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Grain Yield and Resource Use Efficiencies of Upland and Lowland Rice Cultivars under Aerobic Cultivation

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Abstract: Aerobic rice has the potential to replace transplanted flooded rice, as rice cultivation is seriously threatened by environmental and social factors. Although the recently released upland rice cultivars have higher drought tolerance, low yield potential of these cultivars makes them less feasible for high-yielding rice planting regions under aerobic cultivation. In this study, typical lowland rice cultivars (Huanghuazhan and Yangliangyou6) were evaluated for grain yield and resource use efficiencies under aerobic cultivation as compared with upland rice cultivars (Lvhan1 and Hanyou3). Averaged across different years, lowland rice cultivars recorded 26.9%, 14.6%, and 26.6% higher grain yield, water productivity, and nitrogen use efficiency for grain production (NUE_g), respectively, as compared with upland cultivars. The higher grain yield of lowland rice cultivars under aerobic cultivation was mainly attributed to the higher aboveground biomass and the spikelet number per panicle, along with a higher harvest index and panicle number per unit area with respect to upland rice cultivars. During the entire growing season in aerobic cultivation, rainfall accounted for 60% to 85% of the total water use, which indicates that lowland rice cultivars could make better use of the rainfall because of a longer growth duration and a higher growth potential. In summary, this study suggests that with appropriate irrigation, lowland rice cultivars could grow well and furnish higher yield than the current upland rice cultivars under aerobic cultivation.

Keywords: aboveground biomass; crop growth rate; yield components; leaf area index; water productivity; nitrogen use efficiency for grain production

1. Introduction

Rice (*Oryza sativa* L.), a major food crop for more than half of the global population, is grown in over 95 countries worldwide, and about 90% of the world rice is produced and consumed in Asia [1,2]. The stability and sustainability of rice production are important for world's food security. Transplanted flooded rice is still the main rice production system worldwide. In the past, farmers usually preferred transplanted flooded rice over aerobic rice because of better weed control with the practices of transplanting, puddling, and continuous flooding. Nevertheless, the sustainability and productivity of transplanted flooded rice systems are at risk owing to labor shortage, water scarcity, and high greenhouse gas emissions in this system. Moreover, effective and eco-friendly herbicides have been developed to suppress the weeds in rice fields [3], which makes a transplanted flooded rice system unnecessary for weed control. Compared with wheat and maize, transplanted flooded rice consumes two or three times more water because a huge amount of water is lost through percolation, surface evaporation and puddling [4]. Chauhan and Opeña (2012) concluded that puddling in a transplanted flooded rice system consumes up to one-third of the total water requirement of rice [5]. In China, more than 50% of fresh water is used for rice fields every year [6]. Tuong and Bouman (2003) indicated that 39 million ha of transplanted flooded rice may face "physical water scarcity" or "economic water scarcity" in Asia by 2025 [7]. At present, per capita water resource share in China is the lowest amongst different countries in Asia [8]. Therefore, the need to make better use of the limited water resource is inevitable, particularly, for rice cultivation. Furthermore, continuous flooding has been proven to be unnecessary for rice physiological requirement, because aerobic cultivation and AWD (alternation of wetting and drying) irrigation have both provided suitable conditions for rice growth and recorded equivalent or an even better grain yield [9,10]. The transplanted flooded rice is also a major source of greenhouse gas emissions, especially methane (CH_4), since puddling and continuous flooding provides an anaerobic condition in the rice field, which promotes the activity of methanogenic bacteria to produce CH_4 [11,12]. Several previous studies have reported that reducing the flooding period through decreasing water input is an effective way to reduce CH_4 emissions [13–15]. Kang and Eltahir (2018) indicated that climate change and heavy irrigation in the North China Plain has led to deadly heatwaves and an increase in air temperature, which could be a significant threat to crop growth and human health in the near future [16]. All these issues support the need for of an alternative rice production system, particularly, for those regions having limited availability of water and labor resources.

Aerobic rice is a lowland rice planting system without puddling, which not only saves water and labor, but also lowers the emissions of greenhouse gases as compared with transplanted flooded rice [17–19]. As reported by [20], water use under aerobic culture was around 60% less than that of lowland irrigated rice, total water productivity was around 1.8 times higher, and net returns to water use were two times higher. In the past, grain yield of 5 to 6 t ha^{-1} has been frequently reported with high-yielding rice cultivars in aerobic rice systems [21–23]. In Brazil, upland cultivars with high grain yield (5 to 7 t ha^{-1}) have been developed [24], whereas Wang et al. (2002) found that the rice grain yield of 8 t ha^{-1} and even higher can be accomplished using high-yielding upland cultivars with suitable management practices in northern China [20]. The highest record of grain yield under an aerobic rice system (11.4 t ha^{-1}) was observed in Japan during 2007 [25]. Grain yield of rice cultivars under aerobic culture was closely associated with water regime. Pancile size was considered as one of the main constrains for rice yield under aerobic conditions [26,27], as water restriction during the early reproductive stage can reduce panicle size by up to 40% [28]. In a previous study in North China, water restriction during vegetative stages could reduce leaf area index, and therefore delay canopy cover and decrease light interception. All these changes contributed to the decrease of aboveground biomass under water limited conditions [22].

The differences in grain yields from multi-location experiments have made the yield performance of aerobic rice complicated, and no such studies have been done in Central China, where transplanted flooded rice is a dominant rice planting system. The soil water conditions, such as ground water level and soil water capacity are totally different from North China and other countries. In Central China, there is not enough rainfall for planting irrigated rice, but farmers are able to grow rice under an aerobic culture. With the labor and water scarcity, replacing the transplanted flooded rice with a more water and labor efficient rice planting method may be a promising solution for this crisis. However, information is quite limited for researchers to estimate the performance of aerobic rice culture in this region. Moreover, the rice cultivars used in most of the previous studies were aerobic or upland rice cultivars, while the current lowland cultivars usually have longer growth duration and higher yield potential, especially the super hybrid rice cultivars which are suitable for the intensive cultivation and are sensitive to the unfavorable conditions [29]. As reported, lowland rice cultivars have a higher yield decline under severe water stress in aerobic rice system than the upland rice cultivars in North China [22]. Whether the irrigated lowland rice cultivars are suitable for aerobic cultivation or not in Central China is still a question. Moreover, nitrogen losses though volatilization and leaching are usually more serious in aerobic land than flooded fields [14]. Whether the nitrogen use efficiency could be improved by using suitable cultivars under aerobic culture needs to be explored.

In this study, we assumed that grain yield, as well as water and nitrogen use efficiencies of lowland rice cultivars with high yield potential were comparable to or even higher than those of aerobic rice cultivars under aerobic cultivation. A three-year field experiment was carried out to explore the performance of aerobic rice in Central China. To provide more information for assessing the feasibility of aerobic cultivation in Central China we evaluating the growth, grain yield, and resource use efficiencies of irrigated lowland rice cultivars as compared with upland rice cultivars under aerobic cultivation

2. Materials and Methods

2.1. Site Description

This experiment was carried out at Zhougan Village (29°51′ N, 115°33′ E) located in Dajin Town, Wuxue County, Hubei Province, China during the rice growing seasons from 2012 to 2014. The organic matter, total nitrogen, available phosphorus, and potassium content in topsoil were 17.7 g kg^{-1}, 0.17%, 30.4 mg kg^{-1}, and 80.7 mg kg^{-1}, respectively. The clay, silt, and sand content of topsoil were 10%, 64%, and 26%, respectively. The detailed meteorological data during the growing season in each year are listed in Table 1.

Table 1. Meteorological data at the experimental station during the growing season from May to October in 2012, 2013, and 2014.

Year	Solar Radiation (MJ m^{-2} d^{-1})	Average Temperature (°C)	Average Relative Humidity (%)	Average VPD (kPa)	Average Wind Speed (m s^{-1})
2012	15.9	25.6	75.0	2.41	1.32
2013	16.2	26.0	74.3	2.51	0.12
2014	13.4	24.7	79.2	2.48	0.40

VPD means vapor pressure deficit.

2.2. Experimentation

Four different cultivars (Lvhan1, Hanyou3, Huanghuazhan, and Yangliangyou6) were arranged in a randomized complete block design, with three replications, and the area of an individual plot for one cultivar in each replication was 30 m^2. Each plot was an independent replicate for a cultivar. In total, there were 12 plots (4 cultivars and 3 replicates) in each year. Lvhan1 is a typical drought resistant inbred rice cultivar with a short growth duration; Hanyou3 is a hybrid cultivar with high yield potential and high drought resistance. These two cultivars are considered as typical upland rice cultivars. Huanghuazhan and Yangliangyou6 are well-known lowland rice cultivars in Central China. Huanghuazhan is a resource efficient, widely adapted high-yielding cultivar, and is considered as "green super rice". Yangliangyou6 is the dominant super hybrid rice cultivar in the Yangtze river basin, with high yield potential and high resource use efficiencies.

Before sowing, the experimental soil was dry plowed and harrowed without puddling. In all three years, dry rice seeds were manually sown in 25 cm wide rows during the first week of May using a seed rate of 60 kg ha^{-1} for each cultivar. No irrigation was applied to the field unless severe drought stress (groundwater level < −40 cm) occurred.

A fertilizer dose of 150:40:100:5 kg N:P_2O_5:K_2O:Zn ha^{-1} was applied equally to all the treatments. All of the P_2O_5 and Zn, 26% of N, and 50% of K_2O were applied as basal dose. The remaining N was equally split at the mid-tillering and panicle initiation stages, while the remaining 50% of K_2O was top dressed at the panicle initiation stage. Weeds, diseases, and insects were controlled intensively during the whole growing season. Manual weeding was adopted to avoid phytotoxicity. Rice blast and sheath blight were the main diseases, stem and leaf borers were the main insects in Central China, which were frequently checked and carefully controlled by chemicals in this study, and therefore no obvious disease or insect damage was observed during all three years.

2.3. Data Collection

The level of groundwater was monitored using 200 cm long PVC tubes (5 cm diameter) installed at a soil depth of 150 cm, and the lower circular surface (120 cm) of these tubes was perforated with 0.5 cm holes at 2 cm intervals. The amount of irrigation water was recorded using a flow meter installed in the irrigation pipelines. Data regarding daily rainfall were measured by a rain gauge installed in the center of the experimental field. Total water use and water productivity were computed based on the water used for irrigation and rainfall during each rice growing season of each cultivar [30].

$$\text{Water productivity} = \frac{\text{Grain yield}}{\text{Irrigation} + \text{Rainfall}} \quad (1)$$

At the panicle initiation and heading stages, plants from 0.5 m^2 (1 m long two adjacent rows) were sampled from each plot. After detaching all the green leaves, the leaf area was measured using a Li-3100 meter (Li-Cor Inc., Lincoln, NE, USA). Later, the stems and leaves from each plot were separately oven dried at 70 °C to calculate the aboveground biomass. The crop growth rate before heading and the mean leaf area index from panicle initiation to heading were calculated as:

Crop growth rate between t_1 and [31]

$$t_2 = \left(\text{aboveground biomass at } t_2 - \text{aboveground biomass at } t_1\right) / (t_2 - t_1) \quad (2)$$

Mean leaf area index between t_1 and [31]

$$t_2 = (\text{leaf area index at } t_2 - \text{leaf area index at } t_1) / \{(\ln(\text{leaf area index at } t_2) - \ln(\text{leaf area index at } t_1)\} \quad (3)$$

At maturity, all plants from 0.5 m^2 (1 m long, 2 rows) from each plot were harvested to determine the aboveground total biomass, yield attributes, and harvest index. The number of panicles in each sample was counted manually to determine the panicle number per m^2, and then plants were dissected into straw and panicles. The panicle was hand-threshed, and filled grains were separated by submerging all the spikelets into tap water. To separate the half-filled and unfilled spikelets, further screening was done using a winnowing cleanliness instrument (FJ−1; China Rice Research Institute, China). Three subsamples of filled spikelets (30.0 g), unfilled spikelets (2.0 g), and half-filled spikelets (all) were chosen to record the number of spikelets. The dry weights of straw, rachis, as well as unfilled, half-filled, and filled spikelets were recorded after oven drying (70 °C) till a constant weight. Total aboveground dry biomass represents the aggregate of all the spikelets, rachis, and straw. The spikelet number per panicle was counted manually. Grain filling percentage was calculated as the percent ratio of filled spikelet number and total spikelet number, and the harvest index was computed as the percent ratio of filled spikelet weight and total aboveground biomass. Grain yield was recorded from an area of 5 m^2 in each plot and adjusted to standard moisture content (0.14 g H_2O g^{-1} fresh weight).

Tissue N concentration (grains and straw) was recorded using a CN analyzer (Vario Max CN, Hannau, Germany). Nitrogen use efficiency for grain production (NUE_g) was computed as the ratio of filled grain weight to total N uptake.

2.4. Statistical Analysis

Analysis of variance (ANOVA) was performed using the generalized linear model procedure in Sigma Plot 14.0 to assess the effects of the cultivar group, year, and cultivar group × year interaction on grain yield, aboveground biomass at maturity, harvest index, and yield components. Statistical significance was reported at $p < 0.05$. When the ANOVA result was significant, we compared pairs of values between two cultivar groups or any two of the three years using Fisher's least significant difference (LSD) test. Regarding the biomass accumulation before heading, leaf area index, crop growth rate, water productivity, and nitrogen use efficiency for grain production, an individual analysis of variance (ANOVA) was conducted for each year in the generalized linear model to assess the differences among cultivar groups.

3. Results

3.1. Precipitation and Irrigation

The total precipitation at the experimental station during the rice growing season was 576, 489, and 809 mm in 2012, 2013, and 2014, respectively. On the basis of the groundwater level, irrigation was applied four times in 2012 and 2013, and only two times in 2014. The corresponding irrigation water was 186, 292, and 137 mm in 2012, 2013, and 2014, respectively (Figure 1).

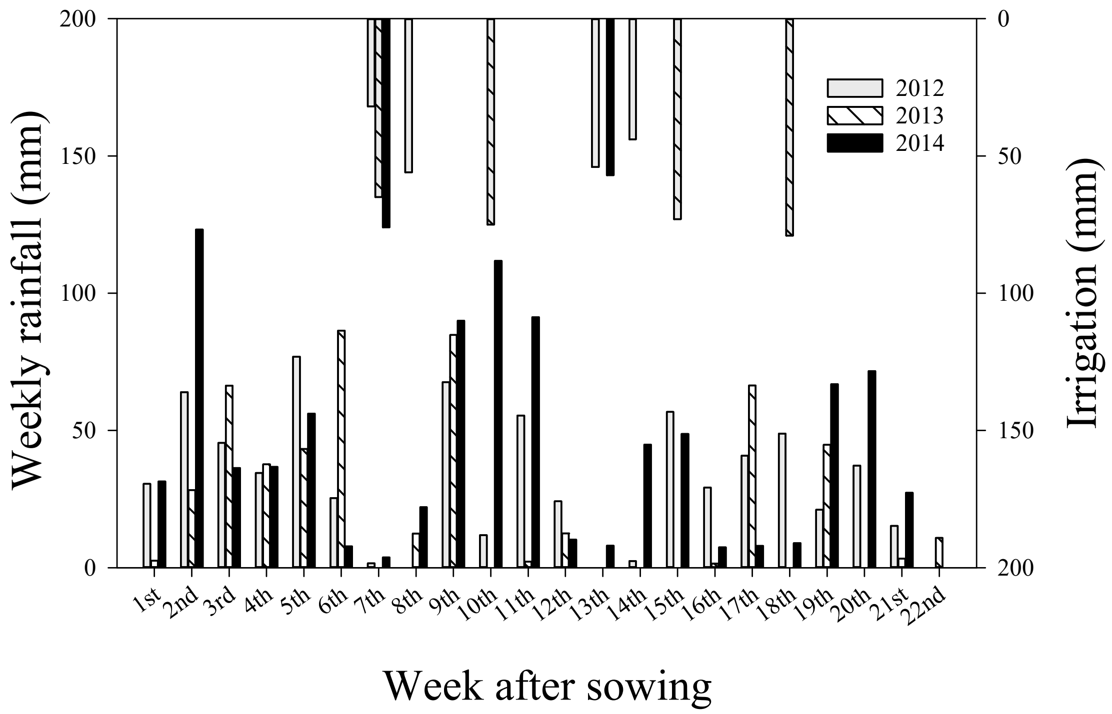

Figure 1. Precipitation (bottom) and irrigation (top) distribution during the rice growing season in all three years, from 2012 to 2014.

3.2. Crop Growth and Phenological Traits

To dissect the characteristics of plant growth in Lvhan1, Hanyou3, Huanghuazhan, and Yangliangyou6, aboveground biomass, leaf area index (LAI), and crop growth rate were calculated (Figures 2 and 3). On average, Lvhan1 (upland inbred cultivar) had 25.5% higher aboveground biomass accumulation and 20.2% higher LAI than Huanghuazhan (lowland inbred cultivar) at the panicle initiation stage, across all three years (Figure 2A,C), while the result was the reverse at the heading stage, higher aboveground biomass and LAI was found in Huanghuazhan, rather than Lvhan1 (Figure 2B,D). The aboveground biomass and LAI of Hanyou3 at the panicle initiation stage were 6.2% and 3.0% higher than those of Yangliangyou6, respectively, however, these differences were statistically nonsignificant during all three years. Whereas at the heading stage, the aboveground biomass and LAI of Hanyou3 were 8.8% and 3.3% lower than those of Yangliangyou6, respectively. The difference in aboveground biomass at the heading stage between Hanyou3 and Yangliangyou6 were significant ($p < 0.05$) during all three years.

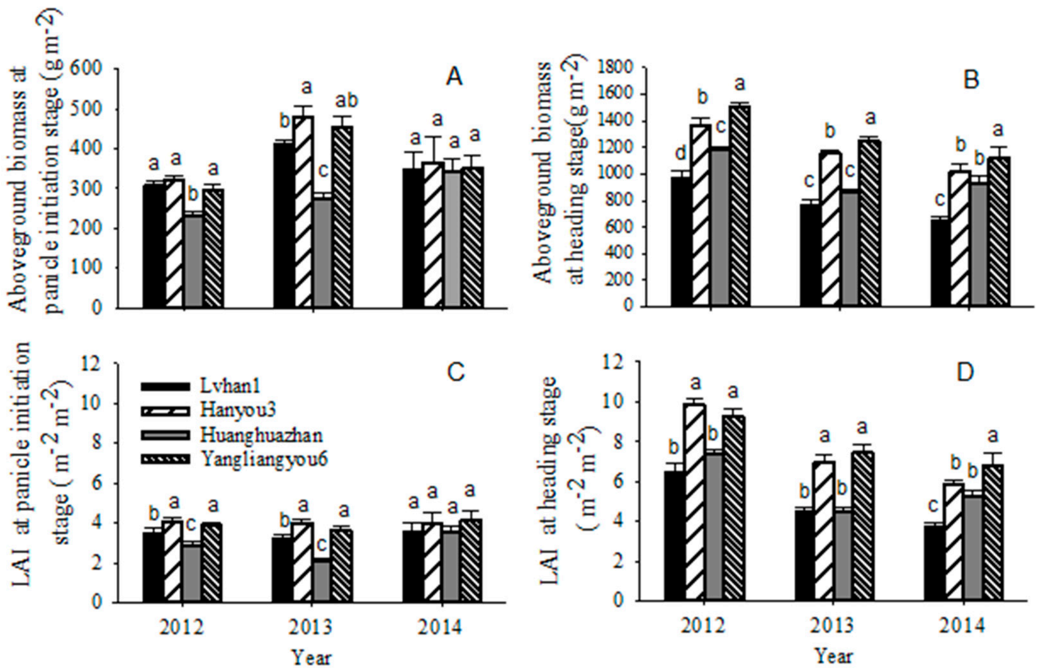

Figure 2. Aboveground biomass at the panicle initiation (**A**) and the heading (**B**) stages, and leaf area index (LAI) at panicle initiation (**C**) and heading (**D**) of four tested cultivars in all three years. Lvhan1 (inbred) and Hanyou3 (hybrid) are typical upland rice cultivars. Huanghuazhan (inbred) and Yangliangyou6 (hybrid) are well-known lowland rice cultivars. Error bars represent SE. Different letters in each year means the significant differences at 0.05 level. Data were recorded based on the sampling area of 0.5 m^2.

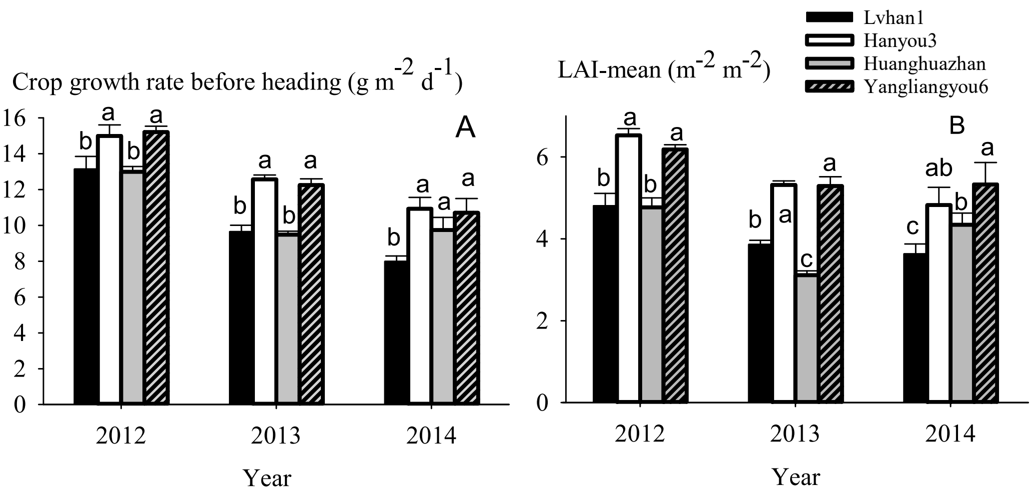

Figure 3. Crop growth rate (CGR) from sowing to heading (**A**) and mean leaf area index (LAI) from panicle initiation to heading (**B**). Lvhan1 (inbred) and Hanyou3 (hybrid) are typical upland rice cultivars. Huanghuazhan (inbred) and Yangliangyou6 (hybrid) are well-known lowland rice cultivars. Error bars represent SE. Different letters in each year means the significant differences at 0.05 level. Data were recorded based on the sampling area of 0.5 m^2.

Compared with upland cultivars, lowland cultivars did not show any disadvantages in crop growth rate before the heading stage, across all three years (Figure 3). In 2014, the crop growth rate and mean LAI of Huanghuazhan was significantly higher ($p < 0.05$) than that of Lvhan1 (Figure 3A,B).

Phenological traits, including days to heading and growth duration, both largely varied among cultivars (Table 2). Lvhan1 had the shortest growth duration (around 110 days) among the four cultivars during all three years. Growth durations of both Hanyou3 and Huanghuazhan were around 125 days, and Yangliangyou6 had a 15-day longer growth duration (around 140 days) than that of Hanyou3 and Huanghuazhan. The gap of growth duration among cultivars mainly emerged in the vegetative stage, from sowing to heading. On average, lowland cultivars had around a 15-day longer growth duration than that of the upland cultivars (Table 2). With a longer growth duration, the aboveground biomass of Huanghuazhan and Yangliangyou6 at the heading stage was even higher as compared with Lvhan1 and Hanyou3, respectively (Figure 2B).

Table 2. Days to heading and growth duration of four tested cultivars under aerobic cultivation in all three years.

Cultivar	Days to Heading			Growth Duration (Day)		
	2012	2013	2014	2012	2013	2014
Lvhan1	74	80	82	110	108	108
Hanyou3	91	92	95	125	124	127
Huanghuazhan	91	91	95	125	124	127
Yangliangyou6	99	102	105	142	138	141

Lvhan1 (inbred) and Hanyou3 (hybrid) are typical upland rice cultivars. Huanghuazhan (inbred) and Yangliangyou6 (hybrid) are well-known lowland rice cultivars.

3.3. Grain Yield, Water and Nitrogen Use Efficiencies for Grain Production

Specifically, the average grain yield of tested cultivars across all three years varied from 6.58 to 9.78 Mg ha^{-1} and the highest grain yield was observed in Yangliangyou6, followed by Huanghuazhan, Hanyou3, and Lvhan1. Among these four cultivars, the highest aboveground biomass was the key contributor to the highest yield production of Yangliangyou6, and the smallest panicle size ccould be responsible for the lowest grain yield of Lvhan1 (Table 3).

Table 3. Grain yield, aboveground biomass, harvest index of two cultivar groups including four rice cultivars under aerobic culture in all three years.

Factors	Grain Yield (Mg ha^{-1})	Aboveground Biomass (g m^{-2})	Harvest INDEX
Cultivar			
Lvhan1	6.58	1262	0.48
Hanyou3	7.56	1679	0.42
Huanghuazhan	8.16	1504	0.49
Yangliangyou6	9.78	1824	0.48
Cultivar group (C)			
Upland cultivars	7.07	1471	0.45
Lowland cultivars	8.97	1664	0.48
Year (Y)			
2012	8.52	1881	0.41
2013	8.02	1574	0.49
2014	7.51	1246	0.50
LSD (0.05)			
Cultivar group (C)	0.57	151	0.04
Year (Y)	0.70	185	0.02
C × Y	ns	ns	ns

ns means no significant difference at 0.05 probability level. Lvhan1 (inbred) and Hanyou3 (hybrid) are typical upland rice cultivars. Huanghuazhan (inbred) and Yangliangyou6 (hybrid) are well-known lowland rice cultivars. Grain yield was harvested at a sampling area of 5 m^2, other parameters were recorded based on the sampling area of 0.5 m^2.

On average, grain yield of the lowland cultivars under aerobic conditions was 26.9% higher than that of the upland cultivars across all three years. This was mainly attributed to the significantly higher ($p < 0.05$) aboveground biomass accumulation in lowland cultivars. The harvest index was not significantly different between the two cultivar groups (Table 3). In another aspect, a higher spikelet number per unit area was also responsible for the higher grain yield in lowland cultivars as compared with upland cultivars. No significant difference was found in grain filling percentage between the two cultivar groups, however, grain weight in upland cultivars was significantly higher ($p < 0.05$) than that of lowland cultivars (Table 4). Significant declines in grain yield, aboveground biomass, panicle number, and spikelet number per unit area were observed from 2012 to 2014.

Table 4. Yield components of two cultivar groups including four rice cultivars under aerobic culture in all three years.

Factors	Panicle Number (m^{-2})	Spikelets Per Panicle	Spikelets (m^{-2})	Grain Filling Percentage (%)	1000-Grain Weight (g)
Cultivar					
Lvhan1	340	88	29,977	80.4	25.2
Hanyou3	300	95	27,917	81.7	30.5
Huanghuazhan	390	118	46,339	79.8	20.2
Yangliangyou6	319	116	36,696	84.7	28.2
Cultivar group (C)					
Upland cultivars	320	91	28,947	81.0	27.9
Lowland cultivars	354	117	41,517	82.2	24.2
Year (Y)					
2012	405	106	43,337	71.8	25.7
2013	320	110	35,391	86.3	25.6
2014	286	96	26,968	86.7	26.8
LSD (0.05)					
Cultivar group (C)	32	11	3665	Ns	2.6
Year (Y)	39	11	4489	4.1	ns
C×Y	ns	11	ns	ns	ns

ns means no significant difference at 0.05 probability level. Lvhan1 (inbred) and Hanyou3 (hybrid) are typical upland rice cultivars. Huanghuazhan (inbred) and Yangliangyou6 (hybrid) are well-known lowland rice cultivars. Grain yield was harvested at a sampling area of 5 m^2, other parameters were recorded based on the sampling area of 0.5 m^2.

Averaged across three different years, lowland cultivars under aerobic cultivation recorded 14.6% higher water productivity than upland cultivars. No significant difference in water productivity was found between inbred cultivars, Lvhan1, and Huanghuazhan, in 2012, while the differences were significant in 2013 and 2014. As for hybrid cultivars, there was a large gap (averagely, 0.21 kg grain/kg water) in water productivity between Yangliangyou6 and Hanyou3 (Figure 4).

Nitrogen use efficiency for grain production (NUEg) of lowland cultivars under aerobic cultivation was 26.6% higher than that of upland cultivars (Figure 5). The NUEg of Huanghuazhan was 12.9% and 24.5% higher than that of Lvhan1 in 2012 and 2013, respectively, while in these two years, Yangliangyou6 had 46.3% and 26.4% higher NUEg than that of Hanyou3, respectively. In 2014, the data on NUEg were not presented because N analysis was not conducted due to fund limitations.

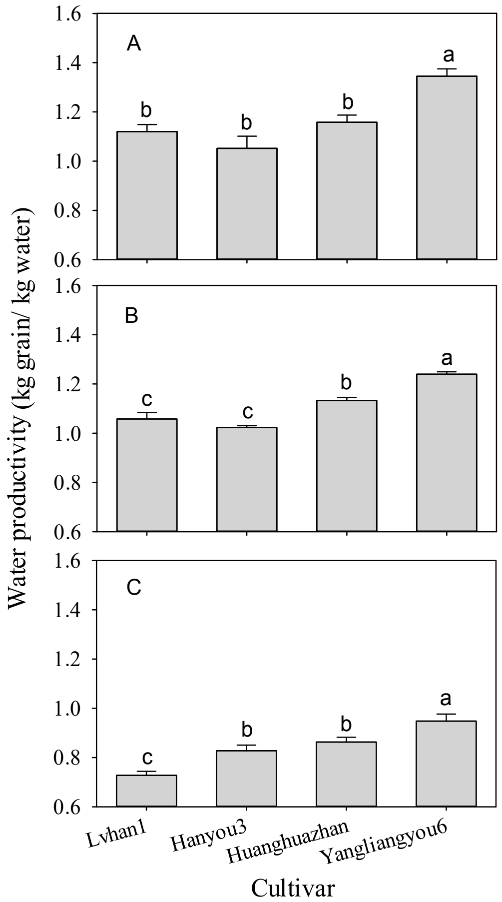

Figure 4. Comparison of water productivity (WP) among tested rice cultivars in 2012 (**A**), 2013 (**B**), and 2014 (**C**). Lvhan1 (inbred) and Hanyou3 (hybrid) are typical upland rice cultivars. Huanghuazhan (inbred) and Yangliangyou6 (hybrid) are well-known lowland rice cultivars Error bars represent SE. Different letters in each year means the significant differences at 0.05 level.

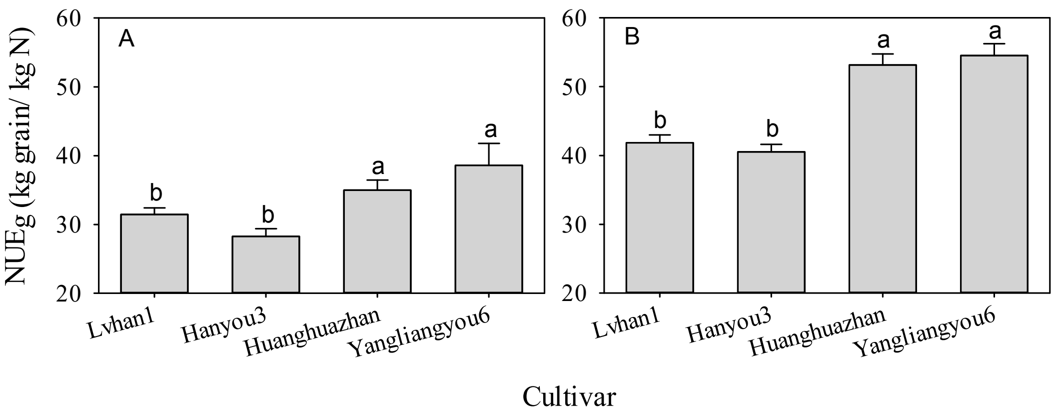

Figure 5. Comparison of nitrogen use efficiency for grain production (NUEg) among tested cultivars in 2012 (**A**) and 2013 (**B**). Lvhan1 (inbred) and Hanyou3 (hybrid) are typical upland rice cultivars. Huanghuazhan (inbred) and Yangliangyou6 (hybrid) are well-known lowland rice cultivars. Error bars represent SE. Different letters in each year means the significant differences at 0.05 level.

4. Discussion

The present study evaluated the growth, grain yield, and resources use efficiencies of irrigated lowland rice cultivars as compared with upland rice cultivars under aerobic cultivation. In this study, total water input was 762 to 945 mm during the three years of the study, which was consistent with previous researches that reported the total water use of aerobic rice including irrigation and precipitation was usually around 750 to 1400 mm [10]. Throughout the three years, precipitation was sufficient in May and early June, reporting that after dry seeding in the first week of May, precipitation could provide enough water for rice germination and early seedling growth. Under aerobic cultivation, irrigation was supplied two to four times per season as compensation when needed during the whole crop period. Irrigation only accounted for 14.5% to 37.4% of the total water input. These results suggested that aerobic cultivation was more conducive to water saving, although making better use of precipitation, and reducing irrigation and evaporation [9]. Moreover, aerobic rice cultivation has also been known to reduce the emissions of greenhouse gases, including methane, vapor, and carbon dioxide, because of the environmentally-friendly irrigation practice as compared with traditional rice farming [32–34].

The lower yield performance of upland cultivars as compared with lowland cultivars under aerobic cultivation in Central China was because upland cultivars were bred with the specialty of shorter growth duration and lower aboveground biomass accumulation [35–37]. The upland cultivars were usually planted in the drought-prone regions in the past. In order to ensure the rice performance in drought-prone areas, different strategies including drought escape, drought tolerance, and drought avoidance were used to improve the drought resistant ability of upland rice cultivars, which was usually combined with a short growth duration [36], low shoot and root ratio [38], and a low photosynthesis rate [39–41]. All these features were responsible for the low grain yield of upland cultivars. Nevertheless, as observed in this study, precipitation in Central China is not a limiting factor for rice to complete its life cycle, thus high drought resistant ability combined with short growth duration and low biomass accumulation of upland cultivar becomes a disadvantage for achieving high yields, which differed from previous research results in North China, where precipitation was limited and ground water was usually at a relatively low level [22].

As compared with upland cultivars, lowland cultivars accumulated more aboveground biomass and maintained higher functional leaf area (Figure 2), which are essential for high-yielding ability. Moreover, a two-week longer growth duration of lowland cultivars was helpful for higher biomass accumulation before flowering, which could be one of the main reasons for higher yields of Huanghuazhan and Yangliangyou6 [42], however, early vigor ability was obvious in upland cultivars, which helped to compete with weeds in the aerobic field conditions [43]. Because lowland cultivars still lack early vigor ability, they could be improved in future lowland rice cultivar breeding programs.

Huanghuazhan and Yangliangyou6 are both mega lowland cultivars, which have the characteristics of high yield potential and multiresistance [44,45]. Although the grain yield of lowland cultivars under aerobic cultivation in this study was decreased as compared with the yield performance in paddy field in other experiments at nearby experimental stations [3,9,46], these cultivars were still better choices in terms of grain yield as comparing with Lvhan1 and Hanyou3 under dry seeding aerobic cultivation.

Yield decline was observed in aerobic rice in three continuous years. Across the cultivars, the average grain yield decreased from 8.52 to 7.51 Mg ha^{-1} in all three years, which was accompanied with the reduction of aboveground biomass, panicle number per m^{-2}, and spikelet number per m^{-2}. This might be related to the soil condition and fertilizer availability in aerobic rice fields. Nie et al. (2012) reported that aerobic rice suffered from biotic and abiotic stresses, which could, therefore, result in yield decline [47], whereas nematodes were generally believed to be the biotic factor that could be responsible for the yield reduction in continuous cropping in aerobic rice [48]. Kreye et al. (2009) found that micronutrient deficiency was also partially responsible for the yield failure under continuous aerobic rice cropping [49]. As reported, suitable crop rotation could mitigate continuous cropping obstacles in aerobic rice [50]. Unfortunately, to eliminate the impact of rotating crops on aerobic rice, and to simplify the field managements, no crops were planted in our experimental field after rice, during all three years. In addition, the results also suggest that yield decline, resulting from monocropping in aerobic rice, happened not only in tropical areas, but also in Central China.

In this study, the water productivity of Yangliangyou6 was 21.5% higher than that of Hanyou3 under aerobic cultivation. Previously, Yao et al. (2012) conducted an experiment to compare the water productivity among different water regimes (alternate wet and dry and continuous flooding) based on transplanted rice in Central China, which showed that Yangliangyou6 had a 15.8% and 10.1% higher water productivity under continuous flooding and alternate wet and dry irrigation, respectively, as compared with Hanyou3 [9]. Usually, higher water productivity is accompanied with higher grain yield [22], and therefore yield decline could be responsible for the water productivity reduction. In contrast, the lower NUEg in 2012, was mainly attributed to the higher total nitrogen uptake and total biomass accumulation, which could be due to the favorable radiation interception and temperature [30].

5. Conclusions

Taking all aspects into consideration, the lowland cultivars, Yangliangyou6 and Huanghuazhan, recorded higher grain yield, higher biomass accumulation, higher water and nitrogen use efficiencies, and longer growth duration than that of the upland cultivars, which indicated that these two lowland cultivars were suitable for aerobic cultivation in Central China, where rainfall was enough to fulfill the basic need of rice growth. In the past, upland rice breeding programs that targeted extreme drought stress had seriously limited the yield potential of upland rice cultivars. Nowadays, rice cultivation systems are changing. Aerobic rice cultivation is not only the forced choice for farmers in semiarid regions, but also the alternative choice to transplanted flooded rice system. In this case, the high-yielding ability of rice cultivars used in an aerobic system is essential for ensuring the food security. Therefore, upland rice cultivars with high yield potential or lowland rice with early vigor ability is needed in aerobic cultivation systems, however, the limited cultivars tested in this study were not enough to conclude that all the lowland cultivars could perform better than upland cultivars. Nevertheless, our study did provide forward-looking information that some lowland cultivars could be directly used in aerobic systems. Selecting the optimum cultivars from the current lowland cultivars for aerobic culture should be urgent work for plant breeders.

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