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The environmental and agronomic benefits and trade-offs linked with the adoption alternate wetting and drying in temperate rice paddies

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ABSTRACT

Context: Alternating wetting and drying (AWD) is an irrigation practice, alternative to continuous flooding, to improve the agro-environmental sustainability of rice cultivation. Benefits include reduction in water consumption, methane (CH_4) emissions and arsenic (As) concentrations in grain. However, drainage periods during AWD can negatively affect nitrogen (N) use efficiency by the crop and grain yields, while increasing nitrous oxide (N_2O) emissions and cadmium (Cd) contents in grain.

Objective: The objective of this study was to provide a holistic evaluation of AWD adoption in temperate rice cropping systems, including associated trade-offs. We hypothesized that the adoption of AWD in water seeded rice paddies can reduce the global warming potential (GWP) without affecting plant N uptake or introducing yield gaps, and also maintain a high quality of rice grain by limiting the uptake of metal(loid)s present in the soil, thereby resulting in an overall positive agro-environmental performance.

Methods: In a two-year field experiment in NW Italy two alternative irrigation practices involving water seeding followed by AWD management of different severity (AWD_{safe} and AWD_{strong}) were evaluated relative to the conventional water seeding and continuous flooding (WFL), comparing three different rice varieties. Yields and yield components, plant N uptake, apparent N recovery (ANR), metal(loid) concentrations in grain, and CH_4 and N_2O emissions were evaluated.

Results: AWD_{safe} and AWD_{strong} maintained or increased yields compared to WFL depending on varieties, despite an increase in sterility. There were no consistent differences in N uptake and ANR. Both AWD_{safe} and AWD_{strong} significantly reduce As concentration in grain, but significantly increase Cd and nickel (Ni). AWD_{safe} and AWD_{strong} reduced CH_4 emissions by 45–55 % and 40–73 %, respectively, compared toWFL, while no increase in N_2O emissions was observed. This resulted in a reduction in the GWP of 46 and 54 % with AWD_{safe} and AWD_{strong}, respectively.

Conclusions and Implications: AWD was shown to be effective for mitigating GHG emissions from temperate rice cropping systems while maintaining high yield performance comparable or higher than WFL. AWD may represent a viable alternative to continuous flooding to improve agro-environmental sustainability of temperate rice cropping systems, but the trade-off between decreasing As and increasing Cd and Ni contents in the grain may represent an important concern for food safety with the adoption of this alternative water management practice.

1. Introduction

Rice is the second most cropped cereal in the world with a production of 776 million tons and a harvested area of 165 Mha in 2022, and is a staple food for more than half of the world's population (FAOSTAT, 2023; Van Nguyen and Ferrero, 2006). Rice cultivation

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receives 34–43 % of total world water irrigation (Bouman et al., 2007) and is a significant source of greenhouse gas (GHG) emissions (Linquist et al., 2012), due to permanent flooding conditions generally adopted during the cropping cycle. Globally, methane (CH_4) emissions from rice cultivation contribute around 10 % (0.5 Gt CO_2-eq) of the total non-CO_2 emissions from agriculture (5.3 Gt CO_2-eq; FAO, 2020). Field flooding may also affect food safety through metal(loid) accumulation in rice grains, resulting in potential health risks associated with ingestion of arsenic (As) and cadmium (Cd) contaminated rice, especially in countries in which rice is a staple food (Banerjee et al., 2013; Zhu et al., 2008).

Alternate wetting and drying (AWD), which generally involves the frequent alternation between field flooding and drainage during the growing season, has been proposed to improve the agro-environmental sustainability of rice cultivation (Lampayan et al., 2015). AWD adoption may mitigate the negative impacts of continuously flooded rice systems, by reducing water use by 23–33 % (Carrijo et al., 2017) and mitigating GHG emissions, in particular CH_4 by 48–93 % (2015; Martínez-Eixarch et al., 2021). On the other hand, the frequent alternations in redox conditions associated with AWD are known to favour both microbial nitrification and denitrification, increasing nitrous oxide (N_2O) emissions, which has a radiative forcing much higher than CH_4 (Lagomarsino et al., 2016; Verhoeven et al., 2018). Consequently, the overall effect of AWD can be an increase (Lagomarsino et al., 2016) or a decrease in the global warming potential (GWP), as a function of factors that affect CH_4 and N_2O emissions (Mazza et al., 2016; Peyron et al., 2016).

Nonetheless, the benefits and trade-offs associated with the adoption of AWD are expected to be related to the severity and frequency of the drainage events and, in particular, to the threshold moisture level or water table depth reached when the fields are reflooded. Various studies have reported the influence of AWD on rice grain yields as a function of AWD severity and timing during the cropping season, and interactions with rice variety (Carrijo et al., 2017). Generally no significant reduction in grain yields are observed when a safe/mild AWD is applied (i.e., field reflooding is applied when a soil water potential of > -20 kPa or a water level of no more than –15 cm below the soil surface is reached), whereas with more severe AWD thresholds (i.e. soil water potential < -20 kPa), yield gaps as high as 22.6 % have been reported with respect to conventional water management (Carrijo et al., 2017). Some studies have also shown that AWD can increase grain yields compared to continuous flooding (Yang et al., 2009, 2017; Zhang et al., 2009).

Alternation between oxic and anoxic soil conditions under AWD affects the nitrogen (N) cycle with important implications on plant N uptake and N use efficiency of rice plants (Xu et al., 2019). Changes in soil hydrology and redox status with the adoption of AWD could lead to increased nitrification, greater N losses through denitrification, volatilization and leaching, and consequently reduced plant N availability and uptake (Hussain et al., 2015; Pandey et al., 2014; Shekhar et al., 2021). Depending of the severity, AWD was shown to reduce by about 6–12 % (Shekhar et al., 2022), maintain (Cheng et al., 2022; Ku et al., 2017) or improve N use efficiency with respect to continuous flooding (Liu et al., 2013; Ye et al., 2013), probably due to the confounding effects of AWD on the synchronization between water management and fertilizer distribution, and plant root development (Santiago-Arenas et al., 2019; Wang et al., 2016).

Adoption of AWD has also been reported to reduce As availability, plant uptake and its concentration in rice grains, primarily due to the limited mobilization and uptake of As under oxic soil conditions (LaHue et al., 2016; Linquist et al., 2015; Norton et al., 2017a). On the other hand, a general increase in soil redox potentials and an associated decrease in soil pH with field drainage under AWD (Das et al., 2016) may favour Cd accumulation in rice grain (Carrijo et al., 2022; Cattani et al., 2008). The impact of water management strategies on the mobility of other potentially toxic elements, such as nickel (Ni), is still less understood and deserves specific attention. While a decrease in redox potential was shown to enhance Ni release from soil to solution (Rinklebe and Shaheen, 2017), some reports suggest that rice grown in more oxidative soil conditions can accumulate greater Ni concentrations (Norton et al., 2017b). Even here, the severity of AWD cycles is expected to influence metal(loid) availability and uptake (Carrijo et al., 2018), but there is also an important varietal effect linked to the rice genotypes cultivated (Monaco et al., 2021). In order to ensure food safety, the European Union regulates the maximum limits for inorganic As species (iAs) (i.e. 0.15 mg iAs kg^{-1} of white rice; Commission Regulation EU, 2023) and total Cd (0.15 mg kg^{-1}; Commission Regulation EU, 2021) in rice grain, and is currently considering amending the maximum limit of total Ni in husked rice (2.0 mg kg^{-1}). Thus, understanding the influence of water management on grain metal(loid) contents is important for both food safety and to protect the economic sustainability of rice cropping systems and livelihood of farmers.

Most of the studies evaluating the effects of AWD on grain yield and quality as well as on the environmental sustainability of rice paddies focus on tropical and subtropical rice cropping areas (Bouman and Tuong, 2001; Lampayan et al., 2015; Yang et al., 2017), while only a few have investigated the adoption of AWD in European temperate rice cropping systems (Gharsallah et al., 2023; Lagomarsino et al., 2016; Martínez-Eixarch et al., 2021; Mazza et al., 2016; Monaco et al., 2021; Oliver et al., 2019; Orasen et al., 2019; Peyron et al., 2016). Furthermore, to date the extent of AWD adoption in temperate rice systems is still limited and mostly constrained to marginal cropping areas where water availability is already scarce. The diffusion of AWD has been mainly limited by an incomplete appreciation of the linked environmental and agronomic benefits and trade-offs, especially when compared to the more conventional water management practices, as well as due to the paucity of information on the pedoclimatic and hydrological suitability of different rice farming areas to AWD (Sander et al., 2017). Although various studies have evaluated the effects of AWD on rice yields, N dynamics and environmental impacts separately (Monaco et al., 2021; Peyron et al., 2016; Verhoeven et al., 2018), few studies have quantified different agro-ecological indicators simultaneously in order to provide a holistic evaluation of AWD adoption in temperate rice paddies. Furthermore, considering that the severity of AWD adoption in the field and the suitability of paddy soils for AWD management may be rather variable (Nelson et al., 2015), results on the agro-ecological implications of AWD adoption are often contrasting. Most of the studies in temperate regions tested “safe” or “mild” AWD with a low level of severity, and some of them limited the application of AWD cycles exclusively to the vegetative stages to avoid yield losses related to sterility during rice flowering. In addition, all of these experiments, with the exception of Gharsallah et al. (2023) and Martínez-Eixarch et al. (2021), applied AWD in combination with dry seeding and delayed flooding at the tillering stage rather than with water seeding. Recently, Gilardi et al. (2023) have highlighted the benefits of applying AWD in combination with water seeding in Italian rice context. They show how anticipating water use in April-May, when water resources are usually more abundant, may ensure sufficient groundwater recharge in spring thereby reducing the paddy water requirements in June-July when irrigation needs for other crops like corn increase. Since AWD results are influenced by site-specific conditions, there is a need to test AWD with different forms of severity in different regions to enable larger adoption of this technique, and to adapt AWD regimes to local production environments and field scales (Carrijo et al., 2017; LaHue et al., 2016).

Building upon these considerations, this work aims to simultaneously evaluate the agronomic and environmental sustainability of water seeded rice cropping systems under AWD as a function of different severity levels. We hypothesized that (1) AWD, even when applied in a severe way, does not lead to water stress that can compromise grain yield with respect to continuously flooded systems, although some varieties are better adapted than others; (2) the higher N losses that may occur with AWD compared to continuous flooding do not negatively affect N uptake and apparent N recovery; (3) AWD maintains a high quality of rice grain by limiting the availability and plant uptake of metal(loid)s present in the soil; and (4) despite the possible increase in N_2O emissions with repeated alternations in redox conditions under AWD, this management mitigates CH_4 emissions and reduces the overall GWP. We tested these hypotheses at field-scale over two cropping seasons by comparing two AWD managements, characterized by different severity, with conventional continuous flooding and evaluating yields and yield-related traits, N uptake, grain metal(loid) contents as well as variations in CH_4 and N_2O emissions and their specific contribution to the GWP.

2. Materials and methods

2.1. Experimental site description

This study was conducted in 2021 and 2022 in the experimental fields of the Rice Research Centre (Ente Nazionale Risi) in Castello d’Agogna (45°14’48’’N, 8°41’52’’E, NW Italy). The site is located in the western area of the plain of the Po river within the most extensive Italian rice district. The soil of the experimental field was a Fluvaquentic Epiaquept coarse silty, mixed, mesic (Soil Survey Staff, 2014). The topsoil (0–30 cm) was characterized by a loam texture, with a pH in water of 5.6, 11.3 g kg^{-1} organic carbon (C), 1.1 g kg^{-1} total N, 19.5 mg kg^{-1} Olsen phosphorus (P), and cation exchange capacity of 9.6 cmol$_{(+)}$ kg^{-1}. The concentrations of aqua-regia extractable As, Cd and Ni were 13.0, 0.2 and 31.3 mg kg^{-1}, respectively.

The climate is temperate subcontinental, characterized by hot summers and two main rainy periods in spring (April–May) and autumn (September–November). The mean annual temperature was 13.4 °C and 14.7 °C in 2021 and 2022, respectively, higher than the mean over the last 20 years (12.9 °C); during the growing season (May–September) the mean temperature was 21.8 °C and 23.5 °C, respectively (Fig. 1). The annual cumulative precipitation over the experimental period was 468 and 357 mm in 2021 and 2022, respectively (Fig. 1), lower than the mean over the last 20 years (659 mm).

2.2. Experimental design and treatments

The experiment was laid out in a split-split-plot design. The main experimental factor was water management, and included (i) water seeding and continuous flooding (WFL); (ii) water seeding and moderate AWD (AWD$_{\text{safe}}$; water potential threshold of –5 kPa at 5 cm above ground level); and (iii) water seeding and severe AWD (AWD$_{\text{strong}}$; water potential threshold of –20 kPa at 5 cm above ground level), with two replicate 1500 m^2 plots for each water treatment. In order to manage distinct water regimes in an economically and logistically feasible way, replicate plots for each water management were kept adjacent as described by de Vries et al. (2010) and Miniotti et al. (2016). Packed levees (50 cm above soil surface), covered with plastic film inserted below the soil surface to minimize the lateral movement of water, and two-side canals (25 cm deep) were created to maintain each plot hydraulically independent and to allow the independent management of water level. All plots were maintained with the same water regime during both years of the study.

Every main plot was divided in three 500 m^2 subplots where three varieties were sown, representing the second experimental factor. These included Selenio, Cammeo and CL26, which according to the CODEX classification (FAO and WHO, 2019) based on the grain length, belong to the short, medium and long rice grain groups, respectively. The varieties were selected on the basis of their representativeness in each group and different morphological characteristics. In each subplot, 32 m^2 sub-sub plots were established in which three different N fertilization doses were applied, each replicated twice: (1) *N+* fertilization with a conventional N rate for the different varieties considered (140 kg N ha^{-1} for Selenio and Cammeo, and 160 kg N ha^{-1} for CL26), (2) *N* fertilization with a rate of 40 kg ha^{-1} less than *N+* (100 kg N ha^{-1} for Selenio and Cammeo, and 120 kg N ha^{-1} for CL26), and (3) *N0* fertilization as a non-fertilized control. The N fertilizer (urea, 46 % N) was split in 40 % of total N applied in pre-seeding and incorporated into the soil by harrowing during seedbed preparation, 30 % at tillering stage and 30 % at panicle differentiation stage. The timing of N fertilizer application reflected the different development of the crop under the different water managements: panicle differentiation stage in the AWD treatments was delayed by a few days compared to WFL, and consequently the second topdressing N fertilization was also delayed (Table 1). In addition, 42 kg P_2O_5 ha^{-1} (18.3 kg P ha^{-1}) and 114 kg K_2O ha^{-1} (94.6 kg K ha^{-1}) were applied at tillering stage across all treatments.

Soil tillage involved ploughing and laser levelling in the spring and harrowing with a power harrow for seedbed preparation. In all plots the rice crop was established by broadcast water seeding on May 7 and 12 in 2021 and 2022, respectively (Table 1), with the same seeding rate (150 kg ha^{-1}) for the three varieties. During winter all plots were maintained drained and fallow following typical practices in the region.

After initial flooding and water seeding, pinpoint flooding method

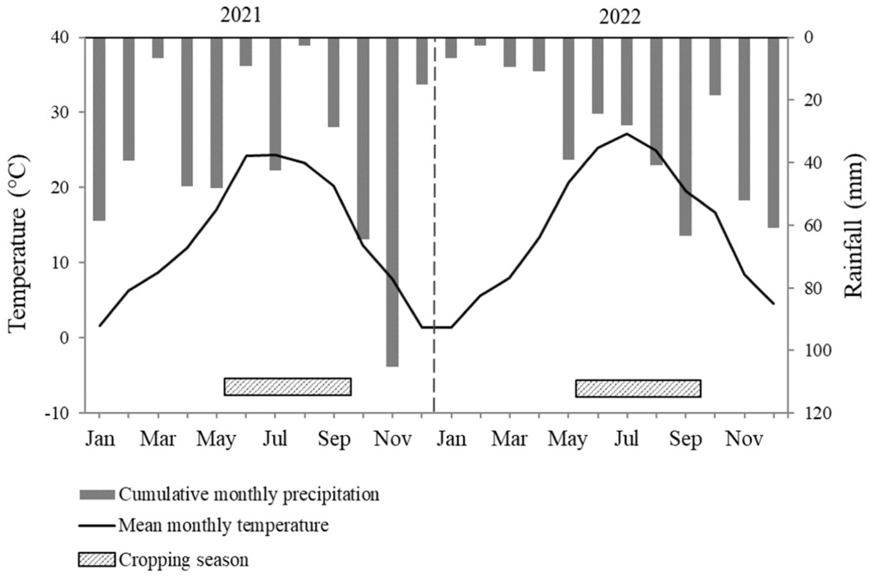

Fig. 1. Average monthly temperature and total precipitation over the 2021–2022 experimental period.

Table 1
Crop management under the different water management practices during the two years of the study (2021 and 2022).

Management practice	WFL		AWD$_{safe}$		AWD$_{strong}$	
	2021	2022	2021	2022	2021	2022
Spring tillage	15-Mar	14-Mar	15-Mar	14-Mar	15-Mar	14-Mar
Basal fertilization	5-May	10-May	5-May	10-May	5-May	10-May
Field flooding	6-May	11-May	6-May	11-May	6-May	11-May
Seeding	7-May	12-May	7-May	12-May	7-May	12-May
Post-emergence herbicide treatments (2 application)	8-Jun 16-Jun	20-May 13-Jun	8-Jun 16-Jun	20-May 13-Jun	8-Jun 16-Jun	20-May 13-Jun
First topdressing N fertilization	17-Jun	14-Jun	17-Jun	14-Jun	17-Jun	14-Jun
Second topdressing N fertilization	7-Jul	4-Jul	12-Jul	11-Jul	12-Jul	11-Jul
Field drainage before harvest	2-Sep	29-Aug	2-Sep	29-Aug	2-Sep	29-Aug
Harvest						
Selenio	29-Sep	20-Sep	29-Sep	20-Sep	29-Sep	20-Sep
Cammeo	24-Sep	19-Sep	24-Sep	19-Sep	24-Sep	19-Sep
CL26	23-Sep	16-Sep	23-Sep	16-Sep	23-Sep	16-Sep

was applied in the WFL treatment (Hardke and Scott, 2013). This involved repeatedly draining and flooding the soil during the seedling stage to promote root extension, avoid soil hardening and keep algal growth under control. After this period, continuous flooding (10 cm of ponding water) was maintained throughout the cropping season, except for two 3–5 d drainage periods at the start of tillering (middle of June) and panicle initiation stage (early/mid July) for fertilizer and herbicide application. In both drainage periods, field flooding was restored within one day from top-dressing fertilization, to avoid significant N losses by ammonia volatilization (Fig. 2).

In the AWD treatments, water management was the same as WFL until tillering, and then AWD cycles were applied. Plots were irrigated to a ponding water depth of 10 cm above the soil surface and then the water was progressively left to dissipate through evapotranspiration and percolation until the AWD threshold was reached, after which the plots were reflooded and a new AWD cycle repeated. The hydrological conditions of AWD plots were monitored by measuring (i) soil water potential with four tensiometers (one for each AWD plot) placed at 5 cm depth, (ii) soil volumetric water content with four soil moisture probes (Drill & Drop, Sentek Sensor Technologies, Stepney, Australia) to a depth of 5 cm, and (iii) water table depth with eight piezometers (two for each AWD plot) consisting of perforated PVC tubes of 50 cm length and 15 cm diameter, inserted vertically to a depth of 30 cm from the soil surface. The AWD thresholds adopted were based on previous studies involving *safe/mild* AWD and *severe/strong* AWD (Bouman et al., 2007; Lampayan et al., 2015; Carrijo et al., 2017). The threshold for AWD$_{safe}$ was set at a soil water potential of –5 kPa at 5 cm depth, corresponding to soil volumetric moisture of 40 % and a depth of water table of –10/–15 cm, while in AWD$_{strong}$ the threshold was set at a lower soil water potential (–20 kPa at 5 cm depth), corresponding to soil volumetric moisture of 36 % and a depth of water table of –20/–25 cm.

In the AWD$_{safe}$ and AWD$_{strong}$ treatments, 6 and 5 flood irrigation events occurred in 2021 while 6 and 7 in 2022, respectively (Fig. 2). In 2022, reduced rainfall in the first half of the season and high mean temperatures during the growing season (Fig. 1) led to drought and reduced water availability. As a result, slightly more severe AWD thresholds were reached in the second experimental year than in 2021. Net irrigation (mean 2021–2022) applied was 1351 mm in WFL, 1006 mm in AWD$_{safe}$ and 932 mm in AWD$_{strong}$. Herbicide and fungicide treatments were conducted following the standard practices of the area and were the same for all varieties and water management. When rice reached the ripening stage around 20 d before harvest, all plots were drained and harvest was carried out when the grain moisture was

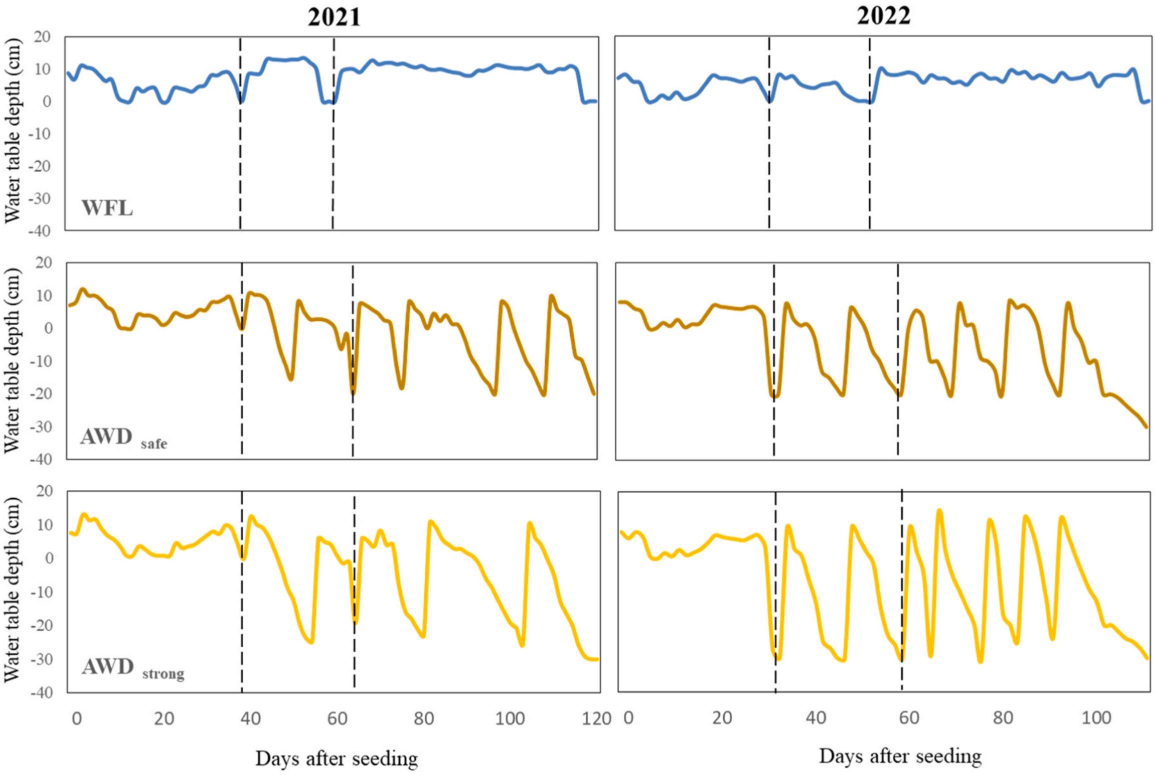

Fig. 2. Water regime of experimental plots under WFL (water seeding and continuous flooding), AWD$_{safe}$ (water seeding and moderate AWD) and AWD$_{strong}$ (water seeding and severe AWD) in the two years of the study (2021 and 2022). Dashed lines represent the date of topdressing N fertilizations.

around 20–22 % during the last 15 d of September depending on the variety and year.

2.3. Sampling and measurements

2.3.1. Yields and yield components

Grain yields for all varieties were determined with a combine harvester in each 32 m^2 sub-sub plot. Collected grain was dried, weighed and the values expressed on the basis of a 14 % moisture content. Panicle density per m^2 was determined at heading by counting panicle number in three sampling areas (0.25 m^2) for each sub-sub plot. The other yield components (i.e. number of spikelets per panicle, 1000-grain weight and percentage panicle sterility) were measured from 20 panicles randomly sampled in each sub-sub plot. Plant height was measured on the highest tiller of 4 randomly selected plants at the late ripening stage (87 BBCH code).

2.3.2. N contents and apparent N recovery

Total N content in dried grain and straw samples was determined by elemental analysis (UNICUBE Elemental Analyzer, Elementar, Germany). Total N uptake was obtained by multiplying grain and straw dry weight by their respective N content. Apparent N recovery (ANR) was calculated for *N* and *N+* treatments according to the following equation by Zavattaro et al. (2012):

$$ANR = \frac{(Nuptake_N) - (Nuptake_0)}{F_N} \quad \times 100\%$$

where $N\ uptake_N$ is total plant (grain + straw) N uptake expressed as kg N ha^{-1} for *N* and *N+* rate fertilization, $N\ uptake_0$ is total plant uptake expressed as kg N ha^{-1} in the *N0* treatment, F_N is the amount nitrogen applied with mineral fertilizer (as kg N ha^{-1}).

2.3.3. Arsenic, cadmium and nickel contents in grain

Grain metalloid and metal contents (total As, Cd and Ni) were determined on milled white rice grains from plots with standard *N+* fertilization only. Aliquots of milled white rice (0.5 g) were digested with 6 mL 65 % nitric acid (HNO_3) and 1 mL 30 % hydrogen peroxide (H_2O_2) in a heating block system in 50 mL polypropylene tubes at 95 °C for 2 h. The digested solutions were filtered with 0.45 µm teflon filters after appropriate dilution with ultra-pure water. Total As, Cd and Ni concentrations were determined by inductively coupled plasma mass spectrometry (ICP-MS NexION 350X, Perkin Elmer, USA). NIST 1568a and NIST 1568b rice flour were used as certified reference material to ensure the accuracy of analytical procedures for total As and Cd, respectively. Total As and Cd were quantified in the rice grain produced in both years while Ni was only quantified in 2022.

2.3.4. Greenhouse gas emissions

CH_4 and N_2O fluxes were measured during the entire growing period in both years for the Selenio variety with standard *N+* fertilization by adopting a non-steady-state closed chamber technique and following the protocol described by Bertora et al. (2018a), with four replicates for each water management (two in each main plot). Stainless steel anchors (75 × 36 × 40 cm high) were inserted into the soil up to a depth of 40 cm from the soil surface. Chambers were positioned at least 1 m inside the plots and wooden boards were adopted to access the anchors during sampling to avoid soil compaction or crop disturbance. During each flux measurement event, a rectangular stainless steel chamber (75 × 36 × 20 cm high) was sealed over each anchor by means of a water-filled channel, including the growing rice plants within when present. Chambers were covered with a 5 cm thick light-reflective insulation to limit temperature variations inside the chamber during flux measurements, and were equipped with a pressure vent valve designed according to Hutchinson and Mosier (1981), a battery-operated fan to ensure sufficient mixing of headspace air, and a gas sampling port. Steel chamber extensions (15 cm high) were added, when necessary, between anchor and chamber in order to accommodate the growing rice plant throughout the entire cropping season (maximum of four around harvest). Headspace gas samples from inside the chambers were collected by propylene syringes at 0, 10, 20 and 30 min after the chamber closure, and subsequently injected into 12-mL pre-evacuated vials closed with butyl rubber septa (Exetainer® vial from Labco Limited, UK). All gas-sampling events occurred between 10:00–13:00 hrs to minimize variability due to diurnal variations in gaseous fluxes, as also applied by Pittelkow et al. (2013). Collected samples were analyzed for CH_4 and N_2O by gas chromatography on a fully automated gas chromatograph (Agilent 7890 A with a Gerstel Maestro MPS2 auto sampler, Santa Clara CA, USA). Gas flux measurements were conducted at weekly intervals with higher sampling frequency in correspondence with fertilization, irrigation, flooding and drainage, when higher fluxes were expected.

Fluxes were calculated from the linear or non-linear (Hutchinson and Mosier, 1981) increase in gas concentration within the chamber headspace with time, as suggested by Livingston and Hutchinson (1995). Cumulative CH_4 and N_2O emissions were determined by linear interpolation of gas emissions across sampling days, assuming a linear trend of emissions in the days between each sampling. Emission factors (EF) for CH_4 for each water management, expressed as kg CH_4 ha^{-1} d^{-1}, were calculated by dividing the cumulative CH_4 emissions over the rice cropping period by the duration of the crop cycle (145 and 131 days in 2021 and 2022, respectively). The overall GWP, expressed in CO_2-equivalent units, was calculated considering a radiative forcing potential relative to CO_2 over a 100-yr time horizon of 28 for CH_4 and 265 for N_2O (Myhre et al., 2013). From the ratio of grain yield (Mg ha^{-1}) and GWP (kg CO_2-eq ha^{-1}), the GHG Eco-Efficiency (kg grain kg^{-1} CO_2-eq) that represents the amount of rice grain obtained per unit GHG emitted, was calculated. Moreover, to better understand the drivers and dynamics of CH_4 emission, soil redox potentials in each treatment were monitored potentiometrically at a soil depth of 10 cm throughout the cropping seasons.

2.4. Statistical analyses

All data were tested for normal distribution and homogeneity of variances using the Shapiro–Wilk test and the Levene test, respectively. Data that did not pass the test were log transformed. The Analysis of variance (ANOVA) was performed using the "*lme*" R function to assess significance of water management, variety, fertilization and year and their interactions. When significant ($p < 0.05$), treatment averages were separated through Bonferroni post hoc test. Statistical analysis was performed using R software, version 4.3.0.

3. Results

3.1. Yields and yield components

No significant effects of *N* and *N+* fertilization were recorded for yield and yield components, and these data were therefore presented as the average between the two fertilization treatments. Water management significantly affected grain yields with unexpectedly lower yields in WFL compared to both AWD managements that showed similar yields, with no differences between the two experimental years (Table 2). Significant interaction between water management × variety evidenced a different response of the three tested varieties to water management. In fact, similar grain yields under all water management practices were observed for Selenio and CL26, while higher yields were noted for Cammeo under both AWD managements compared to WFL. AWD_{strong} caused higher straw and total biomass than AWD_{safe} and WFL, although these differences were not consistent over the two years. Water management also significantly affected plant height, with values decreasing in the order $WFL < AWD_{strong} < AWD_{safe}$ in 2021, while in 2022 no significant differences among treatments were observed.

Table 2

Performance of the three water managements alone and in interaction with the two years and with the three varieties in terms of grain yield, straw and total biomass, and plant height. Data are presented as average between *N* and *N*+ fertilization. Within each parameter, means followed by different letters denote differences among water managements within each year or variety (p(F)<0.05), while the absence of letters suggests no significant differences.

Year (Y)	Variety (V)	Water manag.[a] (WM)	Grain yield (Mg ha^{-1})		Straw yield (Mg ha^{-1})		Total biomass (Mg ha^{-1})		Plant height (cm)	
2021		WFL	10.1		9.0	c	19.1	b	71.5	a
		AWD_{safe}	10.4		9.7	b	20.1	a	68.3	b
		$\text{AWD}_{\text{strong}}$	10.4		10.4	a	20.8	a	70.1	ab
2022		WFL	10.4		10.2	a	20.6	a	68.6	a
		AWD_{safe}	10.4		10.0	a	20.4	a	67.7	a
		$\text{AWD}_{\text{strong}}$	10.8		10.4	a	21.2	a	69.4	a
Average		WFL	10.3	b	9.6	b	19.9	b	70.1	a
		AWD_{safe}	10.4	ab	9.8	b	20.2	b	68.0	b
		$\text{AWD}_{\text{strong}}$	10.6	a	10.4	a	21.0	a	69.7	a
Average	Selenio	WFL	10.9	ab	10.0		20.9		72.9	a
		AWD_{safe}	10.7	b	10.1		20.7		68.8	b
		$\text{AWD}_{\text{strong}}$	11.1	a	10.7		21.8		71.5	a
	Cammeo	WFL	10.4	b	9.5		19.9		72.2	a
		AWD_{safe}	11.0	a	9.9		20.9		71.6	a
		$\text{AWD}_{\text{strong}}$	11.2	a	10.3		21.5		73.4	a
	CL26	WFL	9.4	a	9.4		18.8		65.1	a
		AWD_{safe}	9.5	a	9.5		19.1		63.6	a
		$\text{AWD}_{\text{strong}}$	9.5	a	10.2		19.7		64.2	a
p(F)	WM		0.007		0.000		0.000		0.000	
	V		0.000		0.006		0.000		0.000	
	Y		0.020		0.000		0.000		0.001	
	WM × Y		ns		0.004		0.034		0.049	
	WM × V		0.013		ns		ns		0.046	
	V × Y		ns		ns		ns		0.002	
	WM × V ×Y		ns		ns		ns		ns	

[a] WFL: water seeding and continuous flooding; AWD_{safe}: water seeding and moderate AWD; $\text{AWD}_{\text{strong}}$: water seeding and severe AWD.

Table 3

Performance of the three water managements alone and in interaction with the two years and with the three varieties in terms of yield components (panicle density, spikelets per panicle, 1000 grain weight and sterility). Data are presented as average between *N* and *N*+ fertilization. Within each parameter, means followed by different letters denote differences among water managements within each year or variety (p(F)<0.05), while the absence of letters suggests no significant differences.

Year (Y)	Variety (V)	Water manag.[a] (WM)	Panicle density (m^{-2})		Spikelets ($panicle^{-1}$)		1000 grain weight (g)		Sterility (%)	
2021		WFL	656	b	97		29.6	a	9.4	
		AWD_{safe}	674	a	101		29.3	ab	10.9	
		$\text{AWD}_{\text{strong}}$	677	a	103		28.1	b	11.6	
2022		WFL	695	a	86		30.5	ab	10.8	
		AWD_{safe}	663	b	84		30.7	a	11.9	
		$\text{AWD}_{\text{strong}}$	666	b	87		30.3	b	11.9	
Average		WFL	675		91	b	30.0	a	10.1	b
		AWD_{safe}	668		93	ab	30.0	a	11.4	a
		$\text{AWD}_{\text{strong}}$	671		95	a	29.7	b	11.7	a
Average	Selenio	WFL	725		92		25.7		9.4	b
		AWD_{safe}	730		92		25.5		12.9	a
		$\text{AWD}_{\text{strong}}$	716		94		25.4		12.2	a
	Cammeo	WFL	518		78		42.6		9.2	a
		AWD_{safe}	538		79		42.8		9.0	a
		$\text{AWD}_{\text{strong}}$	530		84		42.1		9.6	a
	CL26	WFL	783		103		21.8		11.8	b
		AWD_{safe}	737		106		21.7		12.3	ab
		$\text{AWD}_{\text{strong}}$	768		107		21.5		13.5	a
p(F)	WM		ns		0.006		0.000		0.000	
	V		0.000		0.000		0.000		0.000	
	Y		ns		0.000		0.000		0.006	
	WM × V		ns		ns		ns		0.002	
	WM × Y		0.026		ns		0.032		ns	
	V × Y		ns		ns		0.000		ns	
	WM × V ×Y		ns		ns		ns		ns	

[a] WFL: water seeding and continuous flooding; AWD_{safe}: water seeding and moderate AWD; $\text{AWD}_{\text{strong}}$: water seeding and severe AWD.

Water management also affected yield components to some extent (Table 3). The effects of water management on panicle density showed a significant interaction with year, as in 2021 AWD_{safe} and $\text{AWD}_{\text{strong}}$ showed higher densities than in WFL, while in 2022 the opposite was true. $\text{AWD}_{\text{strong}}$ showed higher spikelets per panicle than WFL, while intermediate values were obtained for AWD_{safe}. AWD_{safe} and $\text{AWD}_{\text{strong}}$ significantly decreased the 1000 grain weight compared to WFL in 2021 but not in 2022. In general, both AWD managements resulted in significantly higher sterility than WFL, but the effects varied between the three varieties. Although sterility in Cammeo was not affected by

Table 4

Performance of the three water managements alone and in interaction with the two years, the three varieties and with two N fertilization treatments in terms of grain and straw N contents, total N uptake in fertilized and control plots, and apparent N recovery. Within each parameter, means followed by different letters denote differences among water managements within each year or variety or differences between N fertilization treatments within each irrigation (p(F)<0.05), while the absence of letters suggests no significant differences.

Year (Y)	Variety (V)	Water manag.[a] (WM)	Fertilization (F)	Grain N (%)		Straw N (%)		Total N uptake (kg ha^{-1})			Apparent N recovery (%)
								Fertilized		Control	
2021		WFL		1.12	a	0.58		165.7		97.2	52.6
		AWD$_{safe}$		1.06	ab	0.53		162.0		100.5	48.7
		AWD$_{strong}$		1.04	b	0.53		163.8		104.7	46.4
2022		WFL		1.13	b	0.65		184.0		111.0	57.9
		AWD$_{safe}$		1.21	a	0.60		185.7		113.4	57.5
		AWD$_{strong}$		1.19	ab	0.57		187.5		115.2	57.6
Average		WFL		1.13		0.62	a	174.8		104.1	55.3
		AWD$_{safe}$		1.14		0.56	b	173.8		107.0	53.1
		AWD$_{strong}$		1.12		0.55	b	175.7		110.0	52.0
Average	Selenio	WFL		1.06		0.61		177.5		100.3	64.7
		AWD$_{safe}$		1.11		0.56		175.0		109.3	62.4
		AWD$_{strong}$		1.07		0.53		175.9		99.4	55.2
	Cammeo	WFL		1.11		0.59		171.1		108.5	49.2
		AWD$_{safe}$		1.07		0.55		172.9		109.9	51.9
		AWD$_{strong}$		1.04		0.51		169.1		107.6	51.3
	CL26	WFL		1.21		0.65		176.0		104.3	51.6
		AWD$_{safe}$		1.24		0.58		173.7		110.6	45.1
		AWD$_{strong}$		1.24		0.62		182.1		113.0	49.6
		WFL	N	1.10		0.60		164.9	b		55.2
			N+	1.15		0.64		184.8	a		55.4
		AWD$_{safe}$	N	1.11		0.55		162.4	b		52.4
			N+	1.17		0.57		185.2	a		53.8
		AWD$_{strong}$	N	1.10		0.54		165.5	b		52.1
			N+	1.13		0.56		185.9	a		51.9
p(F)	WM			ns		0.000		ns		ns	ns
	V			0.000		0.000		ns		ns	0.000
	F			0.005		0.013		0.000		-	ns
	Y			0.000		0.000		0.000		0.000	0.000
	WM × V			ns		ns		ns		ns	ns
	WM × F			ns		ns		0.010		-	ns
	WM × Y			0.000		ns		ns		ns	ns
	F × V			ns		ns		ns		-	ns
	F × Y			ns		ns		ns		-	ns

[a] WFL: water seeding and continuous flooding; AWD$_{safe}$: water seeding and moderate AWD; AWD$_{strong}$: water seeding and severe AWD.

water management, Selenio and CL26 showed a higher sterility under AWD$_{strong}$ with respect to WFL, with AWD$_{safe}$ showing intermediate effects in the latter and similar values to AWD$_{strong}$ in the former.

3.2. N uptake and apparent N recovery

Grain N contents were significantly affected by water management in interaction with year (Table 4). In 2021 higher values were found in WFL with respect to AWD$_{strong}$ while AWD$_{safe}$ showed intermediate values. In 2022 higher grain N contents were recorded in AWD$_{safe}$ with decreasing values in AWD$_{strong}$ and WFL. In general, straw N contents were significantly affected by water management, with the lowest values in both AWD treatments independently of the variety and year. In contrast, no water management-related differences were observed in total N uptake from both fertilized and control sub-sub-plots in both years and across all varieties. The supply of a higher amount of mineral nitrogen in the *N+* compared with the *N* treatment resulted in a significant increase in total N uptake in all water managements, although N content in grain and straw were not statistically affected by level of N applied. AWD$_{safe}$ and AWD$_{strong}$ slightly reduced the apparent N recovery (ANR) compared to WFL, although the differences were not significant. There is, however, a small effect of varieties on this parameter, with Cammeo showing a greater but not significant ANR under AWD compared to WFL, in contrast to the other varieties.

3.3. Metal(loid) grain concentrations

The adoption of AWD strongly affected the total grain content of metal(loid)s such as As, Cd and Ni (Table 5). Irrespective of the level of severity, lower concentrations of total As in the grain were observed under AWD. Also the influence of variety was relevant for As uptake. Although both AWD$_{safe}$ and AWD$_{strong}$ significantly reduced total As grain concentrations in Selenio and CL26 compared to WFL, concentrations in Cammeo grains were comparable across the three water managements. In contrast, Cd concentrations in the grain were significantly higher in plots managed with AWD than WFL, increasing in the order WFL<AWD$_{safe}$<AWD$_{strong}$. Higher concentrations of Cd were registered in 2022 than 2021 under both AWD$_{safe}$ and AWD$_{strong}$. The effects of water management on grain Cd contents were similar across the three varieties, with CL26 showing an increasing trend in Cd contents with increasing AWD severity, whereas Selenio and Cammeo did not show significant differences between the two AWD treatments. As for Cd, Ni concentrations in the grain increased significantly with the adoption of both AWD treatments with respect to WFL, albeit without a significant interaction with rice variety.

3.4. Greenhouse gas emissions

Greenhouse gas emissions occurred throughout the entire cropping cycle and were strongly influenced by water management and soil reduction potential (Fig. 3 & 4). Similar measured redox potentials were

Table 5

Grain concentrations of total arsenic (As), cadmium (Cd) and nickel (Ni) under the three water managements alone and in interaction with the two years and with the three varieties. Ni was monitored only in 2022. Within each parameter, means followed by different letters denote differences among water managements within each year or variety (p(F)<0.05), while the absence of letters suggests no significant differences.

Year (Y)	Variety (V)	Water manag.[a] (WM)	As		Cd		Ni	
			μg kg^{-1}					
2021		WFL	214.8	a	16.2	b		
		AWD_{safe}	173.8	b	75.3	b		
		AWD_{strong}	158.2	b	165.0	a		
2022		WFL	245.1	a	18.9	b	94.9	b
		AWD_{safe}	149.2	b	255.8	a	492.0	a
		AWD_{strong}	129.4	b	309.3	a	632.4	a
Average		WFL	229.9		17.3		94.9	b
		AWD_{safe}	161.5		169.1		492.0	a
		AWD_{strong}	143.8		237.1		632.4	a
Average	Selenio	WFL	254.1	a	28.5	b	71.7	b
		AWD_{safe}	185.4	b	140.1	a	392.1	a
		AWD_{strong}	147.3	b	186.1	a	503.1	a
	Cammeo	WFL	184.9	a	12.3	b	60.3	b
		AWD_{safe}	137.9	b	185.7	a	471.0	a
		AWD_{strong}	150.5	ab	249.2	a	509.7	a
	CL26	WFL	250.9	a	11.0	c	152.8	c
		AWD_{safe}	161.1	b	169.6	b	612.9	b
		AWD_{strong}	133.6	b	276.1	a	884.5	a
p(F)	WM		0.000		0.000		0.000	
	V		0.003		ns		ns	
	Y		ns		0.000		-	
	WM × V		0.036		0.027		0.041	
	WM × Y		0.017		0.000		-	
	V × Y		ns		ns		-	

[a] WFL: water seeding and continuous flooding; AWD_{safe}: water seeding and moderate AWD; AWD_{strong}: water seeding and severe AWD.

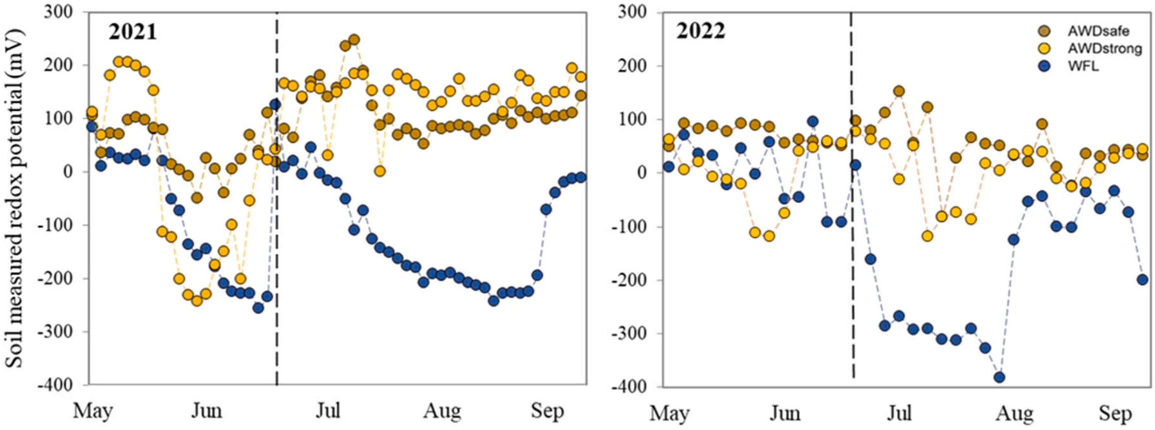

Fig. 3. Seasonal variation in soil measured redox potential over two years (2021 and 2022) as a function of water management practices involving WFL (water seeding and continuous flooding), AWD_{safe} (water seeding and moderate AWD) and AWD_{strong} (water seeding and severe AWD). The dotted line represents the beginning of AWD cycles.

recorded for all water managements up to the tillering stage; subsequently, higher redox potentials were recorded for the AWD treatments compared to WFL, where it dropped to negative values (Fig. 3). CH_4 fluxes reflected these changes in soil redox conditions as a function of water management. In both years and irrespective of water management, CH_4 fluxes were immediately observed in correspondence with the first week after seeding and increased rapidly showing a first major peak at the end of the "pin-point" period when flooding was restored (Fig. 4). Fluxes strongly decreased during the drainage periods performed to facilitate herbicide treatment and top-dressing fertilization at the tillering and panicle initiation stages, and after final field drainage before harvest. Before tillering, CH_4 fluxes were similar in all three treatments due to the similar water management. After tillering, the introduction of AWD cycles significantly affected CH_4 fluxes, with a general reduction with respect to WFL, which was more pronounced in the later stages of crop development, particularly in 2022. After flooding, CH_4 emissions from WFL were rather high and relatively constant with highest emission peaks observed in early July, a few days before the panicle initiation stage, and a few days after the final drainage, in both years but particularly in 2021. On the other hand, under both AWD treatments, emissions tended to increase and decrease in correspondence with repeated field flooding and drainage during AWD cycles, with lowest fluxes measured for AWD_{strong}. Indeed, in 2022 during the reproductive and ripening stages, emissions under AWD were more constant and significantly lower than under WFL.

N_2O fluxes were relatively low over the two years across all water management practices except for a few significant peaks in correspondence with top-dressed mineral N fertilization events at tillering, although no relationship with water management was noted (Fig. 4). An additional important peak was recorded under AWD_{safe} only in 2022

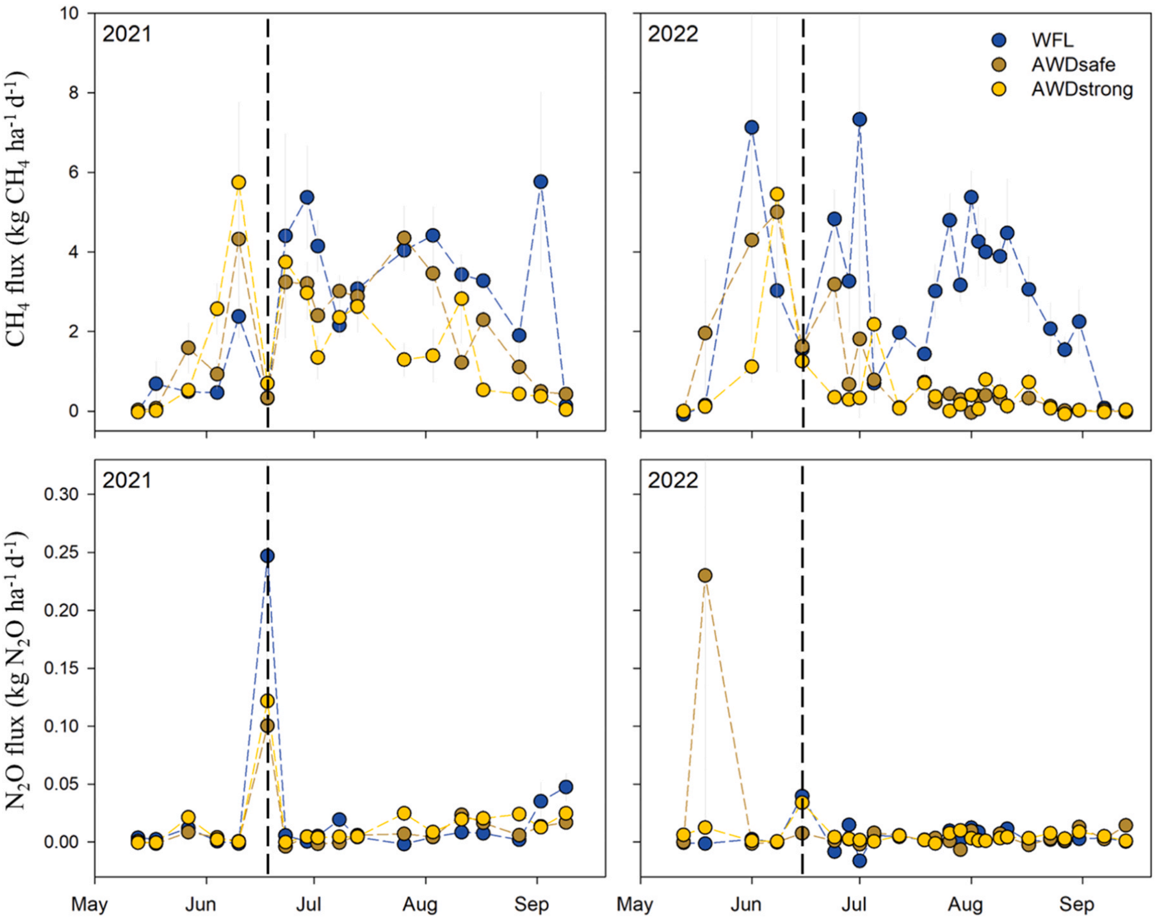

Fig. 4. Seasonal variation in CH_4 and N_2O emissions fluxes over two years (2021 and 2022) as a function of water management practices involving WFL (water seeding and continuous flooding), AWD_{safe} (water seeding and moderate AWD) and AWD_{strong} (water seeding and severe AWD). The dotted line represents the beginning of AWD cycles.

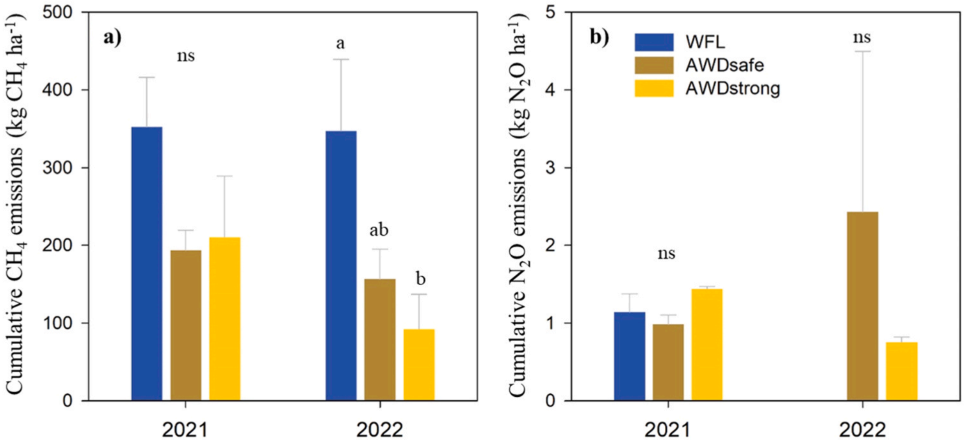

Fig. 5. Cumulative emissions of CH_4 (a) and N_2O (b) over the cropping season for WFL (water seeding and continuous flooding), AWD_{safe} (water seeding and moderate AWD) and AWD_{strong} (water seeding and severe AWD) in both years. Measured N_2O emissions for WFL in 2022 were not quantifiable. Error bars represent the standard deviation of four replicates. Treatments p(F) was equal to 0.046 in 2022 for CH_4. Different letters represent significant differences among water managements within each year ($p(F)<0.05$).

corresponding to the beginning of drainage operated at seedling stage for root anchoring. However, no other significant N_2O emissions were recorded under both AWD managements during the later stages of the cropping season, when AWD cycles could have promoted nitrification-denitrification.

In both years, adoption of AWD_{safe} and AWD_{strong} reduced cumulative CH_4 emissions with respect to WFL, although differences in 2021 were not statistically significant because of the high spatial variability of measured data (Fig. 5). Compared to total emissions of 352.4 and 347.4 kg CH_4 ha^{-1} under WFL in 2021 and 2022, adoption of AWD_{safe}

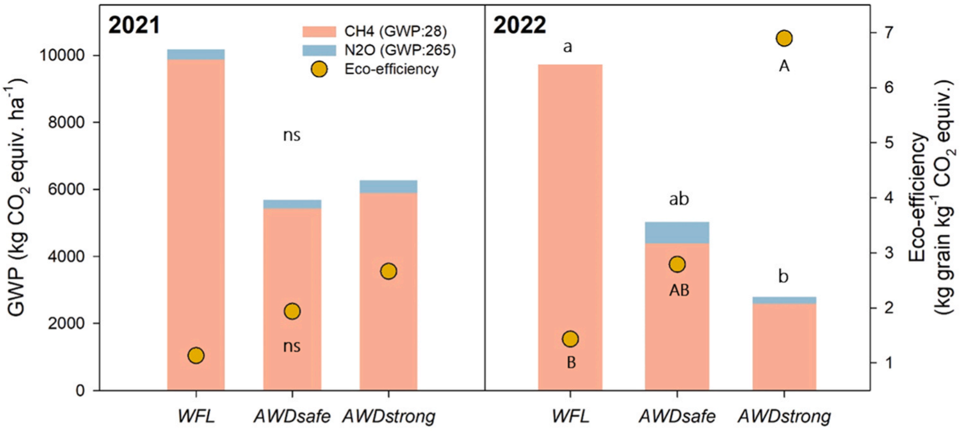

Fig. 6. GWP (Global Warming Potential) as sum of N_2O and CH_4 and Eco-Efficiency for WFL (water seeding and continuous flooding), AWD_{safe} (water seeding and moderate AWD) and AWD_{strong} (water seeding and severe AWD) in the 2021 and 2022 cropping seasons. Treatments p(F) was equal to 0.041 and 0.039 in 2022 for CH_4 and N_2O, respectively. Different lowercase and capital letters represent significant differences among treatments in GWP and Eco-Efficiency, respectively (p (F)<0.05).

and AWD_{strong} reduced total CH_4 emissions by 40–45 % and 55–73 %, respectively. However, a significant trend in CH_4 mitigation with increasing severity of AWD was only observed in 2022 where 92.3 kg CH_4 ha^{-1} total emissions under AWD_{strong} were measured. Cumulative N_2O emissions under WFL management were of 1.14 kg N_2O ha^{-1} in 2021, while in 2022 emissions were below the limits of quantification. In both years, no significant differences were observed in cumulative N_2O emissions with the adoption of AWD compared to WFL, irrespective of the severity (Fig. 5).

Irrespective of the water management, CH_4 rather than N_2O was the main contributor to the GWP, accounting for 97–100 % in WFL, 95–87 % in AWD_{safe} and 94–93 % in AWD_{strong} (Fig. 6). Considering the entire experimental period, AWD_{safe} and AWD_{strong} reduced the GWP by 46 and 54 %, respectively, compared to WFL. Although the adoption of AWD consistently decreased the GWP, there was a large variability in the mitigation effect of the two AWD managements between the two years, particularly for AWD_{strong} that led to a reduction in the GWP of 71 % in 2022 and only 38 % in 2021, with respect to WFL. GHG Eco-efficiency increased in the order WFL < AWD_{safe} < AWD_{strong} in both years, but significant differences were only found in 2022, where AWD_{strong} showed highest values for this index while WFL and AWD_{safe} did not differ substantially (Fig. 6).

Mean EF calculated for CH_4 and expressed as kg CH_4 ha^{-1} d^{-1}, showed significantly lower values with the adoption of AWD with respect to WFL, although differences between the two severities of AWD were not significant (Table 6).

Table 6
Annual and mean emission factor for CH_4 in the three water managements. Means followed by different letters within each year denote differences among water managements (p(F)<0.05), while the absence of letters suggests no significant differences.

Water management[a]	CH_4 emission factor 2021 (kg CH_4 ha^{-1} d^{-1})	CH_4 emission factor 2022 (kg CH_4 ha^{-1} d^{-1})		Mean CH_4 emission factor (kg CH_4 ha^{-1} d^{-1})	
WFL	2.43	2.63	a	2.54	a
AWD_{safe}	1.34	1.20	ab	1.27	b
AWD_{strong}	1.45	0.70	b	1.08	b
p(F)	ns	0.045		0.008	

[a] WFL: water seeding and continuous flooding; AWD_{safe}: water seeding and moderate AWD; AWD_{strong}: water seeding and severe AWD.

4. Discussion

4.1. Rice productivity

The adoption of AWD is often accompanied by variable yield gaps with respect to conventional water management mainly due to changes in plant phenology (e.g. root development), tolerance to water stress, and nutrient uptake by plants (Miniotti et al., 2016; Volante et al., 2017; Zhang et al., 2009). Frequent changes in soil redox status are also known to influence a variety of processes controlling N distribution, transformation, losses, and consequently, bioavailability for rice (Cucu et al., 2014; Said-Pullicino et al., 2014), that could have important effects on rice productivity. All these confounding factors are probably responsible for the different effects of AWD on grain yields reported in literature, that vary from lower to higher yields with respect to continuous flooding. Several authors reported no yield gaps when AWD with a soil water potential threshold of around –5/–10 kPa was adopted (i.e. AWD_{safe}) in temperate rice cropping systems (Carrijo et al., 2018; Monaco et al., 2021; Runkle et al., 2018), while others noted significant losses in grain yields when more severe AWD cycles (down to –20 kPa) were adopted, especially in light textured soil (Ishfaq et al., 2020), or when AWD was applied in conjunction with dry seeding over the whole cropping season (Carrijo et al., 2017; Miniotti et al., 2016), or when rice varieties less tolerant to AWD were grown (Martínez-Eixarch et al., 2021). In this study we evidenced similar or higher grain yields under AWD with respect to WFL. Nonetheless, the tested varieties had a different adaptability to AWD with Cammeo obtaining the highest yield gain with respect to conventional water management. These results are in line with the minor effects of mild AWD on the grain yields of different European rice cultivars tested in Italy (Monaco et al., 2021). The different levels of severity in AWD_{safe} and AWD_{strong} did not result in different grain yields, with the exception of Selenio, for which the observed differences were not related to different yield component responses to AWD. This indicates that AWD_{strong} was not the threshold level in this study, and more severe levels could presumably be applied without incurring in yield losses. We speculate that the good performance of rice under both safe and strong AWD in water seeded rice was probably due to the loamy soil texture of our study site that allowed for good root establishment, limited water stress during dry periods, and the lower incidence of physiological stresses typically related to the reducing conditions of continuous flooding, such as nutritional disorders (e.g. Akiochi), caused by sulfides, reduced iron, and volatile fatty acids, which can lead to early crop decline and lower nutrient uptake, especially in the reproductive stage with negative impacts on productivity (Pan et al., 2009). Furthermore, a higher incidence of stem rot of rice (*Sclerotium oryzae* Catt.) was observed under WFL (data not shown), especially in Cammeo, probably responsible for the lower grain yield respect to AWD.

The variability in grain yield among different rice varieties under different water managements highlighted in this study suggests the need for further investigation to identify the phenotypic characteristics that endow rice varieties with a better adaptability to water stress under AWD.

AWD_{safe} reduced plant height compared to continuous flooding, as also observed by Norton et al. (2017a) and Santiago-Arenas et al. (2021), despite the similar straw yield and total biomass. Our results that panicle density and 1000 grain weight were not affected by water management, also in interaction with variety, are also confirmed by the findings of Monaco et al. (2021) and Norton et al. (2017a). Higher yield potential under AWD was attributed to a higher number of spikelets per panicle, as already observed by Chu et al. (2018) and Yushi et al. (2013), despite higher sterility in all studied cultivars except Cammeo, related to a water-deficit stress that probably occurred during flowering (Pascual and Wang, 2017).

Water management can also strongly affect nutrient availability for plant uptake. Several studies have reported that the frequent alternation between field flooding and drainage during AWD cycles may promote N losses as N_2O and N_2 emissions during nitrification/denitrification processes and nitrate leaching, and enhance microbial N immobilization, thereby contributing to a lower N availability for plant uptake and consequently lower nutrient use efficiency (Cucu et al., 2014; Dong et al., 2018; Li et al., 2018; Shekhar et al., 2021). On the other hand, improved soil aeration under AWD may accelerate organic matter (and organic N) mineralization and promote belowground C allocation by plants as their roots explore deeper soil layers for enhancing nutrient uptake and consequently grain and biomass yield (Dong et al., 2012; Kato and Katsura, 2014; Zhang et al., 2009). In line with other studies (Carrijo et al., 2018; Cheng et al., 2022; Ye et al., 2013), total plant N uptake was not affected by water management even though straw N content was slightly but significantly lower under AWD with respect to WFL. We also observed a slight but not significant reduction in ANR with both AWD_{safe} (53 %) and AWD_{strong} (52 %) compared to continuous flooding (55 %), in line with the findings of Cheng et al. (2022) and Pan et al. (2017).

Vitali et al. (2024) have recently shown that AWD can influence the contribution of different N sources to plant uptake, not only by resulting in a slightly lower fertilizer-N use efficiency due to higher losses (Chu et al., 2015; Wang et al., 2016), but also by decreasing the soil N supply with respect to continuous flooding. However, they also show that these effects also depend on the management of crop residues and timing of fertilizer N application in relation with water management. In our study, the minimal differences between the two AWD regimes were probably due to a correct management of fertilizer application and irrigation management by which field flooding was carried out immediately after N application thereby minimising N losses (Lampayan et al., 2015; Yang et al., 2017). Irrespective of water management, the tested varieties showed significantly different ANR with Selenio showing a higher N recovery (on average 60.8 %) than Cammeo and CL26 (50.8 and 48.8 %, respectively), suggesting that varietal selection plays an important role in the management of N use efficiency under different water management practices. The specific root systems of the varieties, together with the greater root growth and activity under AWD (Islam et al., 2020a), may have influenced nutrient absorption capacity and consequently ANR by the different varieties.

4.2. *Grain quality / Metal(loid) grain concentrations*

Total grain As concentrations under continuous flooding were on average 230 μg kg^{-1}, which is similar to those reported by Monaco et al. (2021), but lower than values reported by Linquist et al. (2015). AWD_{safe} and AWD_{strong} reduced As concentration by 30 and 37 %, respectively, compared with continuous flooding, in line with results observed in other studies across Europe (38–40 %) (Martínez-Eixarch et al., 2021; Monaco et al., 2021). In contrast, adoption of AWD_{safe} in fine textured paddy soils in California did not diminish grain As contents because reducing soil conditions persisted even during dry periods after drainage due to a higher water retention (Carrijo et al., 2018). In our experiment, the loamy soil allowed for a rapid increase in measured redox potential immediately after field drainage, thereby reducing As concentration in the soil solution via coprecipitation/adsorption with Fe oxy(hydr)oxides (Zecchin et al., 2017). AWD_{strong} showed a slightly higher potential to reduce As accumulation than AWD_{safe}. Although the differences observed in this work were not significant, this trend corroborates the findings of Linquist et al. (2015) and Carrijo et al. (2018), (2022), who assessed a direct relationship between the severity and number of periods of field drainage during AWD cycles and the decrease of grain As concentration. We also observed a significant varietal effect, in line with previous studies (Tenni et al., 2017). Moreover, the tested varieties responded differently to water management in terms of As uptake, as reported for tropical rice varieties (Norton et al., 2017b). In fact, Cammeo showed the lowest grain As content under WFL among all varieties, but AWD practices had the least beneficial effect in decreasing As uptake. However, altogether, the reductions in total As content achieved with AWD in our study show that this water management represents a valuable tool for keeping As concentration in rice grain within the legal limit stated by the European Commission for inorganic As.

As expected, the effects of water management on grain Cd contents had an opposite trend with respect to As, as the adoption of AWD resulted in 10- to 13-times higher Cd contents compared to continuous flooding. Monaco et al. (2021) reported grain Cd concentrations of 135 μg kg^{-1} with AWD_{safe}, which is lower than the 169 and 237 μg kg^{-1} measured in our experiment under AWD_{safe} and AWD_{strong}, respectively. This could be attributable to the application, in our work, of AWD drying periods during the flowering and ripening stages, which are known to increase Cd mobility in soil during the phenological stages at which the greatest Cd translocation towards the grain occurs (Carrijo et al., 2022). In contrast to As, no significant varietal effect for Cd uptake was observed, while the effect of the different climatic conditions characterizing the two years of our experiment was evident. The drier summer in 2022 probably favoured Cd mobilization because of a faster decrease in soil moisture, involving rapid changes in soil redox potentials and pH, while the higher temperatures (Fig. 1) may have increased plant transpiration and thus Cd uptake and translocation to the grain (Cattani et al., 2008). Under both AWD managements, Cd grain contents exceeded the 150 μg kg^{-1} limit imposed by the European Union (Commission regulation EU, 2021), thereby confirming a critical water management-related trade-off between As and Cd grain contents, with important implications for food safety and human health. The management of AWD (severity, timing and number of soil drying periods) has been shown to be more critical for Cd than for As (Carrijo et al., 2022), hence, the best trade-off between As and Cd uptake could be achieved implementing AWD cycles during those phenological stages when rice is less sensitive to Cd accumulation, taking advantage of the beneficial effect of soil drying at stem elongation for As decrease (Zecchin et al., 2017), while keeping the soil flooded during the flowering stage to reduce Cd uptake (Carrijo et al., 2022).

Although Ni concentration was only investigated in 2022, our results evidenced that the adoption of AWD also led to an important increase in grain Ni content (5- to 7-time higher) compared to continuous flooding. The varietal effect was the same observed for Cd and indeed, while Ni and Cd concentrations in rice grain were positively related, both contaminants were inversely related with respect to As. However, while the different mechanisms linking As and Cd release from the soil solid phases to porewater in redox-fluctuating environments and the consequent uptake by rice plants are quite well understood, the same cannot be said for Ni, since the concentration of this element in soil solution is generally enhanced under reducing conditions (Rinklebe and Shaheen, 2017), even though our results corroborate the increasing evidences that more oxidizing conditions favour the accumulation of Ni in the rice grain (da Silva et al., 2020; Norton et al., 2017b; Orasen et al., 2019). Further studies are thus needed to better elucidate the apparent decoupling between Ni solid/solution partitioning in paddy soils and its accumulation in rice as a function of changing redox potentials and pH, in order to contrast this adverse effect with the application of AWD.

4.3. Greenhouse gas emissions

Total methane emissions over the cropping season under conventional water management (347–352 kg CH_4 ha^{-1}) were in line with values reported by Bertora et al. (2018b) and Peyron et al. (2016) for similar cropping systems in the region where rice was water seeded, paddy fields were continuously flooded and crop residues were incorporated more than 30 d before seeding. Moreover, our results confirmed that AWD significantly reduced cumulative CH_4 emissions particularly when lower soil water potentials were reached with the adoption of more severe AWD thresholds, even though these trends were stronger and more significant in the drier year (i.e. 2022). Mitigation of CH_4 emissions by AWD is generally due to the more aerobic soil conditions during the cropping season that are known to inhibit methanogenesis and favour aerobic decomposition and mineralization of labile organic matter, with respect to the conventional continuous flooded practice (Said-Pullicino et al., 2016), thereby resulting in substantially lower mean fluxes. However, continuous flooding also led to the production of high emission peaks in correspondence with field drainage that contributed substantially to the total cumulative emissions, but that were not observed under AWD. Similar peaks have been reported elsewhere (Linquist et al., 2015; Peyron et al., 2016) and have often been attributed to the rapid loss of entrapped CH_4 during field drainage (Pittelkow et al., 2013; Runkle et al., 2018). The absence of this phenomenon under AWD management was probably due to the higher soil redox potentials that limited production and accumulation of entrapped CH_4 in soil pores (Linquist et al., 2015).

The effectiveness of AWD to reduce total CH_4 emissions with respect to WFL (by 40–45 % and 55–73 % with AWD_{safe} and AWD_{strong}, respectively herein) are in line with the mitigation effects reported by Lagomarsino et al. (2016), LaHue et al. (2016), Martínez-Eixarch et al. (2021) for temperate rice systems, even though reductions in excess of 90 % were often observed when AWD management was combined with dry seeding and delayed flooding (Lagomarsino et al., 2016; Linquist et al., 2015; Peyron et al., 2016) or winter flooding (Martínez-Eixarch et al., 2021). These latter practices allow for a better aerobic decomposition of crop residues before the beginning of the cropping season that further reduces the amount of labile organic substrates for methanogens after flooding (Said-Pullicino et al., 2016).

Although the potential of AWD to mitigate CH_4 emissions from water seeded temperate rice paddies is evident and clearly related to AWD severity, the extent to which AWD can contribute to the mitigation with respect to conventional practices is highly variable (both spatially and temporally) and strongly depends on the interacting effects of pedoclimate, water availability and land suitability, that still remain hard to elucidate. The spatial variability may be related to different soil permeability properties and soil redox conditions, which are key aspects in influencing GHG emissions under AWD (Cheng et al., 2022). Similarly, the punctual management of water levels in the field for the correct adoption of AWD strongly depends on irrigation water availability, meteorological and hydrological conditions, that may all differ substantially between cropping seasons.

According to the guidelines of Intergovernmental Panel on Climate Change (IPCC), CH_4 emissions from rice paddies can be best estimated by utilizing country-specific daily emission factors (EF) and scaling factor (SF_w), which is a value calculated for different water management practices relative to continuously flooded fields (IPCC, 2019, Chapter 5.5). By adopting the IPCC Tier 1 approach for the estimation of CH_4 emissions from rice paddies, the daily EF for AWD can be estimated by multiplying the default CH_4 baseline EF for continuously flooded rice cultivation in Europe that ranges between 1.06–2.31 kg CH_4 ha^{-1} d^{-1} by the SF_w for multiple drainage periods during the rice cropping season (i.e. AWD) of 0.55, resulting in an EF that ranges between 0.58–1.27 kg CH_4 ha^{-1} d^{-1}. On the basis of the data provided herein we calculated a mean daily EF for AWD of 1.18 kg CH_4 ha^{-1} d^{-1} over the rice cropping season. This would equate to a SF_w of 0.46 when considering an EF for WFL measured in this study of 2.54 kg CH_4 ha^{-1} d^{-1}. Alternatively, a SF_w of 0.48 with an error range of 0.29 – 0.60 resulted when an aggregated mean EF for CH_4 emissions of 2.45 kg CH_4 ha^{-1} d^{-1}, that includes data from other water seeded, continuously flooded managements in the area, is considered (Peyron et al., 2016; Bertora et al., 2018b). The mean mitigation potential of AWD measured in this work is slightly higher than the 45 % reduction for multiple drainages proposed by the IPCC Tier 1 methodology and should therefore be preferentially used for improving the estimation of CH_4 emissions from Italian rice paddies according to a Tier 2 approach (IPCC, 2019).

The adoption of AWD in rice paddies is often associated with a trade-off between CH_4 and N_2O emissions, as frequent field drainage and reflooding cycles intended to mitigate CH_4 emissions, may enhance N_2O emissions by favouring denitrification/nitrification and decreasing N_2O reduction, particularly in the days following N fertilizer application (Lagomarsino et al., 2016; Miniotti et al., 2016; Verhoeven et al., 2018). These emission peaks have been shown to be strongly linked to crop development, and the integrated management of N fertilization and subsequent field flooding (Islam et al., 2020c; Kreye et al., 2007). In fact, as previously reported by Peyron et al. (2016), we measured highest N_2O emissions in correspondence with field flooding after N fertilization during the early vegetative stages, while N fertilization at the panicle initiation stage did not result in significant N_2O fluxes, probably because of the rapid N assimilation by rice plant in active growth (Hashim et al., 2015).

Contrary to many previous studies, the adoption of AWD in our study did not increase cumulative N_2O emissions probably due to a careful water management in the days immediately following N fertilizer application. It was previously shown by Linquist et al. (2015) that reflooding the field within 24 h after the top-dressing fertilizer distribution, and maintaining flooding conditions for 7–10 days after fertilization allow maximum N uptake by the crop. This limits the amount of N available for nitrification/denitrification processes during dry periods, contributing to minimize N_2O emissions.

As already highlighted by various studies (Fertitta-Roberts et al., 2019; Islam et al., 2020b; Mazza et al., 2016), CH_4 emissions accounted for a substantial part of the GWP compared to N_2O emissions (99 % in continuous flooding and 93 % on average in the two AWD managements). Consequently, N_2O emissions only had a slightly higher weight in the GWP of AWD than in continuous flooding (7 % on average in the two AWD managements and 1 % in continuous flooding). The trade-off between CH_4 and N_2O emissions under AWD was previously shown to result in either lower GWP (Linquist et al., 2015; 2021) or higher GWP (Lagomarsino et al., 2016; Liao et al., 2020) compared to continuous flooding. In our study, reduced CH_4 emissions and similar N_2O emissions under AWD resulted in an overall reduction in the GWP of the cropping systems compared to conventional continuous flooding. As for CH_4 emissions, the GWP decreased with increasing AWD severity, by 46 and 54 % on average for AWD_{safe} and AWD_{strong} with respect to continuous flooding, respectively, while the Eco-efficiency increased by 49–79 % (in 2022), confirming the higher agro-environmental performance of AWD managements in line with the findings of Miniotti et al. (2016).

5. Conclusions

This study confirms that the environmental impact of conventional continuous flooding in Italian temperate rice systems can be mitigated through the adoption of AWD while maintaining similar or improved agronomic performance. The higher yield potential under AWD is determined by a higher number of spikelets per panicle, despite higher sterility, balanced by similar plant N uptake compared to continuous flooding. The variability in grain yields among different rice varieties suggests the need to identify genotypes more suitable for AWD. AWD treatments applied in combination with water seeding allow to significantly reduce CH_4 emissions without increasing N_2O emissions, thereby maintaining a lower GWP. The most important insight of this work is that the improvement in Eco-efficiency increased with the severity of AWD management when applied from tillering to maturity, without affecting yield and N uptake. Despite these potential benefits, our results also showed that there are important trade-offs related to food safety that need to be taken into consideration when adopting AWD. In fact, although AWD was found to be an appropriate strategy to reduce rice grain As concentrations, a contemporary increase in Cd and Ni contents may be of concern and requires specific abatement measures. Further studies needed to promote the adoption of AWD in temperate rice cropping systems should focus on the pedoclimatic and hydrological suitability of different rice farming areas (or hydrological districts) for AWD adoption, as well as on the most appropriate methods for implementing specific AWD thresholds (i.e. timing of drainage and reflooding cycles). The interannual variability in the GHG mitigation potential of AWD compared to conventional water management also represents an important limitation that needs further investigation in order to facilitate the diffusion of AWD not only in Italy, but also in Europe and other temperate rice-growing areas.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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