Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China

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HIGHLIGHTS

- GHG emissions and yield were measured under three water regimes and two rice varieties.
- Water-saving irrigation decreased GWP despite trade-offs among CH4, CO2 and N2O.
- WDR rice has potential in reducing GWP, saving water, meanwhile, maintaining yield.

ABSTRACT

As pressure on water resources increases, alternative practices to conserve water in paddies have been developed. Few studies have simultaneously examined the effectiveness of different water regimes on conserving water, mitigating greenhouse gases (GHG), and maintaining yields in rice production. This study, which was conducted during the drought of 2013, examined all three factors using a split-plot experiment with two rice varieties in a no-till paddy managed under three different water regimes: 1) continuous flooding (CF), 2) flooded and wet intermittent irrigation (FWI), and 3) flooded and dry intermittent irrigation (FDI). The Methane (CH4) and nitrous oxide (N2O) emissions were measured using static chamber-gas measurements, and the carbon dioxide (CO2) fluxes increased by 65% and 9%, respectively, under FWI watering regime and by 104% and 11%, respectively, under FDI managed plots. Although CO2 and N2O emissions increased, the global warming potential (GWP) and greenhouse gas intensity (GHGI) of all three GHG decreased by up to 25% and 29% (p < 0.01), respectively, using water-saving irrigation strategies. The rice variety also affected yields and GHG emissions in response to different water regimes. The drought-resistance rice variety (HY3) was observed to maintain yields, conserve water, and reduce GHG under the FWI irrigation management compared with the typical variety (FYY299) planted in the region. The FYY299 only had significantly lower GWP and GHGI when the yield was reduced under FDI water regime. In conclusion, FWI irrigation strategy could be an effective option for simultaneously saving water and mitigating GWP without reducing rice yields using drought-resistant rice varieties, such as HY3.

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1. Introduction

Carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) are all important greenhouse gases (GHG) generated by human activities that affect climate forcing (Zeebe, 2013). Agriculture is recognized as a source of considerable GHG emissions (Burney et al., 2010). Globally, 47% of anthropogenic CH4 and 58% of anthropogenic N2O emissions were derived from agriculture production in 2005 (Smith et al., 2007). Rice paddies are identified as one of the important anthropogenic sources of CH4 (Wassmann et al., 1993; Cai et al., 1997; Yan et al., 2009) because they are continuously flooded for 4–6 months every year. This flooding creates anaerobic conditions that are favorable for methanogens (Cicerone and Oremland, 1988; Buendia et al., 1997). Rice
plants also play a pivotal role in methane generation, oxidation capacity, and transportation (Wassmann and Aulakh, 2000; Kerdchoechuen, 2005; Gutierrez et al., 2014). The global CH₄ emission from rice paddies is estimated to be 20–40 Tg a⁻¹ (1 Tg = 1 million t), which is equivalent to 10–20% of the total anthropogenic CH₄ emissions (Smith et al., 2007; Yan et al., 2009). Thus, minimizing CH₄ emissions in rice paddies represents a significant opportunity for GHG mitigation.

China is a major producer of rice; it accounted for 16% and 28% of the global rice area and global rice production in 2012 (FAO, 2013), respectively. In 2001, 93% of the 28.6 million ha of rice in China was cultivated under irrigated lowland conditions (IRRI, 2003). Irrigated agriculture is the primary consumer of water in China, i.e., it accounts for over 70% of the total water use (Xiong et al., 2010). Approximately 70% of the utilized water is for rice production alone (Zhang, 2007). China’s grain production has already been impacted by water limitations (Li et al., 2006). Future agricultural production will face increasing water restrictions and competition from industrial, domestic, and municipal sectors (Xiong et al., 2010). In addition to the development of water-saving and drought-resistant rice varieties (Luo, 2010; Serraj et al., 2011), water-saving irrigation is another effective and important consideration. Therefore, it is imperative to identify paddy water-management practices that conserve water, increase or sustain rice grain yields, and effectively reduce GHG emissions. Different water-saving irrigation practices have been widely studied across the country, such as intermittent irrigation, alternating wetting and drying irrigation, and midseason flooding and drainage with intermittent irrigation (Cai et al., 1997; Zou et al., 2007; Qin et al., 2010; Peng et al., 2011). These controlled irrigation practices usually leave rice paddies under non-water-logged conditions for 40–80% of the rice growing period (Berger et al., 2013) and save water while maintaining or increasing rice yields (Bouman et al., 2007; Zhang et al., 2009; Yao et al., 2012).

Paddy water management is a promising option for CH₄ mitigation (Yagi et al., 1996; Li et al., 2005; Minamikawa and Sakai, 2006; Tyagi et al., 2010). Water-saving irrigation practices usually comprise one or several drainage periods. This prevents the development of soil reductive conditions (Minamikawa and Sakai, 2006) and markedly reduces CH₄ emissions (Li et al., 2005; Towprayoon et al., 2005; Tyagi et al., 2010; Wang et al., 2012; Yang et al., 2012). Midseason drainage was found to reduce CH₄ emissions by 35–70% in rice paddies (Mishra et al., 1997; Zou et al., 2005). These studies indicate that saving water and CH₄ mitigation can be simultaneously achieved through improved water management practices in paddy fields. However, N₂O emissions were reported to be substantially enhanced due to aeration occurring as water drained and re-flooded (Cai et al., 1997; Zheng et al., 2000; Zou et al., 2007; Wang et al., 2011). Li et al. (2011) reported that the timing and duration of midseason aeration affected the trade-off between CH₄ and N₂O emissions. In contrast, Berger et al. (2013) reported that continuously flooded paddies degassed the largest amounts of N₂O and CH₄ while intermittent and minor flood irrigation methods could also reduce CH₄ and N₂O.

Changing paddy water management does not generate a single pulse emission perturbation but rather an irregular change in net emissions of CO₂, CH₄, and N₂O (Shang et al., 2011). The dynamics of GHG emissions are usually confounded by differences in field management activities across studies. An effective agriculture management strategy for mitigating GHG requires simultaneously considering multiple GHG when evaluating their impacts on radiative forcing (Frolking et al., 2004; Mosier et al., 2006). Recently, global warming potential (GWP) was widely adopted to provide an understanding of agricultural impacts on radiative forcing (Mosier et al., 2006; Qin et al., 2010; Shang et al., 2011). This approach allows for direct comparisons of the overall impacts induced by GHG. Greenhouse gas intensity (GHGI), which is calculated by dividing the GWP by the crop yield, was introduced to assess climatic impacts of agriculture per kg of yield (Li et al., 2006; Mosier et al., 2006; Qin et al., 2010; Shang et al., 2011). Few studies have simultaneously examined the emission dynamics of these three GHG from rice paddies and their trade-offs under water-saving irrigation (Li et al., 2005).

Water shortages and seasonal droughts are prominent issues for rice production in the central region of China. The development of water-saving and drought-resistant rice (WDR) is one of the strategies to produce more rice using less water in China (Luo, 2010). The rice hybrid Hanyou 3, an elite WDR, demonstrated drought tolerance in several field studies (Huang et al., 2008; Liu et al., 2009; Si et al., 2010; Yao et al., 2012). This variety has already been released to the market (Luo, 2010), and farmers can buy it at the same price of other rice varieties. However, further studies are needed to explore its potential for water saving and its effects on GHG emissions in Central China. Alternating wetting and drying irrigation (AWD) has been studied, and it is practiced by some farmers in this region. The practice can save water by 24–38% without rice grain yield loss (Yao et al., 2012). However, it is difficult for farmers to grasp the re-irrigation time and water amount when they practice AWD because simple and visual irrigation indices for farmers have not been developed until now. In recent years, fixed bed-furrows in conjunction with no-tille practices in rice paddies have become increasingly popular in this region. We developed AWD on the basis of bed-furrows using the water level in the furrow and the water status in bed soils as the visual indices for re-irrigation. Few studies have been performed on such methods of water-saving irrigation and their effects on GHG emissions and rice grain yield production. Therefore, two AWD management strategies based on bed-furrows were developed in our study using various amounts of irrigation water, and we examined their effects on yields and the emissions of three GHG from WDR and traditional rice hybrids. Our objectives were to (1) study the possibility of and provide support for developing proper AWD management strategies that can best reduce water input and GHG emissions without yield losses and (2) investigate the potential of WDR varieties for saving water, reducing GHG emissions and sustaining rice yields.

2. Material and methods

2.1. Experiment site

The study site was located at an experimental farm of Huazhong Agricultural University in the town of Huaqiao, Hubei Province, China (30°01’N, 115°74’E). The town is on the middle reaches plain of Yangtze river. Its elevation is 30 m above sea level. This region has a humid mid-subtropical monsoon climate with an average annual temperature of 17.5 ± 0.5 °C and a mean annual precipitation of 1437 ± 305 mm over the past 30 years. According to local Meteorological Bureau, most of the rainfall occurs between April and August. Bed-furrow bases are popular for farmers to grasp the re-irrigation time and water amount when they practice AWD because simple and visual irrigation indices for farmers have not been developed until now. In recent years, fixed bed-furrows in conjunction with no-tille practices in rice paddies have become increasingly popular in this region. We developed AWD on the basis of bed-furrows using the water level in the furrow and the water status in bed soils as the visual indices for re-irrigation. Few studies have been performed on such methods of water-saving irrigation and their effects on GHG emissions and rice grain yield production. Therefore, two AWD management strategies based on bed-furrows were developed in our study using various amounts of irrigation water, and we examined their effects on yields and the emissions of three GHG from WDR and traditional rice hybrids. Our objectives were to (1) study the possibility of and provide support for developing proper AWD management strategies that can best reduce water input and GHG emissions without yield losses and (2) investigate the potential of WDR varieties for saving water, reducing GHG emissions and sustaining rice yields.

2.2. Experimental design and agronomic management

In 2012, the rice paddies at the study site were converted from conventional tillage to no-tille with a bed-furrow base construction
that utilizes three types of irrigation regimes: (1) continuous flooding (CF), (2) flooded and wet intermittent irrigation (FWI), and (3) flooded and dry intermittent irrigation (FDI). The FWI and FDI treatments were developed on the basis of alternating wetting and drying irrigation (AWD) (Tuong et al., 2005) to explore the potential of water saving without rice grain yield loss and to propose easily accessible water management techniques for farmers.

In 2012, the land was soaked for 4 days after the rapeseed harvest on May 18 and was subsequently ploughed and puddled. The bed-furrows were built with beds 1.5 m wide and furrows 0.3 m wide and 0.25 m deep before rice seeding. Then different irrigation regimes were practiced by dividing the study site into a randomized split-plot with three replications. Three water regimes were set up at the base of the bed-furrow for each of the main plots (Fig. S1). The water levels in the furrow are used to determine the time to irrigate again. The specific details regarding the water level and timing of the irrigation, along with other management activities are presented in Table 2. The sub-plots contained two rice varieties: Fengyuanou299 (FYY299) and Hanyou3 (HY3). FYY299, a three-line hybrid indica rice variety, is a popular mid-season rice planted in Hubei Province, China. HY3, a three-line hybrid rice variety, is drought resistant and is available to farmers for commercial use (Yu et al., 2005; Luo, 2010). Each sub-plot was 3.6 m × 8.5 m in size, and each main plot had an area of 61.2 m². The main plots were surrounded by ridges 25 cm high. Strong black plastic film was driven to a depth of 30 cm along the inner edge of the field ridge and covered the ridge to the other side (30 cm at the base and 30 cm in height) to prevent lateral water movement due to leakage or permeable lateral flow. The ditches between the ridges of the main plots for irrigation and drainage were 30 cm wide and deep. Each main plot was irrigated independently by pumping water from a channel which drew water from the Jingzhou reservoir. The amount of irrigation for each main plot was recorded by a water meter installed on the pump.

The bed-furrows were kept after rice harvest and planted by rapeseed with on-til in October, 2012. In 2013, the three irrigation treatments were continuously conducted on their former plots with on-til after rapeseed harvest. The field was soaked over four days before the rice seeding in 2013. The rice seeds were soaked in water for 24 h and kept damp until germination prior to sowing. Rice seeds for both hybrids were sown manually on the flooded bed on June 3 at a hill spacing of 13 cm × 30 cm, with 3–4 seeds per hill. From sowing to the three-leaf stage of the rice, shallow water (1–2 cm) was kept in all plots of the three water regimes to facilitate rice seedling development. At the three-leaf rice stage, three different water regime treatments were initiated, as shown in Table 2. The fertilizer application and the maturity dates of the two varieties with the three water regimes are presented in Table 2. Herbicides were sprayed over the field 2 days before rice sowing. Weeds were manually removed throughout the entire rice growth periods. Diseases and insects were intensively controlled in all experimental treatment plots. No noticeable crop damage from weeds, insects or diseases was observed in the experiment.

### Table 1

<table>
<thead>
<tr>
<th>Month</th>
<th>Temperature (°C)</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The past 30 years</td>
<td>2013</td>
<td>2013</td>
</tr>
<tr>
<td>June</td>
<td>26.1 ± 0.9</td>
<td>26.5</td>
</tr>
<tr>
<td>July</td>
<td>29.5 ± 1.2</td>
<td>30.9</td>
</tr>
<tr>
<td>August</td>
<td>28.7 ± 1.0</td>
<td>31.5</td>
</tr>
<tr>
<td>September</td>
<td>24.5 ± 1.0</td>
<td>24.3</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Management activities</th>
<th>CF</th>
<th>FWI</th>
<th>FDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land preparation</td>
<td>No tillage after rapeseed harvest; land soaked for 4 days before directly seeding</td>
<td>The soaked seeds were directly and manually sown on the beds on 3 June; spacing was 13 cm × 30 cm, with 3–4 seeds per hill</td>
<td>The soaked seeds were directly and manually sown on the beds on 3 June; spacing was 13 cm × 30 cm, with 3–4 seeds per hill</td>
</tr>
<tr>
<td>Crop preparation</td>
<td>Urea split application (35/15/20/20) of 210 kg N/ha on May 31, Jun 19, Jul 25 and Aug 18; P basal application: 150 kg P₂O₅/ha as Ca(H₂PO₄)₂ on May 31; K split application (50/50/0/0) of 225 kg K₂O/ha as KCl on May 31 and Jul 25</td>
<td>FYY299 on Sep 26; HY3 on Sep 29</td>
<td>FYY299 on Sep 26; HY3 on Sep 29</td>
</tr>
<tr>
<td>Fertilizer application</td>
<td>Flooded with 1–2 cm water until the rice attained the three-leaf stage; then, it was continuously flooded with 2–5 cm water; irrigation stopped 15–20 days before harvest</td>
<td>Flooded with 1–2 cm water until the rice attained the three-leaf stage; then, it was irrigated to full-ditch water again once the water disappeared in the furrow with wet-bed soil; repeated the cycle of full and no-furrow water until irrigation stopped 15–20 days before harvest</td>
<td>Flooded with 1–2 cm water until rice attained the three-leaf stage; then, it was irrigated to full-furrow water again once there was no water in the ditch and a dry soil bed; repeated the cycle of full and no-furrow water until irrigation stopped 15–20 days before harvest</td>
</tr>
<tr>
<td>Harvest date</td>
<td>FYY299 on Sep 26; HY3 on Sep 29</td>
<td>FYY299 on Sep 26; HY3 on Sep 29</td>
<td>FYY299 on Sep 28; HY3 on Oct 1</td>
</tr>
</tbody>
</table>

2.3. CH₄ and N₂O measurements

The static chamber-gas chromatograph method was adopted to determine CH₄ and N₂O emissions (Li et al., 2013). Before the gas was sampled, two steel rings were placed in the middle of the bed in each plot. The top edge of the ring had a groove (8 cm in depth) for water to seal the rim of the chamber with a leveled surface. The steel cylinders, which had a diameter of 38 cm and a height of 110 cm, were temporarily placed on the ring on the gas sampling day. Each steel cylinder covered four hills of rice. Fans installed on the tops of the chambers were run to mix the air within the chamber. The gases in the chamber were then drawn off with a syringe and immediately transferred into a 25-ml vacuum glass container. Four gas samples from the chamber headspace were collected at 8-min intervals using 25-ml plastic syringes during a 24-min period after the chamber closure. Samplings were conducted in the morning (8:30–11:00 am) because the soil temperature during this period was close to the mean daily soil temperature (Zou et al., 2005). The air temperature inside the chamber was monitored during the gas collection. CH₄ and N₂O gas samples were collected one day before the rice seeding and then at intervals of 7–10 days from the three-leaf stage to the rice harvest.

CH₄ and N₂O concentrations were measured using a gas chromatograph meter (Shimadzu GC-14B) fitted with a 6′–1/8′ stainless steel column (Porapack N, length × inner diameter: 3 m × 2 mm). A flame ionization detector (FID) and an electron capture detector (ECD). N₂ (flow rate: 330 ml min⁻¹), H₂ (flow rate: 30 ml min⁻¹), and zero air (flow rate: 400 ml min⁻¹) were used as the carrier, fuel, and supporting gas, respectively. The temperatures of the column, injector, FID and ECD were set to 55 °C, 100 °C, 200 °C and 330 °C, respectively. The changes in the CH₄ and N₂O concentrations remained linear throughout the sampling period. The gas emission flux was calculated from the difference in the gas concentrations according to the equation given by Zheng et al. (1998).

\[
F = \rho \times h \times \frac{dC}{dt} \times \frac{1}{273 + T} \]

where \( F \) is the CH₄ and N₂O flux (mg m⁻² h⁻¹), \( \rho \) is the CH₄ and N₂O density at the standard state, h is the height of the chamber above the

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1052

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1085
2.4. CO₂ measurement

The CO₂ fluxes from the paddy soils were monitored using an LI-8100A soil CO₂ flux system (LI-Cor Inc., Lincoln, NE, USA). The soil fluxes were measured within 2 h, between 9:00 and 11:00 am, which was considered a representative time for the daily average by Lou et al. (2003). Each soil CO₂ flux was determined every 20 s for 180 s (Li et al., 2013). Three measurements were obtained from each plot on each sampling day, and each CO₂ flux measurement from a plot was the average of three individual measurements. The CO₂ flux was expressed as mg m⁻² h⁻¹. The date of the CO₂ measurement was the same as that of the CH₄ and N₂O gas sampling.

2.5. Cumulative GHG emissions and GWP and GHGI estimates

The cumulative seasonal CH₄, CO₂ and N₂O emissions were calculated for each plot according to the following equation, as described by Li et al. (2013):

\[
\text{CE} = \frac{(F_i + F_{i+1})}{2} \times 10^{-3} \times d \times 24 \times 10
\]

where CE is the seasonal total emissions (kg ha⁻¹), Fᵢ and Fᵢ₊₁ are the measured fluxes of two consecutive sampling days (mg m⁻² h⁻¹), and d is the number of days between two adjacent sampling days.

The GWP based on the CH₄, CO₂ and N₂O emissions was used to account for the climatic impact of both rice varieties under different fertilizer regimes. Based on a 100-year time frame, the GWP coefficient is 25 for CH₄ and 298 for N₂O when the GWP value for CO₂ is taken as one (IPCC, 2007). We calculated the combined GWPs for 100 years using the following equation:

\[
\text{GWP} = 1 \cdot \text{CE}_(CO_2) + 25 \cdot \text{CE}_(CH_4) + 298 \cdot \text{CE}_(N_2O)
\]

where GWP is the combined global warming potential (kg CO₂-equivalents ha⁻¹).

The GHGI is calculated following Shang et al. (2011):

\[
\text{GHGI} = \frac{\text{GWP}}{\text{grain yield}}
\]

where GHGI is expressed in kg CO₂-equivalents per kg of grain yield.

2.6. Other data measurements

At maturity, rice plants were taken diagonally from three sample areas of 3 m² in each sub-plot where the grain yields were determined. At the same time, six hills of straw at each sub-plot were randomly sampled and oven-dried at 85 °C to a constant weight to obtain the aboveground biomass. The final yield for all treatments was adjusted to the standard moisture content of 0.14 g H₂O g⁻¹ (fresh weight) (Yao et al., 2012). The soil temperature and soil water content (m² m⁻³) at a 5-cm depth were measured using a ProCheck digital sensor (Decagon Devices, Pullman, WA, USA) on the gas sampling dates. The depth of the groundwater table was monitored using 200-cm-long PVC pipes with a diameter of 5 cm; the pipes were installed in each main plot to a depth of 150 cm from the soil surface. The lower circular surface (120 cm) of the pipe was perforated with 0.5-cm holes at 2-cm intervals before installation (Yao et al., 2012). The soil pH was measured in a suspension of 1:2.5 (w/v) soil to water ratio after shaking for 1 h using a pH meter (Jones, 2001).

2.7. Statistical analysis of the data

A two-way ANOVA analysis was performed with SAS software (SAS Institute, 2003) to analyze the effects of water regimes and rice varieties on seasonal-averaged GHG fluxes, seasonal cumulative GHG emissions, GWPs, GHGI and rice yields. A least significant difference (LSD) was calculated only when the analysis of variance F-test was significant at the p < 0.05 probability level. Pearson’s correlation analysis was conducted to evaluate the relationships among the GHG emissions and soil properties.

3. Results

3.1. Weather conditions, irrigation water input, soil water status and rice production

The rice growing season in 2013 was hotter and drier than the season’s average weather for the past 30 years. The monthly average temperature in August and September 2013 reached 30.9 °C and 31.5 °C, respectively, which were higher than the averages of the past 30 years (Table 1). Compared with the same period over the past 30 years, the monthly rainfall from June to September 2013 was lower, and the total rainfall of these four months was 455 mm, compared with the average of 681 mm. Moreover, almost half of the rainfall during the rice growing season occurred in June. Only a small fraction occurred in late July, August, and September 2013. The lack of rainfall increased the water stress of the rice plants in the study.

A summary of the water parameters determined between sowing and the end of irrigation prior to harvest is shown in Table 3. On average, FWI and FDI saved 38% and 41% of irrigation water compared with CF, respectively. As shown in Fig. 1a, the soil water content (SWC) at CF and FWI fluctuated smoothly. However, FDI exhibited undulant fluctuations in the SWC, which had an average of 0.28 m³ m⁻³ (Fig. 1a and Table 3). Because of the reduction in irrigation, SWC for FWI and FDI was 85% and 70% of CF, respectively. The groundwater table decreased with decreasing irrigation during the period from June 3 to August 17 (Fig. 1b and Table 3). During this period, the average groundwater table depth at CF and FWI were maintained over 0 cm and —10 cm, respectively. However, the groundwater table at FDI fluctuated between —45 and —2 cm.

The water regime had a significant effect on the grain yields and aboveground biomass of both rice varieties (Table 4). Although HY3 showed higher grain yields than FYY299 with FWI treatment, no significant interaction was detected between water regimes and rice varieties. For the two rice varieties, the grain yield with the FDI treatment significantly decreased by 13%, on average, compared with CF treatment (p < 0.05). There was no difference in the grain yields between CF and FWI or between FWI and FDI. However, a significant effect on the aboveground biomass was observed from the interaction between the water regimes and rice varieties. Neither FYY299 nor HY3 exhibited significant differences in the aboveground biomass between the CF and FWI treatments (p > 0.05). However, the reduction in the irrigation water using FDI did significantly decrease the aboveground biomass of HY3 and FYY299 by 9% and 20%, respectively, compared with CF (p < 0.05). Compared with FYY299, HY3 exhibited superior aboveground biomass with FWI and FDI treatments (p < 0.05). Compared with FYY299, HY3 was more tolerant of FWI irrigation regime for maintaining yields and of FDI regime for maintaining aboveground biomass.

3.2. Seasonal dynamics of CH₄, CO₂ and N₂O emissions

The water regime also had dramatic influence on GHG emissions during the 2013 rice growing season (Fig. 2). The seasonal pattern of the CH₄ emissions of the two rice varieties varied with water regimes (Fig. 2a and b), in which CH₄ fluxes were initially low and then peaked during the 2013 rice growing season (Fig. 2). The seasonal pattern of the CH₄ emissions of the two rice varieties varied with water regimes (Fig. 2a and b), in which CH₄ fluxes were initially low and then peaked
during late July and early August for all treatments. Moreover, CF exhibited peaks as high as 68.49 mg m$^{-2}$ h$^{-1}$ for HY3 and 79.68 mg m$^{-2}$ h$^{-1}$ for FYY299 in early September after rice heading. The CF treatment had the highest CH$_4$ emission flux, with a seasonal average of 34.26 mg m$^{-2}$ h$^{-1}$ for rice variety HY3 and 32.44 mg m$^{-2}$ h$^{-1}$ for FYY299, which accumulated to 955 kg CH$_4$ ha$^{-1}$ for HY3 and 919 kg CH$_4$ ha$^{-1}$ for FYY299. Then, CH$_4$ emissions significantly decreased under the FWI and FDI irrigation regimes ($p < 0.01$) for each rice variety. The seasonally averaged CH$_4$ fluxes of HY3 were 13.08 mg m$^{-2}$ h$^{-1}$ for FWI and 5.28 mg m$^{-2}$ h$^{-1}$ for FDI, respectively. In contrast to CF treatment, the cumulative seasonal amounts of CH$_4$ emissions for the average of the two rice varieties were significantly reduced by 60% at FWI and 83% at FDI (Table 5).

Contrary to CH$_4$, CO$_2$ emissions increased with reducing in irrigation water input for CF, FWI and FDI treatments (Fig. 2c and d). The soil CO$_2$ fluxes were relatively low for all treatments after sowing until June 18 (at approximately the three-leaf stage). The three treatments showed distinctive discrepancy in CO$_2$ dynamics after implementation of different irrigation practices at the three-leaf stage. Soil CO$_2$ flux in CF plots remained relatively lower and then increased after irrigation was stopped, approximately two weeks before rice harvest. The soil CO$_2$ fluxes at FWI and FDI plots fluctuated due to alternating soil flooding and drying. The seasonally averaged CO$_2$ flux of FWI and FDI treatments were 509 mg m$^{-2}$ h$^{-1}$ and 631 mg m$^{-2}$ h$^{-1}$, respectively, for the average of the two varieties, which were 1.6 and 2.0 times that at CF (309 mg m$^{-2}$ h$^{-1}$) ($p < 0.01$). Therefore, the water regimes had a significant effect on the seasonal cumulative CO$_2$ emissions, which were enhanced 2.2 times by FDI and 1.7 times by FWI for the average of the two varieties, compared with that of CF (Table 5). The significant interaction between the water regimes and rice varieties was observed by the fact that FYY299 had a higher seasonal cumulative CO$_2$ emission than HY3 at the FWI plots and a lower emission than HY3 at the CF plots (Table 5).

For the HY3 hybrid, similar seasonal patterns of N$_2$O emissions were observed for all three water regimes (Fig. 2e). The N$_2$O emission fluxes peaked at 1.34, 1.52 and 0.97 mg m$^{-2}$ h$^{-1}$ in early August for HY3 at CF,
FWI and CF, respectively, with seasonal average fluxes of 0.38, 0.34 and 0.31 mg m\(^{-2}\) h\(^{-1}\), respectively. In contrast, the FY299 hybrid had additional small peaks in early July at FWI plots and in middle July at FWI plots. The averaged \(N_2O\) flux for FY299 under CF treatment was significantly lower than that under FWI and FDI treatments. There was no significant difference in \(N_2O\) flux between FWI and FDI. The seasonal cumulative \(N_2O\) emissions exhibited a similar trend to the CO\(_2\) for the CF, FWI and FDI treatments (Table 5). In contrast to CF, FWI and FDI increased the seasonal cumulative \(N_2O\) emissions 1.35 and 1.41 times CFI, FWI and FDI treatments (Table 5). In contrast to CF, FDI and FWI increased the seasonal cumulative \(N_2O\) emissions 1.35 and 1.41 times CF, respectively, for the two rice varieties. The seasonal N losses by \(N_2O\) emissions accounted for 2.2%, 2.9% and 3.1% of the applied N fertilizer at CF, FWI and FDI, respectively. The \(N_2O\) emission was significantly influenced by the interaction of the water regimes and rice varieties. The seasonal cumulative \(N_2O\) emission of FY299 was higher than that of HY3 under FWI treatment. However, it was lower under the CF irrigation regime (\(p < 0.01\)). There was no difference in the seasonal cumulative \(N_2O\) emissions between the two varieties managed with the FDI regime.

### 3.3. Seasonal GWPs and GHGI

As shown in Table 5, on average, the water-limiting irrigation regimes applied to the two varieties of rice decreased the GWP by 23% and 26% for FWI and FDI, respectively, compared with CF irrigation regime. Limited irrigation also changed the contribution of different GHG to the GWP. With a reduction in water input, the contribution of CH\(_4\) emission to GWP was reduced from 71% to 15%; however, contributions of CO\(_2\) and \(N_2O\) emissions increased from 23% to 73% and 6% to 12%, respectively (Table 5). Interactions between water regimes and rice varieties had significant effects on the GWP. The GWP generated at the HY3 sub-plots were higher than those generated at the FY299 sub-plots with CF treatment. Conversely, the GWP were dramatically lower at the HY3 sub-plots compared with those at FY299 sub-plots with FWI treatment (\(p < 0.01\)).

The water regimes had a significant effect on the GHGI (Table 5). On average, for the two rice varieties, GHGI was 4.56 kg CO\(_2\)-equivalents per kg of grain yield for CF treatment. This was significantly higher than GHGI for FWI (3.84 kg CO\(_2\)-equivalents per kg of grain yield) and FDI (3.88 kg CO\(_2\)-equivalents per kg of grain yield) irrigation regimes (\(p < 0.05\)) (Table 5). HY3 had the lowest GHGI for FWI treatment, which was 29% lower compared with CF irrigation method (\(p < 0.01\)). There was no difference in the GHGIs for the HY3 hybrid between FDI and FWI irrigation strategies. The GHGI of the FY299 hybrid under the CF water regime was not significantly different from the FWI treatment; however, it was significantly higher than FDI treatment by 10% (\(p < 0.05\)).

### 4. Discussion

#### 4.1. Water regimes and their effects on rice production

Compared with CF, FWI saved 38% of the irrigation water without grain yield or biomass losses for HY3 (Tables 3 and 4); this outcome is in agreement with the results reported by Yao et al. (2012), who conducted AWD studies in the same region and reduced irrigation water by 24–38%. However, the rice grain yield and aboveground biomass of both rice varieties were significantly reduced as the irrigation water was further controlled at FDI compared with CF (Table 4). Previous reports on AWD irrigation displayed disparate performances of rice grain yields (Bouman and Tuong, 2001; Zhang et al., 2009; Yao et al., 2012; Ye et al., 2013) due to variations in external and internal factors, such as rice varieties, irrigation intervals, weather conditions, soil properties and hydrological conditions across the experiments (Tuong et al., 2005; Dong et al., 2012). The rice variety is considered as a major factor in the performance of AWD (Luo, 2010; Bueno et al., 2010; Serraj et al., 2011). In our study, the WDR variety (HY3) outperformed the traditionally planted hybrid rice variety (FY299) under the two AWD treatments during drought, as was observed in 2013 (Table 4). Such performance of HY3 during drought had been reported previously (Yu et al., 2005; Huang et al., 2008; Si et al., 2010), in which up to 50% of the irrigation water could be conserved without yield loss. This study, along with the previous research, indicates that HY3 is a rice variety that could potentially be used for maintaining a steady yield while using water-saving irrigation schemes in the lowland region of Central China. However, both hybrids showed significant reductions in grain yields and aboveground biomasses compared with CF during the FDI treatment (Table 4). These results suggest that soil hydrological properties, which are partially affected by adverse weather conditions, might restrict the potential performance of rice varieties under water-saving irrigation. Groundwater table above a -40 cm depth, which can let rice plants easily extract water from the groundwater, was identified as the indices for “safe” water-saving irrigation (Belder et al., 2005; Yao et al., 2012). At the FDI irrigation plots, the groundwater table depth occasionally dropped below ~40 cm. In 2013, this was particularly pronounced during the period of rice panicle initiation (Fig. 1b). Thus, the use of irrigation regimes, such as FDI, with volumetric soil water contents lower than 0.3 m\(^3\) m\(^{-2}\), groundwater tables under 40 cm, and long cycles of re-irrigation with dry surface soil beds, may not be ideal water management strategies during drought years in terms of maintaining rice grain yields.

#### 4.2. Effects of water management on GHG emissions

There are many factors that impact the seasonal dynamics and flux of CH\(_4\) emissions from paddies through production control, oxidation and transport (Guo and Zhou, 2007). Soil moisture content was reported to have a significantly positive correlation with CH\(_4\) fluxes (Mori et al., 2008). Higher soil water content corresponds to quicker CH\(_4\) emission (Ahmad et al., 2009; Tyagi et al., 2010), continuously flooded paddy fields (CF) exhibited higher CH\(_4\) emission fluxes than the fields with FDI and FWI treatments, as shown in Fig. 2a and b. In contrast to flooding, dry-wet cycles negatively affect methane production (Estop-Aragonés et al., 2013) by preventing the development of soil reductive conditions (Minamikawa and Sakai, 2006). As shown in Fig. 1c and d, although the plots from FWI and FDI treatments had similar soil temperature and soil pH dynamics (\(p > 0.05\)), their soil water contents and groundwater tables
Fig. 2. Dynamics of CH$_4$, CO$_2$ and N$_2$O fluxes of the two rice varieties, i.e., Fengyuanyou (FYY299) and Hanyou3 (HY3), under the three water regimes, i.e., continuous flooding (CF), flooded and wet intermittent irrigation (FWI), and flooded and dry intermittent irrigation (FDI), during the rice growing season in 2013.

Table 5
Seasonal cumulative CO$_2$, CH$_4$ and N$_2$O emissions from the paddies of two rice hybrids, Fengyuanyou (FYY299) and Hanyou3 (HY3), their contributions to the global warming potentials (GWP; kg CO$_2$-equivalent ha$^{-1}$), and greenhouse gas intensities (GHGI; kg CO$_2$-equivalents per kg of grain yield) as affected by each of three water regimes, i.e., continuous flooding (CF), flooded and wet intermittent irrigation (FWI), and flooded and dry intermittent irrigation (FDI).

<table>
<thead>
<tr>
<th>Water regime</th>
<th>Variety</th>
<th>CO$_2$ (kg ha$^{-1}$)</th>
<th>CH$_4$ (kg ha$^{-1}$)</th>
<th>N$_2$O (kg ha$^{-1}$)</th>
<th>GWP (kg CO$_2$-equiv ha$^{-1}$)</th>
<th>Contribution to GWP (%)</th>
<th>GHGI (kg CO$_2$-equiv per kg grain yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF</td>
<td>HY3</td>
<td>924.9 D</td>
<td>955 A</td>
<td>8.2 b</td>
<td>35550 aA</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>FYY299</td>
<td>745.4 E</td>
<td>919 A</td>
<td>6.2 c</td>
<td>32257 bB</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>FWI</td>
<td>HY3</td>
<td>12137 C</td>
<td>365 B</td>
<td>9.2 b</td>
<td>23990 eD</td>
<td>51</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>FYY299</td>
<td>15467 B</td>
<td>379 B</td>
<td>10.2 aA</td>
<td>27972 cC</td>
<td>55</td>
<td>11</td>
</tr>
<tr>
<td>FDI</td>
<td>HY3</td>
<td>18046 A</td>
<td>176 C</td>
<td>10.3 aA</td>
<td>25502 dD</td>
<td>71</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>FYY299</td>
<td>17834 A</td>
<td>147 C</td>
<td>10.0 aA</td>
<td>24489 deD</td>
<td>73</td>
<td>12</td>
</tr>
</tbody>
</table>

F value

|                  | W         | 263.8**                | 391.0**               | 39.2**                  | 343.9**                      | 26.9*                     | 0.37                                      |
|                  | V         | 0.96                   | 0.51                  | 4.94                    | 0.02                         |                           | 4.06                                      |
|                  | W × V     | 11.30**                | 0.44                  | 18.75**                 | 8.73*                        |                           |                                           |
significantly decreased during the rice growth period (p < 0.05). The dry-wet cycles of the FWI and FDI treatments might alter the availability of alternative electron acceptors during the process of CH₄ production. Oxygen penetration during drying led to CO₂ and CH₄ degassing and a regeneration of dissolved electron acceptors (NO₃⁻, Fe³⁺ and SO₄²⁻) (Estop-Aragonés et al., 2013), which might consume H₂ to weaken the reduction of CO₂ or acetate for CH₄ production (Jain et al., 2004). The drying intensity controlled the extent of the electron acceptor regeneration and might result in different CH₄ emissions between FWI and FDI treatments (Fig. 2a and b). Because of the lower soil water content, the plots with FDI treatment suppressed CH₄ emissions to a very low level, and there were no obvious peaks during the rice growth period. Compared with CF treatment, the averaged seasonal CH₄ fluxes for both rice varieties were significantly reduced (p < 0.01) by 59% in FWI plots and 83% in the FDI plots. Our results support an earlier study by Katayanagi et al. (2012) who found a 73% mitigation of CH₄ emission using an AWD irrigation strategy during rice cultivation. Thus, decreasing soil water content through water management is thought to be the most promising option for methane mitigation (Yagi et al., 1996; Li et al., 2005; Minamikawa and Sakai, 2006; Tyagi et al., 2010).

Both CO₂ and CH₄ are the products of the decomposition of organic carbon under quite opposite conditions (Yao and Conrad, 2000). Notably, soil moisture regulates CO₂ emissions from soil; CH₄ also regulates emission, albeit in a different way. At the CF plots, CO₂ emissions peaked after the drainage prior to the harvest (Fig. 2c and d), similarly to the results reported by Ahmad et al. (2009). These drained paddy fields potentially resulted in aerobic conditions and increased soil respiration. CO₂ emissions from paddy soils under water-saving irrigation have not received much attention in earlier studies, and Zou et al. (2004) reported that there was no significant correlation between CO₂ and CH₄. The result from this study contradicts this earlier finding. We observed significant negative correlations between CO₂ and CH₄ that are likely due to the differences in soil water content between treatments (Table 6). In comparison with CF treatment, increased CO₂ fluxes were observed for FWI and FDI plots (Fig. 2c and d). The CO₂ fluxes for FWI and FDI plots peaked after the rice fully developed, likely because mature plants have more roots and root exudates for soil microbes (Aulakh et al., 2001). On average, for the two rice varieties, the seasonal CO₂ emissions for FWI and FDI plots were 1.6 and 2.0 times higher than CF treatment, respectively.

Conventional rice paddies release the lowest N₂O emissions due to two processes. First, the intermediary product of denitrification can be further reduced to N₂ under continuous flooding conditions (Zou et al., 2007; Peng et al., 2011). Second, the high soil water content inhibits N₂O exchange between soil and the atmosphere (Pathak et al., 2002). The seasonal N₂O emission was 7.2 kg N ha⁻¹ from the CF plots for both rice varieties (Table 5) and is in agreement with the result of 7.2 kg N ha⁻¹ measured by Ahmad et al. (2009) for no-till and continuously flooded paddies. The seasonal pattern of N₂O emissions was the same for all three irrigation strategies; however, the N₂O flux was higher for the water-saving irrigation regimes (Fig. 2e and f); this finding is consistent with previous studies (e.g., Zou et al., 2005; Liu et al., 2010; Wang et al., 2011). The seasonal pattern was governed by a substantial release of N₂O due to a burst of nitrification and denitrification under alternating wetting and drying cycles and the diffusion of trapped N₂O from the soil to the atmosphere (Cai et al., 1997; Yan et al., 2000; Huang et al., 2007). In contrast with CF treatment, alternate flooding and drainage in rice paddies triggered substantially higher N₂O fluxes, specifically, higher by 34% and 41% for FWI and FDI treatments, respectively (Fig. 2e and f). However, there was no significant correlation detected between N₂O flux and the soil water content (Table 6). A recent study by Berger et al. (2013) also showed that there was no significant statistical correlation between the N₂O flux and soil water level, regardless of the observations of N₂O emission peaks during midseason aeration. Intensive N₂O fluxes at all treatments were observed during late July and early August (Fig. 2e and f); this observation may be the result of fertilizer topdressing applications and higher air temperatures during this period. Hayakawas et al. (2009) observed increased N₂O emissions were positively correlated to the recorded temperature. The N₂O emission is usually boosted within 7 days after applying N fertilizer due to more available N for soil microbes (Xiong et al., 2007). However, our study did not find other pronounced N₂O emissions after N fertilizer topdressing (Fig. 2e and f); this might be due to longer gas-sampling intervals at our experimental field and the varied duration between re- watering plots under the different treatments.

### 4.3. Rice varieties and GHG emissions

Rice plants play a pivotal role in CH₄, CO₂ and N₂O emissions of rice fields. CH₄ production in rice fields largely depends on plant-borne material from either decaying tissue or root exudates (Wassmann and Aulakh, 2000; Kerdchoechuen, 2005). The CH₄ oxidation localized in the rhizosphere is controlled by the capacity of the transport of oxygen through the aerenchyma (Wassmann and Aulakh, 2000), and up to 90% of the CH₄ diffusion is rice-plant-mediated through the well-developed intracellular air spaces (aerenchyma) (Schutz et al., 1989). No significant difference was found between the rice varieties regarding CH₄ emissions (Table 5). Although the CH₄ flux rate has a positive correlation with rice biomass (Kerdchoechuen, 2005), the rice variety HY3, which had a higher biomass production in the AWD plots, did not exhibit it higher CH₄ emissions compared with FY299. This might indicate that the two rice varieties had equivalent or counterbalanced capacities for CH₄ production, oxidation, and diffusion. CO₂ is produced in soils by a variety of processes, including root respiration and heterotrophic oxidation of soil organic matter. Significant differences in the CO₂ emissions between the two rice varieties were observed for CF and FWI treatments (Table 5). This phenomenon might be partly due to the discrepant adaptability of the two rice varieties to soil water. The FY299 hybrid experienced a significant decrease in grain yields and aboveground biomass under FWI watering regime (Table 4). This water stress could prompt a partition of assimilates to roots for deeper elongation (Lilley and Fukai, 1994; Toorchi et al., 2002) or require more energy to absorb water and nutrients from the soil and thus increase root respiration. The reduction of the growth for the FY299 hybrid at the FWI plots also reduced the uptake of nitrogen. This allowed more N₂O to be emitted (Table 5). Compared with FY299, HY3 could adapt to a wider range of soil water status and impact CO₂ and N₂O emissions differently. This finding might be due to difference

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CH₄</th>
<th>CO₂</th>
<th>N₂O</th>
<th>SWC</th>
<th>SpH</th>
<th>St</th>
<th>At</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td></td>
<td>0.315**</td>
<td>0.193</td>
<td>0.396**</td>
<td>0.215*</td>
<td>0.071</td>
<td>0.149</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.172</td>
<td>0.036</td>
<td>0.311**</td>
<td>0.022</td>
<td>0.225*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td>0.193</td>
<td>0.172</td>
<td>0.124</td>
<td>0.024</td>
<td>0.030</td>
<td>0.056</td>
<td></td>
</tr>
</tbody>
</table>

The single asterisk represents a significance level of p < 0.05; and the double asterisk represents a significance level of p < 0.01.
in root physiology that influences root exudates, oxygen supply, and redox status at the rhizosphere. Further studies are needed to verify and understand the influences of rice types on GHG emissions under different water regimes, especially the effects by root-induced changes in the rhizosphere.

4.4. Impact of water regimes and rice varieties on GWP and GHGI

The production and emission of CO$_2$, CH$_4$ and N$_2$O in paddy soils were simultaneously regulated by the soil water status (Shang et al., 2011). Previous studies reported consistent observations of the trade-off between CH$_4$ and N$_2$O emissions under different water regimes (e.g., Zou et al., 2007; Li et al., 2011; Wang et al., 2011). However, few studies have examined how differences in irrigation regimes can impact the global warming potential of three greenhouse gases, CO$_2$, CH$_4$, and N$_2$O, simultaneously (Frolking et al., 2004). This study demonstrated that there was a trade-off between CH$_4$ and CO$_2$, as well as between CH$_4$ and N$_2$O (Table 5). Similar to previous reports (Zou et al., 2005; Shang et al., 2011), the water-saving irrigation strategies significantly decreased the GWP and GHGI by 23% and 16% for FWI treatment and 26% and 15% for FDI treatment ($p < 0.05$), respectively, compared with continuous flooding (CF) (Table 5). There was no additional reduction in the GWP or GHGI when using more aggressive water-saving strategies (FDI) compared with FWI watering regime due to the trade-offs among the three GHG.

The rice varieties also differently impacted the GWP and GHGI. HY3 exhibited the lowest GWP and GHGI for FWI treatment. In contrast, FYY299 had the lowest GWP and GHGI under FDI treatment. However, this result was likely due to the significantly reduced ($p < 0.01$) yield and biomass production of FYY299. Because the goal of this study was to identify irrigation strategies that conserve water and reduce GHG emissions while preserving yields, an irrigation strategy such as FDI treatment did not meet our requirement for grain yields, even though there was a reduction in the GWP and GHGI. This study provides support for the evaluation of trade-offs among GHG and adaptability of rice varieties to soil water status.

There are several reasons for possible uncertainties in the GHG emissions in our study. Although the chamber-based method is widely used to measure surface gas fluxes in croplands due to its low cost and ease of use (Wood et al., 2013), the potential impacts of the sampling frequency in space and time associated with chambers should be considered, particularly when integrating fluxes to estimate total emissions over extended periods (Wood et al., 2013). For our study, infrequent sampling (intervals of approximately 7–10 days) due to the extremely labor-intensive process may mischaracterize seasonal GHG flux variances and place greater weight on individual observations, thereby yielding biased estimates and potentially increasing the impact of outliers. In addition to the genetics of rice varieties, the performance of rice under AWD water-saving systems varies greatly with climate, soil type, and hydrological conditions (Tan et al., 2013), which in turn influences the behaviors of GHG emissions. Furthermore, GHG emissions are highly variable in time and space because of soil heterogeneity and climate variability, even under the same treatment. Because of these factors and the limited length of the study, these results need to be confirmed through future research at both the study site and elsewhere. Further research is warranted to determine the effects of sampling strategies, number of experiment years, and additional rice varieties on GHG emissions and their GWP under different water regimes.

In central lowland of China, most of paddies are flooded, except drainage for 7–10 days during tillering stage and two weeks before rice harvest. Irrigation water for paddies is drawn from the reservoir or river. Drought often occurs between July and September in this region. The capacity of the reservoir often cannot meet the rice consumption for irrigation water. The farmers here are willing to adopt water-saving irrigation in order to save water and labor cost. Moreover, they start to realize importance of mitigating GHG emissions from paddies with publicity by government and media reports. Though further studies are needed to testify our results, we can provide irrigation technique for farmers to practice, and give some practical advice for WDR rice planting which can be bought from the market.

5. Conclusions

This study showed that AWD irrigation could simultaneously conserve water and mitigate CH$_4$ in rice paddies. However, there are some trade-offs between CH$_4$ and two other GHG (i.e., CO$_2$ and N$_2$O). In contrast to continuous flooding, both AWD irrigation methods (FWI and FDI) reduced CH$_4$ emissions while largely triggering an increase in CO$_2$ and N$_2$O emissions. Thus, further reduction in irrigation water input using the FDI treatment did not significantly decrease the GWP and GHGI compared with the FWI treatment; however, this irrigation strategy significantly reduced yields. In addition to irrigation strategies, GHG emissions were impacted by the rice variety. The drought-resistance rice variety (HY3) exhibited superiority in both maintaining yields and reducing the GWP and GHGI over the ordinary rice variety (FY299) using FWI water-saving irrigation strategy. Although both of the rice varieties had significantly lower GWP and GHGI under this treatment, the irrigation strategy was capable of reducing GHG for the HY3 hybrid without yield losses. The FY299 hybrid had a yield reduction in addition to a GHG reduction. FWI irrigation strategy paired with the HY3 hybrid could be used to minimize GHG while maintaining yields in lieu of traditional management practices for rice paddies in the lowland region of Central China.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.10.073.

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