 2003 there was no difference.

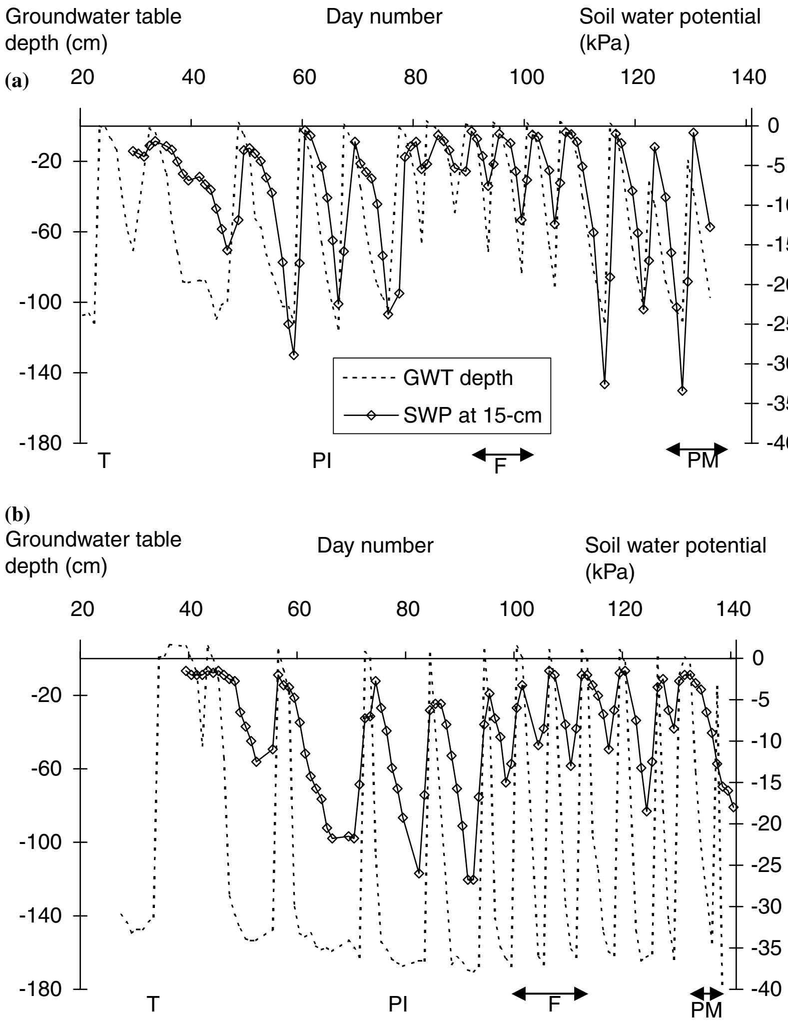

Figure 1. Groundwater table (GWT) depth (----) and soil water potential (SWP) at 15-cm depth (–◇–) in aerobic plots in 2002 (a) and 2003 (b); in 2002 the lines represent averages over four replicates and in 2003 the lines represent only one replicate. T = transplanting, PI = panicle initiation, F = flowering, PM = physiological maturity.

Yield components are presented in Table 2. Sink size, represented by the number of grains per m^2, showed a strong response to N and reflected LAI and biomass growth. Grain filling was significantly ($P < 0.05$) affected by water regime in both seasons and was below 77% in aerobic plots. In comparison, around 90% of the grains were filled in 0-N flooded plots. Individual grain weight showed a slight but significant effect of N ($P < 0.001$) in 2002 and water regime ($P < 0.01$) in 2003. All three components of yield were lower for aerobic than flooded conditions so that there was no positive feed-back mechanism between yield components. This finding means that water deficit under aerobic cultivation lasted from around panicle initiation until physiological maturity, and even lowering the threshold of re-irrigation to −10 kPa around flowering still led to reduced grain filling. Flowering in 2003 occurred shorter after the soil water potential reached −30 kPa than in 2002 (Figure 1). This stress might have caused the lower growth rate between panicle initiation and flowering and the reduction in percentage grain filling and individual grain weight as compared with 2002 (Table 2).

Water productivity was increased by application of 150 kg N ha^{-1} in both flooded and aerobic plots and was highest for aerobic 150-N

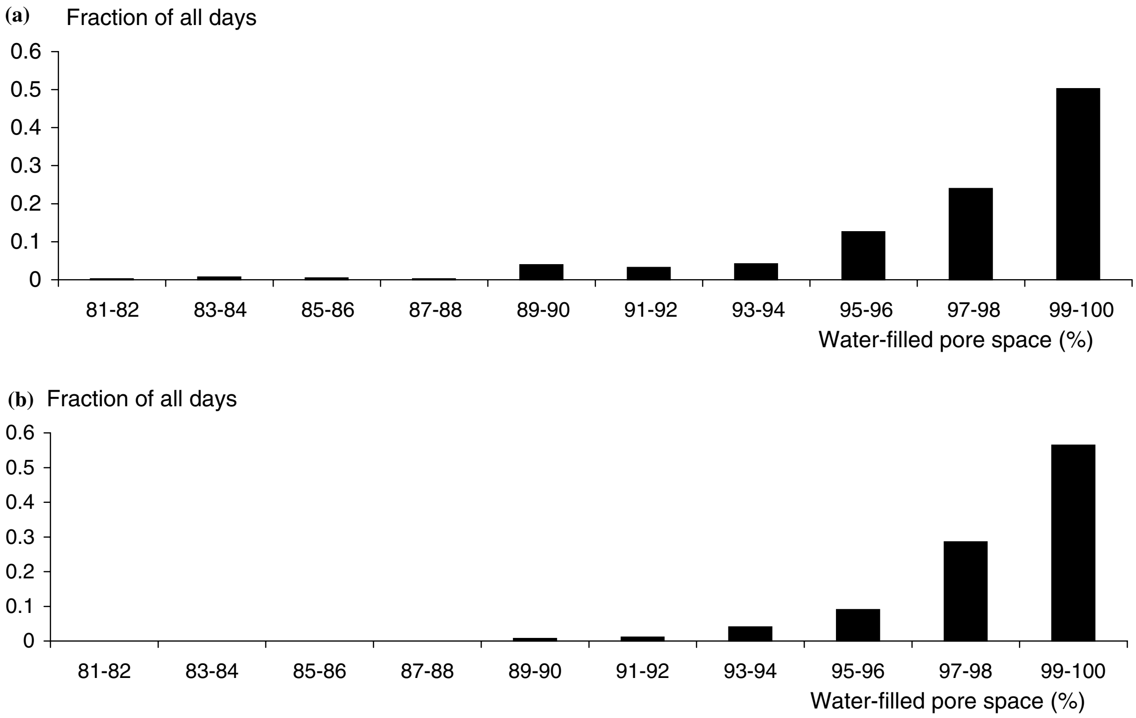

Figure 2. Frequency distribution of water-filled pore space in aerobic plots at 15-cm depth in (a) 2002 and (b) 2003.

plots in 2002: 0.75 kg m^{-3} (Table 1). In 2003, water productivity in all treatments was lower than in 2002 and the effect of N on water productivity was smaller in both flooded and aerobic plots.

N content, uptake, and recovery

The dynamics of N content in leaves and total plant are presented in Figure 5. Differences in N content of both leaves and total plant were significant in 2002 and 2003 between 0-N and 150-N plots. In 2002, the leaf-N content did not differ significantly between aerobic and flooded plots for most sampling dates at both N levels. Only in 2003, the leaf N content in 150-N plots was significantly lower under aerobic conditions than under flooded conditions at two sampling dates in the vegetative phase. The same trends were observed in N content of the total plant.

Total plant N in the 150-N plots was on average 89 kg ha^{-1} under aerobic conditions, which was only 65% of the total plant N under flooded conditions (Table 1). In the 0-N plots, total plant N was on average 62 kg ha^{-1} and barely differed between year and water regime. The ANR was in both seasons significantly lower in aerobic plots (average 0.22 kg kg^{-1}) than in flooded plots (average 0.49 kg kg^{-1}, Table 3).

Microplots

The recovery of ^{15}N in grain and straw was higher under flooded than under aerobic conditions, in both 2002 ($P < 0.102$) and 2003 ($P < 0.003$) (Tables 4–5). Averaged over the different timings, plant-N recovery was 0.22 kg kg^{-1} in aerobic plots and 0.36 kg kg^{-1} in flooded plots. Timing of fertilizer-N application also influenced plant ^{15}N recovery, but only significantly so in 2003. The amount of ^{15}N recovered increased with later N application. Plant ^{15}N recoveries were lower in aerobic plots than in flooded plots at all timings of urea-N application. ^{15}N recovered by roots was not significantly affected by water regime or timing of N application, and was a fairly constant fraction of 0.03 of total applied ^{15}N.

The lower N recovery under aerobic conditions than under flooded conditions is corroborated by a ^{15}N isotope study by De Datta et al.

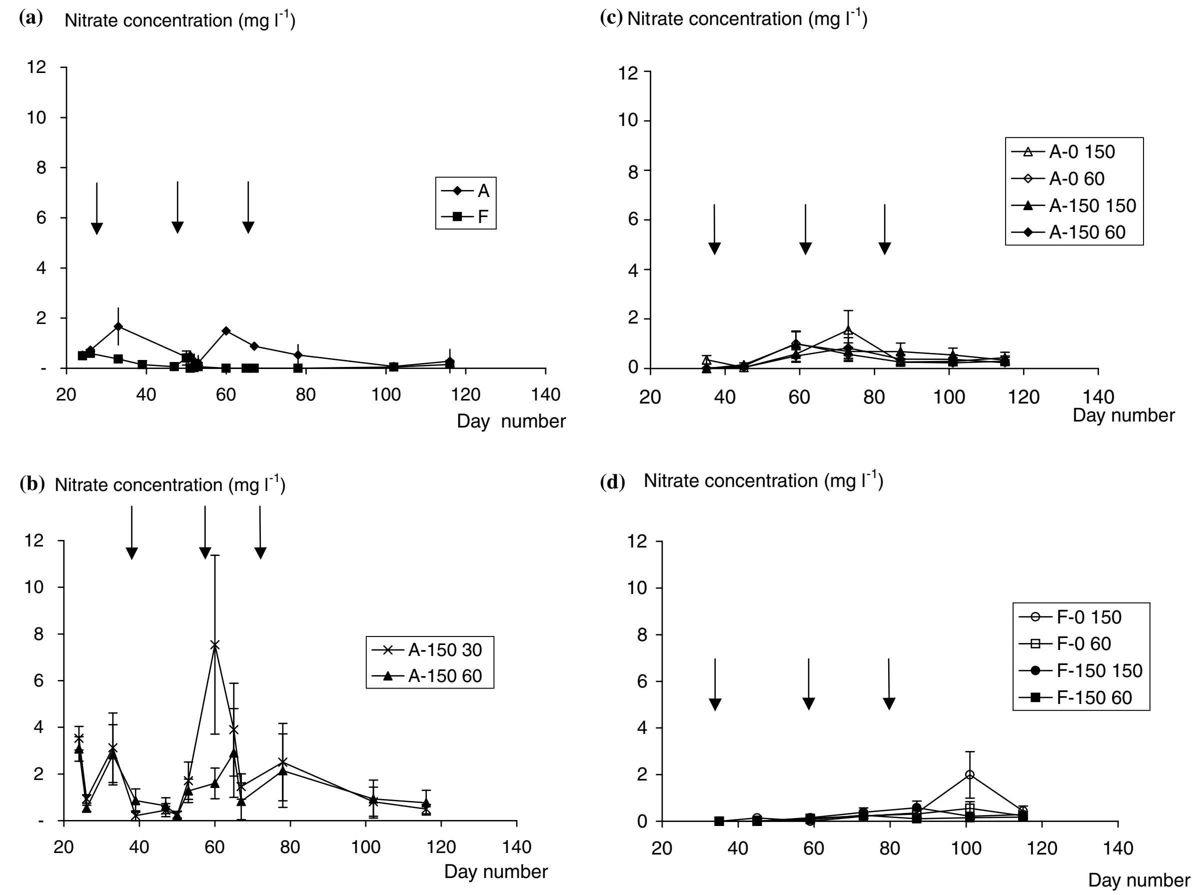

Figure 3. Nitrate concentrations in (a) 2002 in groundwater in aerobic, (A,♦) and flooded (F, ■) plots; (b) 2002 in soil solution at 30-cm (A 30, ×) and 60-cm (A 60,▲) in aerobic plots; (c) 2003 in 0-N aerobic plots at 60-cm (A-0 60, ◇) and 150-cm (A-0 150,Δ) depth and in 150-N plots at 60-cm (A-150 60, ♦) and at 150-cm (A-150 150, ▲); (d) 2003 in flooded 0-N plots at 60-cm (F-0 60, □) and at 150-cm (F-0 150, ○) depth and in 150-N plots at 60-cm (F-150 60, ■) and at 150-cm (F-150 150, ●). Bars indicate the standard error; arrows indicate fertilizer-N applications.

(1983) in intermittently flooded and continuously flooded water regimes. They reported a recovery of 0.41 under continuously flooded conditions and 0.20 under intermittently flooded conditions.

The fraction of ^{15}N measured in the top 30 cm of the soil in 2002 was higher under flooded conditions (0.33) than under aerobic (0.24) conditions. In 2003, however, the ^{15}N recovered from the soil was higher in aerobic (0.31) plots than in flooded (0.22) plots. For all applications, more than 50% of ^{15}N found in the soil was found in the top 5 cm (Tables 6–7). Relatively more ^{15}N was measured in the top 5 cm in flooded plots than in aerobic plots, indicating that fertilizer N moved deeper in the aerobic soil than in the flooded soil. Of the total soil N in the top 30 cm, 21% was present in the top 5 cm (Table 8), indicating that relatively more native N stayed in the two deeper layers than the fertilizer N applied during the experiment. This can be explained by the fact that, except for the basal-N application, the fertilizer N was not mixed with the soil. Averaged for both years, unaccounted ^{15}N fractions were higher in aerobic (0.47) plots than in flooded (0.35) plots.

There were some differences between N recovery obtained with the difference method in the main plots and N recovery as determined using ^{15}N in the microplots. Under aerobic conditions, the recoveries were about the same, whereas under flooded conditions, recoveries were 14 and 32% higher with the difference method than with

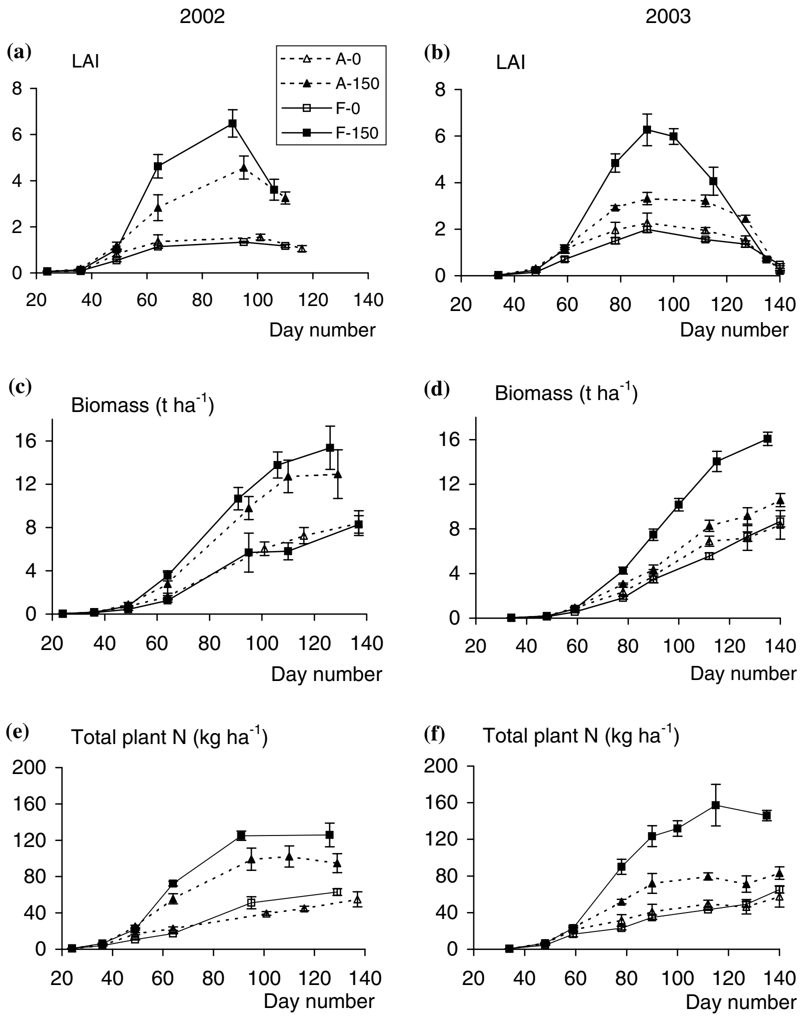

Figure 4. LAI in time in (a) 2002 and (b) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, △) and with 150-N (A-150, ▲); aboveground biomass in time in (c) 2002 and (d) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, △) and with 150-N (A-150, ▲); and total plant N in time in (e) 2002 and (f) 2003, under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, △) and with 150-N (A-150, ▲). Bars indicate the standard error.

the ^{15}N method. Higher values of N recovery with the difference method than with the ^{15}N method for rice were also reported by Schnier (1994), Cassman et al. (1993), and Bronson et al. (2000). Bronson et al. (2000) found that added N interaction through isotope substitution of the labile N pool was the reason for the discrepancy between the two methods in flooded soil. The N fraction not accounted for, measured with the ^{15}N method in our study, remains valid because N transformation processes (NH_3 volatilization, denitrification) will hardly be affected by pool substitution (Bronson et al., 2000).

In our study, biomass and total plant N were on average 15% lower in the microplots than in the main plots. Bufogle et al. (1997) also found lower biomass and total plant N for rice in microplots (of 75×75 cm) than in the main field.

Discussion

Aerobic rice was developed for water-short environments where water is insufficient to keep paddy fields flooded, while maintaining high

Table 1. Biomass (t ha^{-1}), total plant N (kg ha^{-1}), grain yield (t ha^{-1}), water productivity (kg m^{-3}), and crop duration (days) of Apo at maturity in 2002 and 2003 with analysis of variance

Year	Treatment	Biomass	Total plant N	Grain yield	Water productivity	Crop duration[a]
2002	Flooded 0-N	8.6	66	3.8	0.31	113
	Flooded 150-N	16.0	133	7.3	0.59	102
	Aerobic 0-N	8.7	58	3.3	0.40	113
	Aerobic 150-N	13.4	98	6.3	0.75	105
2003	Flooded 0-N	8.7	65	4.1	0.28	106
	Flooded 150-N	16.1	146	6.8	0.47	101
	Aerobic 0-N	8.4	58	3.7	0.40	106
	Aerobic 150-N	10.6	83	4.2	0.45	106
	Analysis of variance					
2002	Water	ns[b]	ns	ns	ns	
	N level	***[c]	**	***	***	
	Water × N level	ns	ns	ns	ns	
	CV[d]	16.0	21.7	8.5	10.5	
2003	Water	ns	ns	*	ns	
	N level	***	***	**	**	
	Water × N level	**	**	**	*	
	CV	12.4	11.3	12.8	14.2	

[a]Maturity per treatment was determined in the field as average over four replicates and, therefore no statistics were calculated.
[b]ns = nonsignificant ($P > 0.05$).
[c] * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[d]CV = coefficient of variance.

Table 2. Yield components of the Apo cultivar in the dry seasons of 2002 and 2003 under aerobic and flooded conditions

Year	Treatment	Grain number (nr m^{-2})	Filled grains (%)	Individual grain weight (mg)
2002	Flooded 0-N	21858	90.1	20.9
	Flooded 150-N	39285	82.1	21.4
	Aerobic 0-N	23367	76.7	19.9
	Aerobic 150-N	33660	74.7	20.7
2003	Flooded 0-N	21891	89.6	20.0
	Flooded 150-N	43573	80.4	20.6
	Aerobic 0-N	24218	74.4	18.2
	Aerobic 150-N	31751	72.6	18.6
	Analysis of variance			
2002	Water	ns[a]	*[b]	ns
	N level	***	ns	***
	Water × N level	ns	ns	ns
	CV[c]	14.1	5.8	1.1
2003	Water	ns	*	**
	N level	***	*	ns
	Water × N level	ns	ns	ns
	CV	13.1	4.2	2.2

[a]ns = nonsignificant ($P > 0.05$).
[b]* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[c]CV = coefficient of variance.

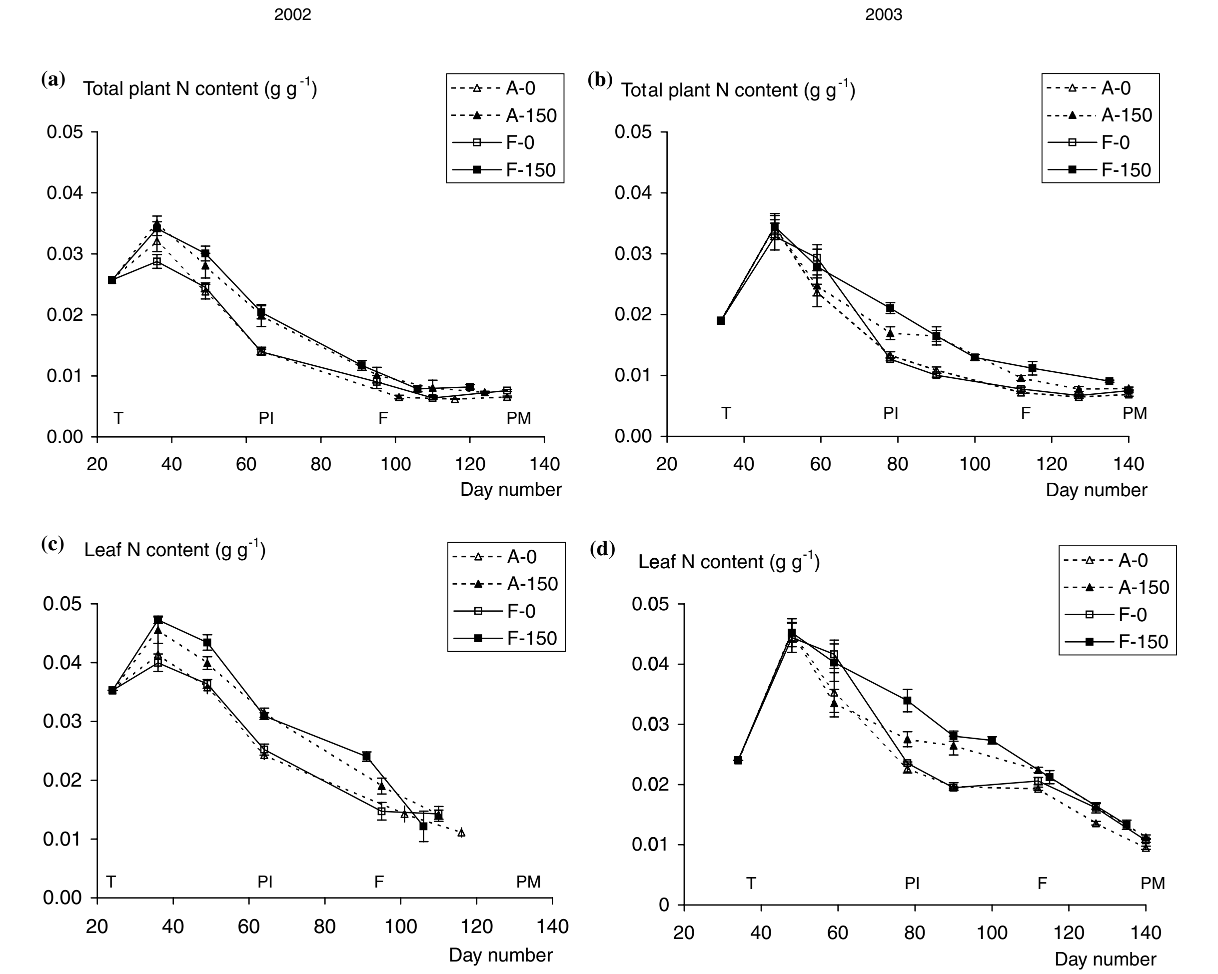

Figure 5. Plant-N content in time in (a) 2002 and (b) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, △) and with 150-N (A-150, ▲); and leaf-N content in time in (c) 2002 and (d) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, △) and with 150-N (A-150, ▲). Bars indicate the standard error. T = transplanting, PI = panicle initiation, F = flowering, PM = physiological maturity.

yields thereby increasing water productivity. Achieving yields of 70–80% of attainable yields of nonwater limited lowland rice is still a challenging target for aerobic rice. Attainable yield of IR72, an elite lowland cultivar, without water limitation at 200 kg fertilizer N ha^{-1} in the same years and with the same sowing and transplanting dates as in our experiment, was calculated at 9.1 t ha^{-1} in 2002 and 8.8 t ha^{-1} in 2003 using the crop growth model ORYZA2000 (Bouman et al., 2001). These yields are in the range of those found by Kropff et al., (1993) and Peng and Cassman (1998) with IR72 at the IRRI farm. The actual yield of Apo with 150 kg N ha ha^{-1} under aerobic conditions was 69% in 2002 and 48% in 2003 of that of the simulated yield of IR72 with 200 kg N ha^{-1}. Increased N fertilization may have resulted in a higher grain yield with Apo but would also increase the risk on lodging, because Apo is a rather tall (up to 140 cm) cultivar. In the field

Table 3. Mean apparent N recoveries (kg kg^{-1}) with standard error in aerobic and flooded plots in 2002 and 2003

Year	Aerobic	Flooded
2002	0.27 ± 0.08	0.44 ± 0.10
2003	0.17 ± 0.04	0.54 ± 0.05

Table 4. Recovery fraction of ^{15}N-enriched fertilizer N in microplots in 2002 with analysis of variance

Treatment	Grain	Straw	Roots	Soil	Unaccounted for
Aerobic					
Basal	0.13	0.10	0.02	0.21	0.55
25 DAT[a]	0.14	0.13	0.04	0.24	0.45
45 DAT	0.17	0.14	0.03	0.26	0.40
Average	0.14	0.12	0.03	0.24	0.47
Flooded					
Basal	0.23	0.10	0.04	0.44	0.20
25 DAT	0.21	0.09	0.02	0.25	0.43
45 DAT	0.32	0.14	0.02	0.29	0.23
average	0.25	0.11	0.03	0.33	0.29
Analysis of variance					
Water	*[b]	ns[c]	ns	*	ns
Timing	ns	ns	ns	ns	ns
Water × timing	ns	ns	*	*	ns
CV[d]	23.6	21.7	19.6	12.8	18.7

[a]DAT = days after transplanting.
[b]$*P < 0.05$, $**\ P < 0.01$, $***\ P < 0.001$.
[c]ns = nonsignificant ($P > 05$).
[d]CV = coefficient of variance.

Table 5. Recovery fraction of ^{15}N-enriched fertilizer N in microplots in 2003 with analysis of variance

Treatment	Grain	Straw	Roots	Soil	Unaccounted for
Aerobic					
Basal	0.05	0.06	0.02	0.42	0.44
25 DAT[a]	0.09	0.08	0.04	0.26	0.53
45 DAT	0.14	0.14	0.04	0.25	0.43
Average	0.09	0.09	0.04	0.31	0.47
Flooded					
Basal	0.11	0.08	0.02	0.21	0.58
25 DAT	0.18	0.13	0.02	0.24	0.42
45 DAT	0.30	0.28	0.02	0.19	0.20
Average	0.20	0.17	0.02	0.22	0.40
Analysis of variance					
Water	*[b]	ns[c]	*	ns	ns
Timing	***	**	ns	ns	ns
Water × timing	ns	ns	ns	ns	ns
CV[d]	13.3	20.3	16.1	16.1	17.1

[a]DAT = days after transplanting.
[b]$*P < 0.05$, $**\ P < 0.01$, $***\ P < 0.001$.
[c]ns = nonsignificant ($P > 0.05$).
[d]CV = coefficient of variance.

experiments, irrigation water savings were 36% in 2002 and 41% in 2003 in the aerobic treatment as compared with the flooded treatment, thereby resulting in a higher water productivity in 2002 but a lower water productivity in 2003 in the aerobic as compared to the flooded regime. Future studies comparing aerobic and flooded rice should include an elite lowland cultivar, bred for flooded (well-watered) conditions. This would enable a more accurate comparison of water use and yield under both flooded and aerobic rice systems.

Table 6. Recovery fraction of ^{15}N-enriched fertilizer N per soil layer in microplots in 2002

Treatment	0–5	5–15	15–30
Aerobic			
Basal	0.12	0.07	0.02
25 DAT[a]	0.16	0.06	0.03
45 DAT	0.15	0.08	0.03
Flooded			
Basal	0.26	0.11	0.09
25 DAT	0.19	0.04	0.03
45 DAT	0.23	0.04	0.02
Analysis of variance			
Water	**[b]	ns[c]	ns
Timing	ns	ns	ns
Water × timing	ns	ns	ns
CV[d]	14.0	36.1	49.5

[a]DAT = days after transplanting.
[b]*$P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[c]ns = nonsignificant ($P > 0.05$).
[d]CV = coefficient of variance.

Table 7. Recovery fraction of ^{15}N-enriched fertilizer N per soil layer in microplots in 2003

Treatment	0–5	5–15	15–30
Aerobic			
Basal	0.20	0.10	0.10
25 DAT[a]	0.12	0.10	0.02
45 DAT	0.14	0.09	0.02
Flooded			
Basal	0.17	0.04	0.01
25 DAT	0.19	0.04	0.01
45 DAT	0.15	0.03	0.01
Analysis of variance			
Water	ns[b]	**[c]	ns
Timing	ns	ns	ns
Water × timing	ns	ns	ns
CV[d]	12.5	25.7	75.8

[a]DAT = days after transplanting.
[b]ns = nonsignificant ($P > 0.05$).
[c]*$P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[d]CV = coefficient of variance.

The absence of an effect of water regime on LAI, biomass, total plant N, and yield at 0-N suggests that indigenous soil N supply was nearly the same under aerobic and flooded conditions. It also suggests that, in 0-N aerobic plots, N limited growth more than water. In the 150-N plots, biomass, LAI, total plant N, N recovery, and grain yield were significantly lower under aerobic

Table 8. Total N (kg ha^{-1}) per soil layer (cm) as determined in the microplots with pair-wise comparison for water regime

Year	Water regime	0–5	5–15	15–30
2002				
	Aerobic	676	1388	1159
	Flooded	700	1259	1571
	Pair-wise comparison			
	Aerobic versus flooded	ns[a]	*[b]	ns
	CV[c]	24.9	19.0	12.1
2003				
	Aerobic	636	1210	1099
	Flooded	602	1225	1159
	Pair-wise comparison			
	Aerobic versus flooded	ns	ns	ns
	CV	14.2	9.8	15.9

[a]ns = nonsignificant ($P > 0.05$).
[b]*$P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[c]CV = coefficient of variance.

conditions than under flooded conditions. Despite the lower total plant N and ANR, the contents of leaf N and total plant N under aerobic conditions were nearly the same as under flooded conditions. Therefore, in 150-N aerobic plots, water limited growth more than N.

Beyrouty et al. (1994) compared crop growth and N dynamics in a field experiment with flooded and alternately submerged–nonsubmerged conditions in lowland rice with an N application rate of 150 kg ha^{-1}. Their threshold of soil water potential for re-flooding was also −30 kPa, and they found biomass and total plant N to decrease from panicle initiation onward, while N content in plant tissue remained unaffected. In our experiment, the 2002 season shows a similar pattern, whereas in 2003, biomass and total plant N in aerobic plots decreased already before panicle initiation. Beyrouty et al. (1994) also recorded no differences in total plant N content between alternately submerged–nonsubmerged and flooded rice. They gave two explanations for the reduced total plant N, that correspond with the findings in our experiment: (1) water stress reduced crop N demand and (2) soil conditions led to increased N losses via nitrification–denitrification and/or ammonia volatilization. The interaction between water regime and fertilizer N management was also studied in rainfed lowland rice systems. In this system, Wade et al. (1999) found that nutrient application (notably N) substantially increased yields only when water limitation was minimal.

The relatively low uptake of N under aerobic conditions (versus flooded conditions) was also reflected by the relatively low fertilizer-N recovery under aerobic conditions. Of the 150 kg N ha^{-1} applied, only an average of 22% was taken up by the crop while 31% was left in the soil and roots after harvest. The intensive weed control applied during the experiment prevented growth reduction and N uptake by weeds; both might have caused reduction in ANR of aerobic rice. Since nitrate concentrations in groundwater and soil water were negligible, most of the 47% N unaccounted for must have left the system as gaseous-N losses promoted by rapid nitrification–denitrification processes. Higher nitrification–denitrification rates maybe explained by differences in redox potential in aerobic and flooded plots. In aerobic plots at 5 cm depth, the redox potential had values above 300 mV some 30 DAT (Buresh, pers. comm.) and had similar values as soils under which wheat and barley are produced (Bohrerova et al., 2004). Around flowering, the redox potential of the aerobic soil reached even values above 400 mV which is considered as a well-oxidized soil (Yu et al., 2001). On the contrary, redox potential in flooded soil at 5 cm depth was below −100 mV some 30 DAT until after flowering (Buresh, pers. comm.). More measurements on redox potential at more depths in the soil may explain the pathway of N transformation processes in an aerobic rice soil.

A higher recovery of N in aerobic rice than the 22% we found, is desirable and would not only increase N application efficiency, thereby reducing fertilizer costs to farmers, but would also reduce gaseous-N losses to the environment such as N_2O, which is a potent greenhouse gas. Since the amount of irrigation water determines yield under conditions when N is not limiting, we suggest combining water treatments with N treatments to optimize yield and resource-use efficiency. Fertilizer N application as basal just before transplanting showed the lowest N recovery. Further experiments should determine whether later timing of fertilizer N will increase N recovery. For the cultivar Apo, trials with a range of N levels are suggested for optimizing N application rates. High N recoveries of up to 0.6–0.7 kg kg^{-1} in arable cereal crops show that higher N recoveries in aerobic rice might be possible when N dose and timing better match the N requirement of the crop.

Currently, the yield potential of cultivars adapted to aerobic rice systems is much lower than that of modern lowland cultivars such as IR72 (the plants of Apo lodged at yields of around 7 t ha^{-1}). However, breeding programs may soon deliver higher yielding cultivars than Apo or other currently "most suitable" cultivars. When breeding programs develop germplasm for aerobic rice systems, these should replace Apo in the above proposed irrigation and N optimization trials to obtain higher yields.

The plant–water relationships we found for the cultivar Apo correspond well with results obtained in alternately submerged–nonsubmerged lowland rice systems under low to moderate water-stress levels. Both the results with Apo in our experiment, and reports of the behavior of lowland cultivars under submerged–nonsubmerged conditions, confirm water-stress effects at soil water potentials of 0 to −30 kPa (Belder et al., 2004; Bouman and Tuong, 2001; Lu et al., 2000; O'Toole and Baldia, 1982; Wopereis et al., 1996). These water-stress effects express themselves through reduced leaf area development, reduced biomass growth, and reduced yield.

The lower biomass, LAI, total plant N, yield, and water productivity in 2003 than in 2002, could not be explained by the average soil water potential. A possible explanation could be the later timing of lowering the threshold to −10 kPa in 2003 than in 2002. The later imposition could have caused extra stress for the crop just before flowering. Further improvements should be made in water regimes in aerobic rice systems to reduce crop water stress.

The difference between 2002 and 2003 could also have been caused by sustainability problems of continuously or repeatedly growing of aerobic rice (even though there was a break crop of flooded rice in between the dry seasons of 2002 and 2003). Sustainability problems with monocropping of rice under aerobic conditions have been reported by George et al. (2002) for the Philippines and by Wang et al. (2002) for China. The reason for possible yield decline is not known yet, though the build up of soil-borne pathogens such as nematodes is a likely candidate (Lafitte et al., 2002). Another reason might have been a decline in soil organic matter under aerobic cultivation. However, such decline was not likely in our experiments, because total soil N at physiological maturity in the microplots was not significantly lower in aerobic than in continuously flooded soil in both 2002 and 2003 (Table 8). Since soil-extractable NO_3 + NH_4 (data not shown) did not constitute more than 0.2% of total N at physiological maturity, almost all N was in organic form. Assuming that C:N ratios were not different between flooded and aerobic soils leads us to the conclusion that soil organic matter content did not differ between the two water regimes after both seasons. We did not investigate total N under continuous aerobic cropping. There could be a decline in soil organic matter under this system as compared with permanent flooding or the rotation flooded rice – aerobic rice. The reduction in yield under continuous aerobic rice cropping should be further investigated and remedial measures developed.

Aside from the crop-water-nitrogen management issues, the feasibility of aerobic rice also depends on socio-economic factors such as farmers' income, temporal water availability, water pricing, and food demand. Feasibility of aerobic rice in uplands depends on availability of supplementary irrigation and inputs such as fertilizers and herbicides. Moreover, with increasing water shortage, other crops with less drought sensitivity may be more suitable and replace rice.

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