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REVIEW ARTICLE

# Aerobic rice for water-saving agriculture. A review

**Lixiao Nie · Shaobing Peng · Mingxia Chen · Farooq Shah · Jianliang Huang · Kehui Cui · Jing Xiang**

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**Abstract** The increasing shortage of water resources has led to the development and adoption of aerobic rice system, which saves water input and increases water productivity by reducing water use during land preparation and limiting seepage, percolation, and evaporation. Aerobic rice also reduces labor requirement and greenhouse gaseous emission from rice field. In an aerobic rice system, the crop can be dry direct-seeded or transplanted and soils are kept aerobic throughout the growing season. Supplemental irrigation is applied as necessary. Aerobic rice cultivars are adapted to aerobic soils and have higher yield potential than traditional upland cultivars. Grain yields of 5–6 $tha^{-1}$ can be reached in aerobic rice system. However, yield decline or even complete failure of aerobic rice under continuous monocropping threatens the widespread adoption of aerobic rice technology. Here, we review research findings on possible causes responsible for yield decline of continuous aerobic rice. Our main findings are: (1) both biotic and abiotic factors are involved in the continuous cropping obstacle of aerobic rice; (2) recent research focused on abiotic factors related to the continuous cropping obstacle, such as soil pH increase, ammonia toxicity, and nutrient deficiencies; and (3) strategies which will help in mitigating the continuous cropping obstacle of aerobic rice include selection of new aerobic rice cultivars, nutrient management practice, crop rotation, and soil acidification. Identifying the causes responsible for continuous cropping obstacle of aerobic rice and adopting effective strategies are crucial to achieve sustainability of aerobic rice.

**Keywords** Aerobic rice · Continuous monocropping · Yield decline · Biotic factors · Abiotic factors · Mitigating strategies

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## 1 Definition, characteristics, and constraints of aerobic rice

More than 75% of the rice production comes from 79 million ha of irrigated lowland. However, the sustainability of the irrigated rice systems is increasingly threatened by scarcity of fresh water resources. It was estimated that 17 million ha of Asia's irrigated rice may experience "physical water scarcity" and 22 million ha may experience "economic water scarcity" by 2025 (Tuong and Bouman 2003). The increasing shortage of water resources accel-

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erates the development and adoption of aerobic rice system. Aerobic rice is a new term coined by the International Rice Research Institute (IRRI), for high-yielding rice grown under nonflooded conditions in nonpuddled and unsaturated (aerobic) soil, which is responsive to nutrient supply, can be rainfed or irrigated, and tolerates (occasional) flooding (Bouman and Tuong 2001). This system has been developed and adopted by farmers in Brazil, China, and other Asian countries (Pinheiro et al. 2006; Saito et al. 2006; Wang et al. 2002). The pictures in Fig. 1 show aerobic rice in a farmer's field and experimental plots in Beijing, China.

In broad sense, upland rice can be considered as aerobic rice because of the availability of oxygen in the soil. In this review paper, however, aerobic rice is defined in the context of a water-limited irrigated lowland system without puddling. The comparisons among irrigated lowland rice, aerobic rice, rainfed lowland rice, upland rice in water availability, fertilizer input level, soil preparation, crop establishment, drought tolerance, and yield level are presented in Tables 1, 2, and 3.

In aerobic rice production system, soils are kept aerobic throughout the growing season. Supplemental irrigation is applied as necessary. The cultivars used are adapted to aerobic soils and have higher yield potential than traditional upland cultivars (Atlin et al. 2006). In Asia, upland rice is aerobically grown with minimal inputs and it is usually planted as a low-yielding subsistence crop in the adverse upland conditions (Lafitte et al. 2002). Upland rice cultivars are drought tolerant, but have a low-yield potential and tend to lodge with high levels of external inputs such as fertilizer and supplementary irrigation.

Aerobic rice can be adopted in the following areas: irrigated areas where water has become so scarce or expensive that lowland rice cannot be maintained anymore; rainfed areas where rainfall is insufficient to allow lowland rice production, but sufficient for aerobic rice; favorable upland areas where supplementary irrigation is available and soil problem is minimum; or rainfed areas where uncontrolled flooding and waterlogging caused by heavy rainfall and overflowing rivers often threaten the adoption of upland crops such as maize and soybean (Bouman et al. 2007; Wang et al. 2002).

A key component of success in aerobic rice system is selection of appropriate cultivars (Wang et al. 2002). Compared with lowland rice breeding, the aerobic rice breeding program is extremely small and the genetic basis is very narrow. Only a few successful aerobic rice cultivars with high-yield potential and broad biotic and abiotic stress tolerance are commercially grown. A group of temperate aerobic rice cultivars, called Han Dao, has been developed by the breeders from China Agricultural University and are being commercially grown by farmers in northern China since the early 1990s (Yang et al. 2002). In 2001, IRRI started a breeding program to develop tropical aerobic rice cultivars for the Asian tropics (Bouman 2001) and some improved tropical upland rice cultivars (such as Apo) that performed well under aerobic conditions were identified (George et al. 2002; Lafitte et al. 2002). To achieve high yields under aerobic conditions, aerobic rice cultivars should combine the drought-tolerance characteristics of upland cultivars with the high-yielding characteristics of lowland cultivars (Lafitte et al. 2002). In northern China and Brazil, aerobic rice cultivars with high yield potential and moderate tolerance of drought stress have been developed through crosses of traditional upland cultivars with improved irrigated cultivars (Guimaraes and Stone 2000; Wang and Tang 2000).

By reducing water use during land preparation and limiting seepage, percolation, and evaporation, aerobic rice had about 51% lower total water use and 32–88% higher water productivity, expressed as gram of grain per kilogram of water, than flooded rice (Bouman et al. 2005). The labor use is also saved in aerobic rice because more labor is required for land preparation such as puddling, transplanting, and irrigation activities in flooded rice (Wang et al. 2002). Furthermore, aerobic rice cultivation has another

**Fig. 1** Aerobic rice in a farmer's field (*left*) and experimental plots (*right*) in Beijing, China

Table 1 Continuous cropping obstacle reported in aerobic rice since 1970

| Year | Observation | Location | Author |
|---|---|---|---|
| 1971 | Yield decline | Japan | Nishizawa et al. |
| 1978 | Yield decline | Philippines | Ventura and Watanabe |
| 2000 | Yield decline | Brazil | Guimaraes and Stone |
| 2003 | Yield decline | Brazil | Fageria and Baligar |
| 2006 | Yield decline | Philippines | Peng et al. |
| 2009 | Yield failure | Philippines | Kreye et al. |

merit, which is reducing greenhouse gas emission from rice field (Mandal et al. 2010).

The grain yields of 5–6 $t ha^{-1}$ have been reported in aerobic rice system with high-yielding rice cultivars (Bouman et al. 2005, 2006; George et al. 2002; Peng et al. 2006). In Brazil, aerobic rice cultivars with high grain yields of 5–7 $t ha^{-1}$ have been developed (Castaneda et al. 2002). While, in northern China, the grain yields of 8 $t ha^{-1}$ and even higher have been achieved using high-yielding aerobic rice cultivars under appropriate management practices (Wang et al. 2002).

It is well-known that weeds are the most severe constraints to widespread adoption of aerobic rice (Rao et al. 2007). Weed pressure in dry direct-seeded aerobic rice is significantly greater than that recorded in transplanted rice (Singh et al. 2008). Weeds in plots with a lower seeding rate have more chances to emerge, grow, and build up a strong population and thus pose a serious crop–weed competition. Mahajan et al. (2010) recommended a higher seeding rate to reduce weed biomass in dry direct-seeded aerobic rice.

Reduction in plant growth and yield, even yield failure of aerobic rice, has been reported under continuous cropping since the 1970s (Table 1). Yield reduction under continuous monocropping was also reported in other upland crops such as mungbean, cowpea, and corn (Ventura and Watanabe 1978). Yield decline/failure of monocropped aerobic rice is a constraint to the widespread adoption of aerobic rice technology. The growth inhibition and yield decline/failure of monocropped aerobic rice are generally believed to be caused by soil sickness, which was coined by Nishizawa et al. (1971). Soil sickness may include biotic factors, such as nematodes (Nishizawa et al. 1971) and soil-borne 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 (Fageria and Baligar 2003; Nishio and Kusano 1975a). Researchers have studied the causes of yield decline/failure in continuously monocropped aerobic rice, however, the results were difficult to interpret definitively (Table 2). The magnitude of yield decline after continuous cropping of aerobic rice depends strongly on the number of seasons that aerobic rice was continuously cropped, soil properties, climates, rice cultivars, and management practices. Despite of many constraints such as continuous cropping obstacle and weed infestation in aerobic rice, it still can be considered as a useful strategy for maintaining the sustainability of rice production under future water shortage caused by global climate changes.

## 2 Causes for continuous cropping obstacle in aerobic rice

### 2.1 Biotic factors

Nematodes were generally believed to be the first candidate among biotic factors responsible for continuous cropping obstacle in upland rice (Nishizawa et al. 1971; Watanabe et al. 1963; Watanabe and Yasuo 1960). Kreye et al. (2009a) reported severe yield failure in continuous aerobic rice even

Table 2 Causes for continuous cropping obstacle in aerobic rice reported in the literature

| Cause | Source |
|---|---|
| **Biotic factors** | |
| Nematode | Watanabe and Yasuo (1960), Watanabe et al. (1963), Nishizawa et al. (1971), Kreye et al. (2009a) |
| Fungi | Nishio and Kusano (1973, 1975b) |
| **Abiotic factors** | |
| Toxic substances | Nishio and Kusano (1975a), Fageria and Baligar (2003) |
| N deficiency | Nie et al. (2008) |
| Increase in soil pH | Kreye et al. (2009c), Xiang et al. (2009) |
| Ammonia toxicity | Haden et al. (2011) |
| **Interaction among biotic and abiotic factors** | |
| Biotic and abiotic factors | Tuckey (1969), Ventura and Watanabe (1978), Ventura et al. (1981) |
| Nematode and micronutrient deficiency | Kreye et al. (2009b) |

**Table 3** Comparisons among irrigated lowland rice, aerobic rice, rainfed lowland rice, and upland rice

| | Irrigated lowland rice | Aerobic rice | Rainfed lowland rice | Upland rice |
|---|---|---|---|---|
| Water availability | High | Moderate | Moderate | Low |
| Fertilizer input level | High | High | Moderate | Low |
| Puddling | Yes | No | Yes | No |
| Crop establishment | T/WDS/DDS | DDS | T/WDS/DDS | DDS |
| Drought tolerance | Low | Low to Moderate | Moderate | High |
| Yield level | High | Moderate | Moderate | Low |

*T* transplanting, *WDS* wet direct seeding, *DDS* dry direct seeding

with high N application (160 or 200 kg $\mathrm{N\,ha^{-1}}$). Further research showed that root knot nematodes were the major contributor to yield failure. However, some researchers suggested that nematodes were not involved in the soil sickness of continuous upland rice cropping because no yield reduction was observed when high population of nematode was added to soil (Ventura et al. 1981). Nishio and Kusano (1973, 1975b) examined the fungal flora on and in roots of continuously cropped upland rice and found that only *Pyrenochaeta* sp. was remarkable. *Pyrenochaeta* sp. affected the growth of aerobic rice by producing some substances inhibiting the growth of upland rice seedlings.

The interaction of nematodes and fungi in causing plant disease due to continuous monocropping has been discussed by Christie (1960). Ventura et al. (1981) also reported that the association of nematodes with fungi was suspected because mere presence of nematode may not be sufficiently enough to induce growth reduction caused by continuous cropping. Mountain (1960) documented that nematode infection even improved the pathogenicity of other microorganisms in continuously cropped crops. Continuous cropping changed component, reproduction, and activities of microorganisms in soil and rhizosphere (Vancura et al. 1977). In addition to nematodes and fungi, other microorganisms were also associated with continuous upland rice cropping (Ventura et al. 1984). Vlasta et al. (1982) reported that many soil microorganisms were involved in causing continuous cropping obstacle.

## 2.2 Abiotic factors

Toxic substances from root residues may cause the crop growth inhibition in continuously nonflooded rice system (Ventura and Watanabe 1978). Allelopathy or autotoxicity (which involves complex plant and plant chemical interactions) was frequently reported, when upland rice was grown in monoculture for more than 2–3 years on the same land (Fageria and Baligar 2003).

The mitigating effects of macro and micronutrients on yield decline caused by continuous cropping of aerobic rice have been examined in a series of pot and field microplot experiments conducted at IRRI by Nie et al. (2008). The results indicated that only N application was effective in alleviating continuous cropping obstacle in aerobic rice, while P, K, and micronutrients had no effect. So, N deficiency might be associated with the continuous cropping obstacle in aerobic rice. In contrast, Kreye et al. (2009a) found that micronutrient deficiency was partially responsible for the continuous cropping obstacles at Central Luzon plain in the Philippines, where yield failure was observed under continuous aerobic rice cropping.

Increase in soil pH after continuous aerobic rice monocropping appeared to be the main reason for yield decline/failure. A long-term field experiment conducted at IRRI farm with fertile and alluvial clay soil showed a gradual soil pH increase, which rose from 6.4 at the start of the experiment to nearly 7.1 after 12 seasons of aerobic cultivation (Xiang et al. 2009). While the soil pH did not change significantly after 12 seasons of flooded rice monocropping, suggesting that increase in soil pH after continuous aerobic rice monocropping may not be related to the possible alkalinity of irrigation water. Similarly, Kreye et al. (2009a) also reported an increase in soil pH from 6.5 to 8.0 over 2 years, when aerobic rice was continuously cropped for several seasons at Dapdap Experimental Station with relatively infertile and alluvial sandy soil in Central Luzon plain of the Philippines. While in Northern China, aerobic rice is rotated with winter crops such as wheat and vegetables and no increase in soil pH has been reported. Soil acidification using sulfuric acid solution significantly improved plant growth and N uptake of aerobic rice grown in the soil with continuous-cropping obstacle (Xiang et al. 2009). The improvement of aerobic rice growth after soil acidification suggested that continuous cropping obstacle is probably associated with a reduction in soil N availability or plant N uptake as the result of a gradual increase in soil pH after continuous cropping of aerobic rice.

## 2.3 Interaction between biotic and abiotic factors

Some scientists believe that both biotic and abiotic factors partly caused the continuous cropping obstacle in aerobic rice. Ventura et al. (1981) suggested that interactions among biotic and abiotic factors were involved in the continuous cropping obstacle in aerobic rice. Tuckey (1969) reported that the yield decline of continuous monocropping may be produced from interwoven factors such as the build-up of soil-borne pathogens, depletion of a certain mineral nutrient, adverse change of soil structure due to similar tillage, and the accumulation of toxic substances. Kreye's research indicated that the interaction of root knot nematode and micronutrients deficiency with increasing soil pH led to yield failure of continuous aerobic rice (Kreye et al. 2009b).

To separate biotic factors which influence continuous aerobic rice from the abiotic factors, studies were conducted by sterilizing the soil, such as biocides application (Kreye et al. 2009b) and soil-heating treatment (Nie et al. 2007; Sasaki et al. 2010) and soil irradiation by $\gamma$-rays (Ventura et al. 1981). Soil sterilization significantly mitigated continuous cropping obstacle in aerobic rice (Ladd et al. 1976; Kreye et al. 2009b; Nie et al. 2007; Rovira 1976), which suggested that some or all biotic factors were removed by soil sterilization. However, these soil treatments may have increased soil nutrient availability due to faster mineralization or transformation of nutrients to available forms or changed other soil physical and chemical properties that have an influence on plant growth improvement (Moritsuka et al. 2001, 2006). Nie's research showed that oven heating of the continuous aerobic rice soil increased the release of $NH_4^+$ by 62% compared with untreated soil although heating did not change the total N content of the soil (Nie et al. 2007). Sasaki et al. (2010) reported that inorganic N in the heat-treated soils was three to seven times higher than that in the untreated continuous aerobic rice soil. It was suggested that the high concentration of inorganic N in the heat-treated soils was caused by the decomposition of easily decomposable organic N in the soil such as microbial biomass N (Bonde et al. 1988; Inubushi et al. 1984, 1985; Jenkinson and Ladd 1981). So, the positive effect of soil sterilization on the plant growth could not confirm whether continuous cropping obstacle in aerobic rice was caused by biotic or abiotic factors. Both biotic and abiotic factors may involve in the continuous cropping obstacle of aerobic rice, however, recent research focused more on abiotic factors associated with continuous cropping obstacle including soil pH increase, nutrient deficiencies, and ammonia toxicity (Haden et al. 2011; Kreye et al. 2009c; Nie et al. 2008; Sasaki et al. 2010; Xiang et al. 2009).

## 3 Strategies for mitigating continuous cropping obstacle in aerobic rice

First of all, new aerobic rice cultivars with tolerance to continuous cropping obstacle should be developed for widespread adoption of aerobic rice technology. For this purpose, a pot experiment was conducted to compare the growth of different aerobic rice cultivars on the soil collected from the IRRI field where aerobic rice has been continuously monocropped for 12 seasons (Nie et al. 2009a). The results indicated that different aerobic rice cultivars showed variations in tolerance to continuous cropping obstacle. The cultivars with tolerance to continuous cropping obstacle produced much more vigorous root systems and much more biomass than intolerant cultivars. Selection of rice cultivars with a large and deep root system should be considered as an important strategy for achieving yield stability of continuous aerobic rice. It is interesting to examine if the growth obstacle will appear eventually after these tolerant cultivars have been grown for many seasons.

Nitrogen management practices played important roles in continuous aerobic rice cropping system. It was reported that N application significantly alleviated continuous cropping obstacle of aerobic rice (Nie et al. 2008). Further research showed that different N forms had different effects on plant growth of rice plants grown aerobically in the soil with a monocropping history of aerobic rice (Nie et al. 2009a). Among N forms, ammonium sulfate was the most effective on alleviating the growth inhibition of continuous aerobic rice (Kreye et al. 2009c; Nie et al. 2009a), which was demonstrated by a pot experiment showing differences in aerobic rice growth under five N sources at the N rate of 1.2 gN $pot^{-1}$ in the continuously monocropped aerobic soil (Fig. 2). In general, $NH_4^+$ is the dominant N form in paddy soil (Savant and De Datta 1982) and $NO_3^-$ is stable only in the oxidized rhizosphere (Shen 1969). Yamagata and Ae (1999) reported that aerobic rice preferentially takes up $NH_4^+$-N compared with $NO_3^-$-N. Oji and Izawa (1970) found that $NO_3^-$-N was converted to proteins at the same rate as $NH_4^+$-N in young rice seedlings, but $NO_3^-$-N was not absorbed or assimilated as effectively as $NH_4^+$-N. A higher maize yield was obtained with the application of ammonium sulfate than with urea due to faster N immobilization–mineralization turnover and higher N assimilation by maize plants in the ammonium sulfate treatment than in the urea treatment (Cabezas et al. 2005). These results suggest that the increase in soil pH associated with continuous cropping of aerobic rice could be mitigated by using the right source of N fertilizer (e.g. ammonium sulfate).

The culture practices reducing soil pH could maintain the yield stability of continuous aerobic rice. Yield failure of aerobic rice has been reported by Kreye et al. (2009a) on a site where the soil pH increased from 6.5 to 7.4 in 2006 and again from 7.0 to 8.0 in 2007 (Kreye et al. 2009b). As the pH increases, nutrients generally become less available for plant uptake (Dobermann and Fairhurst 2000). High soil pH is also known to affect the losses of N fertilizers from soil. As the pH rises, an increasing fraction of soil N is converted from stable ammonium to gaseous ammonia,

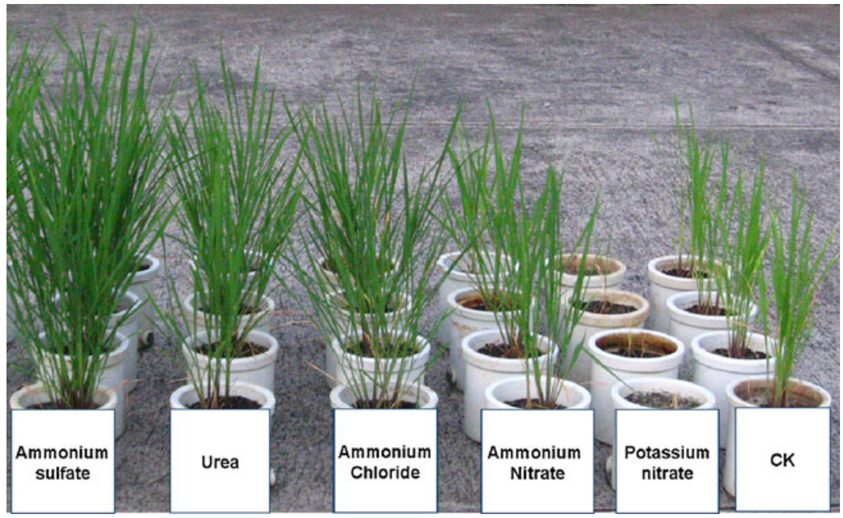


**Fig. 2** Growth performance of aerobic rice (Apo) in soil under five N sources (ammonium sulfate, urea, ammonium chloride, ammonium nitrate, and potassium nitrate) at the N rate of 1.2 g N pot$^{-1}$ and in zero-input control (*CK*) in a pot experiment. The soil was from an aerobic rice field where aerobic rice has been grown continuously for 11 seasons

which can be lost to the atmosphere (Ernst and Massey 1960). Soil acidification with sulfuric acid solution significantly improved growth and N uptake of continuous aerobic rice, regardless of N rates or N sources (Kreye et al. 2009c; Xiang et al. 2009). As a management practice, sulfur application is usually used to reduce soil pH (Roig et al. 2004).

Fallow and crop rotation mitigates continuous cropping obstacle in aerobic rice. Two seasons of fallow and three seasons of rotation with flooded rice significantly reversed the yield decline of continuous aerobic rice (Nie et al. 2009b). Converting monocropped aerobic rice soil with sickness into flooded soil substantially improved the plant growth (Ventura and Watanabe 1978). Soil organic matter content was increased during conversion from aerobic to flooded conditions (Nishimura et al. 2008). Changes in soil organic matter due to different soil management practice, tillage, and crop rotation were reported to affect crop yields (Freixo et al. 2002; Friesen et al. 1997). The beneficial effects of fallow and crop rotation on mitigating continuous cropping obstacle in aerobic rice were attributed to improving soil fertility and control of diseases, insects, and weeds.

Soriano and Reversat (2003) reported that cowpea–aerobic rice rotation reduced nematode populations and improved the yield of aerobic rice crop by 30–80%. Among the upland crops rotated with aerobic rice, maximum yield of aerobic rice was observed in soybean–aerobic rice systems (Nie et al. 2009b). In Brazil, the poor yields of aerobic rice observed after 5 years of monocropping were reversed after just 1 year of soybean; while after 3 years of soybean, the effect was even more dramatic (Pinheiro et al. 2006). There are two reasons that may explain the beneficial effect of soybean–aerobic rice rotation. First, soybean is a $N_2$-fixing legume which enriches soil N nutrition. Second, soybean breaks the pests, diseases, and weeds cycles as found in the case of maize–soybean rotational systems (Meissle et al. 2010). Even though the exact causes responsible for yield decline of aerobic rice monocropping are not fully understood, above strategies may be helpful to alleviate continuous cropping obstacle in aerobic rice.

## 4 Conclusion

Yield decline resulting from continuous cropping of aerobic rice is a major constraint to the widespread adoption of aerobic rice technology. The exact causes of the yield decline in the continuous aerobic rice system are still not known. Identifying the causes responsible for continuous cropping obstacle of aerobic rice and developing mitigation strategies are crucial to achieve sustainability of aerobic rice production. Research on identifying biotic and abiotic factors associated with continuous cropping obstacle of aerobic rice has been conducted. Both biotic and abiotic factors were reported to be responsible for the yield decline of continuously monocropped aerobic rice, however, abiotic factors such as soil pH increase, nutrient deficiencies, and ammonia toxicity have received more attention in recent years. Strategies to overcome continuous cropping obstacle of aerobic rice have been developed. These strategies include crop rotation, N management practice, soil acidification, and cultivar improvement. Most of the current research on yield stability of aerobic rice has been conducted at IRRI farm and the results could be site-specific. It is necessary to study the sustainability of aerobic rice in diverse environments with different soil physical and chemical properties, soil fertility, and water availability.

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