Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission

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\textbf{ABSTRACT}

To meet the major challenge of increasing rice production to feed a growing population under increasing water scarcity, many water-saving regimes have been introduced in irrigated rice, such as an aerobic rice system, non-flooded mulching cultivation, and alternate wetting and drying (AWD). These regimes could substantially enhance water use efficiency (WUE) by reducing irrigation water. However, such enhancements greatly compromise grain yield. Recent work has shown that moderate AWD, in which photosynthesis is not severely inhibited and plants can rehydrate overnight during the soil drying period, or plants are rewatered at a soil water potential of $-10$ to $-15$ kPa, or midday leaf potential is approximately $-0.60$ to $-0.80$ MPa, or the water table is maintained at 10 to 15 cm below the soil surface, could increase not only WUE but also grain yield. Increases in grain yield WUE under moderate AWD are due mainly to reduced redundant vegetative growth; improved canopy structure and root growth; elevated hormonal levels, in particular increases in abscisic acid levels during soil drying and cytokinin levels during rewatering; and enhanced carbon remobilization from vegetative tissues to grain. Moderate AWD could also improve rice quality, including reductions in grain arsenic accumulation, and reduce methane emissions from paddies. Adoption of moderate AWD with an appropriate nitrogen application rate may exert a synergistic effect on grain yield and result in higher WUE and nitrogen use efficiency. Further research is needed to understand root–soil interaction and evaluate the long-term effects of moderate AWD on sustainable agriculture.

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Abbreviations: AGP, ADP glucose pyrophosphorylase; AWD, alternate wetting and drying; CI, conventional irrigation; GHG, greenhouse gases; GWP, global warming potential; HNI, nitrogen harvest index; LWP, leaf water potential; IEN, internal N use efficiency; NUE, nitrogen use efficiency; ROA, root oxidation activity; SBE, starch branching enzyme; SPS, sucrose-phosphate synthase; StS, starch synthase; SuS, sucrose synthase; SWP, soil water potential; WUE, water use efficiency; Z, zeatin; ZR, zeatin riboside.

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1. Introduction

Global agriculture in the 21st century faces the tremendous challenge of providing sufficient and healthy food for a growing population under increasing water scarcity, while minimizing environmental consequences [1–3]. Rice (Oryza sativa L.) is one of the most important food crops in the world and is consumed by more than 3 billion people [4]. It is estimated that, by the year 2025, it will be necessary to produce about 60% more rice than currently produced to meet food needs [4,5]. About 75% of total rice production comes from irrigated lowlands [5,6]. Irrigated rice accounts for about 80% of the total fresh water resources used for irrigation in Asia [7]. Fresh water for irrigation, however, is becoming increasingly scarce because of population growth, increasing urban and industrial development, and decreasing availability resulting from pollution and resource depletion [1,8]. Rice fields have been identified as an important source of atmospheric methane (CH4), one of the major potent greenhouse gases (GHG), and contribute approximately 15–20% of global anthropogenic CH4 emissions [9,10]. Nitrous oxide (N2O), another potent GHG, may be emitted from rice fields as a combined effect of nitrogen (N) fertilization and water management [11–13]. Furthermore, there have been recent health concerns associated with arsenic (As) concentrations in rice grain [3,14–16]. In certain parts of the world, As concentrations in rice grain are high and exert adverse health effects [3,14–17].

These concerns posed by rice may be addressed by changes in water management, in particular from continuously flooded anaerobic systems to those in which aerobic cycles are introduced periodically during the growing season. This regime is often referred to as alternate wetting and drying (AWD) [3,18,19]. It is proposed [20,21] that adoption of moderate AWD such that soil drying in the AWD regime is controlled properly, plant water status is not adversely affected during the drying period, and an appropriate nitrogen application rate is used can result in a synergistic effect on rice yield and in high WUE and nitrogen use efficiency (NUE). It would advance the development of sustainable agriculture to disseminate the effectiveness of moderate AWD, identify the mechanism by which moderate AWD increases both grain yield and WUE, and elucidate the effects of interaction between moderate AWD and N application rates on yield, WUE, and NUE. This review addresses these topics.

2. Effectiveness of water-saving techniques and the irrigation index for moderate AWD

To counter water shortage and increase WUE, many water-saving regimes have been introduced, including an aerobic rice system [22–24], a system of rice intensification [25–27], non-flooded mulching cultivation [28–30], and AWD irrigation [31–33]. These regimes could substantially enhance WUE by reducing irrigation water. However, such enhancement greatly compromises grain yield [20,22,28,31]. Among these technologies, AWD has been applied mostly in China in an area of more than 12 million ha each year [18,32–37] and is being adopted in Asian countries such as Bangladesh, India, The Philippines, and Vietnam [1,8,22,31]. It also remains debatable whether the technology can achieve the dual goals of increasing grain yield and saving water [31–38]. The discrepancies between studies are attributed to variation in soil hydrological conditions and timing of the irrigation methods applied [31–33]. The work of Yang et al. [15,18], Chu et al. [19], and Zhang et al. [33–36] has shown that the drying condition in AWD is the most important factor affecting yield. If moderate AWD is adopted, such that soil drying in the AWD regime is controlled properly, photosynthesis is not severely inhibited and plants can rehydrate overnight, such a regime could not only save water but also increase grain yield (Table 1). Furthermore, moderate AWD improves rice quality, including a reduction in As accumulation in grain. It reduces CH4 emissions from the paddy field, thereby decreasing global warming potential (GWP) and greenhouse gas intensity (GWP/grain yield) (Table 1). In contrast, a severe AWD regime in which photosynthesis is severely inhibited and plants cannot rehydrate overnight during the soil drying period could markedly decrease grain yield and quality, although it also increases WUE and reduces grain As and CH4 emission from paddy fields compared to a continuous flooding regime (Table 1).

The question raised is how to control soil drying properly and to develop moderate AWD. There are several ways to control soil drying in AWD, such as by fixing the number of

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**Table 1 – Increase (+) or decrease (−) in grain yield, water use efficiency (WUE), grain quality, grain arsenic (As) content, and emission of greenhouse gases (GHG) from paddy field under alternate wetting and drying (AWD) irrigation relative to those under conventional irrigation in rice (unit: %).**

<table>
<thead>
<tr>
<th>Item</th>
<th>Moderate AWD</th>
<th>Severe AWD</th>
<th>Data adapted from references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain yield</td>
<td>5.6 to 12.8</td>
<td>−18.5 to −35.3</td>
<td>[3,18–21, [33–36]</td>
</tr>
<tr>
<td>Irrigation water</td>
<td>−22.4 to −34.6</td>
<td>−38.4 to −49.5</td>
<td>[34]</td>
</tr>
<tr>
<td>WUE (grain yield/irrigation water)</td>
<td>27.3 to 55.7</td>
<td>21.6 to 36.7</td>
<td>[3,63]</td>
</tr>
<tr>
<td>Head rice</td>
<td>5.6 to 12.8</td>
<td>−18.5 to −35.3</td>
<td>[34]</td>
</tr>
<tr>
<td>Chalkiness</td>
<td>−1.2 to −3.4</td>
<td>3.2 to 5.3</td>
<td>[3,19]</td>
</tr>
<tr>
<td>Amylose content</td>
<td>−0.4 to 0.7</td>
<td>−0.9 to 1.2</td>
<td>[3,63]</td>
</tr>
<tr>
<td>As in grain</td>
<td>−50.3 to −66.5</td>
<td>−54.5 to −70.6</td>
<td>[3,63]</td>
</tr>
<tr>
<td>CH4</td>
<td>−51.4 to −72.5</td>
<td>−90.7 to −112.8</td>
<td>[3,19]</td>
</tr>
<tr>
<td>N2O</td>
<td>15.5 to 98.6</td>
<td>125 to 167</td>
<td>[3,63]</td>
</tr>
<tr>
<td>Global warming potential (GWP)</td>
<td>−48.6 to −67.2</td>
<td>−73.1 to −99.5</td>
<td>[3,63]</td>
</tr>
<tr>
<td>GHG index (GWP/grain yield)</td>
<td>−48.3 to −78.9</td>
<td>−67.5 to −92.7</td>
<td>[3,63]</td>
</tr>
</tbody>
</table>

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non-flooding days, setting certain thresholds of leaf water potential (LWP), soil moisture content, or soil water potential (SWP), or water table below the soil surface, and observing visual symptoms in plant leaves and/or soil [31–38]. Theoretically, using LWP as an irrigation index is the most accurate of these measures because LWP directly reflects plant water status. However, LWP is difficult to determine. Yang et al. [18,39] suggest using SWP as the index for rice irrigation. Although there are several advantages in the use of SWP for water-saving irrigation, it is difficult for some farmers to use tension meters to monitor SWP. To solve this problem, we have recently used the water table below the soil surface as an irrigation index by installing a polymerized vinyl chloride (PVC) tube in the soil (Fig. 1). The method using a PVC tube to monitor water depth in soil is briefly described in the legend to Fig. 1. The depth of water in the PVC tube is observed daily. When the water depth in the PVC tube reaches 10–15 cm below the soil surface in most growth stages (Table 2), a thin (2–3 cm) layer of water is applied to the field. Such a method can be easily used by farmers.

Owing to the variable sensitivity of rice to soil drying in different growth stages [18,40], the thresholds for irrigation should be adapted to a special growth stage. Table 2 presents the thresholds of LWP, SWP, and the water table at each growth stage for moderate AWD. In most growth stages of rice, the threshold of SWP at −10 to −15 kPa, or midday LWP at approximately −0.60 to −0.80 MPa, or a water table at 10 to 15 cm below the soil surface, could be used as indices for moderate AWD (Table 2). Moderate AWD using the values in Table 2 as irrigation indices has been demonstrated and applied in the rice-growing areas of the provinces of Jiangsu, Anhui, Jiangxi, Zhenjiang, Shandong, and Henan in China. Compared with conventional irrigation (CI) employing drainage in midseason and flooding at other times, the moderate AWD technique increased grain yield by 6.1% to 15.2%, reduced irrigation water by 23.4% to 42.6%, and increased

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**Table 2 – Thresholds for alternate wetting and moderate drying (moderate AWD) irrigation in rice.**

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Leaf water potential (MPa)b</th>
<th>Soil water potential (kPa)b</th>
<th>Water level below the soil surface (cm)c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective tillering (from recovery to the critical leaf age of productive tillers)</td>
<td>−0.60 to −0.65</td>
<td>−5 to −10</td>
<td>8 to 12</td>
</tr>
<tr>
<td>Jointing (from the critical leaf age of productive tillers to panicle initiation)</td>
<td>−0.85 to −0.90</td>
<td>−15 to −20</td>
<td>15 to 25</td>
</tr>
<tr>
<td>Panicle differentiating (from panicle initiation to the beginning of heading)</td>
<td>−0.75 to −0.80</td>
<td>−8 to −12</td>
<td>10 to 15</td>
</tr>
<tr>
<td>Heading and flowering (from heading to the end of flowering)</td>
<td>−0.75 to −0.80</td>
<td>−8 to −12</td>
<td>10 to 15</td>
</tr>
<tr>
<td>Early and mid grain filling (7–20 days after heading)</td>
<td>−0.95 to −1.00</td>
<td>−10 to −15</td>
<td>12 to 18</td>
</tr>
<tr>
<td>Late grain filling (21 days after heading to final harvest)</td>
<td>−1.05 to −1.10</td>
<td>−15 to −20</td>
<td>20 to 25</td>
</tr>
</tbody>
</table>

a Irrigation is recommended as soon as the threshold is reached. The upper threshold applies to japonica inbred cultivars or to sandy soil. The lower threshold is used for hybrid rice or for clay soil. The intermediate value relates to indica inbred cultivars or to loam soil.
b Data are adapted from references [18,19,21,33,38,39].
c Unpublished data.
water productivity (grain yield per cubic meter of irrigation water) by 27% to 51% [18,33,41,42].

3. Mechanism by which moderate AWD increases grain yield and WUE

The mechanism by which moderate AWD increases grain yield and WUE is not fully understood. Many agronomic and physiological processes are likely to be involved, such as altered hormonal levels in rice plants, increase in proportion of productive tillers and decrease in the leaf angle of the top three leaves at heading time, greater root biomass in deeper soil and higher root oxidation activity (ROA), and an enhancement in carbon remobilization from vegetative tissues to kernels [18–21,33,41,42], as summarized in Fig. 2.

Three points merit attention. The first is that moderate AWD elevates abscisic acid (ABA) levels in plants during the soil drying period [43–47]. ABA is generally regarded as a very sensitive signal and has been observed to increase during the soil drying period [43–48]. It has been proposed that ABA has a major role in relation to sugar-signaling pathways and enhances the ability of plant tissues to respond to subsequent sugar signals [49]. There are many reports that ABA can enhance the movement of photosynthetic assimilates towards developing seeds by enhancing activities of sucrose phosphate synthase (SPS) in stems and sucrose synthase (SuS), ADP glucose pyrophosphorylase (AGP), starch synthase (StS), and starch branching enzyme (SBE) in kernels [46,47,50,51]. SPS is believed to play a major role in the resynthesis of sucrose [52,53]. The significance of enhanced SPS activity by elevated ABA during the soil drying period in moderate AWD is that it can not only accumulate the disaccharide as a response to the soil drying, but also sustain the assimilatory carbon fluxes from source to sink [52–54]. SuS, AGP, StS, and SBE are generally considered to be key enzymes involved in the sucrose-to-starch pathway in kernels [55,56], and the activities of these enzymes are significantly correlated with grain filling or starch accumulation rates in rice and wheat kernels [36,57–59]. It would be understandable that elevated ABA levels in rice plants under moderate AWD promote carbon remobilization from vegetative tissues to sink organs and grain filling by enhancing sink activity via regulation of the key enzymes involved.

The second point is that a “rewatering” effect has been observed in AWD [21,33,35]. In comparison with a CI regime or with during the soil drying period, moderate AWD markedly increases cytokinin levels (zeatin + zeatin riboside) (Z + ZR) in roots and leaves, ROA, and leaf photosynthetic rate during the rewatering period (Table 3). Both Z and ZR are believed to be very active cytokinins in plants and play a major role in promoting cell division and delaying senescence [60,61]. High cytokinin concentrations under moderate AWD during grain setting and filling periods may contribute to better grain filling by promoting endosperm cell division, delaying senescence, and/or regulating key enzymes involved in the sucrose-to-starch pathway in rice kernels [18,35].

The third point is that there is a compensatory effect in AWD. Compared with a CI regime, a moderate AWD regime can reduce the maximum number of tillers by 21–23% and total leaf area by 14%, but the number of productive tillers and effective leaf area (leaf area of main stems and productive tillers) show no significant difference between the two regimes [20]. As a result, moderate AWD markedly increases the percentage of productive tillers and the proportion of effective leaf area. The improved canopy quality would be expected to reduce the water used in production of unproductive tillers and transpiration from redundant leaf area. Furthermore, reduced redundant vegetative growth and increased carbon remobilization from vegetative tissues to kernels during grain filling can contribute to a higher harvest index, leading to increases in grain yield and WUE [20,21,33,36].

Fig. 2 – The mechanism involved in increases in grain yield, water and N use efficiencies under moderate AWD irrigation in rice. AWD: alternate wetting and drying; SPS: sucrose phosphate synthase. The figure is drawn based on references [20,21], [33–36] and [41–47].
The mechanism by which an AWD regime decreases grain As concentrations remains unclear. A likely explanation is that As can be reduced from As (V) to As (III) under flooded anaerobic soil conditions or in a CI regime, increasing the phytoavailability and uptake of As by rice [62–64]. In contrast, an AWD regime increases soil oxidation potential and thereby inhibits the reduction of As (V) to As (III), consequently decreasing As uptake by rice [2,19,63].

4. Effect of interaction between moderate AWD and N application rate on rice yield, WUE, and NUE

Besides water, N is another key factor determining crop yield, and also represents the main input in rice production [65–67]. However, the use of N fertilizer is generally inefficient, and the apparent recovery efficiency of N fertilizer (the percentage of fertilizer N recovered in aboveground plant biomass at the end of the cropping season) is only 33% on average [68–70]. The adoption of AWD-based technologies could reduce total cumulative plant N and NUE by stimulating N losses through enhanced root and shoot growth, and increased pre-stored N.

Recent work of Wang et al. [21] has demonstrated that grain yield, WUE, and NUE in rice are determined not only by irrigation regimes but also by their interaction with N rates (Table 4). They conclude that a synergistic water–N interaction can be achieved by adoption of a moderate AWD regime with a normal amount of N application, consisting of rewatering at SWP of −15 kPa and N rate at 200 kg ha−1 or midday LWP at approximately −0.69 and −0.86 MPa and specific leaf N content at 2.2–2.3 g m−2 at early and late growth stages, respectively. Such a synergistic interaction could achieve the goal of increasing grain yield, WUE, and NUE. Reduced redundant vegetative growth, enhanced root and shoot growth, and increased pre-stored

### Table 3 – Re-watering effects of alternate wetting and drying (AWD) irrigation on root oxidation activity (ROA), zeatin + zeatin ribside (Z + ZR) content in leaves, and leaf photosynthetic rate (Pr) of rice.

<table>
<thead>
<tr>
<th>Irrigation regime</th>
<th>ROA (µg o-naphthylamine g−1 DW h−1)</th>
<th>Z + ZR content (pmol g−1 DW)</th>
<th>Pr (µmol m−2 s−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>W</td>
<td>D</td>
</tr>
<tr>
<td>CI</td>
<td>549 a</td>
<td>545 b</td>
<td>138 a</td>
</tr>
<tr>
<td>Moderate AWD</td>
<td>536 a</td>
<td>612 a</td>
<td>132 a</td>
</tr>
<tr>
<td>Severe AWD</td>
<td>382 b</td>
<td>526 b</td>
<td>101 b</td>
</tr>
</tbody>
</table>

1 CI, D, and W represent conventional irrigation, soil drying period, and rewatering period, respectively. Data are adapted from references [20,21,35].

2 Different letters within the same column indicate significance at the 0.05 probability level.

### Table 4 – Grain yield, nitrogen use efficiency, and water use efficiency of rice under various irrigation and nitrogen treatments.

<table>
<thead>
<tr>
<th>Irrigation regime</th>
<th>N rate (kg ha−1)</th>
<th>Grain yield (t ha−1)</th>
<th>N uptake (kg ha−1)</th>
<th>IEN2 (%)</th>
<th>PFPN3 (kg kg−1)</th>
<th>NH4 (%)</th>
<th>WUE5 (kg m−3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>100</td>
<td>7.79 f</td>
<td>109.6 f</td>
<td>71.0 b</td>
<td>77.9 b</td>
<td>65.2 a</td>
<td>0.72 e</td>
</tr>
<tr>
<td>Moderate AWD</td>
<td>200</td>
<td>9.26 b</td>
<td>142.7 c</td>
<td>64.9 c</td>
<td>46.3 e</td>
<td>61.7 b</td>
<td>0.85 c</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>8.69 d</td>
<td>149.9 b</td>
<td>57.9 d</td>
<td>29.0 h</td>
<td>56.3 c</td>
<td>0.79 d</td>
</tr>
<tr>
<td>Severe AWD</td>
<td>100</td>
<td>8.31 e</td>
<td>112.9 e</td>
<td>73.6 a</td>
<td>83.1 a</td>
<td>66.9 a</td>
<td>0.87 c</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>9.81 a</td>
<td>142.0 c</td>
<td>69.1 b</td>
<td>49.1 d</td>
<td>65.1 a</td>
<td>1.01 a</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>9.89 a</td>
<td>154.9 a</td>
<td>63.9 c</td>
<td>33.0 g</td>
<td>61.6 b</td>
<td>1.02 a</td>
</tr>
</tbody>
</table>

1 CI, D, and W represent conventional irrigation, alternate wetting and moderate drying irrigation, and alternate wetting and severe drying irrigation, respectively. Data are adapted from reference [21].

2 IEN, Internal N use efficiency: grain yield (kg)/N uptake of plants (kg).

3 PFPN, Partial factor productivity of applied N: grain yield in N application plots (kg)/N rate (kg).

4 NH4, N Harvest index (%): N in grain (kg)/N uptake of plants (kg) × 100.

5 WUE, water use efficiency: grain yield (kg)/(amount of irrigation water + precipitation) (m³).

6 Different letters indicate statistical significance at the 0.05 probability level within the same column.
carbon remobilization from stems during the maturity period and harvest index contribute to higher grain yield and higher resource use efficiency in a moderate AWD regime with a normal amount of N application. The authors also observed that a severe AWD regime may save irrigation water, but reduces grain yield, and that increase in N application under this regime could increase grain yield and WUE.

Interestingly, either a moderate or a severe AWD regime shows a higher internal NUE (IEi, grain yield/N uptake of plants) than a CI regime at the same N rate (Table 4). Similar observations have also been reported by Liu et al. [38], Xue et al. [41], and Chu et al. [42]. The mechanism underlying a higher IEi in both AWD regimes is not understood. A probable explanation is that a moderate or severe AWD regime leads to a higher harvest index [18–21]. A higher harvest index means less N to produce the biomass of vegetative tissues and more N to produce grain yield [20,21], resulting in a higher IEi.

It is noteworthy that the IEi observed by Wang et al. [21] is higher than that reported elsewhere under similar experimental conditions [68,70]. This higher IEi may be explained by the separation of the plots in their experiments by an alley 1 m wide with plastic film inserted into the soil to a depth of 0.50 m to form a barrier, which could reduce N loss caused by runoff. The higher IEi may also be attributed to a reduction in N application at the basal and early vegetative stages and a delayed in-season N application. Such N management can increase N uptake and accumulation in plants by reducing unproductive tillers and increasing dry matter accumulation during the grain filling period, leading to a higher IEi [21,38,41,68].

5. Concluding remarks

The soil drying condition in AWD is the most important factor affecting rice yield. Adoption of moderate AWD, such that photosynthesis is not severely inhibited and plants can rehydrate overnight during the soil drying period, or plants are rewetted at an SWP of −10 to −15 kPa or a midday LWP at approximately −0.60 to −0.80 MPa, or the water table is maintained at 10 to 15 cm below the soil surface, can not only save water, but also increase grain yield. Furthermore, moderate AWD can improve rice quality, reduce arsenic accumulation in grain, and reduce CH4 emission from the paddy field, thereby decreasing GWP and greenhouse gas intensity. However, a severe AWD regime, in which photosynthesis is severely inhibited and plants cannot rehydrate overnight during the soil drying period, may markedly decrease grain yield and quality, although it may also increase WUE and reduce As in grain and CH4 emission from the paddy field compared to a CI regime. Reduced redundant vegetative growth and improved canopy structure, enhanced root growth, namely a greater root biomass in deeper soil and ROA, elevated ABA levels during the soil drying period, and increased cytokinin levels during the rewatering period, which promote carbon remobilization from vegetative tissues to grain and grain filling by enhancing the activities of key enzymes involved in resynthesis of sucrose in stems and in the sucrose-to-starch pathway in kernels, contribute to the increases in both grain yield and WUE under moderate AWD. A synergistic water-N interaction can be achieved by adoption of a moderate AWD regime with an appropriate N application rate. Such a synergistic interaction could achieve the goal of increasing grain yield, WUE, and NUE. Several questions including root-shoot and root-soil interactions and N losses via ammonia volatilization, nitrification, and denitrification under water-saving irrigation; the mechanism involved in rewatering effects and compensatory effects under AWD; and the long-term effects of moderate AWD on sustainable agriculture, such as on soil quality, merit further investigation.

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R E F E R E N C E S


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