Synergic Effect of Flooding and Nitrogen Application on Alleviation of Soil Sickness Caused by Aerobic Rice Monocropping

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Abstract: The “aerobic rice” system is the cultivation of high yielding rice cultivars under non-flooded conditions in non-puddled (aerobic) soil with supplemental irrigation. The major constraint in wide adoption of aerobic rice technology is soil sickness caused by continuous monocropping due to still unknown factors. The possible role of flooding and nitrogen application in alleviating the soil sickness caused by continuous monocropping of aerobic rice was examined by pot experiments. Plants were grown aerobically or anaerobically on the soil collected from a field grown with aerobic rice for 12 consecutive seasons. The results showed that flooding alleviated soil sickness, but not as much as soil oven-heating treatment (120ºC for 12 hr). Application of ammonium sulfate improved plant growth up to the level of oven-heating treatment, while ammonium sulfate application and flooding exceeded the soil oven-heating treatment significantly. The synergy of flooding with ammonium sulfate application was greater than that with urea. These results suggest that soil sickness caused by continuous aerobic monocropping can be alleviated by flooding and ammonium sulfate application.

Key words: Aerobic rice, Ammonium sulfate, Flooding, Monocropping, Plant growth improvement, Soil oven-heating.

“Aerobic rice” is a new term coined by the International Rice Research Institute (IRRI): high yielding rice grown under non-flooded conditions in non-puddled and unsaturated (aerobic) soil. It is responsive to nutrient supply, can be rainfed or irrigated, and tolerates (occasional) flooding (Bouman and Tuong, 2001). In regions facing water scarcity for paddy rice production, aerobic rice cultivation was well developed because of high grain yield with less water input (George et al., 2002; Bouman et al., 2005). However, yield decline or yield failure in continuously monocropped aerobic rice (CMAR) system has been reported since 1970s (Nishizawa et al., 1971; Ventura and Watanabe, 1978; George et al., 2002; Peng et al., 2006; Kreye et al. 2009a), which was a major constraint to the widespread adoption of aerobic rice technology. The growth inhibition and yield decline or yield failure of aerobic rice continuously monocropped are generally believed to be caused by soil sickness (Nishizawa et al., 1971). Soil sickness may include biotic factors, such as nematodes (Nishizawa et al., 1971) and soil-born pathogens (Ventura et al., 1981), and abiotic factors, such as changes in soil nutrient availability (Lin et al., 2002) and toxic substances from root residues (Nishio and Kusano, 1975; Fageria and Baligar, 2003). Some researchers studied the causes of yield decline or yield failure in continuous aerobic rice cultivation. However, the results were difficult to interpret because the causes were associated with the number of factors such as soil properties, climates, rice cultivars, and management practices.

Oven-heating of soil with a continuous aerobic rice history at 120ºC for 12 hr increased rice plant growth significantly as compared with the untreated control (Nie et al., 2007). Anderson and Magdoff (2005) documented that soil sterilization by oven-heating remedied soil sickness, but soil heating is not applicable for farmers. Aerobic rice-flooded rice rotation (Ventura and Watanabe, 1978) and application of ammonium sulfate (Nie et al., 2009a) have been reported to reduce the soil sickness due to continuous monocropping of aerobic rice. In this study, we first examined comparatively the effects of flooding, N
application and soil oven-heating treatment on plant growth on the soil after continuous aerobic rice cultivation, and then examined whether the soil sickness caused by continuous monocropping of aerobic rice can be alleviated by flooding and/or proper N management.

**Materials and Methods**

Two pot experiments were conducted in the greenhouse at IRRI using the soil collected from the top 25 cm of an aerobic rice field where aerobic rice has been grown continuously for 12 seasons since 2001. The rice yield in that field declined gradually during that period (Peng et al. 2006). The soil was Aquandic Epiaquoll with soil chemical and physical properties described by Sasaki et al. (2010). Four-L porcelain pot filled with 3.0 kg air-dried soil was used in both experiments. Before filling the pots, the soil was air-dried, pulverized, and well mixed. Oven-heating of soil was done by placing the pots with CMAR soil in an oven and treating at 120°C for 12 hr. In both experiments, the aerobic rice variety Apo was used.

In experiment 1, the effects of soil oven-heating under aerobic and flooded conditions were examined without nutrient input. In experiment 2, the effects of the application of ammonium sulfate and urea at a N rate of 1.2 g pot⁻¹ in comparison with that of soil oven-heating were examined under both aerobic and flooded conditions. Ammonium sulfate and urea were applied one day before sowing and then pots were watered until the soil reached saturation. In both experiments 1 and 2, 10 pots were used for each treatment.

In both experiments, pots with untreated CMAR soil were used as a control. All pots were placed in a greenhouse with a completely randomized design. The distance of 30 cm between pots was kept to avoid shading. Six pre-germinated seeds of Apo were sown in each pot on 6 December 2006 in experiment 1 and on 29 March 2007 in experiment 2, respectively. One week after sowing, seedlings were thinned to three uniform seedlings per pot. Then five pots from each treatment were kept under aerobic conditions, the other five were kept under flooded conditions. So each treatment was replicated five times with five pots. The pots kept under aerobic condition were watered once 1–3 d to keep the soil moisture tension at 15 cm depth of −15 to −25 kPa. For the flooded pots, 3–5 cm of standing water was kept in the pots throughout the experiment. Weeds were removed manually. Pesticides were sprayed 3–4 times to control insect damage.

The plants were sampled at 35 and 54 d after sowing for experiments 1 and 2, respectively. Before plant sampling, the number of stem per pot were counted and the height of the plants from the base to the tallest leaf tip in each pot was measured. Plants were separated into leaves, stems including sheath and roots. Roots were washed over a sieve with tap water to remove the soil particles. Leaf area was measured with a leaf area meter (LI-3000, LI-COR, Lincoln, Nebraska, USA). Dry weights of plant organs were determined after oven drying at 70°C to constant weight in both two experiments. Aboveground biomass was the sum of leaf and stem dry weights.

The N concentration in the leaf and stem was determined by micro Kjeldahl digestion, distillation, and titration (Brenner and Mulvaney, 1982) to calculate aboveground N uptake. Data were analyzed following analysis of variance (SAS ver.9.1.2, Institute, NC, USA) and mean comparison between treatments was performed based on the least significant difference (LSD) test at the 0.05 probability level.

**Results**

In experiment 1, flooding significantly improved all measures of plant growth and N nutrition compared with aerobic conditions except for the root/shoot ratio (Fig. 1). The growth improvement was most notable in leaf area, followed by aboveground N uptake, aboveground biomass, root dry weight, stem number, and plant height in this order. The aboveground N uptake and aboveground biomass under flooded conditions were about four times higher than that under aerobic condition. Oven-heating of soil increased plant height, stem number, leaf area, root biomass, aboveground biomass, and aboveground N uptake over the untreated control under both aerobic and flooded conditions, while root/shoot ratio was significantly reduced by soil oven-heating (Fig. 1). However, soil oven-heating was much more effective on plant growth improvement than flooding.

In experiment 2, both soil oven-heating and ammonium sulfate application significantly increased the plant growth (Fig. 2). However, the plant growth improved by the application of urea was under flooded conditions, but not under aerobic conditions. Urea application inhibited the root growth of Apo in comparison with the control in aerobic pots (Fig. 2d). Over all, plants grown under either aerobic or anaerobic conditions responded more to ammonium sulfate than to urea. Under aerobic conditions, application of ammonium sulfate significantly improved all plant growth parameters and aboveground N uptake compared to urea. While under flooded conditions plant height (Fig. 2a), leaf area (Fig. 2c), aboveground biomass (Fig. 2e), and aboveground N uptake (Fig. 2g) were greater in the treatment with ammonium sulfate application than with urea, there was no difference in root dry weight between these treatments (Fig. 2d). On the contrary, plants treated with urea produced more tillers than with ammonium sulfate under the flooded condition (Fig. 2b). Soil oven-heating and application of ammonium sulfate or urea significantly reduced the root/ shoot ratio compared with the untreated control under both aerobic and flooded conditions (Fig. 2f).
Plant growth performance was improved by application of ammonium sulfate at 1.2 g N pot$^{-1}$ under the aerobic condition to the level improved by oven-heating treatment. However, ammonium sulfate application under the flooded condition outperformed the oven-heating treatment significantly (Fig. 2). Under aerobic conditions, plant height, stem number, leaf area and aboveground N uptake were significantly higher with ammonium sulfate application compared to the oven-heating treatment. Under flooded conditions, the opposite was true, with the oven-heating treatment showing improved performance.

![Graphs showing plant growth parameters under aerobic and flooded conditions](image)

**Fig. 1.** Plant height (a), stem number (b), leaf area (c), root dry weight (d), aboveground biomass (e), root/shoot ratio (f), and aboveground N uptake (g) of Apo grown in untreated control (CK) and oven-heated soil under aerobic and flooded conditions in pot experiment 1. Soil was from an aerobic field where aerobic rice has been grown continuously for 12 seasons. Soil oven-heating was done at 120ºC for 12 hr. Error bars represent standard error of mean (SE). Under each condition, different letters above bars indicate significant differences at 0.05 probability level according to least significant difference (LSD) test.

Plant growth performance was improved by application of ammonium sulfate at 1.2 g N pot$^{-1}$ under the aerobic condition to the level improved by oven-heating treatment. However, ammonium sulfate application under the flooded condition outperformed the oven-heating treatment significantly (Fig. 2). Under aerobic conditions, plant height, stem number, leaf area and aboveground N uptake were significantly higher with ammonium sulfate application compared to the oven-heating treatment. Under flooded conditions, the opposite was true, with the oven-heating treatment showing improved performance.
application than soil oven-heating; however, there were no difference between the effects of ammonium sulfate application and soil oven-heating on root dry weight and aboveground biomass. Application of ammonium sulfate under flooded conditions significantly increased all the growth parameters and aboveground N uptake compared
With soil oven-heating treatments under aerobic conditions. Under both aerobic and flooded conditions, leaf N concentration, leaf SPAD value, stem N concentration, and aboveground N concentration were lowered by application of ammonium sulfate than that of urea (Fig. 3). Plant tissue N concentrations under aerobic conditions were significantly higher than under anaerobic conditions, regardless of N forms.

**Discussion**

Soil oven-heating significantly improved plant growth on sick soil due to continuous monocropping of aerobic rice and provided a simple and quick test to determine whether a soil is sick (Nie et al., 2007). However, soil oven-heating may not only remove biotic factors, but also increase soil nutrient availability due to faster mineralization or transformation of nutrients to available forms or improve other soil physical and chemical properties that have an influence on plant growth (Moritsuka et al., 2001, 2006). In this study, plant growth improvement by some treatments, such as flooding, ammonium sulfate or urea application was compared with that improved by soil oven-heating treatment.

Conversion of monocropped dryland sick rice soil into flooded soil has been reported to substantially improve plant growth and grain yield (Ventura and Watanabe, 1978), and flooding can reverse the yield decline of continuous aerobic rice cultivation (Nie et al., 2009b). In the present experiments, flooding alleviated soil sickness caused by CMAR, but not as much as soil oven-heating treatment (Figs. 1 and 2). The aboveground biomass under the flooded condition was about four and one fold higher than that under the aerobic condition in experiments 1 and 2, respectively (Figs. 1e and 2e). Root/shoot ratio was significantly reduced by soil oven-heating and application of ammonium sulfate or urea at 1.2 g N pot\(^{-1}\) in comparison with untreated control under both aerobic and flooded conditions (Figs. 1f and 2f), suggesting that soil sickness caused by aerobic rice monocropping may be reduced by these soil treatments.

Ammonium sulfate was much more effective on plant growth improvement than urea at 1.2 g N pot\(^{-1}\) on CMAR soil, which was consistent with the findings of previous.
research (Stephen and Waid, 1963; Nie et al., 2009a). The reason why ammonium sulfate was more effective than urea on plant growth in alleviating the soil sickness due to CMAR is still unknown. Decrease in soil pH by ammonium sulfate application may be associated with the improvement of plant growth. The soil pH was reduced by 0.64 by the application of 1.2 g N per 3.0 kg of air-dried sick aerobic soil as ammonium sulfate, while the soil pH value was decreased by only 0.28 by application of urea (Nie et al., 2009a). A long-term aerobic rice cultivation for 1-3 seasons in the field experiment conducted at IRRI showed a gradual soil pH increase from 6.4 at the outset of the experiment to nearly 7.1 after 13 seasons of aerobic cultivation, however, the soil pH value did not significantly increase in a adjacent field where flooded rice were continuously cropped. Increase in pH of CMAR soil appeared to be one of the key determinants of yield failure or yield decline. Kreye et al. (2009b) reported that reduced soil pH with ammonium sulfate increased plant micronutrient contents and plant growth in CMAR. Xiang et al. (2009) observed that soil acidification using sulfuric acid solution significantly improved plant growth and N uptake on CMAR soil. Changes in nutrient availability and microbial community caused by the acidification of soil due to ammonium sulfate application remain to be identified in the future.

When N was applied as ammonium sulfate, more N was taken up by aerobic rice than flooded rice. However, the aboveground N uptake in flooded rice was higher than that in aerobic rice when N was applied as urea (Fig. 2g). Regardless of N forms, plant tissue N concentrations of flooded rice were lower than that of aerobic rice, which was consistent with the leaf SPAD value (Fig. 3). This was because flooded rice produced more biomass than aerobic rice irrespective of N forms (Fig. 2e). In general, NH₄⁺ is the dominant N form in paddy fields (Savant and De Datta, 1982) and NO₃⁻ is the stable N form only under aerobic conditions (Shen, 1969). N availability and form of N present in the soil are influenced by different water management (Savant and De Datta, 1982). Soil oven-heating accelerated the N mineralization (Moritsuka et al., 2006) and inhibited nitrification (Moritsuka et al., 2001).

Application of ammonium sulfate improved the plant growth to the level improved by oven-heating treatment, while the effect of ammonium sulfate application and flooding exceeded that of the soil oven-heating treatment significantly (Fig. 2). A synergy on plant growth improvement of flooding with N application was observed. However, the synergy of flooding with ammonium sulfate was greater than that with urea. Under aerobic conditions, application of ammonium sulfate at 1.2 g N pot⁻¹ produced 38.42 (±0.65, standard error) g pot⁻¹ of aboveground biomass. The aboveground biomass of Apo on flooded untreated control soil was 7.51 (±0.21) g pot⁻¹, while that on flooded soil treated with ammonium sulfate was 57.93 (±1.68) g pot⁻¹. These results suggest that soil sickness caused by CMAR may be alleviated by flooding and application of ammonium sulfate. This research on soil sickness caused by CMAR was conducted at IRRI lowland farm and the results could be site-specific.

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