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From flooded to aerobic conditions in rice cultivation: Consequences for zinc uptake

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Abstract

Scarcity of water causes a shift from flooded to aerobic conditions for rice production in zinc deficient areas in Northern China. This shift alters soil conditions that affect zinc availability to the crop. This paper concerns the effect of aerobic compared to flooded conditions on crop biomass production, grain yield and zinc content. A field experiment was done with six rice genotypes (*Oryza sativa* L.) grown on a calcareous soil, both with (23 kg Zn ha^{-1}) and without Zn fertilization. Sampling was conducted at tillering and physiological mature stage. Zn concentration in the shoots was significantly lower at both stages in plants grown in the aerobic field. At maturity, Zn uptake, biomass production, grain yield and Zn-harvest index [grain Zn/(shoot + grain Zn)] were lower under aerobic cultivation. Rice genotypes including aerobic rice and lowland rice differ in degree of response to low Zn supply. A twofold difference was found among aerobic genotypes in grain yield and Zn uptake. Also Zn-harvest index varied significantly. Zn application affected neither grain yield nor grain Zn content, although it significantly improved biomass production in both systems in most genotypes. These results demonstrate that introduction of aerobic rice systems on calcareous soils may increase Zn deficiency problems.

Introduction

Zn deficiency in cereal plants is a well-known problem that causes reduced agricultural productivity all over the world (Cakmak et al., 1999; Fageria et al., 2002). In addition, it causes widespread Zn deficiency in humans, especially in developing countries where diets are cereal-based and poor in animal and fish products (Cakmak et al., 1999; Frossard et al., 2000).

Because of water constrains, rice production in China is now undergoing important changes from traditional high water-consuming lowland (paddy) rice cultivation to a promising new cultivation method of “aerobic rice”. Aerobic rice is grown as a dry field crop in irrigated but non-flooded and non-puddled fertile soils (Bouman et al., 2002). In China, breeders have produced aerobic rice varieties with an estimated yield potential of 6–7 t ha^{-1} which are now being pioneered by farmers on some 190,000 ha in Northern China where water is increasingly getting scarce and where water scarcity makes lowland rice uneconomic (Wang et al., 2002).

Many of the soils under flooded rice cultivation in North China are Zn-deficient (DTPA-extractable Zn < 1.0 mg kg^{-1}; Sims and Johnson, 1991). The major causes are high pH, high carbonate content and low redox potential (Marschner,

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1993; Mandal et al., 2000). Fe oxidation by root-released oxygen causes a reduction of the rhizosphere pH and limited release of Zn from highly insoluble fractions (Kirk and Bajita, 1995). Many factors that determine Zn bioavailability are expected to change after a shift to aerobic cultivation. Bulk soil pH may either increase or decrease depending on the original soil pH (Liu, 1996). Redox potential will increase (Gao et al., 2002), causing Fe oxidation, with concomitant acidification, precipitation of $Fe(OH)_3$ and adsorption of Zn on these oxides. Increased nitrification may cause plants to take up NO_3^- instead of NH_4^+ (Sanchez, 1976; Voesenek and Veen, 1994), which also causes the rhizosphere pH to decrease. Organic matter, onto which Zn can be adsorbed, will be oxidized. Furthermore, reduction of the water content of the soil may restrict Zn transport towards the plant root (Yoshida, 1981). The consequence of all these changes for Zn bioavailability is hard to predict.

The shift from flooded to aerobic conditions sets the problem of Zn deficiency in rice in a new perspective. Considerable effort has been attributed to identifying Zn-efficient genotypes to improve productivity on Zn-deficient soils. Many studies have shown that there is considerable variation in tolerance to Zn deficiency in the lowland rice germplasm (Sakal, 1977; Sakal et al., 1989; Singh et al., 1981). The mechanism, by which a genotype thrives well in Zn-deficient soil whereas others fail, is not well understood. The change of water management from flooded to aerobic conditions will raise new scientific questions on this subject. Few papers report on Zn efficiency and the mechanisms that are involved in Zn efficiency for lowland rice (Dobermann and Fairhurst, 2000; Sakal et al., 1989). Yet, studies regarding the variation in Zn efficiency within and among aerobic rice varieties are not available.

In order to evaluate the consequences of this shift in cultivation system we compared Zn efficiency of rice genotypes under aerobic and flooded cultivations. We used one lowland and five aerobic genotypes to assess genotype variation in the response to this shift.

Materials and methods

A field experiment was conducted in 2003 at an experimental station of China Agricultural University in Dongbeiwang, a northern suburb of Beijing. The soil is a calcareous alluvial soil (calcareous Cambisoil, ISSS, ISRIC, and FAO, 1998). Previous crops on this site showed Zn deficiency, but due to Zn application in the previous year Zn availability is above critical levels (Sims and Johnson, 1991; Table 1). This field was used in the previous 3 years for research on water use efficiency and nitrogen use efficiency of rice on both aerobic and flooded fields. The flooded field in this experiment had been under flooded conditions and aerobic field under aerobic conditions in the earlier years (2000–2002). Some soil properties are given in Table 1.

The experiment was designed as a randomized complete block with a split-plot arrangement and four blocks under both aerobic and flooded cultivation, with four replicates. Main plots were Zn fertilizer rates (0 and 23 kg ha^{-1} Zn as $ZnSO_4$, 3 days prior to sowing) and subplots were different rice genotypes (*Oryza sativa* L.). The area of each subplot was 6 m^2 (3×2 m). Flooded and aerobic areas were separated by 6 m-wide protection rows, on which aerobic rice was sown.

All rice genotypes (*Oryza sativa* L.) were known to have similar growth duration. Zn concentration of the seeds in mg kg^{-1} was: 15.3, 18.6, 26.9, 26.5, 17.0, 20.2, for Qiuguang, Han297, Han277, Han72, 89B271-17hun (89B) and K150, respectively. Genotype Qiuguang is a japonica lowland genotype, widely used in Northern China. The other genotypes are

Table 1. Physical and chemical properties of the soil

Depth (cm)	Texture	Bulk density (g cm^{-3})	pH (H_2O)	CEC (cmol kg^{-1})	OM[1] (g kg^{-1})	Total N (g kg^{-1})	Olsen-P (mg kg^{-1})	NH_4OAc-K (mg kg^{-1})	DTPA-Zn (mg kg^{-1})
0–30	Loam	1.33	8.0	11.1	21.4	1.17	34.6	145	2.0

[1]OM = organic matter.
All analyses were done before fertilizer application.

aerobic varieties. Han297 is a widely used genotype. Han277, 89B and Han297 had shown relatively high Zn efficiency in preliminary experiments, whereas K150 and Han72 had shown a low Zn efficiency.

Seeds were sown in rows 20 cm apart on May 12 at a rate of 150 kg ha^{-1}. Nitrogen was applied as urea (225 kg N ha^{-1}), of which 40% was applied at sowing, 30% at tillering stage and 30% at booting stage. Thirty nine kg P ha^{-1} as $NH_4H_2PO_4$ and 75 kg K ha^{-1} as KCl were applied as base fertilizers at sowing. The plots were kept free of weeds by an application of pre-emergence herbicide and hand weeding after crop establishment.

Two water treatments as aerobic and flooded cultivation were imposed. For aerobic cultivation, the irrigation was commenced at sowing and at visual symptoms of drought stress. Four sprinkler irrigations were applied: on May 12, May 21, July 15 and August 13. The fields that were used for rice cultivation under flooded conditions were submerged from June 16 (35 days after sowing (DAS)) until September 25 (130 DAS) with water delivered using flexible hoses connected to a deep groundwater well. Prior to submergence, these fields received the same irrigation as the aerobic fields.

The crop was sampled twice because plant Zn deficiency symptoms usually show early in crop development. The first sampling was at the tillering stage (July 5, 53 DAS); the other at the physiological maturing stage when the grains become hard and have about 20% moisture in them (October 15, 156 DAS, Yoshida, 1981). At the tillering stage, two 50 cm segments of a row were sampled. Shoot samples from these two segments were bulked. At maturing stage, 1.5 m^2 (2.5×0.6) in the center of each plot was harvested to determine grain and straw yield. Samples were washed briefly in 0.1% HCl followed by tap water and deionized water. Total dry matter and grain weight were then determined by oven drying the sampled plants at 80°C for 72 h.

After grinding, the oven dried sub-samples of straw and whole grains were digested in acid mixture (HNO_3 + $HClO_4$) (Jackson, 1973). Zn in plant digests was analyzed using an atomic absorption spectrophotometer (Pye Unicam SP 9 800, Cambridge, UK).

Statistical analysis of the data was performed using the SAS analytical software (SAS, 1990). Analysis of variance (ANOVA) was employed and LSD ($P < 0.05$) was used to test the difference among treatments.

Results

Tillering stage

Cultivation effects. Cultivation significantly affected shoot dry weight and shoot Zn concentration, but did not affect shoot Zn content (Table 2, Figure 1). Shoot Zn concentrations were lower under aerobic than under flooded conditions (Figure 1). This effect of cultivation was similar for both Zn rates (Table 2) and for all genotypes except Han297. In aerobic fields, shoot Zn concentration without Zn application in three genotypes (Qiuguang, K150 and Han297) was below the sufficiency level for adequate growth (20 mg kg^{-1}), but well above the level below which Zn is deficient (10 mg kg^{-1};

Table 2. Results of three factor ANOVA (*P*-values) for shoot dry weight, shoot Zn concentration and shoot Zn content at tillering stage

Sources	DF	Shoot dry weight	Shoot Zn concentration	Shoot Zn content
Cultivation (C)	1	0.0001	0.0001	0.4067
Zn rate (Zn)	1	0.0001	0.0001	0.0001
Genotype (G)	5	0.0001	0.0030	0.0001
C * Zn	1	0.0918	0.9892	0.6122
C * G	5	0.1939	0.8247	0.8709
Zn * G	5	0.9655	0.4057	0.3575
C * Zn * G	5	0.0689	0.4854	0.8382

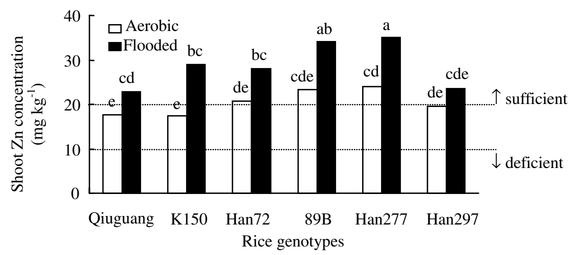

Figure 1. Cultivation effect on shoot Zn concentration of plants without Zn application at tillering stage. Means with the same letter are not significantly different ($P < 0.05$).

Dobermann and Fairhurst, 2000). Zn application resulted in an increase in shoot Zn concentration to levels above sufficiency level for all genotypes (data not shown).

Genotype and Zn application significantly affected shoot dry weight, shoot Zn concentration and shoot Zn content (Table 2). Shoot dry weight of the genotypes Qiuguang, K150 and Han297 in aerobic fields was significantly increased when Zn was applied. This effect of Zn application was absent in flooded fields (Figure 2).

Genotype effects. Shoot dry weight, shoot Zn concentration and shoot Zn content varied significantly among genotypes (Table 2). Zn efficiency, defined as the capacity of a genotype to maintain growth under low Zn conditions (Graham and Rengel, 1993), was higher for aerobic genotypes (Table 3). There was considerable variation among aerobic genotypes.

No interaction effects were found among cultivation type, Zn application rate and genotype (Table 2). Zn application increased the level of all three parameters given in Table 2, independent of cultivation type and genotype.

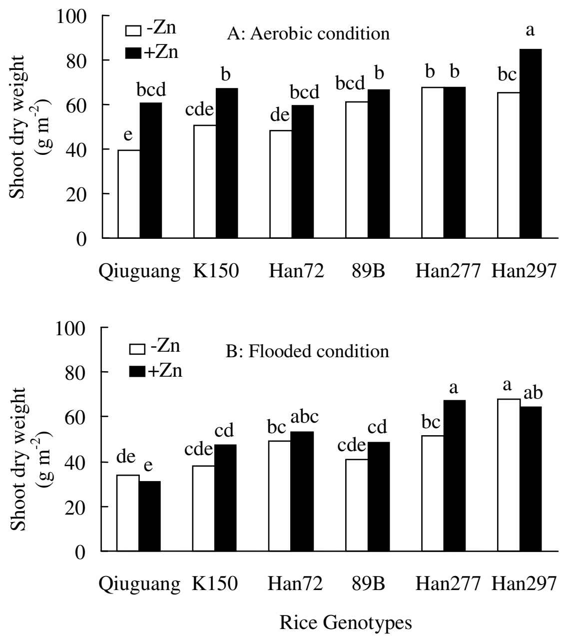

Figure 2. Effect of Zn application on shoot dry weight under aerobic (A) and flooded (B) condition at tillering stage. Means with the same letter are not significantly different ($P < 0.05$).

Table 3. Zn efficiency of rice genotypes grown under aerobic condition

	Genotypes					
	Lowland	Aerobic				
	Qiuguang	K150	Han72	89B	Han277	Han297
Zn efficiency*	64	75	81	92	100	77

*Zn efficiency = shoot dry weight (–Zn)/shoot dry weight (+Zn) × 100%.

Mature stage

Cultivation effects. Similar to the results of tillering stage, the cultivation system had a significant effect on shoot Zn concentration (Table 4). Shoot Zn concentration was lower in aerobic than in flooded fields for genotypes K150, 89B and Han297 (Figure 3). Grain Zn concentration was unaffected (Table 4).

Grain yield was significantly affected by cultivation for all genotypes. This was, however, not the case for shoot dry weight. Plants grown under aerobic conditions had significantly lower grain yields than those grown under flooded conditions (Table 4; Figure 4). This effect of cultivation system was similar for both Zn rates (Table 4).

Harvest index under aerobic conditions was significantly lower than under flooded conditions (Tables 4 and 5). The same was true for Zn-harvest index (Table 5), defined as the grain Zn content (in g or mol) divided by the shoot Zn content, which was 27% lower under aerobic cultivation.

Genotype effects. Genotypes varied significantly in shoot Zn concentration but not in grain Zn concentration (Table 4). Genotypes 89B, Han277 and Han297 yields were significantly higher than yields of the other three genotypes under aerobic conditions (Figure 4). Genotype 89B also had the highest harvest index, both for dry matter and for Zn (Table 5). Significant variation in Zn-harvest index was found among the other genotypes (Table 5).

Zn application effects. Zn application significantly increased shoot Zn concentration and shoot dry weight. Grain yield, grain Zn concentration (Table 4), and harvest index (Table 5),

Table 4. Results of three factor ANOVA (*P*-values) for shoot dry weight, grain yield, shoot Zn concentration, grain Zn concentration, harvest index and Zn-harvest index at mature stage

Sources	DF	Shoot dry weight	Grain yield	Shoot Zn concentration	Grain Zn concentration	Harvest index	Zn-harvest index
Cultivation (C)	1	0.0028	0.0001	0.0001	0.7908	0.0001	0.0001
Zn rate (Zn)	1	0.0022	0.4873	0.0003	0.4828	0.0149	0.0043
Genotype (G)	5	0.0001	0.0001	0.0003	0.1032	0.0001	0.0003
C * Zn	1	0.1555	0.8768	0.5566	0.5022	1.0000	0.6085
C * G	5	0.0120	0.0001	0.0044	0.0656	0.0001	0.0001
Zn * G	5	0.5920	0.7184	0.8593	0.9824	0.9411	0.8397
C * Zn * G	5	0.1452	0.9908	0.0031	0.8680	0.4300	0.1449

Harvest index = grain yield/(grain yield + shoot dry weight).
Zn-harvest index = grain Zn content/(shoot + grain Zn content).

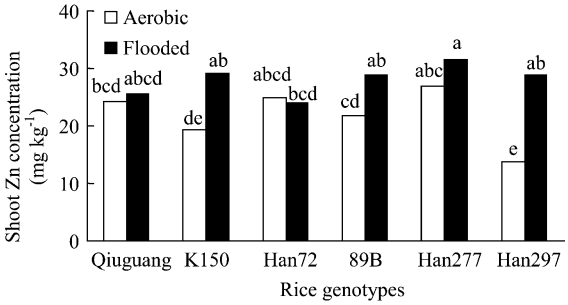

Figure 3. Cultivation effect on shoot Zn concentration of plants without Zn application at mature stage. Means with the same letter are not significantly different ($P < 0.05$).

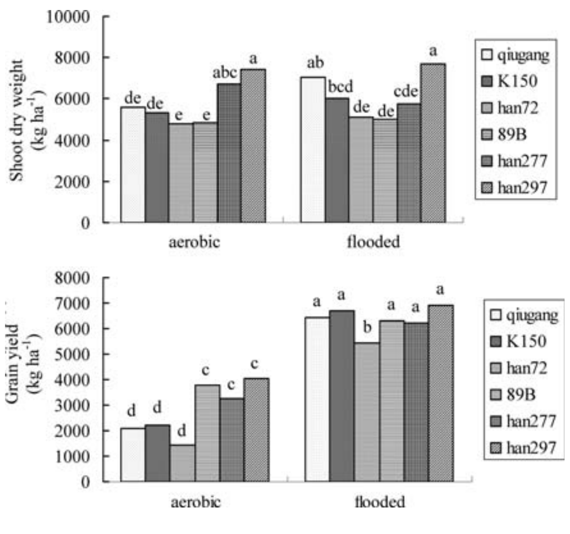

Figure 4. Shoot dry weight and grain yield of six genotypes under aerobic and flooded condition when no Zn was applied. Means with the same letter are not significantly different ($P < 0.05$).

however, were unaffected. This effect of Zn application was independent of cultivation system (Table 4). Zn-harvest index was lower under the high Zn application rate (Table 5).

Discussion

Our results demonstrate that there is reason for concern about increased Zn deficiency problems as a result of cultivation change from flooded to aerobic conditions in calcareous soils with high pH. Under aerobic conditions, Zn shoot concentration (Figures 1 and 3), grain yield and Zn-harvest index (Table 5) were significantly lower than under flooded conditions. The fact that biomass production, grain yield and shoot Zn concentration responded positively to Zn application (Tables 2 and 4) indicates that Zn was a growth-limiting factor in our experiment. Our results are in line with Giordano and Mortvedt (1974), who reported that Zn deficiency symptoms were more pronounced under moist conditions compared to flooded conditions on a soil with pH 7.5.

From a human nutritional point of view, high Zn concentration in the grain is of paramount importance. However, no significant differences were found in grain Zn concentration between two cultivation systems in this study. From flooded to aerobic cultivations, no significant reduction in grain Zn concentration was observed (Table 4). It was not clear whether this was related to Zn status in tested soil in our study. To carefully evaluate the effect of cultivation system on Zn concentration of the edible part of the whole grain and Zn distribution

Table 5. Effect of cultivation, Zn rate and genotype on harvest index and Zn-harvest index

Treatment	Harvest index (%)	Zn-harvest index (%)
Cultivation		
Aerobic	31 b	33 b
Flooded	50 a	45 a
Zn rate (kg ha^{-1})		
0	39 a	42 a
23	42 a	37 b
Genotype		
Qiuguang	38 b	35 bc
K150	40 b	41 ab
Han72	37 b	37 bc
89B	47 a	47 a
Han277	40 b	33 c
Han297	40 b	41 ab
Average	40	39

Within treatments, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD.

within grain need to be investigated in more detail.

Under aerobic conditions, the newly developed aerobic rice genotypes showed a higher Zn efficiency than the lowland genotype Qiuguang (Table 3). This indicates that breeding has been successful in this respect. Also, Zn-harvest index was higher for most aerobic genotypes compared to the lowland genotype, although not significantly in most cases (Table 5). The variation among aerobic genotypes shows that there are ample opportunities for breeders to improve Zn efficiency.

Zn application significantly decreased Zn-harvest index (Table 5) and did not affect grain Zn content and grain yield (Table 4). This is in agreement with many other studies on wheat (Rengel et al., 1999) and indicates that Zn application to the soil cannot fully meet the objective of increasing the Zn level in edible portions of rice. Development of rice cultivars with higher Zn efficiency and higher Zn-harvest index seems therefore a more promising strategy than fertilization for the purpose of increasing Zn content of the grain. Foliar application of Zn should be considered as an alternative strategy to increase Zn-harvest index and at the same time raise grain Zn concentration.

In line with Gao et al. (2005), we found considerable genotypic variation in Zn efficiency and yield under aerobic conditions. Our results confirm preliminary results demonstrating that K150 is a zinc inefficient genotype (Table 3). Already at tillering, K150 showed a low shoot Zn content (results not shown) and concentration (Figure 1), and a relatively strong response to Zn fertilization (Figure 2). Genotypes 89B and Han277 were more efficient and showed sufficient shoot Zn concentrations (Figure 1), no response to Zn application at tillering stage (Figure 2), and relatively high yields (Figure 4). The results for these genotypes confirm that Zn deficiency has its impact already in early growth stages (Forno et al., 1975). No effect of Zn application was found on grain yield (Table 4). This is largely in agreement with previous results showing that Zn deficiency occurs in the first few weeks after sowing and plants can spontaneously recover 6–8 weeks later (Forno et al., 1975).

It is likely that drought contributed to the yield reduction under aerobic cultivation (Figure 4). Drought has been identified as a major constraint causing yield loss in rice in Asia (Widawsky and O'Toole, 1996), even for aerobic varieties (Bouman et al., 2004). No results of any rice cultivars that consistently grow better in aerobic soil than in flooded soil can be found. It is generally concluded that aerobic conditions in itself imply a low level of stress for rice, particularly if the relative humidity is low (Dingkuhn et al., 1989). An interaction between drought stress and Zn deficiency is highly likely, because low water availability will hamper soil Zn transport towards the roots. It may also hamper Zn transport within the plant.

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