Impact of Aerobic Rice Cultivation on Growth, Yield, and Water Productivity of Rice–Maize Rotation in Semiarid Tropics

M. D. M. Kadiyala, R. S. Mylavarapu,* Y. C. Li, G. B. Reddy, and M. D. Reddy

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ABSTRACT

Limited water availability is a major constraint for cultivation of rice (*Oryza sativa* L.) in the traditional flooded systems, particularly in the semiarid regions of the world. Aerobic rice cultivation provides feasible alternative to traditional rice production in these regions, allowing significant water savings. Field experiments were conducted at the ANGR University Agricultural Research Station, India during 2009–2010 and 2010–2011 to compare crop growth, yield, and water savings under aerobic rice–maize (R–M) and flooded R–M rotation systems. The effect of aerobic rice on the succeeding maize crop was also studied. The total amount of water applied (including rainfall) in the aerobic plots was 967 and 645 mm compared to 1546 and 1181 mm in flooded rice system, during 2009 and 2010, respectively. This resulted in 37 to 45% water savings with the aerobic method. The soil moisture in aerobic treatment was maintained in the –30 to –40 kPa range throughout the crop growth. The aerobic rice system produced significantly lower grain yields in 2009 and 2010, where differences between flooded and aerobic rice were 39 and 15.4%, respectively. The yield differences were attributed to the differences in spikelet number per panicle and grain weight. Significant increase in yields was recorded in both systems with increased N rates up to 120 kg ha^{-1}. Significantly higher yields were obtained in no-till maize grown subsequent to the aerobic rice than flooded rice, possibly due to residual soil N and improved soil physical conditions.

Rice is an important staple food crop around the world. In Asia, the flooded rice production is a key element for economic and social stability as more than two billion people depend on rice for their dietary requirements. Rice production involves submerged conditions, with approximately 5- to 10-cm deep standing water throughout the crop growth period. Worldwide, rice production uses about 30% and within Asia more than 45% of total fresh water (Barker et al., 1999). Increasing scarcity due to increasing demand for water from various sectors threatens the sustainability of irrigated rice production and calls for development of novel technologies that can reduce water requirement without experiencing yield losses. Since the 1990s, traditional flooded rice cultivation has increasingly experienced shortages in irrigation water and labor force and higher labor costs. These factors have adversely impacted rice-farming operations. Puddling is a prerequisite for flooded rice, however, it deteriorates soil structure; therefore, land preparation for the succeeding crops becomes difficult and requires more energy to attain proper soil tilth. These conditions emphasize the need for a shift to water-saving rice cultivation methods, which can reduce labor requirement, save significant irrigation water, shorten the duration of crop and produce comparable grain yields.

Rice crop is very sensitive to water stress and reduction in water inputs can result in decline of yield (Tuong et al., 2004). Researchers developed several technologies to reduce water inputs in rice such as alternate wetting and drying (Tabbal et al., 2002), raised bed rice cultivation (Ockerby and Fukai, 2001), saturated soil culture (Borrell et al., 1997), system of rice intensi fi cation (Stoop et al., 2002), ground cover systems (Lin et al., 2002), and raised bed systems (Choudhury et al.,2007). Some of these technologies also require puddling and ponded water during crop growth and hence significant water saving was not always reported. Aerobic rice offers one such water-saving rice technology (Bouman et al., 2005), where rice crop is cultivated under non-puddled and non-saturated soil conditions. This concept is mainly targeted for irrigated lowlands, where water is not sufficient for rice cultivation and suitable uplands, where facilities for supplemental irrigation are available (Belder et al., 2005). Earlier experimental studies reported aerobic rice yields up to 6.5 t ha^{-1} with 40 to 60% water savings (Castaneda et al., 2002; Belder et al., 2005; Bouman et al., 2005, 2006; Zhang et al.., 2009). But such studies were limited to few parts of the world, without giving much consideration to the prospects of aerobic rice cultivation in the Indian subcontinent, where more than 21.6% of rice worldwide is produced. Exact quantification of water balance and suitability of high yielding flooded rice varieties under aerobic system needs to be evaluated. Rice–maize double cropping is gaining popularity in many Asian countries due to rapidly increasing livestock and

M.D.M. Kadiyala and R.S. Mylavarapu, Soil and Water Science Dep., Univ. of Florida, Gainesville, FL 32611; Y.C. Li, Soil and Water Science Dep., Tropical Research and Education Center, 18905 S.W. 280 St., Homestead, FL 33031; G.B. Reddy, Dep. of Natural Resources & Environmental Design, North Carolina A&T State Univ., Greensboro, NC 27411; M.D. Reddy, Water Technology Center, ANGR Agril Univ., Hyderabad, India. Received 1 May 2012. *Corresponding author (raom@ufl.edu).

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Abbreviations: BCR, benefit/cost ratio; DAP, days after planting; DAT, days after transplanting; LAI, leaf area index; R–M, rice–maize; VWC, volumetric water content.

human populations. The R–M systems currently occupy around 3.5 million hectare in Asia (Timsina et al., 2010). The recent water shortage conditions for continuous rice cultivation have prompted studies to look for alternate rice-based cropping systems. The development of short duration rice varieties coupled with high-yielding maize hybrids provided an opportunity for increasing the area under R–M cropping in India, Bangladesh, Pakistan, and Nepal as an important alternative to bridge productivity gap in rice–wheat (*Triticum aestivum* L.) cropping system. Crops grown after flooded rice typically suffer from poor germination and growth due to altered soil physical and nutrient relations resulting from anaerobic and aerobic transitions. Growing rice aerobically without puddling may have positive implications on succeeding maize (Chandrapala et al., 2010). Studies conducted with a "systems" perspective as resource use are lacking. It is therefore, essential to determine the crop yield and water saving using a comprehensive approach and considering the water productivity. Moreover, little information is available on impacts of aerobic rice cultivation on succeeding maize crop growth and overall system water balance and yields. Hence, a field study was conducted with the objective of determining the integrated effect of aerobic rice-based system (i) on growth and yield, (ii) on water use and water productivity of rice and of succeeding maize crop.

MATERIALS AND METHODS

Site Description

A field experiment was conducted over two consecutive years (2009–2010 and 2010–2011) on a R–M cropping sequence at the ANGR University Research Station, Hyderabad (17°19' N, 78°28' E and 534 m above mean sea level), India. The region has a semiarid climate and receives an annual rainfall of 850 mm, 80% of which occurs during southwest monsoon period (June–October). The soil at the experimental site has a sandy loam texture with a pH of 8.0 in the surface 0- to 15-cm depth. Soil test results showed that Olsen's P was high (24.7 kg ha^{-1}) but had low (250 kg ha^{-1}) ammonium acetate extractable K. The soil was found to be low (202 kg ha^{-1}) in $KMnO_4$ extractable N. Weather parameters such as the maximum and minimum air temperature, bright sunshine hours, and rainfall were measured during the crop growth at the meteorological observatory located on the research station.

Experimental Design and Treatments

The experiment was laid out with three replications in a split plot design with methods of rice establishment, namely aerobic and conventional flooded methods as main treatments and four N rates as subplot treatments (0, 60 120 and 180 kg N ha^{-1}). The aerobic plots were dry plowed, harrowed, and left unpuddled during land preparation. A popular lowland variety, Cotton Dora Sannalu (MTU 1010) was used in this experiment because of its good performance under aerobic conditions. Seeds were hand dibbled in rows at 22.5-cm spacing with a seed rate of 300 seeds m^{-2}. Planting was followed by pre-emergence herbicide application of pendimethalin at 1000 g a.i. ha^{-1}. Manual hand weeding was done at 30 and 45 days after planting (DAP). Aerobic plots were flood irrigated with 5 cm water when the soil moisture tension at the surface 15-cm depth reached –30 kPa during the crop period. There was no ponded water except for parts of the days when irrigation occurred or when a heavy rain was received. Flooded plots were puddled using tractor drawn cage wheel and kept continuously flooded, from transplanting until 1 wk before harvest. Transplanting, using 30-d-old seedlings raised separately in the nursery, was done at a spacing of 20 by 15 cm. Water depth was initially maintained at 2 cm and gradually increased to 5 cm at full crop development. Both aerobic and flooded rice were planted on the same day. The rice crop in both systems received 26 kg P and 33 kg K ha^{-1}. Both P and K fertilizers were applied as basal dosages while N was applied as per the treatments in three splits– at the time of planting/transplanting, active tillering, and panicle initiation stages. The aerobic and flooded plots were separated by a set of drains that were 1 m wide and 40-cm deep between the main plots and 75 cm wide and 30-cm deep between the subplots. Plastic sheets were installed to a depth of 40 cm in the channels between the main plots to prevent any seepage. Irrigation water was distributed to each plot using HDPE pipes installed with water meters to measure the amounts of water applied. After rice harvest, DeKalb 800 M variety of maize was sown at a spacing of 60 by 20 cm under no-till conditions. The maize crop received 120 kg N, 26 kg P, and 33 kg K ha^{-1}. Both P and K fertilizers were applied as basal while N was applied in three splits- at the time of planting, knee-height stage, and at silking. The crop was irrigated with 50 mm water, which was scheduled at irrigation water/cumulative pan evaporation (IW/CPE) ratio of 1.0.

Measurements

Growth Analysis

Plant samples were collected from 0.50 m^2 area from flooded treatments at 30 d, 60 days after transplanting (DAT), and at harvest. Similarly, in aerobic plots, plant samples were collected from 0.50 m^2 area but at 30, 60, 90 DAP and at harvest for growth analysis. Leaf area index (LAI) was measured with LI-3100 area meter (LICOR, Lincoln, NE) for all samples. Dry matter was estimated after oven-drying at 60°C to constant weight. Plants from 1.0 m^2 area were sampled at the time of harvest to determine the aboveground total biomass and the yield components. Number of panicles for each plant within 1.0 m^2 was counted. Plants were separated into straw and panicles. Straw dry weight was determined after oven drying at 60°C to a constant weight. Panicles were threshed by hand and filled spikelets were separated from the unfilled by submerging them in 1.06 specific gravity salt solution. Number of filled spikelets per panicle and 1000 grain weight were calculated. Grain yield was determined from a net plot area of 49 m^2 leaving border rows and was expressed at 14% moisture content. In maize, crop growth parameters such as LAI, aboveground plant biomass, yield components, and final yield were also similarly recorded. Tissue total N concentrations were determined by using micro-Kjeldahl digestion (Bremner, 1965) method and were expressed in kilograms of N per hectare.

Water Balance

The water balance of rice was calculated as

$$\mathrm{IR} + \mathrm{ER} = \mathrm{DP} + \mathrm{ET} + \Delta W \quad [1]$$

where IR is the irrigation, ER is the effective rainfall computed from rainfall data (R), ET is the evapotranspiration, DP is the percolation below the root zone and ΔW is the change in soil water storage in the root zone. The IR and the R were directly measured from the events. Six access tubes were installed in a grid pattern in aerobic plots. The volumetric water content (VWC) was measured using Delta-T Devices theta probe with a PR2 sensor, a multi-sensor capacitance probe. The probe was initially calibrated by gravimetric method. The VWC was measured at each depth increment (10, 20, 30, and 60) in each access tube at weekly intervals and between two irrigations. The directly measured VWC was converted to millimeters of water by multiplying with the corresponding soil depth.

Irrigation

The amount of irrigation (I) water applied was directly measured using water meter connected to the distribution pipes and was later converted to depth of water (mm).

Change in Stored Soil Water Content

The change in stored soil water (ΔW) was determined as the difference in volumetric soil water content in the root zone before each subsequent irrigation from the capacitance probe readings. Estimates of stored soil water were the mean of measurements taken from six access tubes, which were converted to depth of soil water (mm).

Crop Evapotranspiration

Evapotranspiration (ET) in aerobic rice was calculated by determining the reference crop evapotranspiration (ETo) using Penman–Monteith method and multiplying with the appropriate crop coefficient based on the crop growth stages as shown in the Table 1.

Finally, deep percolation was calculated for each irrigation (by the difference between inflows and outflows) and was cumulated to obtain an estimate for the entire season (Willis et al., 1997). To measure deep percolation in flooded rice, four pairs of PVC pipes of 25 cm diam., 0.10-cm wall thickness and 60 cm height were used as lysimeters (Bethune et al., 2001). Each pair included an open top, sealed bottom lysimeter, and the other with both sides open. Lysimeters were installed before transplanting by digging the soil to a depth of 45 cm. The soil was carefully replaced in the same order of layers, to minimize the soil disturbance within the lysimeters. Water was added to the lysimeters to establish equivalent water levels inside and outside the lysimeters. Water was added to the lysimeters thrice a week to maintain the water levels. Deep percolation was calculated as the difference in water additions to the bottom sealed and unsealed lysimeters. The ET was calculated as the remainder from the Eq. [1] and was found to be comparable to the water added to the sealed lysimeters. In maize IR and R were directly measured. The ET was calculated by determining the ETo and adjusting it as per the crop coefficients. The ΔW was calculated from difference in measured soil water contents between maize planting and harvest using theta probe and DP was calculate as the remainder using Eq. [1].

Water Productivity

Water productivity (WP) (g grain kg^{-1} of water) was calculated for rice and maize by following Eq. [2].

$$\mathrm{WP} = \frac{Y}{\mathrm{WA}_{(\mathrm{IR}+R)}} \qquad [2]$$

where Y = yield (kg ha^{-1}) and WA = total water input (IR + R).

Statistical Analysis

Yield and yield attributes of rice and maize, N uptake were analyzed with IRRISTAT for windows (Bartolome et al., 1999), which consisted of ANOVA, with a rice establishment method and N rates as main and subfactors, respectively. Whenever the treatments were found significant, pair-wise testing with t test was done between the main and subplot treatments at 95% confidence interval.

RESULTS AND DISCUSSION

The mean monthly maximum temperature during cropping period (June to April) ranged from 28.2 to 40.3°C and 27.8 to 36.7°C in 2009–2010 and 2010–2011, respectively (Fig. 1). The weekly mean minimum temperature varied from 14.1 to 24.8°C

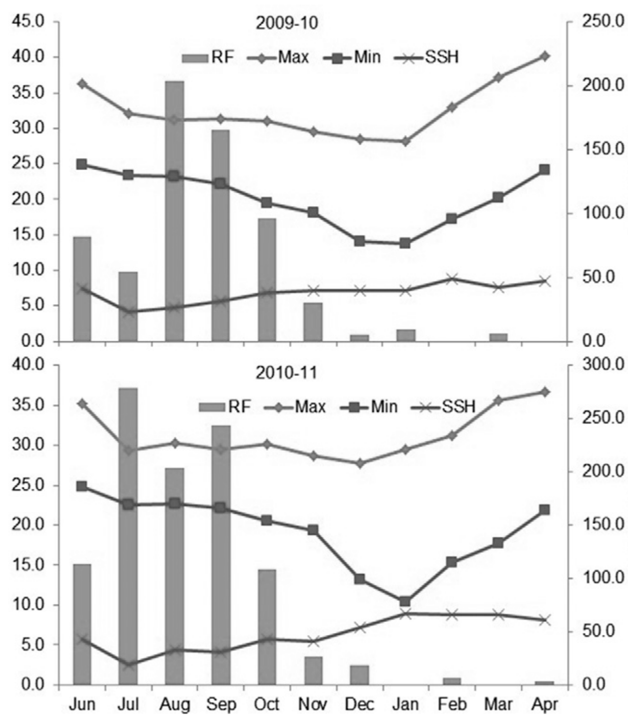

Fig. 1. Monthly rainfall (RF, mm), mean maximum temperature (°C), mean minimum temperature (°C), and mean number of bright sunshine hours (SSH) in Hyderabad during 2009–2010 and 2010–2011.

Table 1. Length of growing stages (days) and values of crop coefficients for rice used in the study

Crop	Planting date	Crop factor† Kc1	Kc2	Kc3	Kc4	Crop stages (days) Initial stage	Development stage	Mid-season	Late season	Total period
Aerobic rice	5 July	0.8–0.9	1.0–1.1	0.9–1.0	0.8–0.9	30	35	35	15	115
Flooded rice	5 Aug.	1.1–1.2	1.1–1.2	1.1–1.15	0.9–1.0	20	30	25	20	95
Maize	15 Nov.	0.3	1.05	1.1	0.65	25	35	40	20	120

† Kc1, crop coefficient at initial stage; Kc2, crop coefficient at development stage; Kc3, crop coefficient at mid-season; Kc4, crop coefficient at late season.

Table 2. Components of the seasonal water balance (mm) of rice and maize during 2009–2010 and 2010–2011under flooded and aerobic conditions.†

Treatment	Rice					Maize				
	I‡	ER	ΔW	ET	DP	I	ER	ΔW	ET	DP
	mm									
2009–2010										
Aerobic	625	342	86	438	443	390	0	46	329	15
Flooded	757	332	0	409	680	380	0	28	342	10
2010–2011										
Aerobic	0	645	17	369	259	340	19	25	324	10
Flooded	550	441	0	355	636	300	19	−16	335	0

† Irrigations shown are the total volumes from planting to harvest in aerobic rice and from transplanting to harvest in flooded rice not including the water applied for puddling (457 mm in 2009 and 190 mm in 2010).

‡ I, irrigation; ER effective rainfall; ET, evapotranspiration; DP, deep percolation; ΔW, change in stored soil water content.

and 10.4 to 24.7°C during the same period. Rainfall of 652 mm was received in 36 rainy days and 1002 mm in 62 rainy days during 2009–2010 and 2010–2011, respectively. The rainfall received was 24% less in 2009 crop season and was 17% excess in 2010 compared to decennial averages from the weather records at the research station. The monthly mean bright sunshine hours per day ranged from 4.2 to 8.8 h during 2009–2010 and 2.5 to 8.9 h during 2010–2011.

Water Balance

Water balance estimates and its components are given in Table 2. Total irrigation input in flooded plots including land preparation was 1214 mm in 2009 and 740 mm in 2010, whereas the total irrigation input in aerobic rice was 625 and 0 mm in 2009 and 2010, respectively, resulting in water savings of 589 and 740 mm in the first and the second years, compared to flooded method. Irrigations were not applied to aerobic rice during 2010 due to adequate and well distributed rainfall (Fig. 1). The average daily deep percolation rates were 2.2 to 3.7 mm in aerobic plots compared to 6.8 to 7.2 mm in flooded plots. The overall deep percolation losses in aerobic plots were 237 and 377 mm lesser than flooded plots during 2009 and 2010, respectively. Daily average ET losses under aerobic conditions ranged from 3.2 to 3.7 mm compared to 3.9 to 4.3 mm in flooded plots during both the years of study. Because of lower deep percolation and ET rates, water application efficiency (total water input/ET × 100) was higher in the aerobic plots (45 and 57%), compared to flooded method (26.4 and 30%) in 2009 and 2010, respectively. Our results suggest that the reduction in water use under aerobic rice was mainly due to water savings during land preparation as it consumed about 190 to 457 mm of water in flooded fields. Under aerobic system, reduced daily drainage and evaporation losses compared to flooded plots were due to lower evaporation rates from dry aerobic soil, lesser leaf area values and also mainly due to maintenance of aerobic plots at field capacity during entire crop growth period. Reduced evaporation rates from dry aerobic soil in rice were also reported by Choudhury et al. (2007) and Sharma et al. (2002). Aerobic rice cultivation resulted in 100% water savings in land preparation, 22.5% savings in field water application and 47.8% savings in percolation losses.

In year 2009, soil moisture content at 10 cm was maintained at an average 0.25 $cm^3\ cm^{-3}$ (0.20–0.31 $cm^3\ cm^{-3}$ range) across the entire field (Fig. 2). This indicated that the water potential in the surface 10 cm was generally at field capacity. However, soil at 20- and 30-cm depth was much wetter and the matric potential ranged between –33 and –10 kPa (equivalent to 0.32–0.35 $cm^3\ cm^{-3}$).

In year 2010, due to high and well distributed rainfall, the surface soil up to 10-cm depth generally remained between –33 and –10 kPa throughout the growing period of aerobic rice. O'Toole and Garrity (1984) reported possibility of spikelet sterility in rice when soil moisture potential during flowering was higher than –10 kPa.

The subsequent maize grown in the flooded rice plots received relatively lower amounts of irrigation water, typically by 10 and 40 mm during 2010 and 2011, respectively, compared to aerobic R–M plots. Lower ET values were found in aerobic plots planted to maize. However, the differences in irrigation water and ET were small between the rice establishment methods and may be attributed to the delay in planting of flooded R–M crop. Choudhury et al. (2007) also observed smaller differences in succeeding wheat irrigation requirements due to type of land preparation adopted in rice.

Water Productivity

Water productivity of rice was significantly influenced by both rice establishment methods and N rates but there was no interaction effect between the two factors on water productivity during both the years of the study (Table 3). Flooded rice

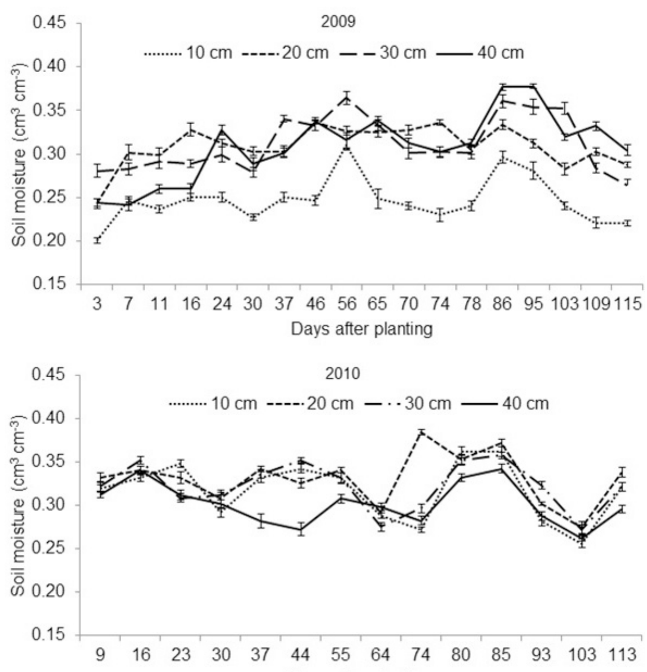

Fig. 2. Volumetric soil moisture content recorded in aerobic plots at 10-, 20-, 20-, and 40-cm soil depth during the 2009 and 2010 growing seasons. Bars indicate the standard error.

Table 3. Water supply (irrigation plus effective rainfall) in millimeters and water productivity (WP) (g grain kg^{-1} water) of rice and maize during 2009–2010 and 2010–2011 under flooded and aerobic conditions.

	Rice				Maize				Rice–maize system			
	Water supply‡		WP_{IR+R}§		Water supply		WP_{IR+R}		Water supply		WP_{IR+R}	
Treatment†	2009	2010	2009	2010	2009–2010	2010–2011	2009–2010	2010–2011	2009–2010	2010–2011	2009–2010	2010–2011
AR-0 N-M-120	967	645	0.19	0.43	390	359	1.47	1.76	1357	1004	0.56	0.90
AR-60 N-M-120			0.28	0.52			1.51	1.80			0.64	0.98
AR-120N-M-120			0.36	0.73			1.51	1.81			0.69	1.12
AR-180N-M-120			0.40	0.81			1.58	1.87			0.74	1.19
Mean			0.31	0.62			1.52	1.81			0.66	1.05
FR-0 N-M-120	1546	1180	0.20	0.24	380	319	1.43	1.87	1926	1499	0.44	0.59
FR-60N-M-120			0.28	0.34			1.44	1.89			0.51	0.67
FR-120N-M-120			0.38	0.48			1.50	1.98			0.60	0.80
FR-180N-M-120			0.40	0.54			1.52	2.01			0.62	0.85
Mean			0.32	0.40			1.47	1.94			0.54	0.73
ANOVA												
Method (M)			**	***			*	***			***	***
N rates (N)			***	***			ns¶	ns			***	***
M × N			ns	ns			ns	ns			ns	ns

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† AR, aerobic rice; FR, flooded rice.
‡ Water supply in flooded plots includes irrigations for puddling.
§ WP_{IR+R}, water productivity irrigation.
¶ ns = nonsignificant ($P > 0.05$).

treatment used 1546 and 1181 mm of water (including water applied for puddling) compared to aerobic rice (967 and 645 mm) during 2009 and 2010, respectively (Table 3). Despite the lower water use under aerobic rice, water productivity remained suppressed due to lower yields in 2009. However, in 2010 due to high rainfall and associated improved yields in aerobic rice, the water productivity was 55% higher than in flooded rice. Higher water productivity in aerobic rice system compared to flooded rice was also reported by Bouman et al. (2005), Kato et al. (2009), and Belder et al. (2005). In the succeeding maize crop, overall water productivity was three to four times higher than the rice water productivity across both methods. During the year 2009, we found that the water productivity of maize after aerobic rice was higher while in 2010 maize followed by flooded rice showed significantly higher water productivity. Lowest water use and highest water productivity (0.66 and 1.05) were found under aerobic R–M system compared to flooded R–M (0.54 and 0.73) system during both the years of the study. The water productivity of R–M system was 22 to 44% higher than that of flooded R–M system during 2009 and 2010, respectively.

Crop Growth and Development

During initial crop growth period (up to 60 DAP), dry matter production was found to be lower in flooded method at 30 DAT. However, at subsequent periods, the flooded method recorded significantly higher dry matter yields compared to aerobic method during both years (Fig. 3). Dry matter production at harvest (average of four N rates) was highest in flooded rice (1082 and 1065 g m^{-2}) compared to aerobic rice (693 and 957 g m^{-2}) during 2009 and 2010, respectively. Nitrogen rates significantly influenced dry matter accumulation of rice grown under both establishment methods. This may be attributed to the availability of N as per crop needs during its growth. The N application rate of 180 kg ha^{-1} produced maximum dry matter at physiological maturity and was significantly superior to lower N rates. Similar responses to increased rates of N in both aerobic and flooded rice were also reported by Belder et al. (2005).

The LAI values showed typical pattern overtime, with highest values during heading (90 DAP) followed by a decreasing trend until maturity in both the years and the establishment methods (Fig. 4). Between the two establishment methods, significantly higher LAI was observed in flooded method at all growth stages. The LAI was significantly higher at heading stage (90 DAP) under

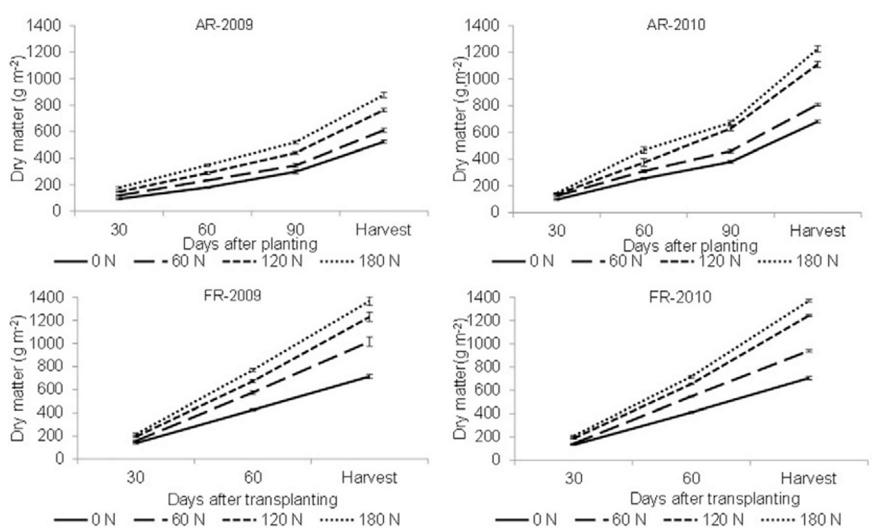

Fig. 3. Dry matter production of rice under aerobic (AR) and flooded (FR) conditions at different N fertilizer rates during 2009 and 2010. Bars indicate the standard error.

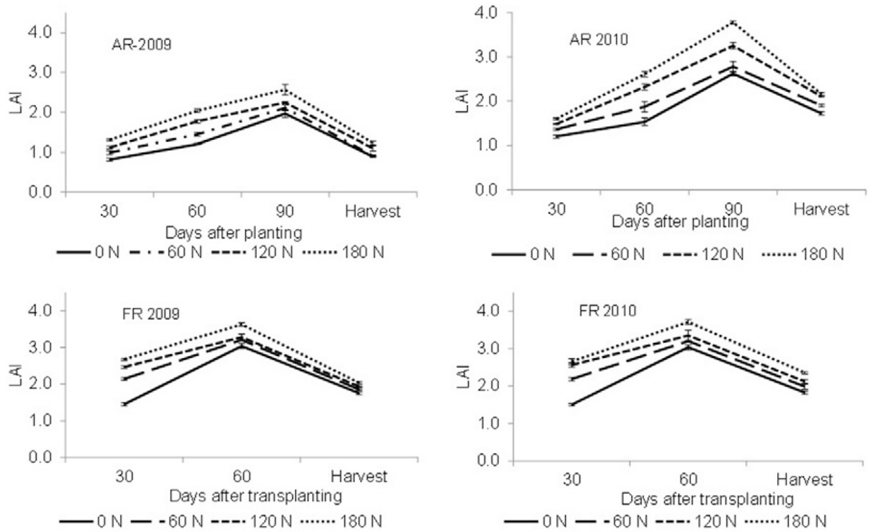

Fig. 4. Leaf area index (LAI) of rice under aerobic (AR) and flooded (FR) conditions at different N fertilizer rates during 2009 and 2010. Bars indicate the standard error.

flooded method (3.29 in 2009 and 3.32 in 2010) over aerobic method (2.22 in 2009 and 3.11 in 2010). Lower LAI values in aerobic plots were associated with reduced total biomass and grain yield at the end of the growing season. Temporal curves of LAI indicated that increased application of N from 0 to 180 kg N ha^{-1} had increased LAI of rice under both systems (Belder et al., 2005; Zhang et al.., 2009).

Rice Yield Attributes and Yield

Rice crop establishment methods and N rates showed significant influence on all the yield attributes during both years of study. There was no interaction effect of crop establishment methods and N fertilization rates on panicle number m^2, 1000 grain weight, and spikelet number during 2009. However during the year 2010, interaction effect between crop establishment methods and N rates was found to be significant (Table 4). Higher value of panicles m^{-2}, spikelet number per panicle, and 1000 grain weight were observed during the second year than in the first year under aerobic rice. Although aerobic method had significantly higher panicles m^{-2}; the other yield attributing characters such as spikelet number per panicle and 1000-grain weight were significantly higher in flooded method (Table 4). All yield-associated characters were found to be lower in aerobic conditions compared to flooded conditions. This effect was particularly pronounced during the year 2009. This indicated that aerobic rice may have suffered water and N stress around panicle initiation stage to maturity causing reduction in grain number and individual grain filling. Water deficits at the anthesis stage of rice induce a high percentage of spikelet sterility and reduce grain yields (De Datta, 1989). Water stress at flowering affects physiological processes such as anther dehiscence (Ekanayake et al., 1990), pollen germination (Saini and Westgate, 2000), panicle exsertion (O'Toole and Namuco, 1983), peduncle length (He et al., 2009), and finally are responsible for increased sterility. Although the number of tillers and panicles per square meter were more under aerobic rice system, panicle length and the lesser number of filled spikelets per panicle resulted in lower grain yields. Belder et al. (2005) also reported significant reduction in yield-attributing characters in the aerobic rice systems compared to flooded systems. Increase in number of tillers and panicles under aerobic rice was mainly due to higher final plant population per square meter as aerobic rice was sown at 300 seeds m^{-2} rather than increase in per hill tiller and panicle number.

Production of panicles m^{-2} under different N rates varied from 230 and 184 with 0 kg N in flooded system to 388 and 367 with aerobic rice treatment receiving 180 kg N ha^{-1} during 2009 and 2010, respectively. There was a general increase in panicle production with increased N application. The other yield-attributing characters such as spikelet number per panicle and 1000-grain weight showed similar trend to increased rates of N. In general, response to incremental rates of N was more pronounced in flooded conditions than aerobic rice treatments. The lower

Table 4. Yield components, yield, and N uptake of rice during 2009 and 2010 under flooded and aerobic conditions.

Treatment	No. of panicles m^{-2}		Spikelet no. $panicle^{-1}$		1000 grain weight		Yield		Nitrogen uptake	
	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
					g		t ha^{-1}		kg ha^{-1}	
Aerobic-0 N	291	210	53	68	17.2	18.1	1.85	2.76	34.0	48.9
Aerobic-60 N	314	287	72	75	18.2	19.0	2.74	3.34	50.0	60.7
Aerobic-120 N	343	328	82	103	18.7	19.5	3.45	4.72	64.0	89.3
Aerobic-180 N	388	367	103	125	19.2	20.4	3.85	5.19	72.0	98.6
Flooded-0 N	230	184	100	97	20.8	20.7	3.07	2.87	55.0	52.2
Flooded-60 N	255	238	122	116	21.6	21.7	4.36	4.00	80.5	74.6
Flooded-120 N	306	308	132	128	22.1	22.2	5.86	5.68	109.4	107.2
Flooded-180 N	341	336	149	142	22.4	22.5	6.21	6.37	120.6	123.5
ANOVA										
Method (M)	***	**	***	***	***	***	***	***	***	***
N rates (N)	***	***	***	***	***	***	***	***	***	***
M × N	ns†	ns	ns	*	ns	***	**	ns	***	ns

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† ns = nonsignificant ($P > 0.05$).

responses to N rates in aerobic rice may be attributed to increased losses of N from aerobic soil and lower N uptake by the moisture-stressed aerobic rice plants (Belder et al., 2005, Reddy et al., 2010).

Grain yields in aerobic rice plots were significantly lower than yields in flooded rice. Highest yields were obtained with flooded rice receiving 180 kg N ha^{-1} in both years but the yields were similar during 2009 at 120 kg N ha^{-1}. The increase in yields under a flooded method was 39.0% and 15.4% higher over an aerobic method during the first and second years, respectively. The yield difference between aerobic and flooded rice ranged from 37 to 41% during 2009 depending on the rate of N fertilizer application. In 2010, the differences between the yields in both plots were narrowed down to 17 to 19%. Such narrowing of yields between the two rice systems was possibly better demonstrated by the well-distributed rainfall in 2010, along with improved weed management with chemical herbicides and spraying of iron sulfate for alleviating iron deficiency in aerobic plots. This suggested that effects of improved cultural and nutrient management practices will be pronounced when combined with a well-distributed rainfall during the crop season and will result in enhanced yields of aerobic systems. However, the conversion of an anaerobic rice system (flooded rice) to an aerobic system to save water will generally result in the rice yield reduction (Belder et al., 2005; Xiaoguang et al., 2005; Peng et al., 2006; Choudhury et al., 2007). The yield difference between aerobic and flooded rice can be attributed to reduced leaf area and biomass which may have resulted in reduced yields under aerobic rice. The yield attributing characters such as number of spikelets per panicle (sink size) and 1000- grain weight has contributed more to the yield gap between the two systems (Peng et al., 2006).

Grain yields responded strongly to N fertilization for both years, in both aerobic and flooded rice treatments (Table 4). Response to applied N was more conspicuous in flooded rice compared to aerobic rice. Mean yield increase across both the years was 32, 77, and 96% in aerobic rice and 41, 94, and 112% in flooded rice at the 60, 120, and 180 kg N ha^{-1} application rates compared to no N application. The response of aerobic rice to N rates was observed up to 120 kg N ha^{-1}. Similarly flooded rice also responded to incremental doses of N up to 120 kg ha^{-1}, but the relative growth and yield levels were higher under flooded conditions. Both rice establishment methods and N fertilizer rates, and their interactions had a significant effect on rice yields (Table 4). During 2009, with flooded method and N rate of 180 kg ha^{-1}, significantly higher yields were recorded. However, during 2010, the interaction effects were not significant. Yield response to applied N was consistent with the observed higher LAI values, aboveground biomass, and increased N uptake. Lampayan et al. (2010) also noticed responses to fertilizer N up to 150 kg ha^{-1} in aerobic rice in a field study conducted on a clay soil in Philippines. Yield losses should be limited to a maximum of 15 to 20% when compared to the yields attained under traditional flooded method to make aerobic rice more adoptable by the farming community. Few studies conducted in Japan reported 7.9 to 9.4 t ha^{-1} of yields under aerobic systems (Kato et al., 2009) with high-yielding varieties. This demonstrates the potential for achieving similar or even higher yield levels than that achieved under traditional flooded methods through high-yielding aerobic rice varieties and optimum cultural management.

Nitrogen Uptake

Nitrogen uptake was significantly influenced by both N fertilizer rates and rice establishment methods. Among different N treatments, the highest N uptake in rice was recorded at the 180 kg N ha^{-1} rate for both systems. Total N uptake at physiological maturity under an aerobic system at the 180 kg N ha^{-1} rate was 72 kg ha^{-1} during 2009 and 99 kg ha^{-1} during 2010. This was 40% lower than the flooded rice (121 kg ha^{-1}) during 2009 and was 20% less during 2010 (123 kg ha^{-1}) indicating higher responses to applied N in flooded rice. Significantly higher N uptake differences were observed between flooded rice and aerobic rice at 60 DAP. The interaction between rice establishment methods and N rates was significant during 2009 only with flooded method at 180 kg N ha^{-1} rate resulting in significantly higher N uptake compared to an aerobic method (Table 4). The lower N uptake in aerobic rice may have been due to increased gaseous N losses under an aerobic system coupled with poor synchrony between crop needs and N availability (Belder et al., 2005). Further, the lower N content in grains under aerobic rice as a result of lower N uptake rates may further reduce the protein content and impact the nutritional quality of diet as rice provides 21% of global human per capita energy and 15% of per capita protein (Maclean et al., 2002).

Economics

Costs of cultivation were worked out separately for both rice establishment methods, taking inputs and other operational expenses into account. The prevailing market rates at harvest were used to compute the gross returns. The cost of cultivation under the flooded method of rice establishment was higher compared to the aerobic method due to costs involved in raising the nursery and due to the transplanting operation. Even though gross returns and benefit/cost ratios (BCR) were higher in flooded rice treatments during the year 2009, under favorable conditions with better cultural practices, the gross returns and BCR for aerobic rice can be improved considerably as observed in the year 2010 (Table 5). Further under present situations energy charges for only pumping water was taken into consideration in calculating irrigation cost. However, in the future, if water is charged, even at a nominal price, the cost of cultivation of rice using flooded method will be significant.

Maize Crop

Dry matter production in maize crop grown under no-till conditions following rice crop was neither affected by the previous crop establishment methods nor by N application to the rice crop. Yield components such as the number of grains per cob and cob weight were lowest in maize grown after flooded rice (Table 6). Maize grown after aerobic rice however, yielded significantly higher in both years. The yield increase in maize grown after aerobic rice was 5.8 and 5.3% during 2009–2010 and 2010–2011, respectively. In the traditional flooded rice method of establishment, the field is flooded and puddled. The puddling operation destroys soil structure impacting the subsequent crop establishment and growth. Further, the too wet conditions after rice crop harvest delay land preparation and timely planting of a following crop causing a yield decline. Adopting aerobic rice cultivation may result in early maturity (Balasubramanian and Hill, 2002; Saharawat et al., 2010) and better residual soil physical

Table 5. Gross returns, cost of cultivation, and benefit/cost ratio (BCR) as influenced by crop establishment methods and N rates in rice.†

Method of establishment	2009 Gross returns	2009 Cost of cultivation	2009 BCR	2010 Gross returns	2010 Cost of cultivation	2010 BCR
	USD ha^{-1}			USD ha^{-1}		
Aerobic-0 N	358	552	0.65	534	522	1.02
Aerobic-60 N	529	566	0.93	643	536	1.20
Aerobic-120 N	662	582	1.14	907	552	1.64
Aerobic-180 N	740	596	1.24	996	566	1.76
Mean	572	574	0.99	770	544	1.41
Flooded-0 N	591	658	0.90	555	648	0.86
Flooded-60 N	839	672	1.25	772	662	1.17
Flooded-120 N	1123	688	1.63	1089	678	1.61
Flooded-180 N	1188	702	1.69	1218	692	1.76
Mean	935	680	1.37	909	670	1.35

† Price of rice grain: US $.0.18 per kg; Price of straw: US $.0.01 per kg.

conditions congenial for succeeding crops. Results in our study showed increased maize yields followed by aerobic rice for both years (Table 6). Similar increased yields for succeeding crops followed by rice grown under unpuddled conditions were reported by Hobbs et al. (2000), Singh et al. (2002), Sharma et al. (2005), and Singh et al. (2008).

Incremental application of N rates to preceding rice crop influenced cob weight and N uptake significantly, but not the maize yields. Nitrogen uptake in maize was significantly influenced by rice establishment methods and N rates applied to rice. Nitrogen uptake was highest in maize grown after aerobic rice. Increased N uptake was noticed in maize grown after rice treatment plots receiving 180 kg N ha^{-1} than treatments receiving no N application possibly due to residual effect of N applied to rice.

CONCLUSIONS

Aerobic rice can be a viable option for growing rice for water deficit regions and by proper management, up to 80% yields attainable under flooded system can be obtained. The main advantage that aerobic rice had over flooded rice was reduction in irrigation water usage. The number of irrigations scheduled during the crop growth period was considerably reduced in aerobic rice. Higher water productivity and water savings up to 37 to 45% over flooded method was observed for aerobic rice. The observed low yields of aerobic rice suggested the need to develop management strategies that could reduce the yield penalty or deficit. Our results also suggested that under favorable weather conditions coupled with proper weed management yield gap between aerobic and flooded rice can be minimized. Further, during failures of monsoon or periods of deficit rainfall, aerobic rice will remain the best option for growing rice as flooded rice cultivation will not be possible. Desired soil physical and chemical properties resulting from aerobic method of cultivation will ensure timely planting, proper establishment, and higher yields of the succeeding maize crop unlike the puddled soil in the flooded rice fields, where field preparation can be challenging. Future research on aerobic should also address the micronutrient deficiencies and also should focus on exclusive breeding program for development of suitable aerobic varieties for the Indian subcontinent and semiarid regions of the world.

Table 6. Yield components, yield and N uptake of maize during 2009–2010 and 2010–2011 as influenced by rice crop establishment methods and N rates.

Treatment†	Cob weight 2009–2010	Cob weight 2010–2011	100 grain weight 2009–2010	100 grain weight 2010–2011	Grain no. cob^{-1} 2009–2010	Grain no. cob^{-1} 2010–2011	Grain yield 2009–2010	Grain yield 2010–2011	Nitrogen uptake 2009–2010	Nitrogen uptake 2010–2011
	g						t ha^{-1}		kg ha^{-1}	
AR-0 N-M-120	131	141	27.7	28.1	418	433	5.74	6.30	127	142
AR-60 N-M-120	135	142	27.2	28.6	428	448	5.90	6.47	135	151
AR-120 N-M-120	137	147	27.7	28.9	428	462	5.88	6.51	140	155
AR-180 N-M-120	141	150	28.1	29.0	435	477	6.15	6.73	147	162
FR-0 N-M-120	125	131	26.9	28.0	396	409	5.42	5.96	119	133
FR-60 N-M-120	131	137	27.0	27.8	408	430	5.47	6.02	122	136
FR-120 N-M-120	132	138	27.6	27.8	419	445	5.72	6.31	130	146
FR-180 N-M-120	129	141	27.3	27.9	426	442	5.77	6.42	133	150
ANOVA										
Method (M)	***	***	*	**	*	**	*	*	**	**
N rates (N)	*	*	ns‡	ns	ns	**	ns	ns	**	**
M × N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† AR, aerobic rice; FR, flooded rice; M, maize; N, nitrogen.
‡ ns = nonsignificant ($P > 0.05$).

REFERENCES

Balasubramanian, V., and J.E. Hill. 2002. Direct seeding of rice in Asia: Emerging issues and strategic research needs for the 21st century. In: S. Pandey et al., editor, Direct seeding: Research issues and opportunities. Proceedings International Workshop, Bangkok, Thailand. 25–28 Jan. 2000. Int. Rice Res. Inst., Los Baños, Philippines. p. 15–42.

Barker, R., D. Dawe, T.P. Tuong, S.I. Bhuiyan, and L.C. Guerra. 1999. The outlook for water resources in the year 2020: Challenges for research on water management in rice production. In: Assessment and Orientation towards the 21st Century. Proceedings 19th Session of the International Rice Commission, Cairo, Egypt. 7–9 Sept. 1998. FAO, Rome. p. 96–109.

Bartolome, V.I., R.M. Casumpang, M.A.H. Ynalvez, A.B. Olea, and C.G. McLaren. 1999. IRRISTAT for Windows- Statistical Software for Agricultural Research. Biometrics, Int. Rice Res. Inst., Los Baños, Philippines.

Belder, P., B.A.M. Bouman, J.H.J. Spiertz, S. Peng, A.R. Castaneda, and R.M. Visperas. 2005. Crop performance, nitrogen and water use in flooded and aerobic rice. Plant Soil 273:167–182. doi:10.1007/s11104-004-7401-4

Bethune, M., N. Austin, and S. Maher. 2001. Quantifying the water budget of irrigated rice in the Shepparton irrigation region, Australia. Irrig. Sci. 20:99–105. doi:10.1007/s002710100035

Borrell, A.K., A.L. Garside, and S. Fukai. 1997. Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. Field Crops Res. 52:231–248. doi:10.1016/S0378-4290(97)00033-6

Bouman, B.A.M., S. Peng, A.R. Castaneda, and R.M. Visperas. 2005. Yield and water use of irrigated tropical aerobic rice systems. Agric. Water Manage. 74:87–105. doi:10.1016/j.agwat.2004.11.007

Bouman, B.A.M., Y. Xiaoguang, W. Huaq, W. Zhimin, Z. Junfang, and C. Bin. 2006. Performance of aerobic rice varieties under irrigated conditions in North China. Field Crops Res. 97:53–65. doi:10.1016/j.fcr.2005.08.015

Bremner, J.M. 1965. Total nitrogen. In: C.A. Black et al., editors, Method of soil analysis. Agron. Monogr. 9. Part 2. ASA, Madison, WI. p. 1149–1178.

Castaneda, A.R., B.A.M. Bouman, S. Peng, and R.M. Visperas. 2002. The potential of aerobic rice to reduce water use in water-scarce irrigated lowlands in the tropics. In: B.A.M. Bouman et al., editors, Water-wise Rice Production. Proceedings International Workshop on Water-wise Rice Production, Los Baños, Philippines. 8–11 Apr. 2002. Int. Rice Res. Inst., Los Baños, Philippines. p. 165–176.

Chandrapala, A.G., M. Yakadri, M. Kumar, and B. Raj. 2010. Productivity and economics of rice (*Oryza sativa*): Maize (*Zea mays*) as influenced by methods of crop establishment, Zn and S application in rice. Indian J. Agron. 55:171–176.

Choudhury, B.U., B.A.M. Bouman, and A.K. Singh. 2007. Yield and water productivity of rice-wheat on raised beds at New Delhi, India. Field Crops Res. 100:229–239. doi:10.1016/j.fcr.2006.07.009

De Datta, S.K. 1989. Spikelet sterility and flowering response of rice to water stress at anthesis. Ann. Bot. (London) 63:257–264.

Ekanayake, I.J., P.L. Steponkus, and S.K. De Datta. 1990. Sensitivity of pollination to water deðcits at anthesis in upland rice. Crop Sci. 30:310–315. doi:10.2135/cropsci1990.0011183X003000020013x

He, H., R. Serraj, and Q. Yang. 2009. Changes in OsXTH gene expression, ABA content, and peduncle elongation in rice subjected to drought at the reproductive stage. Acta Physiol. Plant. 31:749–756. doi:10.1007/s11738-009-0287-2

Hobbs, P.R., Y. Singh, G.S. Giri, J.G. Lauren, and J.M. Duxbury. 2000. Direct-seeding and reduced- tillage options in the rice wheat system of the Indo-Gangetic plains of South Asia. In: S. Pandey et al., editors, Direct seeding: Research issues and opportunities. Proceedings International Workshop, Bangkok, Thailand. 25–28 Jan. 2000. Int. Rice Res. Inst., Los Baños, Philippines. p. 201–215.

Kato, Y., M. Okami, and K. Katsura. 2009. Yield potential and water use efficiency of aerobic rice (*Oryza sativa* L.) in Japan. Field Crops Res. 113:328–334. doi:10.1016/j.fcr.2009.06.010

Lampayan, R.M., B.A.M. Bouman, J. L.de Dios, A.J. Espiritu, J.B. Soriano, A.T. Lactaoen, J.E. Faronilo, and K.M. Thant. 2010. Yield of aerobic rice in rainfed lowlands of the Philippines as affected by nitrogen management and row spacing. Field Crops Res. 116:165–174. doi:10.1016/j.fcr.2009.12.007

Lin, S., K. Dittert, H.B. Tao, K. Kreye, Y.C. Xu, Q.R. Shen, X.L. Fan, and B. Sattelmacher. 2002. The ground-cover rice production system (GCRPS): A successful new approach to save water and increase nitrogen fertilizer efficiency? In: B.A.M. Bouman et al., editors, Water-wise rice production. Proceedings International Workshop on Water-wise Rice Production, Los Baños, Philippines. 8–11 Apr. 2002. Int. Rice Res. Inst., Los Baños, Philippines. p. 187–196.

Maclean, J.L., D.C. Dawe, B. Hardy, and G.P. Hettel, editors. 2002. Rice almanac. CAB Int., Wallingford.

Ockerby, S.E., and S. Fukai. 2001. The management of rice grown on raised beds with continuous furrow irrigation. Field Crops Res. 69:215–226. doi:10.1016/S0378-4290(00)00140-4

O'Toole, J.C., and D.P. Garrity. 1984. Upland rice soil-plant-water relationships. In: An overview of upland rice research. Int. Rice Res. Inst., Los Baños, Philippines. p. 394–411.

O'Toole, J.C., and O.S. Namuco. 1983. Role of panicle exertion in water-stress induced sterility. Crop Sci. 23:1093–1097. doi:10.2135/cropsci1983.0011183X002300060017x

Peng, S., B.A.M. Bouman, R.M. Visperas, A.R. Castaneda, L. Nie, and P. Hong-Kyu. 2006. Comparison between aerobic and flooded rice in the tropics: Agronomic performance in an eight season experiment. Field Crops Res. 96:252–259. doi:10.1016/j.fcr.2005.07.007

Reddy, M.D., S.N. Reddy, and V. Ramulu. 2010. Evaluation of rice cultures for aerobic system. Agric. Sci. Dig. 30:129–132.

Saharawat, Y.S., B. Singh, R.K. Malik, J.K. Ladha, M. Gathala, M.L. Jat, and V. Kumar. 2010. Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in north-western IGP. Field Crops Res. 116:260–267. doi:10.1016/j.fcr.2010.01.003

Saini, H.S., and M.E. Westgate. 2000. Reproductive development in grain crops during drought. Adv. Agron. 68:59–96. doi:10.1016/S0065-2113(08)60843-3

Sharma, P.K., L. Bhushan, J.K. Ladha, R.K. Naresh, R.K. Gupta, B.V. Balasubramanian, and B.A.M. Bouman. 2002. Crop-water relations in rice-wheat cropping under different tillage systems and water-management practices in a marginally sodic, medium-textured soil. In: B.A.M. Bouman et al., editors, Water-wise rice production. Proceedings International Workshop on Water-wise Rice Production, Los Baños, Philippines. 8–11 Apr. 2002. Int. Rice Res. Inst., Los Baños, Phillippines. p. 223–235.

Sharma, S.K., D.K. Pandey, K.S. Gangawar, and O.K. Tomar. 2005. Effect of crop establishment methods on performance of rice cultivars and their effect on succeeding wheat (*Triticum aestivum*). Indian J. Agron. 50:253–255.

Singh, A.K., B.U. Choudhury, and B.A.M. Bouman. 2002. Effects of rice establishment methods on crop performance, water use, and mineral nitrogen. In: B.A.M. Bouman et al., editors, Water-wise Rice Production. Proceedings International Workshop on Water-wise Rice Production, Los Baños, Philippines. 8–11 Apr. 2002. Int. Rice Res. Inst., Los Baños, Philippines. p. 237–246.

Singh, G., O.P. Singh, V. Kumar, and T. Kumar. 2008. Effect of methods of establishment and tillage practices on productivity of rice (Oryza sativa)–wheat (*Triticum aestivum*) cropping system in low lands. Indian J. Agric. Sci. 78:163–166.

Stoop, W.A., N. Uphoff, and A. Kassam. 2002. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: Opportunities for improving farming systems for resource-poor farmers. Agric. Syst. 71:249–274. doi:10.1016/S0308-521X(01)00070-1

Tabbal, D.F., B.A.M. Bouman, S.I. Bhuiyan, E.B. Sibayan, and M.A. Sattar. 2002. On- farm strategies for reducing water input in irrigated rice: Case studies in the Philippines. Agric. Water Manage. 56:93–112. doi:10.1016/S0378-3774(02)00007-0

Timsina, J., L.J. Mangi, and K. Majumdar. 2010. Rice-maize systems of South Asia: Current status, future prospects and research priorities for nutrient management. Plant Soil 335:65–82. doi:10.1007/s11104-010-0418-y

Tuong, T.P., B.A.M. Bouman, and M. Mortimer. 2004. More rice, less water–Integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. In: New directions for a diverse planet. Proceedings International Crop Science Congress, Brisbane, Australia. 26 Sept.–1 Oct. 2004. The Regional Inst. Ltd., Gosford, NSW, Australia.

Willis, T.M., A.S. Black, and W.S. Meyer. 1997. Estimates of deep percolation beneath cotton in the Macquarie Valley. Irrig. Sci. 17:141–150. doi:10.1007/s002710050032

Xiaoguang, Y., B.A.M. Bouman, W. Huaqi, W. Zhimin, Z. Junfang, and C. Bin. 2005. Performance of temperate aerobic rice under different water regimes in North China. Agric. Water Manage. 74:107–122. doi:10.1016/j.agwat.2004.11.008

Zhang, L., S. Lin, B.A.M. Bouman, C. Xue, F. Wei, H. Tao, X. Yang, H. Wang, D. Zhao, and K. Dittert. 2009. Response of aerobic rice growth and grain yield to N fertilizer at two contrasting sites near Beijing, China. Field Crops Res. 114:45–53. doi:10.1016/j.fcr.2009.07.001