Aerobic Rice (Han Dao): A New Way of Growing Rice in Water-Short Areas

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Abstract: Traditional lowland rice with continuous flooding in Asia has relatively high water inputs. Because of increasing water scarcity, there is a need to develop alternative systems that require less water. "Aerobic rice" is a new concept of growing rice: it is high-yielding rice grown in non-puddled, aerobic soils under irrigation and high external inputs. To make aerobic rice successful, new varieties and management practices must be developed. Results are reported of field experiments and farmer-participatory research in the Huang-Huai-Hai plain, northern China, where newly developed aerobic rice varieties are compared with lowland rice. Highest recorded aerobic rice yields were 4.7—6.6 t • ha^{-1}, compared with 8—8.8 of lowland rice. The variety Han Dao 502 is most promising because of its relatively high yield under both aerobic and flooded conditions and because of its good quality fetching a high market price. Compared with lowland rice, water inputs in aerobic rice were more than 50% lower (only 470 mm—650 mm), water productivities 64%—88% higher, gross returns 28%—44% lower (345—633 \$ ha^{-1}) and labor use 55% lower. Pilot farmers were satisfied with these first results. Because of its low water use, aerobic rice can be produced in areas where lowland rice can not (anymore) be grown. Since aerobic rice is targeted at water-short areas, socio-economic comparisons must include water-short lowland rice and other upland crops. The development of high-yielding aerobic rice is still in its infancy and germplasm still needs to be improved and appropriate management technologies developed.

1 Introduction

Rice is the most important staple in Asia where it provides 35%—80% of total calorie uptake (IRRI, 1997). About 55% of the rice area is irrigated and accounts for 75% of total production. Irrigated lowland rice is consequently the most important agricultural ecosystem in Asia, and the present and future food security of most of its population depends on it. However, there are signs that declining water availability is threatening the sustainability of this system. The reasons for this decline are diverse and location-specific, but include decreasing quality, decreasing resources, and increased competition from urban and industrial users (Postel, 1997). In China, many of these factors converge in the Huang-Huai-Hai (HHH) Plain. This plain contains 26% of China's cultivated land, 30% of the irrigated land and 24% of the total grain production (Shu Geng *et al.*, 2001). Rainfall is only barely sufficient to support a one-season crop and grain production relies heavily on irrigation. However, since the plain also contains 24% of China's population and supports many big cities and industry, competition for water is severe. Surface and groundwater water resources are over utilized, leading to lowering of ground water tables, formation of sink holes and diminished river flows. Though the most important food crops are wheat and maize, rice is an important grain crop in many parts as well. Because of it's heavy water use, however, irrigated rice is being taken out of production in many areas, such as around Beijing.

Ways must be found to decrease water use in rice production. Irrigated rice in Asia is typically transplanted into puddled paddy fields. Land preparation consists of soaking followed by plowing and harrowing of saturated soil. After crop establishment, the fields are kept submerged with 5 cm—10 cm of water. Because of the water used for wet land preparation and the large losses by seepage, percolation, and evaporation when the soil is submerged, the production of lowland rice requires much water (Bouman and Tuong, 2001). Crops such as wheat and maize, in contrast, are grown on non-puddled, aerated soils. Irrigation is applied when the soil becomes too dry, and the quantity of applied water is sufficient to bring the soil to field capacity. Savings in irrigation water and increases in water productivity might be possible if rice could be grown under aerobic soil conditions such as wheat and maize. However, new varieties must be developed if this concept of “aerobic rice” is to be successful. Upland rice exists but is targeted at unfavorable environments without access to irrigation, with low external inputs, and hence with a low yield potential. Aerobic rice should be responsive to high inputs (water, nutrients) to reach high yields under non-flooded conditions. In China, the Upland Rice Laboratory of the Chinese Agricultural University (CAU) is breeding aerobic rice varieties, called “Han Dao”. These varieties reportedly are being pioneered on some 120,000 ha in the HHH Plain. However, little is known about its performance or its actual ability to save water. The realization of water savings combined with high yields depends on good water management. The basic understanding of crop-water relationships in aerobic rice is missing and irrigation management recommendations have to be developed. Therefore, in 2001, the CAU and the International Rice Research Institute (IRRI) initiated a joint project to study the performance (biophysical and socio-economical) of aerobic rice and to develop practical water management recommendations. The study consists of controlled field experiments and farmer-participatory research in the HHH Plain. This paper reports on the first results of this study.

2 Method and materials

A field experiment was carried out in 2001 at Changping Experiment Station, (Changping county, Beijing). Three varieties were grown: two elite aerobic cultivars Han Dao 297 (HD297) and Han Dao 502 (HD502) and one popular lowland variety Jin Dao 305 (JD305). Five water treatments were imposed: soil water content in the root zone at 80%—90% throughout the growing season (W1), at 60%—70% from emergence till panicle initiation (PI) and 80%—90% from PI onwards (W2), at 80%—90% from emergence until PI and 60%—70% from PI onwards (W3), at 60%—70% throughout the growing season (W4), and rainfed rice with ‘survival’ irrigation at visual symptoms of severe drought stress (W5). The experiment was laid out in a randomized block design with four replicates. Plot sizes were 6m $\times$ 10 m. Plots were bunded and separated by 1 m wide strips of bare soil. Seeds were sown in rows 30 cm apart. To synchronize flowering time (to establish uniform timing of irrigation application in relation to phenology), the three varieties were sown at different dates: HD502 and JD305 on April 25 and HD297 on May 16. Both Han Dao varieties were harvested October 16 and JD305 was harvested October 18. Nitrogen was applied at the rate of 200 kg • ha^{-1} in three splits. At sowing, 56 kg • ha^{-1} of P and K were applied, 22.5 kg • ha^{-1} iron sulphate and 15 kg • ha^{-1} zinc sulphate. Before the start of the experiment, on April 3, the area had received (unplanned) dry chicken manure and fertilizer with an N-P-K equivalent of 120—52—45 kg • ha^{-1}. The plots were kept weed-free by the use of pre-emergence herbicide and hand weeding. Irrigation was applied through flexible hoses connected to a subsurface pipe system using water from a deep well. The soil type in the upper 50 cm was sandy loam, with 53%—57% sand, 36%—40% silt and 6%—7% clay (USDA classification). Rainfall was measured using a standard rainfall meter. The depth of the groundwater table was observed in a nearby observation well. Irrigation water input was measured with calibrated flow meters. Biomass and grain yield was recorded after air-drying from harvested areas of about 57 m^2 of each plot.

A separate trial was established to estimate the yield potential of the three varieties used in the experiment above under fully flooded conditions. The location was Changle in Shangzhuang village (Haidian district, Beijing), some 15 km away from Changping and presumably experiencing the same weather conditions. This trial was executed at a different location because the cultivation of lowland rice in the Changping area was forbidden by the Government as of 2001. The three varieties were transplanted in plots of 6m$\times$10m without replication. JD305 was transplanted on May 25, HD502 on June 1 and HD297 on June 7. All crops were harvested October 13. Fertilizer N was given at the rate of 190 kg • ha^{-1} in three splits. At transplanting, 30 P kg • ha^{-1} and 60 kg • ha^{-1} P were given. Biomass and grain yield was recorded from harvested areas of 57 m^2.

Pilot sites for farmer-participatory research were selected in Hanjiachuan (Beijing) and in Guanzhuang village (Fengtai county, Anhui province). At Hanjiachuan, a farmer cooperative grew aerobic rice HD297 on 9 ha. The soil in the upper 50 cm was loam to silty loam, with 29 (±14) % sand, 50 (±15) % silt and 21 (±10) % clay. Irrigation was applied using a movable sprinkler system. The water was obtained by pumping from a deep well. The crop was mechanically sown in rows 25 cm apart on May 17 and combine-harvested on October 15. For comparison, a 0.3 ha lowland rice field at Changle planted with JD305 was included in the study. This field got its water by pumping from a small reservoir that was fed by the Jingmi canal (taking water from Miyun reservoir).

Guanzhuang lies in Yongyin irrigation system which gets its water from the Huai river. Being at the tail-end of the system, water is relatively scarce and farmers increasingly abandon lowland rice production. In 2001, 10 farmers tried aerobic rice on 4 ha land originally intended to be left fallow because of water shortage. The crop was mechanically sown in rows 25 cm apart on June 15 and harvested on October 5. Irrigation was applied by flash flooding using water pumped from a small reservoir fed by the irrigation system. We selected three farmers who participated in the aerobic rice trial and who also grew lowland rice in fields surrounding the aerobic rice land. The aerobic rice variety grown was Han Dao 502, and the conventional lowland varieties were Indica hybrid 65,002 (farmer 1), glutinous inbred Yikenuo (farmer 2) and Indica hybrid Xieyou 63 (farmer 3). The soil in the upper 50 cm was similar to that in Hanjiachuan, with 35 (±15) % sand, 48 (±10) % silt and 16 (±9) % clay. At both the Hanjiachuan and the Guanzhuang sites, the farmers were advised on the management of aerobic rice by researchers of CAU. The farmers recorded all the activities, labor use and input use in each of their fields. Prices of all inputs and outputs (rice) were also recorded. At each irrigation, the start and finish time of water delivery was recorded. The amount of irrigation water applied was estimated by multiplying the irrigation duration with the calibrated flow rate of the pump. Rain gauges were installed at the sites. During the season, we measured groundwater table depths within the aerobic rice plots. Farmers estimated their yields by counting the number of standard-size bags with harvested grain.

3 Results

Experiment at Changping. During the experiment, the groundwater was 18 m—23 m deep, which was too deep to contribute to crop water supply through capillary rise. The rainfall measured between May 10 (just before emergence of the early varieties) and October 13—16 (harvest) was 294 mm. The rainfall distribution is given in Fig. 1. The timing and amounts of irrigation application varied per treatment. Fig.1 gives the irrigation applications after emergence for W1 and W5. In this figure, the phenology of HD502 is indicated as well. Each plot received 105 mm irrigation at land preparation (March 19) and 67 mm shortly after sowing. After the irrigation at sowing, the crops did not receive rainfall nor irrigation until June 11 in all treatments, which means an exceptionally long dry period for rice of one month for HD502 and JD305 and of 18 days for HD297. The irrigation application of 50 mm on August 13 (day 225) was given to all water treatments together with fertilizer application.

The yields, water use and water productivity (calculated as grams of grain produced per kg of water input) are given in Table 1. For comparison, the yields under flooded conditions at Changle are included. The lowland variety JD305 recorded the highest yield under flooded conditions; the yield of HD502 was 23% lower and that of HD297 39% lower. All three varieties yielded lower under aerobic conditions, but now the two aerobic varieties yielded higher than the lowland variety. In the most favorable water treatment W1, HD502 yielded highest, with HD297 and JD305 yielding 11% and 21% lower, respectively. Both the aerobic varieties maintained a reasonable yield of 2.5—3.5 $t \cdot ha^{-1}$ in the relatively dry treatments W4 and W5, whereas JD305 just produced 1.2—1.5 $t \cdot ha^{-1}$. The total amounts of water inputted during the crop growth season (excluding the 105 mm at land preparation) were low (470 mm-586 mm) compared with typical values of 1,000 mm—1,500 mm for lowland rice (Bouman and Tuong, 2000; see also Table 2). The water productivities of the two aerobic varieties remained quite high under the relatively dry treatments W4 and W5, whereas that of JD305 reduced to less than 50% of its value in W1. In the two aerobic varieties, yields and water productivities were the same in W2 and W3, indicating little difference in sensitivity for water stress between the vegetative (before PI) and generative (after PI) development phases. JD305, however, was relatively sensitive to water stress in the generative phase since the yield dropped 47% from W2 to W3 despite that the total amount of water inputted was the same.

Farmers' performance. The results of the pilot farmers are summarized in Table 2. Recorded rainfall during crop growth was 337 mm at Changle, 299 mm at Hanjiachuan and only 70 mm at

Guanzhuang where this amount was the least of the last 100 years. Groundwater depths were mostly below 120 cm except for brief periods just after irrigation or heavy rainfall. We estimate that only little amounts of water could reach the root zone by capillary rise (though this needs further investigation).

Table 1　Water input from emergence to harvest (I=irrigation, R=rainfall), yield and water productivity at Changping and Changle

	Water input (mm)		Yield ($t \cdot ha^{-1}$)			Water productivity ($g \cdot kg^{-1}$)		
	I	I+R	JD305	HD297	HD502	JD305	HD297	HD502
Changping								
W1	350	644	4.2	4.7	5.3	0.65	0.73	0.82
W2	283	577	3.8	4.3	4.6	0.66	0.74	0.80
W3	292	586	2.0	4.2	4.3	0.34	0.72	0.73
W4	225	519	1.5	3.4	3.5	0.29	0.66	0.67
W5	175	469	1.2	2.5	3.0	0.26	0.53	0.64
Changle								
	—	—	8.8	5.4	6.8	—	—	—

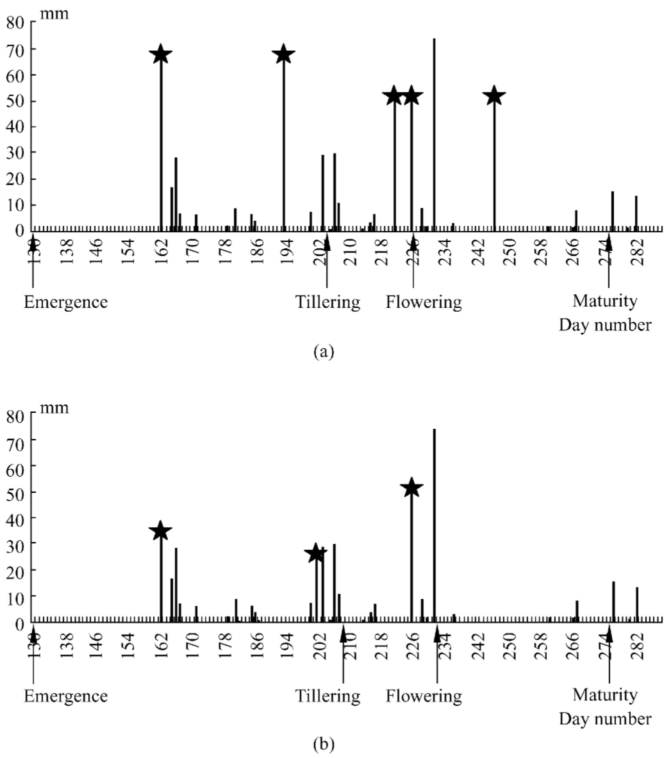

Fig. 1　Amount and timing of rainfall and irrigation at Changping in treatment W1 (a) and W5 (b). The irrigation applications are identified by a star. The phenology of HD502 is indicated with arrows

Like in the field experiment, yields were highest at about 7—8 $t \cdot ha^{-1}$ at both sites in flooded lowland rice. The yield of aerobic rice varied from 4.6 to 6.6 $t \cdot ha^{-1}$, and was about 27% lower than lowland rice at Guanzhuang and 35% lower at Hanjiachuan. At both sides, lowland rice had about the same amount of total water input, 1,350 mm—1,390 mm, from sowing to harvest, which is a typical value for lowland rice in Asia (Bouman and Tuong, 2000). In aerobic rice, total water input was only 45% of the water input in flooded rice at Guanzhuang and 35% of that at Hanjiachuan. If we take water requirements for land preparation into account, these differences would even have been bigger. The water input at Hanjiachuan was especially low with only 476 mm. With this small amount of water, the realized yield (4.6 t • ha^{-1}) was quite high compared with the yield at nearby Changping (2.5 t • ha^{-1} for HD297) with the same amount of water (treatment W5, Table 1). Water productivity of aerobic rice was 164%—188% of that of flooded rice at Guanzhuang and Hanjiachuan, respectively.

Table 2 Biophysical and socio-economic performance indicators of aerobic rice and lowland rice produced by farmers at Guanzhuang and Hanjiachuan

Site	Guanzhuang								Hanjiachuan	
Rice type	Aerobic				Lowland				Aerobic	Lowland
Farmer	1	2	3	*Mean*	1	2	3	*Mean*		
Area (ha)	0.4	0.2	0.3	0.3	0.1	0.1	0.1	0.1	6.0	0.3
Yield (t ha^{-1})	4.7	6.1	6.6	5.8	7.7	7.9	8.3	7.9	4.6	7.1
Irrigation (mm)	550	538	539	542	1,129	1,355	1,390	1,291	177	1,057
Total water (mm)	620	608	609	612	1,199	1,425	1,460	1,361	476	1,394
Total water productivity (g kg^{-1})	0.75	1.01	1.08	0.95	0.64	0.55	0.56	0.58	0.96	0.51
Irrigation water productivity (g • kg^{-1})	0.85	1.14	1.22	1.07	0.68	0.58	0.59	0.61	2.58	0.67
Paid-out costs ($ ha^{-1})	352	375	355	361	266	338	321	308	369	441
Own labor (h • ha^{-1})	270	465	398	378	813	750	931	831	101	435
Price of labor ($ d^{-1})	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	3.1	3.1
Price of grain ($ kg^{-1})	0.15	0.15	0.15	0.15	0.12	0.15	0.12	0.13	0.23	0.23
Production value ($ ha^{-1})	698	920	988	868	899	1,181	969	1,017	1,041	1,639
Gross returns ($ ha^{-1})	345	545	633	508	633	843	649	708	671	1,198
Net returns ($ ha^{-1})	282	437	539	419	443	667	431	513	632	1,028

Note: all costs and prices converted from Yuan into US dollar using 1Y = 0.125 $.

At both sites, the value of production of aerobic rice was lower (15% at Guanzhuang and 36% at Hanjiachuan) than that of lowland rice because of the lower yields. At Guanzhuang, the aerobic HD502 fetched a market price that was about 25% higher than that of the lowland varieties because of better quality. At Hanjiachuan, the price of the aerobic rice was the same as that of the lowland rice, which was considerably higher than at Guanzhuang because of its proximity to Beijing. Because of the higher rice price, the value of production was higher at Hanjiachuan than at Guanzhuang. Aerobic rice used about 55% and 73% less own labor at Guanzhuang and Hanjiachuan, respectively. This difference was caused by the higher degree of mechanization in aerobic rice (see below). At Guanzhuang, the total paid-out costs (i.e., costs of all inputs except own labor) was on average 17% higher for aerobic rice than for lowland rice. The cost for fertilizer was about the same, whereas that for seeds, pesticides, hired labor and harvest were higher and those for irrigation lower (data not shown). The higher cost for pesticides in aerobic rice was caused by the use of pre-emergence herbicides not used in lowland rice. The costs for labor and harvest were higher because land preparation, sowing and harvest was done by contracted labor. In contrast, all activities in the lowland fields were done by own labor. Since especially puddling and transplanting require much labor, the (own) labor requirements for lowland rice were more than two times those for aerobic rice. In contrast to Guanzhuang, total paid-out costs at Hanjiachuan were 16% lower in aerobic rice than in lowland rice. Since the aerobic rice was managed by a farmer cooperative and the lowland rice by a private farmer, the cost structure can not be directly compared. However, a main difference was again that aerobic rice used less hired labor than lowland rice and that water costs were much lower. The gross returns to production (value of production minus paid-out costs) were on average 28% lower for aerobic rice than for flooded lowland rice at Guanzhuang and 44% lower at Hanjiachuan. When taking the costs of own labor into account (valued at the market price for agricultural labor), the net returns to rice production were on average 18% and 39% lower for aerobic rice than for lowland rice at Guanzhuang and Hanjiachuan, respectively.

4 Conclusion and discussion

The results of the first year, in which aerobic rice was completely new to the farmers and researchers who managed the field trial, are encouraging. Yields of aerobic rice were, as expected, lower those of flooded lowland rice. However, under aerobic conditions, the aerobic Han Dao varieties yielded higher than the lowland varieties. Thus, there is an interaction between variety and environment: the lowland varieties had higher yields under flooded conditions, but the aerobic varieties had higher yields under aerobic conditions. This demonstrates the need to breed special varieties for aerobic environments. Also, it shows the success of the current Han Dao varieties. Even in a sandy-loam soil with a 20m deep groundwater table at Changping, aerobic rice yields still reached 4.7 t • ha^{-1}—5.3 t • ha^{-1}. With the same water input, Han Dao 502 generally yielded higher than Han Dao 297, and therefore seems to be the best choice for water-scarce environments in northern China. Two additional advantages are that Han Dao 502 also gave a reasonable yield of close to 7 t • ha^{-1} under flooded conditions (compare with close to 9 t • ha^{-1} of lowland rice), and that it has a good grain quality. In the farmers' fields at Guanzhuang and Hanjiachuan, with a heavier silty loam soil and a shallower groundwater table than at Changping, pilot farmers obtained yields of 4.6 t • ha^{-1} with Han Dao 297 and 4.7 t • ha^{-1} —6.6 t • ha^{-1} with Han Dao 502.

The most salient feature of aerobic rice in our study was the extremely low water input used to realize the reported yields: the combined amount of rainfall and irrigation water from sowing to harvest varied from 470 to 650 mm, compared with 1,350—1,400 mm in lowland rice. This means that aerobic rice can be grown in water-short areas that have insufficient water for the production of lowland rice. Since, compared with lowland rice, the water input of aerobic rice is more reduced than the yields, the water productivity of aerobic rice is higher that that of lowland rice (64%—88% in our study). Consequently, in areas where water is relatively more scarce than land, total rice production can be maximized by growing aerobic rice. The relatively low yields of aerobic rice compared with those of lowland rice in our study, however, may also suggest that our water inputs were too low. The next experiments will include treatments in which water inputs are higher to see if yields can be increased.

The gross returns to aerobic rice farming varied from 345 to 671 \$ ha^{-1} and the pilot farmers were satisfied with these results. Because of the lower yields, these returns were lower than those from the production of lowland rice. There is no clear conclusion on the difference in total (paid-out) costs of production between aerobic and lowland rice: at Guanzhuang, it was 17% higher in aerobic rice, but at Hanjiachuan, it was 16% lower. At both sites, however, the use of (own) labor was more than 50% lower in aerobic rice than in lowland rice because of the absence of puddling and transplanting and because of the possibilities of mechanized sowing and harvesting in aerobic rice. Because of less frequent irrigation applications, the labor associated with irrigation was also smaller in aerobic rice. When the opportunity costs of labor are high, this labor-saving aspect of aerobic rice becomes an important economic consideration. Though the comparison between aerobic rice and (continuously) flooded lowland rice is interesting from an agronomic point of view, socio-economic comparisons should in the future include water-short lowland rice and other upland crops. Aerobic rice is targeted at irrigated areas where water is (getting) too scarce and/or costly to keep paddy fields permanently flooded. Such fields are currently either continued as paddy but without permanent flooding, put under an upland crop or abandoned altogether, such as at Guanzhuang. Under such conditions, the relative attractiveness of aerobic rice should be studied. However, much research still needs to be done to develop germplasm and management packages that optimize aerobic rice farming.

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