Ecophysiology of drill-seeded rice under reduced nitrogen fertilizer and reduced irrigation during El Niño in Central Colombia

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ABSTRACT

Improvement of efficiencies of N fertilizer and irrigation water is needed for large-scale market-oriented rice cultivation without puddling practice as in American continents. Effects of reductions of N fertilizer and irrigation water on grain yield of drill-seeded rice on zero-leveled fields were quantified across five N levels (220, 180) two sources with 5 or 3 splits), 140, and 0 kg N ha⁻¹) and three irrigation strategies (irrigating every 3, 6, or 8 days; W1, W2, and W3, respectively) in dry and wet seasons during an El Niño event in Central Colombia. Reducing the N application rate from 180 kg N ha⁻¹ to 140 kg N ha⁻¹ (22% reduction) did not reduce yield in either season in spite of slightly reduced N uptake, owing to increased N use efficiency in all irrigation strategies. Three split of N fertilizer with slow release urea (180 kg N ha⁻¹) and with basal organic amendment did not reduce yield compared with the conventional 5 split method. Yield in dry season reduced under the 2 water-saving strategies (W2, W3) almost proportionally to the reduced water supply (irrigation + rainfall) by flowering. In wet season, yield in mild water saving (W2, with 26% water saving) was similar to conventional irrigation management (W1), leading to its highest water productivity. Physiological parameters (e.g. stomatal conductance, total N uptake) were greater in wet season than in dry season. This study showed potential reduction of N fertilizer and conditions of climate for water-saving in drill-seeded rice production in Colombia.

1. Introduction

Rice production in tropical American continent is getting important for regional development including food supply and social stability. However, little agronomic information is available for improved agronomic practices for efficient and profitable resource use under variable climate. Colombia produced ca. 2.51 million tonnes of paddy rice with average yield of 4.84 t ha⁻¹...
(FEDEARROZ, 2018a), which is not sufficient to meet with increasing rice demand (e.g. 42.2 kg per capita consumption; FEDEARROZ, 2018b). Nitrogen fertilizer application and irrigation water supply are essential for increasing yield but their high input with low utilization efficiency lead to higher production cost; fertilizers alone costs for 17% of rice production cost (FEDEARROZ, 2009). This may lead to disadvantages in the international market and environmental unsustainability, but quantitative agronomic information for their resource uses are scarcely found.

Rice cultivation (mostly lowland) in Colombia is greatly different from typical Asian lowland system. Rice is grown either on sloping fields segmented by contour levees or on leveled fields in Colombia. In both types of fields, mechanical dry direct-sowing method without soil puddling are major planting method. The unique features of its cultivation are (1) drill seeding system, (2) without puddling, (3) little use of organic amendment, and (4) much larger unit field size and unit farm size. These would lead to (5) continuous flushing irrigation water supply with fixed intervals, without expecting maintenance of standing or stagnated water, as well as (6) 180–220 kgN/ha of synthetic N fertilizers continuously split-applied 5 times with greater emphasis during vegetative stage (Berrio et al., 2002; Okada & López-Galvis, 2018). There are many studies on both N saving and water-saving cultivation efforts in Asian transplanted rice production which is basically by family labor and labor-intensive manner, but much less efforts and less reports in market-oriented larger scale rice production systems as seen in Colombia and American continents (Carrijo et al., 2017). More efficient utilization of N and water must be developed under drill-seeded rice production in Colombia and American continents.

Rainfall in Central Colombia amounts to 1473 mm on average from 1980 to 2012, which generally has two peak seasons, one from October to November (370 mm) and the other from March to April (368 mm). Sunny months of July to September recorded 18.8 MJ m⁻² day⁻¹ of solar radiation compared with 16.8 MJ m⁻² day⁻¹ of months of March to May on average from 1980 to 2012. Irregular climate events are increasing in frequency; El Niño in 2015–2016 decreased irrigation water availability in medium and small river basins, which reduced rice cultivation area (e.g. 300 ha in Coello and Cucuana river basin) and yield (e.g. 40% reduction in 13% of the harvested area) (Pineda et al., 2016). The El Niño raised air temperature, particularly from February to April 2016, causing sporadic yield reduction in the downstream fields. The Oceanic Niño Index (ONI) during 2015–16 was higher (≥2.0) and considered as very strong (Bernard et al., 2017) and second most intense ever since 1950 (Supplementary Fig. 1). To better demonstrate N and water savings for rice production in Colombia, we need to quantify the relationships between resources, such as water and solar radiation, and rice productivity in well-defined climate conditions in different seasons including the El Nino years. Unlike the Asian countries where decision makings of rice production have been guided substantially by long history of farming experiences, newer market-oriented rice cultivation do need such quantified relationships for their decisions in rice farming such as when to plant and how much irrigation to apply. Water-saving irrigation management strategies such as alternate wet and dry irrigation as already established in Asia (Bouman & Tuong, 2001; Bueno et al., 2010; Yao et al., 2012) has been only scarcely studied in Latin America (e.g. De Borja Reis et al., 2018). More efficient use of water by adjusting the irrigation interval or using alternate wetting and drying could save water use and increase N fertilizer use efficiency (Sun et al., 2012). N use efficiency (NUE) can be improved also by optimizing the timing of application, the type of fertilizer, application rate, fertilizer placement (Cassman et al., 1994). However, since absence of puddling may reduce standing water and available soil water and perched water may not be available in drill-seeded rice cultivation system, opportunity for water-saving might be limited, but little quantitative evidence available. Water-saving may lead to development of soil cracks that would increase deep percolation. Balance of evapotranspiration and seasonal rainfall may need to be taken into account for successful water-saving.

Effective management of water and N can improve yield and resource use efficiency and reduce production costs. Basic information on quantities of irrigation water and N fertilizer rates under dry direct sowing is lacking in tropical rice-growing environments in Latin America as in Colombia. This study aimed to investigate the effect of reduced N fertilizer application rate on grain yield, aboveground biomass, and N uptake in both conventional and water-saving cultivations, and to quantify effects of reduced irrigation water supply in dry drill-seeded rice during El Niño in 2015–2016. We set two hypothesis; (1) N application rate can be reduced without yield penalty down to ca. 140 kgN/ha (avings of 22% in 180 N, 36% in 220 N) in drill seeding system including under water-saving irrigation strategy. Whether 5 split times of N fertilizer can be reduced to 3 times would be also tested through combination of slow release fertilizer and basal organic amendment. (2) Success in water-saving strategy is conditioned by climate factors under drill-seeded system without puddling. This study, as the first step, targeted to collect
quantitative eco-physiological information in the leveled fields without puddling in Colombia.

2. Materials and methods

2.1 Experimental site, soil, and fertilizer application

Field experiments were conducted during 2015 (May to October; dry season) and 2016 (February to June; wet season) at FEDEARROZ Las Lagunas Station, Saldaña, Tolima Department, Colombia (3°56′4.99″N, 75°1′13.08″W, alt. 311 m). As located in tropical valley with generally high temperature (average maximum air temperature 33.1°C from 1980 to 2012) and high humidity (in particular during wet season), disease and pest attacks are common in Saldaña.

The soil is a silty loam containing 36% sand, 52% silt, and 12% clay. The pH was 5.4, and the organic matter (OM) content was 13.1 g kg⁻¹ (n = 9). Soil chemical analysis from the soil of 0–15 cm depth before the start of the experiment in 2015 gave the following contents: total N 1559 mg kg⁻¹, total P 460 mg kg⁻¹, B 0.5 mg kg⁻¹, Cu 3.10 mg kg⁻¹, Zn 5.1 mg kg⁻¹, Mn 23.4 mg kg⁻¹, Fe 120.3 mg kg⁻¹, N-NH₄ 3.9 mg kg⁻¹, and N-NO₃ 34.6 mg kg⁻¹. Soil S content was low (16.5 mg kg⁻¹; A Castilla, FEDEARROZ pers. comm.), and ammonium sulfate had to be applied to rectify low content of soil S since no single-S fertilizer is available at the site. The use of ammonium sulfate (21% N) and ‘Micro-essential’ fertilizer (12% N) created application rate of N (N₀) of 39 kg N ha⁻¹ (Table 1). Following the recommendations of local agronomists, five commercial fertilizers (ammonium sulfate, essential micronutrients, KCl, zinc sulfate, and Fertimex (Minerales Exclusivos S. A. Bogota, Colombia); Supplementary Table 1) were applied in all plots. Urea (granular form, N 46%) was split-applied with the different specific rates for different N treatments.

2.2 Plot layout and experimental design

The experiments used three irrigation strategies in three neighboring fields of 22.4 m × 40 m each: conventional (W1), every 3 days; mild water saving (W2), every 6 days; and risky water saving (W3), every 8 days. W1 was considered close to constantly flooded by irrigation supply, whereas W2 and W3 were somehow safe AWD and severe AWD, respectively, according to Bouman et al. (2007). Enough space was allowed between fields to avoid water flow, and the same fields were used in both years. In each field, five N levels were arranged in a randomized block design with three replications (Table 1). Plots are named for the total N rate; e.g. ‘N₂₂₀’ means N at 220 kg ha⁻¹. N₂₂₀ was maximum rate, N₁₈₀ was conventional rate, N₁₄₀ was reduced rate, −22% from N₁₈₀ and −36% from N₂₂₀. N₁₈₀SR was reduced split application times to three (as compared with five of other N fertilized treatments), with 50% of the urea (90 kg N ha⁻¹) from a slow-release (SR) type (ENTEC, Monomer, Barranquilla, Colombia), and with a soil amendment called ‘Gaicashi’ (organic fertilizer made from domestic and on-farm sources, with 2% N, 2% P, 4% K, 1% Ca, 1% S, and 50% OM) was applied before sowing at 667 kg ha⁻¹ in 2015 and at 2000 kg ha⁻¹ in 2016. ENTEC urea has a nitrification inhibitor DMPP (Dimethylpyrazole phosphate) that delays nitrification up to 10 weeks allowing slow release of nitrate from the stabilized ammonium (Eurochemagro, 2020). N₀ was regarded as base level for calculation of NUE parameters. In Each N plot was 2.4 m wide and 11 m long. Strong soil bunds avoided plot-to-plot water flow. N plots were re-randomized in the second season to avoid cumulative N effects.

2.3. Plant cultivation

Fields were disc harrowed and laser-leveled before sowing. Dry seeds of rice (‘FEDEARROZ 60’, a high-yielding, locally adapted cultivar) were directly sown into dry soil by drill seeder at 6.6 g m⁻² in rows 20 cm apart on May 15, 2015 (dry season) and February 17, 2016 (wet season). Emergence dates (when 80% of seedlings had emerged) were May 25, 2015 and February 27, 2016. A minimum density of 200 plants m⁻² was achieved by gap filling.

2.4. Measurements

2.4.1. Climate and soil moisture

Rainfall, solar radiation, minimum and maximum temperatures, and relative humidity (RH) were measured hourly by a weather station (WatchDog 2900ET, Spectrum Technologies Inc., Aurora, IL, USA) located on site. Average reference evapotranspiration rate (ET₀) was calculated by the Penman–Monteith method by using data from weather station. Soil water potential was
measured by soil moisture sensor (Watermark WM100, Spectrum Technologies) at 5 cm depth, one per treatment. A pressure-gauge-type tensiometer 30 cm long (Daiki, Kogyo, Japan) installed in each field was used. The volumetric water content (VWC) was measured by time-domain reflectometer (Field Scout TDR 300, Spectrum Technologies) with a 12-cm probe.

2.4.2. Water depth monitoring and water balance
Irrigation water input was estimated every 10 min \( Q_{10} \text{m}^3 \) from the water depth \( d \text{m} \) measured by a pair of pressure sensors (Baro Diver, Daiki Rika Kogyo, Saitama, Japan), one fixed at the Parshall flume (40 cm width) at the water inlet of each field and the other in the air, as:

\[
Q_{10} = 1.84 \times (0.4 - 0.2d) \times d^{1.5} \times 600
\]  

For initial calibration, water depth was measured manually several times. The duration of each irrigation event was also measured. Irrigation input was calculated from 20 days after the start of treatment (Days after emergence (DAE): June 14, 2015 and March 18, 2016) to 90% flowering and maturity.

2.4.3. Phenology and Chlorophyll content
Phenology was recorded at 90% flowering stage in all plots. The chlorophyll content in the middle of the topmost fully expanded leaf was measured in 5 plants per plot with a SPAD 502 chlorophyll meter (Spectrum Technologies) at 50% flowering stage in all plots (September 1, 2015 in dry season, 11 May 2016 in wet season).

2.4.4. Biomass sampling
Aboveground biomass was sampled at 30, 50, 70, and 90 DAE in 1 m² in each plot. We recorded total fresh weight (FWₙ) and the fresh weight (FWₚ) and dry weight (DWₙ) of subsamples (about 20%). We calculated total dry weight per m² (DWₙ) as:

\[\text{DWₙ} = \frac{\text{FWₙ} \times \text{DWₚ}}{\text{FWₚ}}\]  

2.4.5. Light interception fraction and radiation use efficiency
Photosynthetically active radiation (PAR) was measured around the sampling occasions (i.e., 30, 50, 70, 90 DAE, maturity) between 11:00, 13:00 on clear sunny days with a line quantum sensor (LI-1500, LI-COR, Lincoln, NE, USA). In each plot PAR readings above \( \text{PARₐ} \) and below \( \text{PARₚ} \) the canopy were taken at same time by using two separate sensors. PAR readings below canopy were taken by placing sensor diagonal to rows below the canopy. These PAR readings were used to calculate the fraction of light intercepted (FI) as:

\[
FI(\%) = \frac{\text{PARₐ} - \text{PARₚ}}{\text{PARₐ}} \times 100
\]

The cumulative radiation interception by the rice canopy (RI) was calculated as the sum of daily solar radiation multiplied by daily FI assumed from linear changes between the measured FI values:

\[
\text{RI (MJ m}^{-2}) = \text{daily solar radiation} \times \text{daily FI}
\]

The aboveground biomass was plotted against cumulative RI, and radiation use efficiency was obtained from the slope of the linear regression by using both treatment average data and replicated data (Sinclair & Muchow, 1999).

2.4.6. Photosynthetic parameters
Net photosynthetic rate \( \left( \text{P}_n \right) \), stomatal conductance \( \left( g_s \right) \), transpiration rate \( \left( E \right) \), and intercellular CO₂ concentration \( \left( C \right) \) were measured by portable photosynthesis system (LI-6400, LI-COR) around flowering stage on August 14, 2015 and May 21, 2016. The measurements were taken on the topmost fully expanded leaf and flag leaf of 3 plants in each plot on a clear sunny day between 09:00, 11:30. The RH in the chamber was adjusted to 80%, the reference CO₂ entering the chamber was set to 400 µmol mol⁻¹, and the block temperature was set between 28 and 31°C to be within ±2°C of the air temperature under 1500 µmol m⁻² s⁻¹. The values of reference and sample CO₂ concentrations were matched at 400 µmol CO₂ mol⁻¹ every 30 min during measurement (during matching leaf chamber was empty).

2.4.7. Yield and yield components
At maturity, plant height was measured from the stem base to the tip of the tallest panicle from 5 plants per plot. Grain yield was determined from 4 m² and was adjusted to a 14% moisture content. Panicle density, aboveground biomass, harvest index (HI), and other grain yield components were determined from an additional 0.4 m². All panicles were counted and then threshed manually. After oven drying to a constant weight, the grain and straw dry weights were recorded to calculate HI as the ratio of grain dry weight to grain plus straw dry weight. All grains were soaked in tap water to separate fully filled grains from partially filled and empty grains. Grains that sank were considered to be fully filled, and floating grains were separated into empty (<30% filled) and partially filled grains (≥30% filled) by hand pressing. The separated grains were oven-dried and dry weights were recorded. From each category, 50 grains were counted and weighed, and 1000–fully filled grain weight and number of grains (fully filled + partially filled) per m² were calculated.
Grain filling was calculated as the ratio of fully filled grains to total number of grains.

2.4.8. Nitrogen analysis

The N percentage of grain and straw samples by dry weight was analyzed by Skalar San ++ + Analyzer (Skalar, Breda, The Netherlands). Values were multiplied by dry weights to calculate N weights, which were summed to calculate total N uptake. NUE for biomass was defined following Ra et al. (2012), and the following parameters indicating N utilization were calculated as below.

\[
\text{NUEofbiomass} = \frac{\text{totalabovegroundbiomass}}{\text{totalNuptake}} \tag{6}
\]

\[
\text{NHI} = \frac{\text{grainNweight}}{\text{totalNuptake}} \tag{7}
\]

\[
\text{AgronomicNefficiency} = \frac{[(\text{Graindryweight}_{\text{Nlevel}} - \text{Graindryweight}_{\text{NB}})]}{(\text{Nfertilizer}_{\text{Nlevel}} - 3.9)} \tag{8}
\]

\[
\text{Nrecovery\%} = \frac{[(\text{totalNuptake}_{\text{Nlevel}} - \text{totalNuptake}_{\text{NB}})]}{(\text{Nfertilizer}_{\text{Nlevel}} - 3.9)} \times 100 \tag{9}
\]

The value of 3.9 (g N m^{-2}) was the base value in the N_{B} treatment.

2.4.9. Carbon isotope composition (δ^{13}C) analysis

Straw samples harvested at maturity were ground into a very fine powder for analysis of carbon isotope composition (δ^{13}C) on a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK) at the University of California at Davis, USA.

2.4.10. Water use and water productivity

Cumulative water used (irrigation plus rainfall) is presented as mm measured from 20 DAE. After direct sowing, the soil was irrigated and drained four times (~40 mm in total) before 20 DAE to encourage germination and plant development. Water productivity was calculated as the ratio of grain yield (kg) to cumulative water used (m^{3}) by physiological maturity. Precipitation was summed from sowing to physiological maturity; irrigation was measured from 20 DAE.

2.5. Statistical analysis

Data were analyzed in GenStat v. 17 software. Analysis of variance (ANOVA) tested the main effects of nitrogen (N), irrigation strategy (W), year (Y), and their interactions on the results of both years combined. ANOVA was also conducted on grain yield, aboveground biomass, and HI in each year. Multiple comparison analysis was done by Tukey’s test.

3. Results

3.1 Climate and soil water status

In the dry season (2015), the daily mean air temperature increased slightly from 28.3 ± 1.2°C at the vegetative stage to 29.8 ± 0.9°C at the grain-filling stage, but in the wet season (mid Feb to early April 2016), it was higher, at 28.8 ± 1.7°C, at the vegetative stage, partly owing to the effects of El Niño, and decreased slightly thereafter (Table 2, Supplementary Fig. 2). The average temperature of standing water was particularly high during the vegetative stage (31.2 ± 1.7°C) in the wet season (2016). Daily solar radiation was highest during the grain-filling stage, at 22.3 ± 4.1 MJ m^{-2}, in the dry season (2015) and during the vegetative stage, at 21.0 ± 5.1 MJ m^{-2}, in the wet season (2016). Date of 90% flowering delayed by up to 11 days in W2 and W3 compared with W1 in dry season while no delay in W2 but a few days delay in W3 in wet season (August 25, 2020; Aug and 5 Sep in 2015 and May 20, 2018 May and May 22 in 2016 for W1, W2, and W3 treatments, respectively). Rainfall from plant establishment (20 DAE) to 90% flowering (14 Jun to 5 Sep) was only 14 mm in 2015, compared with 161 mm in 2016 (Mar 18 to May 22) (Figure 1).

Soil VWC measured a few hours before irrigation was clearly higher in the order of W1, W2, and W3 in 2015; for example, on Aug 27 (W2) and 29 Aug (W1 and W3), 41.9 ± 11.1% in W1, 35.5 ± 9.7% in W2, and 23.4 ± 7.6% in W3, and on September 16 193.3 ± 7.7% in W1, 24.0 ± 9.4% in W2, and 15.7 ± 6.1% in W3. VWC on 2 days after irrigation was 46.0 ± 5.8% in W1 and 46.9 ± 3.0% in W2, and

Table 2. Average temperatures of air and standing water, daily solar radiation, and duration of three growth stages (emergence [E] to panicle initiation [PI], PI to 90% flowering [FL], FL to full maturity [M]) during dry season (2015) and wet season (2016) experiments.

| Growth interval | Average air temperature (°C) | Average water temperature (°C) | Daily solar radiation (MJ m^{-2}) | Days |
|-----------------|-----------------------------|---------------------------------|---------------------------------|------|
| Dry season experiment in 2015 | | | | |
| E to PI | 28.3 ± 1.2 | 28.0 ± 1.5 | 19.7 ± 3.7 | 69 |
| PI to FL | 29.7 ± 0.9 | 28.0 ± 1.2 | 21.2 ± 3.1 | 34 |
| FL to M | 29.6 ± 1.4 | 30.2 ± 1.6 | 22.3 ± 4.1 | 26 |
| Wet season experiment in 2016 | | | | |
| E to PI | 28.8 ± 1.7 | 31.2 ± 1.7 | 21.0 ± 5.1 | 52 |
| PI to FL | 28.3 ± 1.3 | 29.1 ± 1.0 | 20.7 ± 4.6 | 33 |
| FL to M | 28.1 ± 1.4 | 28.3 ± 1.0 | 19.5 ± 5.0 | 28 |

\(^{a}\)Average growth stages of W3 were used (dry season 2015: PI 2 Aug, FL 5 Sep, M 29 Sep; wet season 2016: PI 19 April, FL 22 May, M 17 June).

\(^{b}\)Mean ± standard deviation.
VWC on 6 days after irrigation was 25.1% ± 6.2% in W3. In 2015, the average soil water potential (Ψ) in W3 from June 14 to Oct 3 was −12.2 ± 18.3 kPa, weekly reaching down below −40 kPa between mid-August and mid-September to as low as −97 kPa (Figure 1(a)). In 2016, the average in W2 from March 17 to May 25 was −9.3 ± 15.4 kPa (readings were lower after then), and that in W3 from March 17 to June 10 was −20.9 ± 30.8 kPa (Figure 1(b)). When Ψ in W2 fell to −55 and −77 kPa during later growth, the VWC reached down to 31% and 27%, respectively. Ψ in W3 in 2016 reached below −75 kPa three times from panicle initiation to grain-filling stage, to as low as −111 kPa.

Total water use (irrigation + rainfall) from 20 DAE to maturity was 1474 mm in W1, 1365 mm in W2, and 1134 mm in W3 in 2015, and 1347, 993, and 983 mm in 2016 (Table 3; Supplementary Fig. 3). The corresponding values by 90% flowering were 1183, 1039, and 825 mm in 2015, and 1152, 866, and 772 mm in 2016. The total number of water supplies (either irrigation or rainfall of >1 mm) were 36 to W1, 28 to W2, and 27 to W3 in 2015, and 38, 31, and 30 in 2016 (Supplementary Table 2). Average single water inputs were 50 ± 15, 77 ± 42 and 76 ± 26 mm in W3 in 2015, and 75 ± 22, 99 ± 19, and 114 ± 45 mm in 2016. Cumulative reference evapotranspiration (ET₀) and net water balance (ET₀ − rainfall) were 646 and 379 mm, respectively, in 2015, and 526 and 221 mm in 2016.

### 3.2. Grain yield effects by N fertilizer and irrigation strategy

N application rate and N management did not affect grain yield, aboveground biomass, or HI in N₂₂₀, N₁₈₀, N₁₄₀, and N₁₈₀SR (Table 4). Irrigation strategy significantly affected all three. Aboveground biomass did not differ between years, but grain yield and HI were significantly higher in the wet season.

Grain yield did not differ between W1 and W2 but was significantly reduced in W3 in both years (Table 4). It was 16% higher in the wet season than in the dry season. The longer irrigation interval in W3 reduced HI in both seasons and also aboveground biomass in the dry season. HI was 11% higher in the wet season than in the dry season. Grain yield (but not aboveground biomass or HI) showed a small N × water interaction; N₅ in W3 in dry season suffered from smaller stress due to its smaller initial plant mass (less delay in flowering compared with other N treatments in W3) and attained higher grain yield in only W3.

The number of fertile panicles, the number of grains per m², and 1000-grain weight were not significantly different among N levels except N₅ (Table 5). The effect

![Figure 1](image-url)

**Figure 1.** Daily rainfall (mm) and soil water potential (kPa) at 5 cm depth in (a) W3 in 2015 and (b) W2 and W3 in 2016. Soil water potential data of W2 in 2015 and W2 from 25 May 2016 are missing owing to instrument problems. Vertical lines in figures represent timing of fertilizer application.
was highly significant for number of grains per m², number of grains per panicle, and grain-filling percentage, which were reduced in W3. In W2, a significant water × year interaction reflected slightly more grains per m² in the wet season. The number of fertile panicles per m² ranged from 414 to 547 among irrigation strategies in both years, and was 24% higher in the dry season. The 1000-grain weight across irrigation strategies was higher in the wet season (28.1 g) than in the dry season (26.8 g). Plant height and SPAD showed highly significant year effects, being higher in the wet season (Table 5).

3.3. Water productivity

Overall water productivity in both years was higher in W2 (0.590 kg m⁻³) than in W1 and W3 (Table 6). In particular, it was much higher in W2 in the wet season (2016) (0.740 kg m⁻³), with a large water × year interaction.

In 2015, grain yield was linearly related to water supply by 90% flowering; a saving of 100 mm of water reduced yield by 75 g m⁻² (Figure 2). Water supply by flowering data was used as the maturity data had heavy rainfall and irrigation nearby maturity only in W3. W2 saved 14% of water by 90% flowering with 8% lower yield than W1 in 2015 (non-significant difference). In 2016, grain yield increased from W3 to W2 as water supply by 90% flowering increased, and further increase to W1 did not contribute to a yield gain. W2 saved 33% water with similar grain yield to W1. W3 saved 36% water in 2015 and 44% in 2016, but decreased yield by 30 and 17%, respectively. All 3 irrigation treatments in 2016 (W1, W2, & W3) showed faster growth and higher biomass gain with lower water use compared to W1 in 2015 (Figure 3; Supplementary Fig. 4). In 2016, W2 and W3 saved water while maintaining aboveground biomass. In 2015, W3 used the least water but significantly reduced biomass accumulation than W1 and W2.

3.4. Light interception and radiation use efficiency among five N levels

The fraction of intercepted radiation (FI) and radiation use efficiency (RUE) were higher in the wet season than in the dry season (Table 7). Owing to the shorter growth period, the cumulative amount of RUE was lower in the wet season.

3.5. Photosynthesis and carbon isotope composition (δ¹³C)

Air temperature and RH during measurement were 28.6–30.3°C and 34.6–48.4% in 2015 and 31.6–32.8°C and 43.3–50.3% in 2016. Most of the photosynthetic parameters except Pn performed differently between years (Table 8). Transpiration rate (E) differed among irrigation strategies and years: in 2015, E was higher in W1 and W2 than in W3, whereas in 2016, E tended to be higher in W2 than in W1 and W3. Higher soil moisture in 2016 resulted in higher E and gs than in 2015. δ¹³C differed significantly among irrigation strategies and years: δ¹³C values were smaller in W3 than W1 and W2 in both 2015 and 2016; and were more negative in 2016 than in 2015, indicating lower discrimination for ¹³C in 2016 due to greater availability of C4 (because higher soil moisture increased gs and E).

3.6. Total N%, N uptake, and N harvest index

Total N uptake differed significantly among N levels: except for Nb, it was lowest in N140. It ranged from 11.39 to 21.54 g m⁻² in both years, and was 43% higher in the wet season than in the dry season (Table 9). N uptake did not differ among irrigation strategies in either season. It was higher in N180SR during the wet season, with a positive N × year interaction. Grain and straw N% values were highly improved in the wet season in all irrigation strategies. Except in Nb, NH1 was not different among N levels (data not shown). The effect of irrigation strategy was significant at P ≤ 0.001; NH1 was highest in W1 and lowest in W3 in both seasons. Straw N uptake was higher at 90 DAE in W2 and W3 in both seasons, and was higher in the wet season than in the dry season (data not shown).

3.7. N use efficiencies

The agronomic N efficiency (AE_N) was significantly higher in N140 than in N220 (Table 10), with a significant
water × year effect due to negative values in W3 in the dry season (higher grain yield in N8 than in treatments with higher N). AE_N and N recovery efficiency (RE_N) showed significant year effects, with higher values in the wet season.

4. Discussion

4.1. Saving of N fertilizer

A 22% reduction in N application (i.e., 140 kg N ha⁻¹ in N140) from the conventional rate (180 kg N ha⁻¹ in N180) did not reduce grain yield (Figure 2), yield components, or water productivity in either year (Tables 5, Tables 6). Despite a reduction in total N uptake and grain and straw N concentrations in N140 (Table 9), NUE values for aboveground biomass and AE_N were higher in N140 than in N220, N180, and N180SR (Tables 9, Table 10). Significantly higher AE_N in N140 than in N220 indicates a higher yield increase per kg of N application. These on-station data indicate great potential for N saving in tropical lowland rice fields in Colombia. In China, Peng et al. (2006) reduced the N application rate from the conventional 180–240 kg N ha⁻¹ to 60–120 kg N ha⁻¹ by the use of
Table 5. Number of fertile panicles, number of grains, grain filling percentage, 1000-grain weight, plant height at maturity, and SPAD values during flowering averaged over three irrigation strategies and two years among five nitrogen levels.

| N level  | Fertile panicles (m⁻²) | Number of grains (m⁻²) × 10⁵ | Number of grains/panicle | Grain filling (%) | Thousand-grain weight (g) | Plant height (cm) | SPAD |
|----------|-------------------------|------------------------------|--------------------------|-------------------|--------------------------|------------------|------|
| N₂₅₀     | 491 b                   | 26.0 ab                      | 55                       | 68.5 a            | 27.5 ab                  | 108.7 b          | 36.7 b |
| N₅₀₀     | 496 b                   | 28.3 b                       | 58                       | 68.5 a            | 28.0 b                  | 106.9 b          | 36.2 b |
| N₇₅₀     | 492 b                   | 27.9 b                       | 58                       | 71.0 ab           | 27.4 ab                  | 106.0 b          | 35.0  |
| N₁₉₅₀b   | 482 ab                  | 27.5 b                       | 58                       | 70.4 ab           | 27.5 ab                  | 107.6 b          | 35.4  |
| N₇     | 431 a                   | 22.9 a                       | 55                       | 73.5 b            | 26.9 a                  | 94.7 a           | 32.3 a |
| LSD (5%) level | 36                      | 2.5                          | 6.4                      | 3.6               | 0.6                      | 2.4              | 2.6   |

Water × Year

| Year      | Number | N level (N) | Water (W) | Year (Y) | N × W | N × Y | W × Y | N × W × Y | NS | *** |
|-----------|--------|-------------|-----------|----------|-------|-------|-------|-----------|----|-----|
| W₁ 2015   | 547bc  | NS          | NS        | NS       | NS    | NS    | NS    | NS        | NS | *** |
| W₂ 2015   | 535 b  | NS          | NS        | NS       | NS    | NS    | NS    | NS        | NS | *** |
| W₃ 2015   | 506 b  | NS          | NS        | NS       | NS    | NS    | NS    | NS        | NS | *** |
| W₁ 2015   | 414 a  | *           | *         | *        | NS    | NS    | NS    | NS        | NS | NS  |
| W₂ 2015   | 429 a  | NS          | NS        | NS       | NS    | NS    | NS    | NS        | NS | NS  |
| W₃ 2015   | 439 a  | NS          | NS        | NS       | NS    | NS    | NS    | NS        | NS | NS  |
| LSD 5% level | 40      | 2.7         | 7         | 3.9      | 0.7   | 2.6   | 2.8   | 2.8       | NS | NS |

Combined ANOVA

| N level (N) | Water (W) | Year (Y) | N × W | N × Y | W × Y | N × W × Y | NS | *** |
|-------------|-----------|----------|-------|-------|-------|-----------|----|-----|
| NS          | NS        | NS       | NS    | NS    | NS    | NS        | NS | NS  |

Means followed by the same letter are not significantly different at 5% level (Tukey’s test).

Table 6. Total water productivity averaged over three irrigation strategies and two years among five nitrogen levels.

| N level   | Total water productivity (kg m⁻³) |
|-----------|----------------------------------|
| N₂₅₀      | 0.510 b                          |
| N₅₀₀      | 0.563 b                          |
| N₇₅₀      | 0.557 b                          |
| N₁₉₅₀b    | 0.540 b                          |
| N₇        | 0.427 a                          |
| LSD (5%) level | 0.058                     |
| W₁        | 0.475 a                          |
| W₂        | 0.599 b                          |
| W₃        | 0.494 a                          |
| LSD (5%) level | 0.045                     |
| 2015      | 0.430 a                          |
| 2016      | 0.609 b                          |
| LSD (5%) level | 0.037                     |
| W₁ 2015   | 0.442 a                          |
| W₂ 2015   | 0.438 a                          |
| W₃ 2015   | 0.410 a                          |
| W₁ 2016   | 0.508 b                          |
| W₂ 2016   | 0.740 c                          |
| W₃ 2016   | 0.578 b                          |
| LSD (5%) level | 0.064                     |
| N level (N) | ***<sup>a</sup>               |
| Water (W)  | ***                             |
| Year (Y)   | ***                             |
| N × W      | NS                              |
| N × Y      | *                               |
| W × Y      | NS                              |
| N × W × Y  | NS                              |

Means followed by the same letter are not significantly different at 5% level (Tukey’s test).

<sup>a</sup>N₁₉₅₀b 50% of slow release N and OM Gaikashi was applied in 3 splits

<sup>b</sup>N₁₉₅₀ 50% of slow release N and OM Gaikashi was applied in 3 splits

NS, not significant; *P ≤ 0.05, **P ≤ 0.010, ***P ≤ 0.001.

real-time N management and fixed-time adjustable-dose N management. Z. Dong et al. (2015) showed that reduction of N application rate from 270 kg N ha⁻¹ to 180 kg N ha⁻¹ increased N recovery efficiency, AEₙ, and partial factor productivity (grain yield divided by rate of applied fertilizer N) without affecting yield. Site-specific N management and application of slow-release fertilizers reduced N application from 195 kg N ha⁻¹ to 133 kg N ha⁻¹ while increasing NUE and yield (Peng et al., 2010; Y. Yang et al., 2012). For economic efficiency, N application rates should be slightly lower than those for maximum yield (Fageria et al., 2008). Our study showed no interaction between N level and irrigation strategy on yield or N parameters, so the reduction of N fertilizer to 140 kg N ha⁻¹ would be effective even in water-saving management conditions.

The application of slow-release N and OM (Gaikashi) and the use of fewer splits (3) in N₇₅₀b did not reduce grain yield or water productivity or any N parameters including RE and AE. This result indicates potential for the use of OM and slow release fertilizers to continue to supply N nutrients, to improve fertilizer N recovery and to reduce application frequencies and application cost. Under alternate wetting and drying conditions, the incorporation of OM increased N, P, and K uptake (C. Yang et al., 2004). The addition of OM increases soil biological activity (Sanchez et al., 1989), soil aggregate stability, water-holding capacity, and cation exchange capacity (Haynes & Naidu, 1998), all of which help in retaining N and reducing N leaching. The addition of
OM can regulate soil N immobilization and mineralization so as to improve N uptake (Kumazawa, 1984). We could not dissect effects of $N_{180SR}$ into OM or slow-release N but our work indicates possible scope to meet with crop N demand by reducing split-application times.

4.2. Conditioned water-saving

The results of irrigation use, water productivity, and gas exchange identified greater risk of yield penalty in the dry season than wet season. During the dry season (2015), 7% water saving in W2 (1039 mm of irrigation up to 90% flowering) slightly reduced yield and panicle and grain numbers (Table 5), and ~23% water saving in W3 (825 mm up to 90% flowering) reduced yield by 30%. This equated to a reduction of 74 g m$^{-2}$ per 100 mm of water saving (Figure 2). The substantial yield reduction in W3 (Table 4) was associated with reduction in grain number (both per panicle and per area) and grain filling (Table 5), which can be attributed to the reduction in $\Psi$ below −40 kPa, to as low as −100 kPa, during grain filling (Figure 1(a)) owing to the long irrigation intervals of ~10 days (Supplementary Table 2). Under the rather high reference evapotranspiration (calculated as 5.1 mm/day and 4.8 mm/day during dry and wet seasons, respectively), $g_v$, $E$, $P_n$, and $C_i$ decreased and leaf temperature and $\delta^{13}C$ increased (Table 8), all indicating a reduction in plant water status and physiological function. The unique feature of Colombian drill-seeded rice is without puddling; daily reduction in water depth was ca. 17 mm/day at planting time (data not shown), and...
Table 7. Fraction of intercepted radiation (FI), cumulative amount of radiation intercepted (RI), and radiation use efficiency (RUE) averaged over three irrigation strategies and two years among five nitrogen levels.

| N level | FI (%) | Cumulative RI (MJ m⁻²) | RUE (g MJ⁻¹) |
|---------|--------|-------------------------|--------------|
| N_{20} | 90.6 b | 1625 c                  | 1.21         |
| N_{10} | 90.7 b | 1603 bc                  | 1.29         |
| N_{40} | 86.5 b | 1552 b                   | 1.27         |
| N_{180} | 86.6 b | 1600 bc                  | 1.25         |
| N_{30} | 73.3 a | 1211 a                   | 1.23         |
| LSD 5% level | 3.1  | 45                      | 0.08         |

Water x Year

| Year | W1 2015 | 81.2 a | 1691 b | 1.19 b |
|------|---------|--------|--------|--------|
|      | W2 2015 | 82.3 a | 1659 b | 1.12 b |
|      | W3 2015 | 846.6 a| 1801 c | 0.93 a |
|      | W1 2016 | 90.5 bc| 1355 a | 1.35 c |
|      | W2 2016 | 87.9 b | 1315 a | 1.47 cd|
|      | W3 2016 | 89.1 bc| 1290 a | 1.44 cd|
| LSD 5% level | 3.4  | 50       | 0.09    |

Combined ANOVA  

| N level (N) | Water (W) | Year (Y) | N × W | N × Y | W × Y | N × W × Y |
|-------------|-----------|----------|-------|-------|-------|-----------|
| ***         | ***       | ***      | NS    | NS    | NS    | NS        |

*Means followed by different letters are not significantly different at 5% level (Tukey’s test).

**N_{180}** 50% of slow release N and OM Gaikshi was applied in 3 splits.

NS, not significant; *P ≤ 0.05, **P ≤ 0.01, ***P ≤ 0.001.

Table 8. Photosynthesis (Pₜ.), transpiration (E), stomatal conductance (gₛ), intercellular CO₂, leaf temperature reduction from air temperature around flowering (Tₐₑₕ − Tₑₕ), and δ¹³C in straw at maturity among N and irrigation strategies in 2015 and 2016.

| N level | Photosynthesis (µmol CO₂ m⁻² s⁻¹) | Transpiration (mmol H₂O m⁻² s⁻¹) | Conductance (mol H₂O m⁻² s⁻¹) | Intercellular CO₂ (µmol CO₂ mol⁻¹) | Tₐₑₕ − Tₑₕ | δ¹³C (‰) |
|---------|-----------------------------------|----------------------------------|-------------------------------|-----------------------------------|------------|---------|
| N_{20}  | 21.9 ab                           | 9.51 a                           | 0.45 b                        | 301 a                             | 0.02 a     | −29.60 a|
| N_{10}  | 23.0 b                            | 10.33 a                          | 0.44 b                        | 307 a                             | 0.15 a     | −30.22 a|
| N_{40}  | 21.0 b                            | 9.95 a                           | 0.41 b                        | 301 a                             | 0.04 a     | −29.75 a|
| N_{180} | 21.1 ab                           | 9.85 a                           | 0.47 b                        | 307 b                             | 0.08 a     | −29.61 a|
| N₃₀      | 20.1 a                            | 9.74 a                           | 0.30 a                        | 306 a                             | −0.13 a    | −29.76 a|
| LSD 5% level | 2.0  | 0.87     | 0.07  | 8.5    | 0.26    | 0.20    |

Year 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015

| N level | Photosynthesis (µmol CO₂ m⁻² s⁻¹) | Transpiration (mmol H₂O m⁻² s⁻¹) | Conductance (mol H₂O m⁻² s⁻¹) | Intercellular CO₂ (µmol CO₂ mol⁻¹) | Tₐₑₕ − Tₑₕ | δ¹³C (‰) |
|---------|-----------------------------------|----------------------------------|-------------------------------|-----------------------------------|------------|---------|
| N_{20}  | 21.9 b                            | 9.51 a                           | 0.45 b                        | 301 a                             | 0.02 a     | −29.60 a|
| N_{10}  | 23.0 b                            | 10.33 a                          | 0.44 b                        | 307 a                             | 0.15 a     | −30.22 a|
| N_{40}  | 21.0 b                            | 9.95 a                           | 0.41 b                        | 301 a                             | 0.04 a     | −29.75 a|
| N_{180} | 21.1 ab                           | 9.85 a                           | 0.47 b                        | 307 b                             | 0.08 a     | −29.61 a|
| N₃₀      | 20.1 a                            | 9.74 a                           | 0.30 a                        | 306 a                             | −0.13 a    | −29.76 a|
| LSD 5% level | 2.0  | 0.87     | 0.07  | 8.5    | 0.26    | 0.20    |

Year 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015 2016 2015

| N level | Photosynthesis (µmol CO₂ m⁻² s⁻¹) | Transpiration (mmol H₂O m⁻² s⁻¹) | Conductance (mol H₂O m⁻² s⁻¹) | Intercellular CO₂ (µmol CO₂ mol⁻¹) | Tₐₑₕ − Tₑₕ | δ¹³C (‰) |
|---------|-----------------------------------|----------------------------------|-------------------------------|-----------------------------------|------------|---------|
| N_{20}  | 21.9 b                            | 9.51 a                           | 0.45 b                        | 301 a                             | 0.02 a     | −29.60 a|
| N_{10}  | 23.0 b                            | 10.33 a                          | 0.44 b                        | 307 a                             | 0.15 a     | −30.22 a|
| N_{40}  | 21.0 b                            | 9.95 a                           | 0.41 b                        | 301 a                             | 0.04 a     | −29.75 a|
| N_{180} | 21.1 ab                           | 9.85 a                           | 0.47 b                        | 307 b                             | 0.08 a     | −29.61 a|
| N₃₀      | 20.1 a                            | 9.74 a                           | 0.30 a                        | 306 a                             | −0.13 a    | −29.76 a|
| LSD 5% level | 2.0  | 0.87     | 0.07  | 8.5    | 0.26    | 0.20    |

*Means followed by the same letter are not significantly different at 5% level (Tukey’s test).

**N_{180}** 50% of slow release N and OM Gaikshi was applied in 3 splits.

NS, not significant; *P ≤ 0.05, **P ≤ 0.01, ***P ≤ 0.001.

Tₐₑₕ and Tₑₕ are air temperature outside the photosynthesis chamber and leaf temperature measured inside the chamber.

During the wet season (2016), the total water inputs (irrigation + rainfall) from 20 DAE to 90% flowering and to maturity required to attain the highest yield were 866
Table 9. Grain, straw, and total N concentration (%), total N uptake (g m⁻²), NUE of aboveground biomass (AGBM) (g g⁻¹) averaged over three irrigation strategies and two years among five nitrogen levels.

| N level  | Grain N%  | Straw N%  | Total N%  | Total N uptake (g m⁻²) | NUE AGBM (g g⁻¹) |
|----------|-----------|-----------|-----------|------------------------|------------------|
| N220     | 1.205 c   | 0.698 c   | 0.88 c    | 16.51 c               | 122 a            |
| N180     | 1.132 cd  | 0.624 bc  | 0.82 bc   | 16.02 c               | 127 ab           |
| N140     | 1.035 b   | 0.551 b   | 0.74 b    | 13.62 b               | 140 b            |
| N180ab   | 1.111 bc  | 0.732 c   | 0.87 c    | 16.69 c               | 125 ab           |
| N6       | 0.861 a   | 0.578 a   | 0.58 a    | 8.04 a                | 178 c            |
| LSD (5% level) | 0.066 | 0.092 | 0.07 | 1.64 | 12 |
| N level × Year | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| N220     | 0.998 b   | 1.411 cd  | 0.546 b   | 0.850 bc | 0.70 b | 1.06 c | 12.88 b | 20.13 cd | 149 a | 95 a |
| N180     | 0.981 b   | 1.283 c   | 0.503 b   | 0.746 b   | 0.68 b | 0.96 c | 13.17 b | 18.88 c  | 149 a | 105 a|
| N140     | 0.927 b   | 1.143 b   | 0.452 ab  | 0.651 b   | 0.63 b | 0.85 b | 11.39 b | 15.85 b  | 162 a | 118 b |
| N180ab   | 0.956 b   | 1.266 c   | 0.454 ab  | 1.010 c   | 1.04 b | 1.10 bc| 11.84 b | 21.54 d  | 157 a | 92 a  |
| N6       | 0.824 a   | 0.899 a   | 0.336 a   | 0.419 a   | 0.53 a | 0.63 a | 8.21 a  | 7.87 a   | 194 b | 162 b |
| Average  | 0.937 1.200 | 0.458 | 0.735 | 0.63 | 0.92 | 11.50 | 16.49 | 162 | 114 |
| LSD (5% level) | 0.093 | 0.131 | 0.10 | 0.231 | 17 |
| Water × Year | W1 2015 | 0.936 a  | 0.357 a | 0.58 a | 11.44 a | 178 cd |
|           | W2 2015 | 0.896 a  | 0.429 a  | 0.61 a  | 11.09 a | 165 c  |
|           | W3 2015 | 0.98 ab  | 0.588 b  | 0.72 b  | 11.96 a | 144 b  |
|           | W1 2016 | 1.184 b  | 0.775 c  | 0.95 c  | 16.93 b | 110 a  |
|           | W2 2016 | 1.182 b  | 0.74 c   | 0.93 c  | 17.56 b | 113 a  |
|           | W3 2016 | 1.235 b  | 0.691 c  | 0.89 c  | 16.08 b | 119 a  |
| LSD (5% level) | 0.071 | 0.101 | 0.07 | 1.79 | 13 |
| N level (N) | ***  | *** | *** | *** | *** | *
| Water (W) | * | NS | NS | NS | NS |
| Year (Y) | *** | *** | *** | *** | *** |
| N × W | NS | NS | NS | NS | NS |
| N × Y | *** | *** | *** | *** | *** |
| W × Y | NS | *** | *** | NS | NS |
| N × W × Y | NS | NS | NS | NS | NS |

*Means followed by the same letter are not significantly different at 5% level (Tukey’s test).

**N180ab 50% of slow release N and OM Gaikashi was applied in 3 splits.

***NS, not significant; *P < 0.05, **P < 0.01, ***P < 0.001.

Table 10. Agronomic N efficiency (AEₙ) (g g⁻¹) and N recovery efficiency (REₙ) averaged over three irrigation strategies and two years among five nitrogen levels.

| N level  | AEₙ (g g⁻¹) | REₙ |
|----------|-------------|-----|
| N220     | 4.8 a       | 46.8|
| N180     | 11.3 ab     | 56.6|
| N140     | 14.0 b      | 55.2|
| N180ab   | 8.9 ab      | 61.2|
| LSD (5% level) | 6.0 | 13.1|
| Year     | 2015        | 4.4 | 29.5 |
|          | 2016        | 15.0 | 80.5 |
| LSD (5% level) | 4.2 | 9.3 |
| Water × year | W1 2015 | 15.2 | 40.1 |
|           | W2 2015 | 13.4 | 28.4 |
|           | W3 2015 | -15.3 | 20.1 |
|           | W1 2016 | 17.4 | 79.8 |
|           | W2 2016 | 14.1 | 82.9 |
|           | W3 2016 | 13.6 | 78.6 |
| LSD (5% level) | 7.3 | 16.1 |
| Combined ANOVA | | |
| N level (N) | ab | NS |
| Water (W) | *** | NS |
| Year (Y) | *** | NS |
| N × W | NS | NS |
| N × Y | NS | NS |
| W × Y | *** | NS |
| N × W × Y | NS | NS |

*Means followed by different letters indicate significant differences at 5% level (Tukey’s test).

**N180ab 50% of slow release N and OM Gaikashi was applied in 3 splits.

***NS, not significant; *P < 0.05, **P < 0.01, ***P < 0.001.

and 993 mm, respectively, with irrigation of 582 and 690 mm, respectively. The lower requirement as compared with dry season W1 (cf. 1183 and 1474 mm of total water input by 90% flowering and by maturity, respectively) was due in part to lower ET₀ (Supplementary Fig. 3) and to 2 weeks’ shorter growth duration in the wet season (Table 3) due to higher temperatures in the early growth stages, due in turn to El Niño. W2 saved around 26% of water in the wet season without reducing the grain yield, number of grains per m², 1000-grain weight, SPAD value, or photosynthesis (Table 5, Table 8). Irrigation water requirement is ca. 1400 mm per season (including land preparation) on leveled fields (pers. commun. Dr. C. R. M. Pinto, Universidad Nacional, Colombia), which would be saved depending on climate conditions. Lower irrigation water use in wet seasons than in dry seasons has been recorded by Materu et al. (2018, 787 and 1287 mm) and Bouman et al. (2005, 494 and 1027 mm). Bouman et al. (2005) indicated that in the tropics, wetter soil in the wet season helped to reduce the yield penalty arising from water-saving management in aerobic conditions. Desmukh et al. (2017) and Kato et al. (2009) also supported higher yield production in wetter years. De Vries et al. (2010) recorded decreased grain yield in alternate wet and dry treatment in the dry
4.3. Seasonal effects on N recovery and N uptake

Wetter season provided better yield and N use than dry season. Total N uptake at maturity was 43% greater in the wet season than in the dry season and N recovery efficiency was much higher in the wet season (80.5%) than in the dry season (29.5%) (Table 10). The higher N uptake in the wet season caused a higher leaf N status than in the dry season (mean SPAD values across treatments, 38.7 vs 31.6, Table 5), higher RUE (1.42 vs 1.08 g MJ⁻¹) (Table 7), and higher grain N % (1.20% vs 0.94%) (Table 9). Colombian conventional N fertilization is very much early season emphasized high N fertilization. Dry season rice had 2 weeks longer vegetative stage under scarce rainfall, while wet season rice maintained wetter soil and more ponded water due to rainfall during shorter vegetative stage. More rapid biomass production was enhanced in wet season due to consistently supplied N fertilizer toward reproductive stage under moist and hot climate environment during El nino incidence. Our results agree with those of Liu et al. (2019), who recorded higher N uptake (11.58 g m⁻² vs 9.16 g m⁻²) and N recovery (57.5% vs 41.0%) in the wet season (with N fertilizer application of 120 kgN ha⁻¹ vs 150 kg N ha⁻¹) than in the dry season in the Philippines. De Reis et al. (2018) showed slightly higher recovery of δ¹⁵N (51%) under better rainfall and more moist conditions than under drier conditions (43%). N.M. Dong et al. (2012) and Zhou et al. (2012) also showed higher N isotope (¹⁵N) recovery under continuous flooding than under alternate wet and dry irrigation and in drained paddies. Higher ET water loss and less rainfall during crop growth in the dry season may have not only reduced fertilizer N recovery but also increased ammonia volatilization, as Okada et al. (2019) showed that around 5% of applied N was lost by ammonia volatilization in dry direct-seeded rice in Colombia. Urea hydrolysis and ammonia volatilization increase with temperature (Hayashi et al., 2008), and ammonia volatilization is greater at higher temperature, higher wind velocity, and longer sunshine hours than under rainy or cloudy conditions (Freney et al., 1981).

Our results show that in the dry season in central Colombia, when solar radiation is higher and ET₀ is higher, longer interval to next water supply under water-saving management could reduce N recovery and cause yield penalty. In the wet season, on the other hand, much higher N recovery and uptake, together with high RUE, can contribute to higher biomass, grain yield and grain N%. On-farm field trials or crop simulation models would provide a more comprehensive guide to yield and grain N% determination in different seasons with different levels of solar radiation and ET demand.

5. Conclusion

Reducing N to 140 kg ha⁻¹ reduced N uptake but not yield owing to the improvement of NUE and AEₜ in all irrigation strategies in both wet and dry seasons. Lengthening the irrigation interval reduced yield by 74 g m⁻² for every 100 mm of saved water during the dry season, but did not reduce yield during the wet season; best yield in wet season was attained with total water supply of 993 mm as compared with 1474 mm in dry season. The apparent recovery of N fertilizer was much higher in wet season than in dry season (79% vs 30%), leading to higher N uptake, higher RUE, and higher grain N concentration in the wet season. This study showed N fertilizer can be saved at least down to 140 kgN ha⁻¹ while success of mild water-saving strategy depends more on seasonal climate conditions in drill-seeded rice production in Colombia.

Acknowledgments

We thank Mr Nelson Amezquita, head of FEDEARROZ Laguna station, for his assistance for the field experiments. This study was supported by the JICA-JST-funded SATREP project “Development and adoption of Latin America Low-input Rice Production System through Genetic Improvement and Advanced Field-Management Technologies”. We appreciate critical comments by 3 anonymous reviewers and the associate editor.

Disclosure statement

No potential conflict of interest was reported by the authors.

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