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Aerobic rice: crop performance and water use efficiency

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Abstract: Rice (*Oryza sativa*) production largely depends on traditional flooded rice systems whose sustainability is threatened by a progressive decrease in water availability and a constant increase in rice demand due to strong demographic boom in world population. A newly developed water-saving rice system is aerobic rice in which rice grows in non-flooded and unsaturated soil. From 2001, at the International Rice Research Institute in the Philippines, this system has been monitored to identify potentially promising varieties of rice able to grow as an irrigated upland crop and quantify yield potential and water use efficiency. This study reports on the results of cultivating the upland rice variety Apo under different water conditions in 2004-2005 at the IRRI farm in both the dry and wet seasons. The water treatments considered were: aerobic and flooded conditions, alternated flooded and aerobic conditions and aerobic after fallow. Yield and water productivity were compared between aerobic and flooded treatment in both seasons, with the objective of analysing the differences between water treatments. In the experiment the effect of different nitrogen (N) application is also considered. The results indicate that the aerobic rice yield was lower than rice production under flood treatment, confirming that observed over past years. Nevertheless, when the aerobic condition is alternated with the anaerobic condition, or a fallow period, the production under aerobic treatment provides good yields (respectively 4.2 and 4.4 ha^{-1}). The fallow period was introduced to observe the response of rice grown under this management. Water productivity was higher in aerobic fields, especially after fallow (0.88 g kg^{-1}). The nitrogen application induced an increase in yield and water productivity, partially compensating for the lack of water in aerobic fields.

Aerobic fields showed a higher number of nematodes, and was likely one of the probable causes of yield decrease. Our results suggest the development of new aerobic rice varieties and water management strategies before adopting aerobic rice technology in large areas of the tropics.

Keywords: aerobic rice, water savings, water productivity, yield decline

Introduction

Rice (*Oryza sativa*) is the most important staple food crop worldwide for nearly half of the world population, particularly for those living in developing countries. In 2008 the yearly production was 674 million tons, of which 611 million tons was in Asia, where more than 90% of world's rice production is produced and consumed (FAO, 2008). In that continent rice provides on average 35% of total calorie intake (Bauman, 2001; Bauman *et al.*, 2001; Maclean *et al.*, 2002).

Asia has the largest area dedicated to rice cultivation, an estimated 140 million ha out of 156 million ha worldwide (FAO, 2007). Around 79 million ha of rice is grown under irrigated conditions, and although this is only half of the total rice cultivation area, about 75% of the global rice volume is produced using this cropping system (Bouman, 2001). Other rice ecosystems include the rainfed lowland (35% of total cultivation area), characterized by a lack of water control, and upland and deepwater ecosystems (5% of total cultivation area), where yields are both low and extremely variable.

Rice production and food security largely depend on the irrigated lowland rice system, whose sustainability is threatened by fresh water scarcity, water pollution and competition for water use (Gleick, 1993; Guerra *et al.*, 1998; Postel, 1997). Flooded and irrigated rice systems consume two-three times more water than other cereals, such as maize or wheat. Future predications on water scarcity limiting agricultural production have estimated that by 2025 about 2 million ha of Asia's irrigated rice fields will suffer from water shortage in the dry season especially since flood-irrigated rice uses more than 45% of 90% of total freshwater used for agricultural purposes (Bouman, 2001; Bouman *et al.*, 2005; Peng *et al.*, 2006). Hence, the major challenges are to produce more rice, increase water productivity and reduce water input in the fields (Bouman *et al.*, 2001).

Several strategies for water-saving were developed in recent years, to increase water productivity and to reduce water losses in the rice system. Most rice fields are kept flooded for extended periods, consequently seepage, percolation, transpiration and evaporation remain high. Alternative management techniques developed to minimize water outflow from rice fields are: saturated soil culture, alternate wetting and drying, and ground cover system (Peng *et al*., 2006). A recent technology is that of 'Aerobic rice' that combines specific rice varieties to specific land management. Today rice varieties that are available include drought resistant upland varieties with a low production and lowland high-yielding varieties. Aerobic rice grows under non-flooded conditions in non-puddled and unsaturated (aerobic) soil with a supplemental irrigation (Bouman, 2001; Bouman *et al*., 2005). The varieties used in this system combine the drought resistance of upland varieties and the high-yielding characteristic of lowland varieties (Lafitte *et al.,* 2002). Preliminary experimental results regarding this new technique showed a consistent water saving but with a significant yield reduction, particularly under continuous monocropping of aerobic rice where Apo's yields from 2001 to 2003 were 40% lower than production in flooded system (Peng *et al.,* 2006). Apo is a upland variety, developed at IRRI in 2001, and was used for the experiments because of good performance under aerobic conditions.

The causes and physiological processes responsible for yield loss under monocropping aerobic rice, are not still well known. An understanding of the causes of the yield decline will be useful to improve the breeding and selection of varieties that give a good performance. The studies report a soil-born pathogen as a possible candidate of yield decrease. Recently, some improved tropical upland and lowland rice varieties with good performance under high rainfall aerobic conditions were identified and selected (George *et al*., 2002; Lafitte *et al*., 2002). Nevertheless yield potential, water use, water productivity of these varieties and the water requirement under aerobic conditions are not well documented. To obtain some of this information, a long-term field experiment was established at IRRI, in Los Baños, Philippines, from 2001. Several tropical rice varieties were grown under irrigated flooded and aerobic soil conditions in order to compare crop agronomic performances under different conditions. This paper reports the results obtained in the dry and wet seasons of 2004 and the dry season of 2005, specifically highlighting the performances of the upland variety Apo under aerobic conditions.

Materials and Method

The experiment was conducted at IRRI's farm in both the dry season (December-May) and wet season (June-November). In this paper only the year 2004-2005 is considered. The experimental soil, in accordance with the USDA classification, was a typical Tropaqualf composed of 59 % clay, 32 % silt and 9 % sand. The field experiment was laid out in a split-plot design with four replicates, the same for each season, respectively. The main plot was 344 m² and was characterised by three water treatments: AA, aerobic conditions in the dry (DS) and wet season (WS); AF, aerobic in the DS and flooded in WS; FF, flooded in the DS and WS. Each main plot was divided into four subplots of 86 m² and cultivated with different varieties for each year or season, to compare the performance of different cultivars. Only the Apo variety (IR55423-01) was always cultivated every year on the same subplot, two for each main plot, one with nitrogen treatment and one without nitrogen treatment. 2004-05 water treatment in some subplots changed: AF was converted to FF (AF-F) in 2004 and AA (AF-A) in 2005; FF was converted to AA (FF-A) and to FF (FF-F) in 2004 and 2005, respectively; the AA water treatment remained the same. Moreover, four subplots were left fallow in 2004 during both the dry and wet seasons and cultivated with Apo the following year (2005) under aerobic conditions. Until 2003, these four subplots were cultivated under aerobic conditions but cultivating other rice varieties. The change in water treatment was to compare the rice grown under different soil and water management.

From transplanting until two weeks before harvest flooded plots were puddled and kept continuously flooded. The aerobic plots were dry-ploughed and harrowed but not puddled during land preparation: a day before transplanting, the soil was irrigated to facilitate transplanting and, then flooded for a week to promote crop establishment. Thereafter, aerobic plots were irrigated with about 5 cm of water, only when the soil moisture tension reached the -30 kPa at 15 cm depth. At flowering time, the irrigation threshold was reduced to -10 kPa to prevent spikelet sterility.

Measurements

The soil moisture tension was gauged by means of tensiometers, installed at a depth of 15 and 30 cm in each aerobic field. The groundwater table was measured daily in perforated PVC pipes, installed at a depth of 1.75 m in the center of the bunds between each main plot. Drainage outflow was measured using a parshall flume installed at the end of the central collector drain. Weather data, including rainfall, was collected daily from the IRRI's meteorological station.

Rice yield (ton ha^{-1}) at 14% moisture was determined from two areas of 5 m² in each subplot by sampling twenty hill plants samples at harvest time.

Nematode (*Meloidogyne graminicola*) presence was expressed as number per gram of roots.

Water Productivity (WP) was calculated on agronomic yield (g of grain) per unit of water use (kg of water) as follows:

$$WP = \frac{Y}{\sum(I + R)}$$

WP = water productivity
Y = yield
I = water irrigation applied
R = amount of rainfall

Data analysis

For the yield, nematode number and water productivity, the analysis of variance was performed according to a split-split-plot design considering the season as the main plot (factor A) and the water treatment and the nitrogen level as subplot factors (respectively factor B and factor C). Bonferroni multiple pairwise comparison test was performed for each source of variation.

Results

Water inflow

Table 1 shows total water irrigation applied during wet and dry season 2004 and 2005, in both flooded and aerobic fields.

Table 1 – Seasonal and water treatment inflow distribution during 2004 and 2005

WATER TREATMENT	DRY SEASON 2004		WET SEASON 2004		DRY SEASON 2005	
	Irrigation (mm)	Water high (mm)	Irrigation (mm)	Water high (mm)	Irrigation (mm)	Water high (mm)
AA-A	753	72	230	82	239	21
AF-F	847	25	356	24	445	49
FF-A	800	54	317	79	850	43
A - Fallow	-	-	-	-	189	19

For DS in the 2004 irrigation water levels were 753, 800 and 847 mm, respectively, in AA-A, FF-A and AF-F subplots. Irrigation water was applied 36 times in flooded fields and 16 times in aerobic fields. In WS water was applied 15 times in flooded fields and 4 times in aerobic fields, respectively. In this season the average of irrigation water was 230, 356 and 317 mm, respectively, in the AA-A, AF-F and FF-A subplots. In flooded conditions, frequent irrigation was required to maintain standing paddy water depth. In 2004, the difference between irrigation water applied in aerobic and flooded fields was low, due to a bad control of water movement to the fallow area. In 2005, by isolating the boundaries between planted plots and the fallow field with plastic sheets, the values returned on average to that observed in past years. The water requirement in the fields after fallow was lower than other water treatments.

In 2005, DS fallow fields were planted. In AA-A and FF-F subplots irrigation levels were 239 and 850 mm delivered in 11 and 24 applications, respectively. In the A-Fallow, subplot present in 2005, irrigation water was 189 mm. Between 2001 and 2004, the irrigation level was on average 400 mm in DS and 220 mm in WS, while in FF treatments irrigation water was 1100 and 921 mm respectively in DS and WS.

The lower amount of irrigation water delivered in aerobic and flooded subplots during WS compared to DS was due to rainfall that supplied most of the crop water requirements. In 2004 rainfall contribution was 66.2 mm in DS and 805 mm in WS, respectively.

Soil moisture tension

In both dry seasons of 2004 and 2005, the moisture tension remained below -30 kPa. Seasonal average was -13 kPa in 2004 and -16 kPa in 2005. In DS, the soil water tension exceeded -30 kPa only few times, reaching a maximum value of -50 kPa. In the DS of 2005 the moisture tensions fluctuated largely between -30 kPa and -60 kPa.

For the WS in 2004 the water tension was steady, below -20 kPa, because of the frequent rainfall. In this season average tension was -8 kPa.

For the DS between 2001 and 2003, the tension at 15 cm remained below -30 kPa. In WS average tension was between -2 and -5 kPa.

Groundwater fluctuations

The groundwater fluctuation in aerobic fields for DS was 40-160 cm deep in

2004 and 40-180 cm in 2005. After irrigation applications, groundwater ranged between at a depth 0-20 cm, showing a gradual decrease until the next irrigation. In the WS of 2004 the groundwater, in aerobic fields, was lower than 2004 because of the rainfall, with fluctuations comprised between 0-80 cm.

In the DS of 2001-2003 the groundwater depths in aerobic fields were 60-100 cm, reaching a depth of 20 cm after each watering. In WS the water level did not exceed 80 cm.

Yields

In table 2 the ANOVA is reported.

Table 2 – Summary of ANOVA

SOURCE OF VARIATION	SIGNIFICATIVITY		
	Yield	Water productivity	Nematodes
Season	**	**	**
Water treatment	**	*	**
Water treatment x Season	ns	**	ns
Nitrogen	**	**	ns
Nitrogen x Season	**	**	ns
Nitrogen x Water treatment	**	**	ns

* = significant for p<0,05, **=significant for p<0,01, ns=no significant

Yields in aerobic conditions were lower than yields in flooded conditions. The yield ranged from 5.8 t ha^{-1} in flooded subplots to 3 t ha^{-1} in aerobic fields. However, in the fields where aerobic conditions were alternated with flooded conditions, the difference between the two treatments was less pronounced reaching an average of 4.1 t ha^{-1}. In 2005, the subplots that were uncultivated in the previous year produced 4.4 t ha^{-1} under aerobic conditions. During the DS in 2004, the yields were 5 ton ha^{-1}, significantly higher than that obtained in the WS of 2004 and in the DS of 2005 (4 t ha^{-1} and 4.1 t ha^{-1} respectively).

Figure 1 and 2 report the yields in 2004 and 2005, respectively, for each water treatment and season, in relation with nitrogen fertilization (N+ and N-).

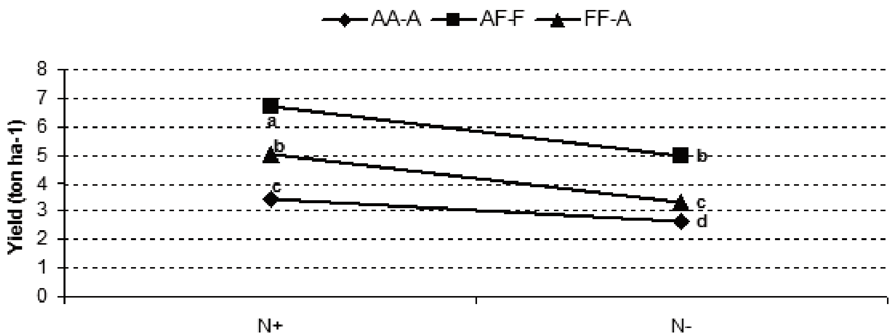

Figure 1 – Effect of water treatment and nitrogen fertilisation on yeld (t ha $^{-1}$)

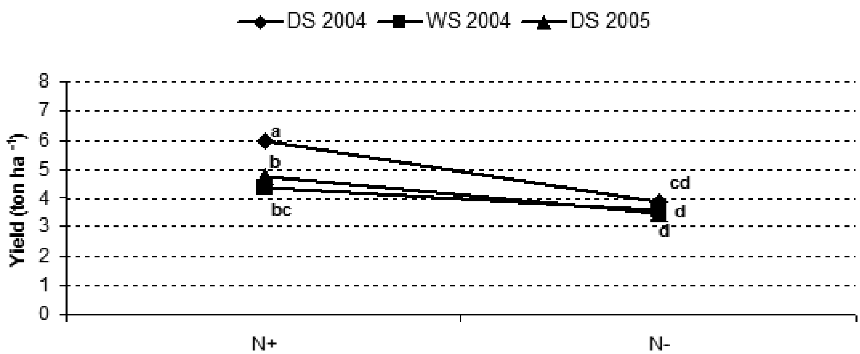

Figure 2 – Effect of nitrogen fertilisation on yield (t ha^{-1}) in the 2004 dry and wet seasons and in the 2005 dry season

The application of nitrogen positively affected the yields both in aerobic and flooded fields. The yields were 3.4 and 6.7 t ha^{-1} respectively in AA-A and in AF-F subplots with nitrogen application, and 2.7 and 5 t ha^{-1} respectively in AA-A and in AF-F subplots without nitrogen applications.

With nitrogen application, yields were significantly higher in the DS of 2004, while no significant differences were detected between seasons without nitrogen supply.

As observed from 2001 to 2003, yields during the DS were higher than yields in the WS probably because of frequent irrigation applications and good climatic conditions, such as a lower cloud cover and a more intensive solar radiation.

As reported in previous studies, the yield decrease observed in aerobic plots was more pronounced in those plots continuously maintained in aerobic conditions. For instance, the yields in continuous aerobic fields from 2001 to 2003 were 32 % and 22 % lower than those in flooded conditions, respectively, in the DS and WS, with a value of 40 % measured in plots grown with the Apo variety.

Water Productivity

In table 2 the ANOVA is reported.

Water productivity was 0.54 and 0.66 g kg^{-1} in AA-A and AF-F with nitrogen treatment and 0.44 and 0.48 g kg^{-1} in AA-A and AF-F without nitrogen treatment. However, these values represent an isolated case due to the wrong water management in 2004. In the aerobic fields after fallow, WP reached the highest value, 1.13 and 0.62 g kg^{-1}, respectively, with and without nitrogen.

Nematodes

In table 2 the ANOVA is reported.

The presence of nematodes in the soil did not seem to be affected by either seasons or nitrogen application. The presence of nematodes in aerobic fields was significantly higher than in flooded fields (Fig. 3), both after fallow and under continuous aerobic management.

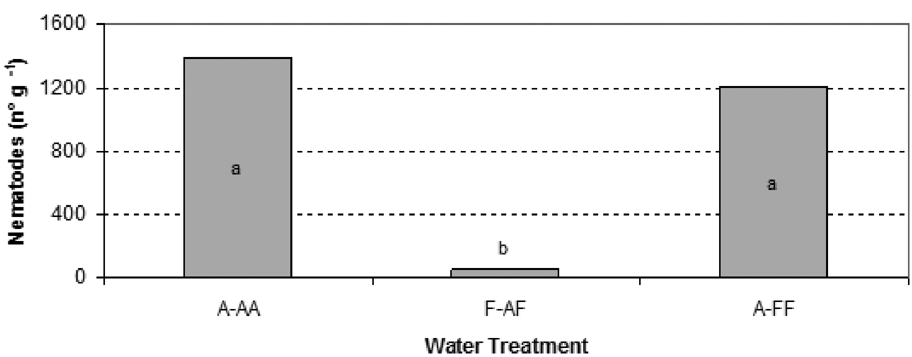

Figure 3 – Effect of water treatment on nematode number

Discussion and Conclusions

In the above mentioned experiment, aerobic rice yields were significantly lower than flooded rice yields, especially under continuous aerobic conditions. According to previous studies, the gap between the aerobic and flooded treatments widened with the increase of the number of cropping seasons. In fact, between 2001 and 2004, the yields in aerobic fields decreased 44% and 24%, respectively, during the dry and wet seasons. The difference between aerobic and flooded yields in the DS was only 15% in 2001 increasing up to 69% in 2004. During the WS the increase in yield difference was lower, ranging from 23% in 2001 to 50% in 2004. Apo variety yields decreased on average 40%, from 6.3 t ha^{-1} in 2001 to 2.6 t ha^{-1} in 2004 (Peng *et al.*, 2006). In the years 2004-05 yields in continuous aerobic fields was 3 t ha^{-1} and 5.9 t ha^{-1} in flooded fields. In 2004 the yields were on average 4.9 t ha^{-1} and 3.9 t ha^{-1} respectively in DS and WS.

The yield decline is a natural trade-off when rice is removed from its natural aquatic habitat to an aerobic condition, which causes a physiological disruptions such as the yield capacity (Castañeda *et al.*, 2004). High yielding flooded rice uses three times more irrigation water than aerobic rice for land preparation and twice during the crop growth. In previous experimental trials carried out in the years 2001-04, total water used in aerobic plots was 27-51% lower than water for flooded plots (Peng *et al.*, 2006).

The seasonal average soil moisture tension in aerobic fields at 15 cm depth in DS was -13 kPa in 2004 and -16 kPa in 2005, and -8 kPa in WS 2004. These values are on average similar to the values of -10 and 12 kPa in DS and -2 and -5 kPa in WS registered in the years 2001-04. Also the groundwater depth followed the trend previously observed. In 2004-05, the water fluctuation ranged between 40 and 160 cm in DS and around 80 cm in WS.

Continuous aerobic rice can not guarantee high yields but if it is alternated with anaerobic conditions, the yields can reach the 4.2 t ha^{-1}. For example during the 2005 cropping season the yields after fallow arose the 4.4 t ha^{-1}, a value comprised between the yields under aerobic and flooded conduction. Moreover, in the plots after fallow, the water productivity was higher than water productivity in aerobic and flooded fields. After fallow, water productivity was on average 0.88 g kg^{-1} (with and without nitrogen supply), while in aerobic and flooded fields it was 0.49 g kg^{-1} and 0.75 g kg^{-1} respectively. Nevertheless the water productivity measured in flooded plots in the period 2004-05 was high due to uncontrolled water movement. In fact, during the previous trials the higher water use values were measured in aerobic plots (0.45 g kg^{-1}), while the average of flooded plots was

0.38 g kg^{-1}.

Nitrogen application induced an increase in yields both in aerobic and anaerobic fields, ranging on average from 3.6 t ha^{-1} to 5 t ha^{-1}. Also water productivity benefited from nitrogen supply, with values of 0.6 g kg^{-1} in N+ plots and of 0.4 g kg^{-1} in N- plots. In particular, nitrogen supply in aerobic fields seemed to compensate for the lack of water in the soil. Nevertheless, the application of nitrogen may increase the risk of lodging, especially in tall varieties such as Apo (Belder *et al.* 2005a; Belder *et al.* 2005b).

The aerobic fields showed high presence of nematodes, not only in continuous aerobic fields, but also after fallow and in fields where aerobic and anaerobic conditions were alternated. Their presence is one of the probable causes of yield decrease in aerobic rice management.

Understanding the causes of yield decline under continuous aerobic conditions is crucial to develop new management strategies and new technologies to reduce water input. Moreover, the development of aerobic rice varieties with a minimum yield gap compared with flooded rice have to be developed before adopting aerobic rice technology in tropical large areas

Aerobic rice is actually grown in some areas of Brazil and China. This rice management is generally a suitable option for areas where water availability is too low or too expensive to grow in flooded lowland rice. Anyhow aerobic rice is not yet a good alternative to flooded rice. Therefore, it is advisable to introduce aerobic rice management in those areas where water is not abundant, preferably alternating aerobic and anaerobic management or growing rice after a fallow period.

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