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Agro-environmental sustainability of different water management practices in temperate rice agro-ecosystems

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Abstract

Water management practices alternative to continuous flooding are highly required to enhance water use efficiency and safeguarding environmental quality in temperate rice agro-ecosystems. In this work, we carried out a two year field experiment (2012-2013) in a rice paddy in NW Italy to evaluate and quantify the agro-environmental sustainability of three different water management practices involving (i) water seeding and continuous flooding (WFL), (ii) dry seeding and flooding at tillering stage (DFL), and (iii) dry seeding and intermittent irrigation (DIR). The effects of water management on agronomic parameters, such as crop yields, yield components and the apparent N recovery were evaluated for four rice varieties (Gladio, Baldo, Selenio e Loto) representing the main Italian grain types. We also evaluated net irrigation, water use efficiency, nitrate leaching and runoff, and greenhouse gas (GHG) emissions for the different management practices. Water management strongly affected grain yields and qualitative yield components. Whereas WFL and DFL showed similar yields, DIR resulted in significant yield reductions by 28, 24, 19 and 14% for the four varieties, respectively. This was related to a lower tillering rate, and reduced N uptake and apparent fertilizer N recovery. Intermittent irrigation however showed lowest net irrigation and consequently a higher water use efficiency (56%) with respect to WFL (22%) and DFL (26%). High soil solution nitrate concentrations and leaching from the root zone as a result of nitrification under oxic soil conditions represented the greatest environmental constrain of dry seeded cropping systems. On the other hand, water management practices alternative to continuous flooding, in particular DIR, strongly contributed to mitigate GHG emissions and reduce the Global Warming Potential of these cropping systems by up to 70-90%.

Keywords

Water use, nitrogen recovery, nitrate fluxes, global warming potential, agro-ecological indicators.

1. Introduction

Rice is the second most important crop in the world and Italy is the leading producer in Europe with around 227,300 ha under cultivation (Ente Nazionale Risi, 2015). Rice is typically grown in flooded paddies for most of the cropping season. Water management in these agro-ecosystems may therefore involve the use of large amounts of freshwater for irrigation with respect to other crops (Yoshinaga et al., 2007; Shao et al., 2014). The increasing need to integrate water requirements with resource availability as well as socio-economic aspects warrants the necessity to identify and adopt alternative water management practices aimed at enhancing water use efficiency and environmental quality (Xiang et al., 2013; Dunn and Gaydon, 2011).

Agronomic practices such as mid-season drainage, dry seeding and delayed flooding or intermittent irrigation have been shown to have positive implications on reducing water use with respect to continuous flooding (Kato et al., 2009; Dunn and Gaydon, 2011). Heenan and Thompson (1984) and Thompson and Griffin (2006) found that delaying field flooding until two weeks before panicle initiation resulted in an increase in water productivity from 0.06 to 0.23 kg m^{-3}, without compromising grain yields. Intermittent irrigation may lead to a further 30-50% reduction in water requirements with respect to continuous flooding, by reducing seepage, percolation and evapotranspiration losses (Bouman and Tuong, 2001; Nie et al., 2009; Facchi et al., 2013). However, the adoption of alternative water management practices often implies reduced yields, enhanced presence of weeds and diseases, and increased labour and pesticide costs (de Vries et al., 2010; Dunn and Gaydon, 2011). Bouman and Tuong (2001) suggested that variations in yield may be explained by different varietal responses to drought stress, as well as timing and number of irrigation events during the cropping season. Studies conducted in both temperate and tropical regions suggest that high-yielding varieties adapted to drier conditions can achieve high yields even in aerobic cropping systems (Kato et al., 2009; Kato and Katsura, 2014). As expected, whereas the yields of lowland rice varieties cultivated under aerobic conditions have been shown to decrease dramatically with decreasing water input, aerobic varieties maintained relatively high yields (Xiaoguang et al., 2005; Mahmod et al., 2014).

However, water management practices do not only influence water use efficiency and grain yields, but may also strongly alter hydrological regimes and soil moisture conditions, as a function of pedoclimatic conditions (Sacco et al., 2012, Zhao et al., 2015). Resulting changes in soil redox conditions are known to influence a variety of processes controlling nutrient distribution, transformation, losses, and bioavailability for rice crops (Cucu et al., 2014; Said-Pullicino et al., 2014), as well as greenhouse gas (GHG) production and emission to the atmosphere (Tyagi et al., 2010).

Under flooded conditions significant amounts of nutrients (especially nitrogen, N) may be lost by leaching and runoff during the cropping season, with important implications on water quality (Katoh et al., 2004). These processes, together with the biotic and abiotic immobilization of N (Cucu et al., 2014; Said Pullicino et al., 2014) and gaseous losses into the atmosphere as NH_3, N_2O and N_2 via volatilization and nitrification/denitrification (Cassman et al., 1998) might strongly limit plant N availability and fertilizer use efficiency, consequently affecting yields (Nie et al., 2009). However, the introduction of water saving practices does not mean an increase in the fertilizer use efficiency. Pittelkow et al. (2014) observed, indeed, a lower recovery (44%) of applied fertilizer N in dry with respect to water (51%) seeded systems, although the efficiency also depended on N application doses and split N applications. Belder et al. (2005) also showed that only 22% of applied fertilizer N was taken up by the crop in aerobic cropping systems, compared to 49% in conventional flooded systems.

Furthermore, rice cropping systems represent an important global source of atmospheric methane (CH_4; Kimura et al., 2004). The anaerobic soil conditions resulting from paddy field flooding creates a favourable environment for methane production (Xu et al., 2015). Linquist et al. (2012) reported that the global warming potential (GWP) of rice cropping systems due to CH_4 emissions is roughly four times higher than either wheat (*Triticum aestivum*) or maize (*Zea mays*). Alternative water management practices have been shown to effectively mitigate CH_4 emissions (Yang et al., 2012), although these same practices can enhance nitrous oxide (N_2O) emissions, another GHG with a GWP around 12 times higher than CH_4 (Hou et al., 2012). Pittelkow et al. (2014) showed that reducing the period of soil submergence during the first part of the growing season by adopting dry seeding may reduce CH_4 emissions by 47% with respect to water seeding. Moreover, Xu et al. (2015) observed that the adoption of intermittent irrigation mitigated CH_4 emissions by 59-83% with respect to continuous flooding, although the changes in soil moisture status as a result of successive field drainage and re-flooding enhanced N_2O emissions by 34-41%.

Based on these considerations, although irrigation systems that involve shorter periods of paddy flooding during the cropping season may require less water, the effects on grain yields, nutrient and water use efficiency, water quality, as well as the trade-offs between CH_4 and N_2O emissions, may render the proper evaluation of these management practices rather complex. Although various studies have evaluated the effects of water management on rice yields, N dynamics and environmental impacts separately (Mahajan et al., 2012; Sun et al., 2012; Ye et al., 2013), few studies have quantified different agro-ecological indicators simultaneously in order to provide a holistic evaluation of different water management practices in temperate rice paddies. This study therefore aims to investigate the effects of three water management practices in a temperate rice agro-ecosystem (NW Italy) on: (i) crop yields and yield components, as well as apparent fertilizer N recovery for four rice varieties; and (ii) water balance, N fluxes from soil to surface and subsurface waters, and cumulative GHG emissions to the atmosphere.

2. Materials and Methods

2.1 Experimental site

The research was carried out over two cropping seasons (2012 and 2013) in an experimental platform located within the Rice Research Centre of Ente Nazionale Risi at Castello d'Agogna (45°14'48"N, 8°41'52"E, NW Italy). The site is situated in the low section of the river Po plain which includes the distal part of the glacial alluvial Würmian flat, and is characterized by the presence of bumps of Holocene fluvial dynamics and levelling due to the more recent agricultural processes. The climate is temperate, characterized by hot summers and two main rainy periods in spring and autumn. The mean annual precipitation was 611 and 756 mm in 2012 and 2013, respectively, while the mean value for the last 20 years was 704 mm. The mean annual temperature was +13°C for both years (Fig. 1), in line with the 20 year mean.

A detailed soil survey, consisting of the description of five soil profiles opened in adjacent fields, as well as 108 soil cores sampled over the whole experimental site (1.2 ha), was carried out before the beginning of the experiment. The topsoil (0-30 cm) and plough pan (30-40 cm) were characterized by a loam and silty loam texture, respectively, with a pH of 6.3 (1:2.5 soil-to-water ratio). Average organic C and total N contents were 9.0 and 0.70 g kg^{-1}, respectively, while cation exchange capacity (CEC) was 10.0 $\mathrm{cmol_{(+)}\ kg^{-1}}$. The ploughed horizons extend uniformly over the whole experimental site due to agricultural operations consistently carried out over many years (Masseroni et al., 2014). Horizons below the ploughed horizons show a greater variability in terms of texture and organic matter content. According to the USDA classification (Soil Survey Staff, 2014), soils in the site were mainly classified as Fluvaquentic Epiaquept, coarse silty, mixed, mesic.

2.2 Experimental design and treatments

The experimental design comprised a split-plot 3×4 factorial arrangement representing: (i) three different water management practices including (a) water seeding and conventional continuous flooding (WFL), (b) dry seeding and flooding at tillering stage (DFL), (c) dry seeding and intermittent irrigation (DIR); and (ii) four rice varieties, corresponding to the main Italian grain types (Gladio, Baldo, Selenio, Loto) all related to the Japonica genotype (Oka, 1988). Gladio is a crystalline long B grain variety (EU standards) suitable for parboiling. It is an early variety (about 135 d), semi-dwarf, with medium-high N requirements. Baldo is a long A grain variety (EU standards). It is a long-cycle variety (about 150 d), with high height, susceptible to lodging and with medium-low N requirements. Selenio is a round grain variety used for puffed rice production. It is a long-cycle variety (about 145 d), that shows high yield performance due to high tillering and number of spikelets per panicle, but susceptible to lodging due to its medium height. Loto is an early (about 125 d), long A grain variety with a vitreous grain and low amylose content (Biloni and Bocchi, 2003), suitable for parboiling. With a height of around 70 cm, this variety is not as susceptible to lodging, and has medium N requirements.

The experimental site was divided into six 20×80 m plots, two for each water treatment. All plots were ploughed in spring and laser levelled. A levee (50 cm above the soil surface) with two side canals of 20-25 cm depth was created between adjacent plots, separating them by approximately 2 meters. In this way water could be drained from each plot separately, and the water level managed independently. The plots of the experimental trial were not assigned randomly, but the two replicates for each water management were kept adjacent, in a similar way as described by de Vries et al. (2010). This was necessary in order to ensure distinct water regimes in an economically and logistically feasible way, as well as to provide for a more affordable setup of instruments used for measuring components of the water balance. In this way, only spatial variability in one direction was assessed (see Statistical Analyses below).

The seedbeds were prepared in a single step using a rotary harrow for WFL, and in two steps in combination with a seeder for DFL and DIR. Since early varieties were used, water seeding was carried out in the second half of May for WFL, and approximately 10 days earlier in the other two dry seeded systems. In WFL broadcast seeding into water was adopted, while drill seeding into dry soil (2-3 cm deep with 12 cm row spacing) was adopted in DFL and DIR. The same seed rates were applied in 2012 and 2013 corresponding to 160, 130, 150 and 170 kg $\mathrm{ha^{-1}}$ for Gladio, Baldo, Selenio and Loto, respectively.

Water management in the WFL plots involved continuous flooding for most of the growing season, except for a 4-6 d drained period after sowing to allow for root extension and a following "pin-point" period, and two 4 d mid-season drainage periods for fertilizer and herbicide application approximately in the second half of June and July. In the DFL treatment, the plots were dry seeded and maintained under drained conditions for approximately one month until tillering stage, towards the second half of June. They were subsequently flooded and managed in a similar way as the WFL treatment. In the DIR treatment, plots were dry seeded and subsequently maintained without ponding water throughout the cropping season, applying irrigation intermittently when the soil water potential at 10 cm approached –30 kPa. In all treatments, drainage was allowed at the ripening stage (grain moisture between 26-28%), around 20–30 days before harvest.

Within each water management plot, 16 sub-plots (2.5×10 m) were further established for each variety, including both N fertilized and control (without N application) sub-plots for estimating the apparent fertilizer N recovery. Nitrogen fertilization (as urea) was applied according to the typical fertilization management of the different varieties (160, 120, 140 and 130 kg N ha^{-1} for Gladio, Baldo, Selenio and Loto, respectively), and split in three times during the cropping season (basal, tillering and panicle differentiation), with the exception of DIR where a fourth application was carried out at the booting stage. All fertilizer applications were top-dressed except for the basal fertilization that was incorporated. Phosphorus and potassium were applied before sowing at a dose of 18 kg P ha^{-1} and 70 kg K ha^{-1}.

Harvest was carried out between the end of September and the first 15 days of October depending on the specific varieties and year.

2.3 Sampling and measurements

Crop yields, yield components and N contents at harvest were determined on all varieties as a function of the three water management practices. Water balance, water quality and nutrient fluxes as well as GHG emissions were only investigated for the Gladio variety.

2.3.1 Crop yields, yield components and N contents

Grain yields for all varieties were determined by sampling a 25 m^2 area in each sub-plot, and expressing results on the basis of a 14% moisture content. Yield components, i.e. number of panicles m^{-2}, spikelets panicle^{-1}, percentage sterility and 10^3 grain weight were determined. The panicle density and the harvest index (i.e. the ratio of dry grain yield to dry aboveground plant biomass at harvest), were calculated on three replicated 0.25 m^2 sampling areas within each sub-plot. The tillering rate was calculated as ratio between the panicle density and the number of plants. The number of spikelets per panicle and the percentage sterility were determined on a sample of 20 panicles for each sub-plot, while the weight of 10^3 grains was determined on two replicates per sub-plot.

The head milled rice and the milled rice yield were obtained using a G390/R dehuller (Colombini & Co. Srl, Abbiategrasso, Milano, Italy) and a TM-05 grain testing mill (Satake Engineering Co., Tokyo, Japan), respectively, through a working range of 11.25-12.75%. The broken kernels were separated by a rice length grader (TRG, Satake Engineering Co., Tokyo, Japan) with the appropriate size cylinders for each variety. Milling quality was also evaluated by measuring damaged kernels and milky white rice (i.e. chalkiness). Total N content in the grain and straw was determined by elemental analysis (NA 2500, Carlo Erba Instruments, Milano, Italy) and expressed on a dry weight basis. Apparent N recovery was calculated as the difference between aboveground plant N uptake in fertilized and control sub-plots, divided by the amount of applied fertilizer N.

2.3.2 Water fluxes

Water inputs, outputs and storages (soil water content and water level above the soil surface) were continuously monitored by means of an integrated multi-sensor system (Chiaradia et al., 2015). In particular, each plot was instrumented with irrigation inflow and outflow discharge meters, a set of piezometers surrounding the plot, a set of four hydraulic tensiometers placed at different soil depths (i.e., 10, 30, 50 and 70 cm) in correspondence with multi-level moisture probes and, finally, sensors for monitoring the ponding water level during flooding. An eddy covariance station was set up on the levee between the WFL and DIR treatments to contemporaneously monitor the evapotranspiration (*ET*) fluxes from these two treatments as a function of the wind direction. Two sets of half-hourly *ET* values, each one comprising one of the two treatments and corresponding to about 10% of the total data over the two agricultural seasons were therefore obtained through a detailed footprint analysis (Facchi et al., 2013; Masseroni et al., 2014). The two eddy covariance data-sets were used to calibrate Penman–Monteith type models allowing for the estimation of rice crop transpiration, soil evaporation and evaporation from the shallow water covering the soil in the case of flooded paddies, over the whole agricultural seasons. Daily and seasonal water balance components for WFL, DFL and DIR were thus calculated at the plot scale. Net percolation *(P)*, corresponding to the net flux at the lower limit of the root zone (defined as the sum of the percolation and the capillary rise fluxes), was obtained as the residual term of the water balance according to the equation:

$$I + R = ET + P + D + \Delta S_s + \Delta S_w$$

where, I and R are respectively the irrigation and precipitation input fluxes, ET is the evapotraspiration, D is the irrigation tail water flowing out of the plot, ΔS_s is the change in the soil water storage of the root zone, and ΔS_w is the difference in the ponded water depth in the case of WFL and DFL.

Water use efficiency (WUE) indices (evapotranspiration over net irrigation plus rainfall) were calculated for each treatment.

2.3.3 Water sampling and analyses

Ceramic suction cups were installed vertically at 25, 50 and 75 cm depths to collect soil solutions, with two replicates per plot. Surface water samples were collected from supply canals (inflow water) and flumes channeling outflow waters from each plot to drainage canals. The groundwater was collected using 300 cm PVC pipes windowed between 220 and 230 cm from the soil surface, and located on the separation levee between adjacent plots characterized by the same water management. Water samples were collected on a weekly basis, filtered through a 0.45 µm nylon membrane filter, and subsequently analyzed for ammonium (NH_4^+) and nitrate (NO_3^-) concentrations. Ammonium concentrations were determined spectrophotometrically by the Berthelot method (Crooke and Simpson, 1971) while NO_3^- concentrations were determined by ion chromatography (AS50, Dionex, California, USA). Daily NO_3^- concentrations in surface (inflow and outflow) and subsurface (50 cm) waters were extrapolated for the entire cropping season by assuming a linear change in concentration between two successive measured data points. Subsequently, daily inflow, outflow and percolation fluxes of NO_3^- (kg N ha^{-1} d^{-1}) were calculated by multiplying the concentration of NO_3^- (mg N l^{-1}) with the water flux (m^3 ha^{-1} d^{-1}), while cumulative fluxes (kg N ha^{-1}) over the cropping season were calculated as the sum of all daily fluxes. Flow-weighted NO_3^- concentrations (mg N l^{-1}) for each water management were calculated by dividing the total NO_3^- flux (kg N ha^{-1}) by the total water flux (m^3 ha^{-1}) over the same period. To identify any variation during the cropping season, cumulative percolation fluxes and flow-weighted NO_3^- concentrations were also calculated for four successive 30 d periods, namely 0-30, 31-60, 61-90 and 90-120 days after seeding (DAS).

2.3.4 Greenhouse gas emissions

Methane and N_2O emissions were measured from March 2012 to March 2014, covering both the growing seasons and the intercropping periods, by the non-steady-state closed chamber technique (Livingston and Hutchinson, 1995). For each water management four stainless steel anchors (75 × 36 × 40 cm high) were inserted into the soil up to a depth of 40 cm from the soil surface. During each measurement event (on average once a week with a higher sampling frequency during field drainage and fertilization), a rectangular stainless steel chamber (75 × 36 × 20 cm high) was sealed over each anchor by means of a water-filled channel, and included the growing rice plants within when present. Special steel chamber extensions (15 cm high) were added when necessary in order to accommodate the rice plant throughout the entire growing season (maximum of 4 towards harvest). Headspace gas samples from inside the chambers were collected at 0, 15, and 30 min after the chamber closure, and subsequently injected into pre-evacuated vials for analysis by gas chromatography. Emission fluxes were calculated from the linear or non-linear resolution of the rate of increase in gas concentrations within the chamber, while cumulative fluxes were calculated for each year assuming a linear increase in emission rates between two successive sampling times (Hutchinson and Mosier, 1981; Yang et al., 2012). Cumulative annual fluxes of both CH_4 and N_2O were used to calculate (i) the overall GWP that takes into consideration the relative measure of how much heat these gases trap in the atmosphere with respect to CO_2, obtained by multiplying the cumulative fluxes by the IPCC factors (25 and 298 for CH_4 and N_2O, respectively), and expressed in Mg CO_2-equivalent units ha^{-1} y^{-1}, and (ii) the GHG Eco-Efficiency that represents the amount of grain yield obtained per unit GHG emitted, expressed in Mg grain Mg^{-1} CO_2-equivalent units.

2.4 Statistical analyses

The position of the sub-plots in the experimental design was such that the repetitions accounted for heterogeneity only in one direction. To test the homogeneity of the experimental platform in the other direction, analysis of covariance was used. As described by de Vries et al. (2010), a covariate was evaluated by determining x (N-S direction) and y (W-E direction) coordinates for each sub-plot (sub-plot center), and then by testing the relationship with each agronomic parameter studied. The applied statistical model was then an ANCOVA accounting for position as a covariate and water management, year and variety, and their two-way interactions as fixed effects. When F test was significant ($p<0.05$), the means were separated using the Bonferroni test. Regarding interactions water management × year and water management × variety, means referred to different water managements were separated within each year or within each variety, respectively. If significant, means were separated through Bonferroni post hoc test. Correlation analysis between yield and yield components was carried out through Pearson correlation.

3. Results

3.1. Yields and yield components

Water management strongly affected grain yield (Table 1) with a higher production in the flooded treatments (WFL and DFL) compared to the intermittently irrigated treatment (DIR) ($P<0.000$) in both years ($P<0.010$). Total and straw biomass decreased in the order WFL>DFL>DIR, although these parameters where not statistically different in the two years. The harvest index was hence lower in WFL compared to DFL and DIR, even if in 2012 no significant differences were observed among treatments.

The four varieties studied were similarly affected by water management with comparable grain yields in WFL and DFL (water management × variety, $P<0.003$). DIR was the least productive treatment with a decrease in yield of 28, 24, 19 and 14% for Gladio, Baldo, Selenio and Loto, respectively. The interaction variety × year was also significant ($P<0.006$). WFL and DFL also resulted in comparable results for total and straw biomass, with the exception of Gladio. This variety showed a significant difference between WFL and DFL, with the former producing higher total biomass and straw (+7 and +11%, respectively). On average, DIR resulted in 20% less total biomass and 22% less straw with respect to the other water management practices.

Water management also strongly affected yield components (Table 2). The different grain yields were related to panicle density only in WFL treatment (r=0.671; $P<0.008$, n=24) which showed the highest values in both years and in all varieties (water management × variety, $P<0.000$). In general, a higher panicle density corresponded to a decrease in the number of spikelets panicle^{-1} (r=–0.636; $P<0.013$; n=96). In fact, WFL showed significantly lower spikelet values than the other two treatments. Instead, a decrease in the 10^3 grain weight was always observed in DIR. Sterility was also affected by water management. In 2012 the particularly low values were not significantly different among treatments, while higher values of sterility were observed in 2013. In this year WFL showed higher values compared to the other two managements. This was observed only for Loto, while Gladio did not display any difference among treatments and Baldo and Selenio presented the lowest sterility in DIR and DFL, respectively.

Water management affected tillering rate with the highest values in DFL and the lowest in DIR. Significant differences were obtained for Baldo and Loto with the best performance in DFL and WFL, respectively. No significant differences in tillering rate among water treatments were found for Gladio and Selenio.

Conversely to grain yield, the derived milled rice yield was positively affected by DIR, with slightly higher values in both years ($P<0.003$; Table 3). This was observed for all varieties, whereas the effect of WFL and DFL was inconsistent. Notwithstanding the observed variability, DFL generally showed the best performance in terms of head rice yield but also the highest percentage of damaged kernels. Although the former parameter was affected by year and variety, no effects were observed for the damaged kernels. Significantly higher percentage of chalkiness were observed in WFL and DFL with respect to DIR, particularly for Baldo and Selenio. Chalkiness in Loto decreased in the order WFL>DFL>DIR, whereas Gladio did not show any significant differences among treatments.

3.2 Nitrogen uptake and apparent recovery

In general grain N content was significantly affected by water management, with the lowest values in WFL independently of the variety (Table 4). Results were affected by interaction with year and differences were only evident in 2012. In contrast, no differences were observed in straw N content among water treatments in both years and in all varieties. In terms of total N uptake from fertilized and control sub-plots, higher values were found in WFL and DFL with respect to DIR in both years. In fact, in the latter treatment total N uptake was between 18 and 23% less with respect to the other two practices. The apparent N recovery was consequently significantly different among treatments with WFL and DFL always showing higher values.

3.3. Net irrigation and water use efficiency

Average net irrigation amounts (i.e. irrigation inflow minus outflow discharges) over both years were found to be 2270, 1760 and 680 mm for WFL, DFL and DIR, respectively (Fig. 2), with significant differences between flooded and intermittently irrigated treatments. However, net irrigation in DFL and WFL showed strong differences between the two years, with higher values in 2012 than 2013. This was a consequence of the water table depth (deeper in 2012, reaching an average value for the flooded fields of 45 cm from the soil surface, and shallower in 2013, with an average value of 30 cm from the soil surface) and its slope (nearly double in 2012). This difference was probably due to the change in the irrigation practice of a large adjacent field downstream of the experimental plots (irrigated soybean in 2012, and flooded rice in 2013) which strongly affected the local groundwater table dynamics in the two years. On the contrary, net irrigation for the DIR plot was slightly higher in 2013, since a change in the irrigation scheduling (9 irrigation events in 2012 compared to 12 in 2013) probably compensated for the shallower groundwater table. Average WUE over the two years was 22, 26 and 56 % for WFL, DFL and DIR, respectively (Fig. 2).

3.4 Inorganic N concentrations and nitrate fluxes

Water management practices influenced NH_4^+ and NO_3^- concentrations in surface waters (inflow and outflow), soil solutions and groundwater over the cropping season (Fig. 3 and 4). In general, higher dissolved inorganic N concentrations were observed at the beginning of the cropping season, with a strong predominance of NO_3^- in correspondence with dry periods.

Ammonium concentrations in inflow and outflow waters were relatively low with concentrations <0.2 mg N L^{-1} in all treatments over both years. In contrast, all treatments showed higher NH_4^+ concentrations in the soil solutions particularly at the first stages of the cropping season in correspondence with fertilization and submergence or irrigation events (Fig. 3). Throughout the cropping season and in both years, NH_4^+ concentrations in WFL remained relatively low at all soil depths with values <2 mg N L^{-1}. Similar results were obtained for DFL, although moderately higher NH_4^+ concentrations with a number of peaks (maximum 4.2 mg N L^{-1} at 25 cm) in correspondence with urea application, were observed exclusively in the 2012 cropping season. The peaks generally also led to a slight increase in NH_4^+ at greater depths. Lowest soil solution NH_4^+ concentrations were obtained in DIR with values generally <1.5 mg N L^{-1} except for two significant peaks corresponding to the first two fertilizer applications. For all the three treatments, NH_4^+ concentrations in the groundwater generally remained relatively low.

Nitrate concentrations in inflow and outflow waters were also low with values never exceeding 2 mg N L^{-1}, except for outflow waters from the DIR treatment that reached maximum concentrations as high as 5.5 mg N L^{-1} during the first phases of the cropping season (beginning to end June). The concentrations of NO_3^- in the soil solution were strongly influenced by water management (Fig. 4). In WFL relatively low NO_3^- concentrations were observed at all depths over most of the cropping season. In DFL, soil solution NO_3^- concentrations were very high throughout the soil profile during the first stages of the cropping season when the plots were still drained (particularly in 2012), but diminished rapidly to low values with the onset of flooding. During the drained period, peak concentrations as high as 35 mg N L^{-1} were obtained in correspondence to N fertilization events in 2012, but not in 2013. Highest NO_3^- concentrations were measured in DIR throughout the soil profile, particularly in correspondence with the first two urea applications at the beginning of the cropping season. The relatively high soil solution concentrations observed in DFL and DIR also resulted in a gradual increase in NO_3^- concentrations in the groundwater with time, particularly evident for DIR where values as high as 7 mg N L^{-1} were observed.

Since nitrates are relatively mobile and can influence both surface and subsurface water quality we calculated cumulative N-NO_3^- fluxes and flow-weighted concentrations in inflow, outflow and percolation waters for each water management over the two years (Table 5). In all treatments and both years higher cumulative NO_3^- fluxes were observed in inflow (7.0-70.9 kg N ha^{-1}) with respect to outflow (1.7-15.5 kg N ha^{-1}) waters. Although cumulative input fluxes evidence a greater input of NO_3^- in WFL and DFL treatments with respect to DIR, similar flow-weighted NO_3^- concentrations across treatments suggest that these differences in NO_3^- inputs were mainly linked to the different water flow rates rather than to surface water NO_3^- concentrations. Over both years, WFL and DFL showed smaller flow-weighted NO_3^- concentrations in outflow (0.1-0.2 mg N L^{-1}) with respect to inflow (0.7-0.8 mg N L^{-1}) waters, while the opposite was found for DIR. Percolation fluxes and flow-weighted NO_3^- concentrations remained relatively low in WFL throughout the cropping season with most leaching occurring in the first 30 DAS (Table 5). In contrast, higher NO_3^- percolation fluxes were measured in DFL and DIR particularly in 2012. Under these water management practices most of the total leached NO_3^- (91-99 %) was lost in the first 60 DAS. Significant nitrate percolation in DFL and DIR over this period also resulted in relatively high flow-weighted NO_3^- concentrations (up to 25.38 mg N L^{-1}) that were generally higher in DIR with respect to DFL.

3.4. Greenhouse gas emissions

In both years, WFL resulted in the highest GHG emissions with CH_4 accounting for 97 and 100% of the total GWP in 2012 and 2013, respectively (Fig. 5). Both DFL and DIR treatments contributed to lowering the GWP by reducing or even eliminating (in the case of DIR) CH_4 emissions. The concurrent increase in the contribution of N_2O emissions to the GWP observed for DFL and DIR in 2012, and only DIR in 2013, was not sufficient to offset the benefit of reduced CH_4 emissions. Considering both CH_4 and N_2O emissions, DIR was the most effective in reducing GHG emissions, with a GWP equal to 27% and 10% of WFL in 2012 and 2013, respectively. The combined effects of water management practices on grain yield and GHG emissions resulted in a GHG Eco-efficiency that increased in the order WFL<DFL<DIR.

4. Discussion

4.1. Water management determines the yield performance of different rice varieties

Water management strongly affected rice productivity with lower performances in the intermittently irrigated system compared to both water and dry seeded flooded treatments. This was in agreement with the results reported by various authors (Mahmod et al., 2014; Bouman and Tuong, 2001; Devkota et al., 2013) who found a net yield decrease with alternative water practices compared with the conventional flooded cultivation. The higher yields in WFL and DFL were related to the compensation between panicle density, which was higher in WFL, and the number of spikelets per panicle, higher in DFL. The better yield performance obtained by the four varieties in both water and dry seeded flooded treatments underlined their better adaptation to submerged conditions. However, among the studied varieties, Gladio and Baldo showed the greatest yield losses in DIR, whereas Selenio and Loto were less affected. This highlighted a genetic variability in adaptability to intermittently irrigated cropping systems (Yao et al. 2012).

Sterility also contributed to the differences in productivity particularly in 2013 when the relatively low temperatures during the spring season were probably responsible for the higher degree of sterility ranging between 13 and 19%. In this year the highest values were observed in WFL while in DIR sterility was generally less expressed, as a consequence of the lower panicle density. Devkota et al. (2013) observed that in temperate environments a low air temperature during the early pollen microspore period can cause a decline of fertility due to sterility. In DIR the soil water potential was not allowed to decrease below –30 kPa, as suggested by Kato and Katsura (2014), limiting temperature fluctuations in the aerobic system.

Kato and Katsura (2014), and references therein, reported that alternating wet and dry systems generally determined a larger exploration of the deeper soil horizons by rice roots, favouring their activity, nutrient uptake, and consequently grain yield. In our system, root development in DIR was limited and shallow (data not shown), probably due to soil compaction during the early field drainage events. This could have negatively influenced root activity and nutrient uptake, leading to the lower total N uptake during grain filling (Mahajan et al., 2012; Mahmod et al., 2014), and consequently the lower apparent N recovery compared to the other two treatments. Under this water management, the relatively low panicle density was not compensated by a higher number of spikelets. Moreover, the lower 10^3 seeds weights observed for DIR were probably related to genetic and morphological characteristics of the four different varieties, as well as a lower plant N availability during the last part of the cropping season in DIR with respect to WFL and DRY systems. This is in line with Ye et al. (2013) who found a reduced weight in alternative wet and dry systems compared to continuous flooding in a subtropical monsoon climate

Apart from a higher grain productivity, WFL and, to a minor extent, DFL also showed higher yields of straw biomass. The growth and biomass productivity of rice cultivars are known to differ in ecosystems with varying water regimes (Rath et al., 1999). In temperate paddies, flooded conditions allowed for a better growth of the plants due to the genetic adaptation of the studied varieties to submerged conditions. Conversely, in DIR the reduced root development limited plant growth, causing a lower straw biomass in all varieties.

In contrast to grain productivity and straw biomass, milling quality was improved by maintaining aerobic conditions with intermittent irrigation, especially for milled rice yield. This was favoured by a consistent filling of starch in the spikelets, and lower chalkiness due to the contemporaneity of ripening and lower tillering rate. The higher performance was presumably due to a better oxygen supply to the root system that limited the availability of toxic species such as reduced sulphur and iron forms (Pan et al. 2009), rather than to a better nutrient supply.

4.2. Intermittent irrigation reduces net irrigation and increases water use efficiency

Flooded systems resulted in a higher net irrigation with respect to the intermittently irrigated system, with a mean WUE that ranged from 22% for continuous flooding up to 56% for intermittent irrigation. In line with the findings of Zhao et al. (2015) in a similar environment, slightly lower irrigation water requirements and a corresponding increase in WUE was observed when comparing dry to water seeded flooded systems. Net irrigation proved to be the most important term of the hydrological balance for both WFL and DFL, being 3-5 times higher than evapotranspiration and therefore governing the WUE. Under intermittent water practice, net irrigation was closer to evapotranspiration values and both terms contributed to the WUE. The net irrigation and WUE values are in line with the findings of other studies (e.g., Sharma et al., 2002; Singh et al., 2002; Cabangon et al, 2004; Dong et al., 2004), and strongly dependent on the groundwater table depth. The rather high value of WUE obtained for intermittent irrigation was probably a consequence of the relatively shallow groundwater table level (about 70 cm as an average of both years) which caused capillary rise to contribute strongly to rice water requirements in the periods between successive irrigation events.

4.3. Nitrates represent a concern for water quality in dry seeded cropping systems

The influence of water management practices on the hydrology of paddy fields do not only affect the fluxes of water and dissolved nutrients, but also the soil moisture status and consequently the soil redox conditions. In this work we evaluated the effect of water management on dissolved inorganic N considering the importance of redox-driven processes on plant N availability, and the implications NO_3^- concentrations and fluxes may have on surface and subsurface water quality. The equilibrium between the supply of bioavailable N and losses indeed depends on the transformation and transport of different N species in the soil-water-plant-atmosphere system (Chowdary et al., 2004). Our results clearly evidenced that NH_4^+ and NO_3^- contents in the soil solution were strongly affected by water management.

The relatively high concentrations of NH_4^+ observed in the early stages of the cropping season could be attributed to the combined effects of fertilizer N application, limited plant uptake, net N mineralization of labile organic matter (e.g. incorporated crop residues), and, in the flooded plots, inhibition of nitrification due to anoxic soil conditions (Cucu et al., 2014). During this period and particularly in the two dry seeded treatments, N supply was probably greater than the crop N requirements resulting in measurable peak soil solution NH_4^+ concentrations in the rooted soil layer. Later on in the cropping season, rapid N uptake by the crop was probably responsible for the relatively low NH_4^+ concentrations even after urea application (Katoh et al., 2004; Qiao et al., 2013; Rahman et al., 2013). Although NH_4^+ is hardly subjected to leaching because of its high affinity for the cation exchange complex (Ghosh and Bhat, 1998) and fixation by 2:1 phyllosilicates (Said-Pullicino et al., 2014), some migration along the soil profile could have occurred in our system and fed the soil solution at greater depths (50 and 75 cm). This could be related to the soil's relatively low cation exchange capacity (10 $\text{cmol}_{(+)}$ kg^{-1}), which limited NH_4^+ retention in the upper horizons. Nevertheless, NH_4^+ fluxes were negligible and their contribution to inflow, outflow and percolation N fluxes were not taken into account.

As expected, maintenance of anaerobic conditions over most of the cropping season by continuous flooding resulted in relatively low NO_3^- concentrations throughout the soil profile. In contrast, highest NO_3^- concentrations were observed in DFL and DIR, particularly at the beginning of the cropping season when maximum concentrations were largely above the limit defined by the European Nitrate Directive (91/676/EEC) referred to groundwater. In these plots, oxic soil conditions present before the onset of flooding in DFL and throughout the cropping season in DIR, favoured the microbial nitrification of available NH_4^+. Nitrate produced by nitrification in the topsoil moved easily along the soil profile into the subsoil with percolating waters (Ghosh and Bhat,

1998) leading to the observed increase in concentrations at all soil depths as well as in the groundwater. This was confirmed by the higher cumulative percolation fluxes of NO_3^- out of the root zone, and flow-weighted concentrations in both DFL and DIR with respect to WFL where no evidence of significant NO_3^- leaching was observed.

In both dry seeded treatments, most of the total NO_3^- leached over the cropping season (91-99%) occurred over the first 60 days after seeding, confirming the importance of appropriate fertilizer N management for limiting NO_3^- leaching when dry seeding is adopted. DFL showed a great variability in soil NO_3^- concentrations, and consequently cumulative NO_3^- fluxes and flow weighted concentrations, between the two years. This was mainly attributed to a different timing in crop residue management operations with respect to field flooding that could have influenced organic matter availability for the soil microbial biomass. Heavy rainfall in 2013 (~150 mm in May) delayed soil tillage and residue incorporation with respect to 2012. This could have possibly favoured the immobilization of important amounts of applied N (Said-Pullicino et al., 2014), consequently limiting nitrification. Nonetheless, the important cumulative fluxes of NO_3^- obtained in 2012 suggest that dry seeding may lead to important N losses to subsurface waters with the onset of flooding at tillering stage. On the other hand, although DIR showed relatively higher soil solution and flow-weighted NO_3^- concentrations over the cropping season with respect to DFL, the vertical fluxes of NO_3^- in the former were limited to some extent by the reduced water percolation fluxes. Nevertheless, intermittent irrigation resulted in the highest increase in groundwater NO_3^- concentrations over the cropping season which however, did not exceed 10 mg N L^{-1}.

Although inflow waters did supply some NO_3^- to the rice paddies over the cropping season (7.0 to 71.0 kg N ha^{-1}), cumulative fluxes of NO_3^- lost with surface waters across treatments were always lower and ranged between 2.0 and 16.0 kg N ha^{-1}. Whereas both WFL and DFL showed lower flow-weighted NO_3^- concentrations in the output with respect to input waters, the opposite was true for DIR. This suggests that under the latter water management, soil processes leading to the relatively high topsoil NO_3^- concentrations could have also contributed to increasing the transfer of inorganic N to surface waters particularly in correspondence with irrigation events.

4.4. Water management practices alternative to continuous flooding reduce GHG emissions

Water management has been recognized as one of the most important factors that affect CH_4 and N_2O emissions from paddy fields (Hou et al., 2012; Xiong et al., 2007). In our study, continuous flooding resulted in the highest CH_4 emissions, while N_2O emissions were negligible. Methane is the end product of organic matter decomposition under anaerobic conditions. This means that apart from reducing the input of labile organic matter, adopting water management strategies that limit the time of soil submergence may serve to mitigate CH_4 emissions (Linquist et al., 2012). Our results confirmed that dry seeding and delayed flooding may serve to reduce CH_4 emissions by 8% with respect to continuous flooding, while intermittent irrigation completely mitigated CH_4 emissions. This was in line with variations in the measured soil redox potentials that only decreased to reach negative values (below –250 mV) in correspondence with field flooding at tillering stage in DFL, and were generally positive (i.e. oxic soil conditions) throughout the cropping season in DIR (Said-Pullicino et al. 2016). Pittelkow et al. (2014) reported that avoiding anaerobic conditions during the first part of the growing season strongly limited methanogenesis and reduced the overall seasonal CH_4 emissions by 35-70% in rice paddies (Xu et al., 2015; Rath et al., 1999). On the other hand, water management practices that involve frequent changes in soil moisture status redox conditions generally result in higher N_2O emissions (Xu et al., 2015) as a consequence of nitrification and incomplete denitrification processes (de Datta, 1981). Although N_2O emissions contributed marginally to total GHG emissions in DFL, in DIR this gas contributed exclusively to the total GHG emissions. This was in line with the relatively high NO_3^- concentrations observed in the soil solution during the first stages of the cropping season in these treatments.

Even considering the trade-off between CH_4 and N_2O emissions, the adoption of water management practices alternative to the conventional continuous flooding nonetheless resulted in a net reduction in the GWP over both years. Dry seeding reduced the GWP by 33 and 73% in 2012 and 2013, respectively, while the adoption of intermittent irrigation resulted in a 70 to 90% reduction in GWP (in 2012 and 2013, respectively). Conversely to DFL and DIR, the high GWP estimated in WFL in 2013 could be related to the delay in crop residue incorporation, which probably limited their decomposition under aerobic conditions (Cucu et al., 2014), leaving more labile organic compounds for methanogenetic processes.

Notwithstanding the lowest grain yield in both years, the mitigation of GHG emissions by intermittent irrigation resulted in the highest GHG Eco-Efficiency. Although better yields were obtained with DFL, the higher CH_4 emissions resulted in a decrease in the GHG Eco-Efficiency by 40 and 60% in 2012 and 2013, respectively, with respect to intermittent irrigation. Despite the best yield performance and the lowest or negligible N_2O emissions, the relatively high CH_4 emissions resulting from water seeding and continuous flooding in both years led to the lowest GHG Eco-Efficiency with values between 59 and 88% lower with respect to DIR in 2012 and 2013, respectively.

4.5. Overall agro-environmental evaluation and concluding remarks

Water management practices greatly affected the agronomic and environmental sustainability of the temperate rice systems. Figure 6 summarises the main results of this study through the comparison of relevant agro-ecological indicators. Yield performance was penalized with intermittent irrigation with respect to conventional flooding or dry seeding and delayed flooding (Figure 6a) even though the different techniques were adjusted to optimize crop growth. This was evident for all varieties, although Selenio and Loto showed a better adaptability to aerobic conditions. Intermittent irrigation nonetheless benefited from a lower net irrigation and GWP per unit cropping surface contributing to the environmental sustainability of this management practice. This was also confirmed when these indicators are expressed on the basis of milled grain yield (Figure 6c). In fact, the production of 1 Mg of milled grain under intermittent irrigation produced lowest GWP (0.4 Mg CO_2-eq with respect to 0.6 and 1.4 Mg CO_2-eq for DFL and WFL, respectively) and showed lowest water requirements (1253 m^3 with respect to 2614 and 3336 m^3 for DFL and WFL, respectively), even though a larger cropping surface (0.15 ha) was required with respect to the other management practices (0.18 ha). When the indicators are reported on grain yield a reduction of 70%, reasonably homogeneous among treatments and corresponding to tillering rate, was obtained (Figure 6b). Dry seeding and delayed flooding probably represented the best overall compromise. In fact, this system provided grain yields comparable to the conventional continuously flooded system, while showing a slightly lower water use and a reduced GWP, primarily linked to the mitigation of CH_4 emissions. Nitrate leaching represented the greatest environmental constrain of this water management, even though the variations between years evidenced an important dependence on fertilizer and crop residue management practices. In this respect, the selection of appropriate basal N fertilization doses, and adequate splitting of fertilizer applications between the different stages of plant growth such that N availability coincides with crop N demands, is essential to limit NO_3^- leaching in dry seeded systems. Moreover, the substitution of part of the mineral N applications with organic sources of relatively labile N (e.g. biogas digestates, livestock-derived organic materials, and sludges) can also contribute to reducing N losses and maintain rice yields.

5. Further insights

This work provides useful insights at field scale, furnishing a holistic evaluation and leading to the quantification of key agro-ecological indicators which can be of extreme importance for the management of temperate rice cropping systems. However, the application of these outcomes at larger scales (e.g., irrigation district, catchment) requires further considerations. The applicability of the different water management techniques may depend on the water availability and irrigation system peculiarities. For instance, although dry seeding and delayed flooding seems to represent the best compromise between production and environmental sustainability, the delay in maximum water requirement for the flooding of paddies to the first half of June would increase the competition for water with other crops, perhaps bringing water requirements to exceed the availability at the basin scale. In relation to water-saving technologies such as intermittent irrigation, the high water use efficiency observed in this study could not be reached at larger spatial scales, as the massive conversion of the irrigation method would lead to a decrease of the recharge to the phreatic aquifer and therefore to a lowering of groundwater levels. Since the water use efficiency depends on the groundwater depth, it follows that a wide conversion of irrigation practices on large areas could result in water savings lower than one might initially expect. On the other hand, the maintenance of flooded cropping systems can provide important ecosystem services such as the preservation of wetland habitats for a range of aquatic and semi-aquatic wildlife, or of local traditional landscapes. As a matter of fact, fflooded paddy fields in the Northern Italy rice district are part of the EU Natura 2000 network.

Based on these considerations, we believe that the outcomes of this work can be useful also at larger spatial scales, in districts that are predominantly cropped with rice in monoculture, where the knowledge of the advantages and disadvantages of each management practice can support the selection of the most appropriate for the different local conditions.

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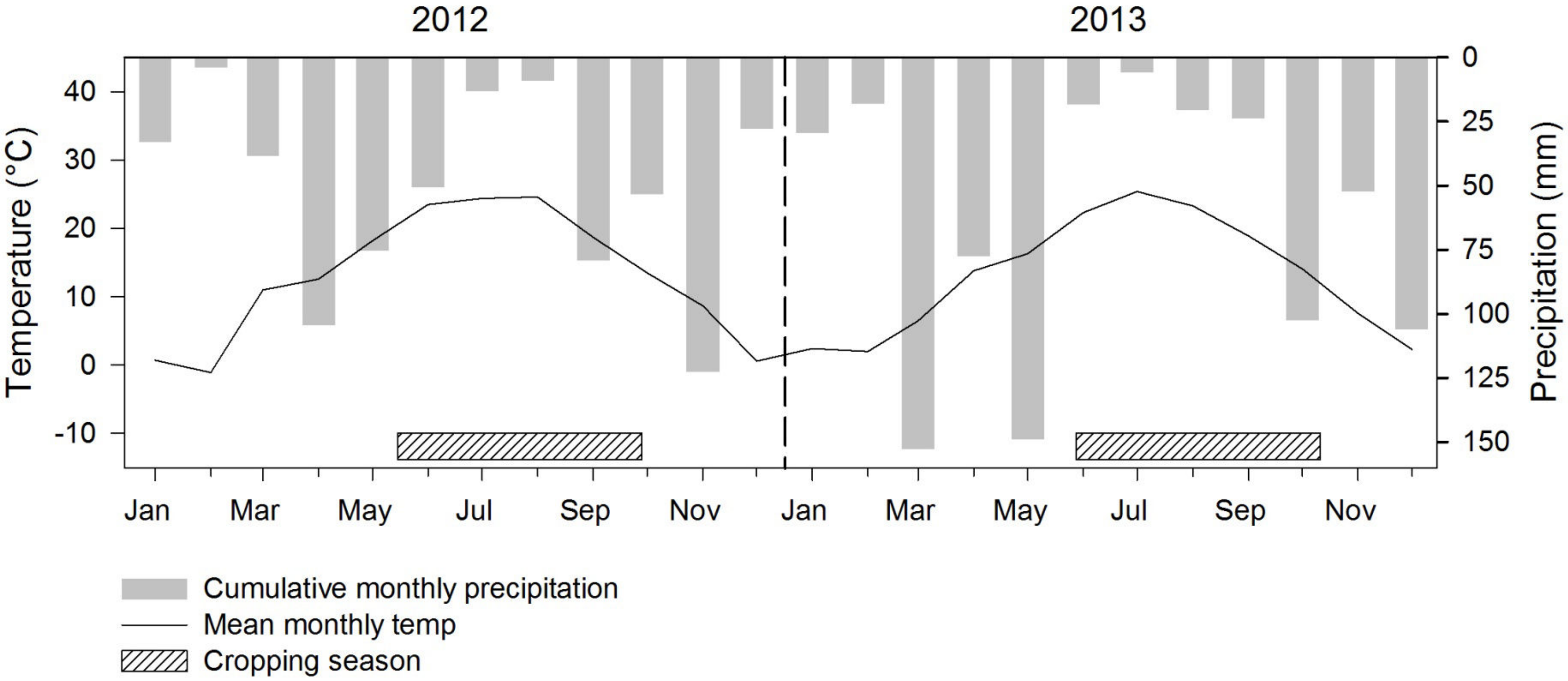

Figure 1: Average monthly temperature and precipitation over the 2012-2013 experimental period.

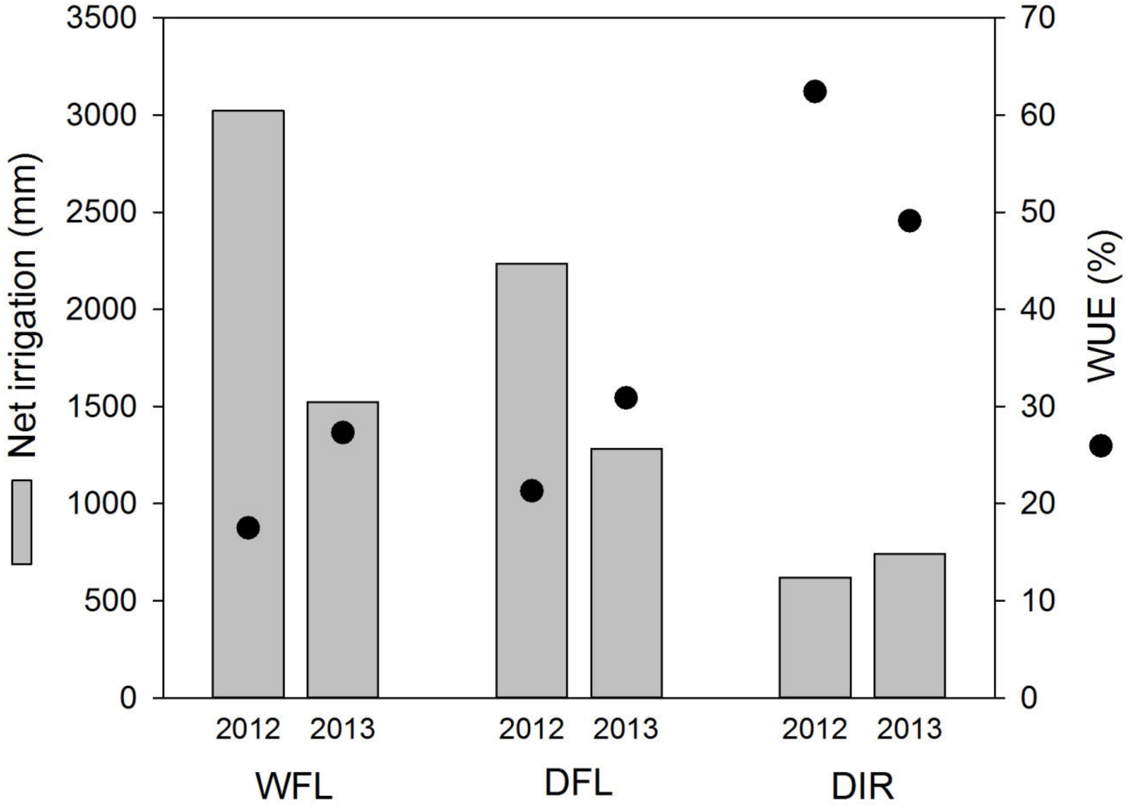

Figure 2: Average net irrigation and Water Use Efficiency (WUE) for the three water management practices in the 2012 and 2013 cropping seasons.

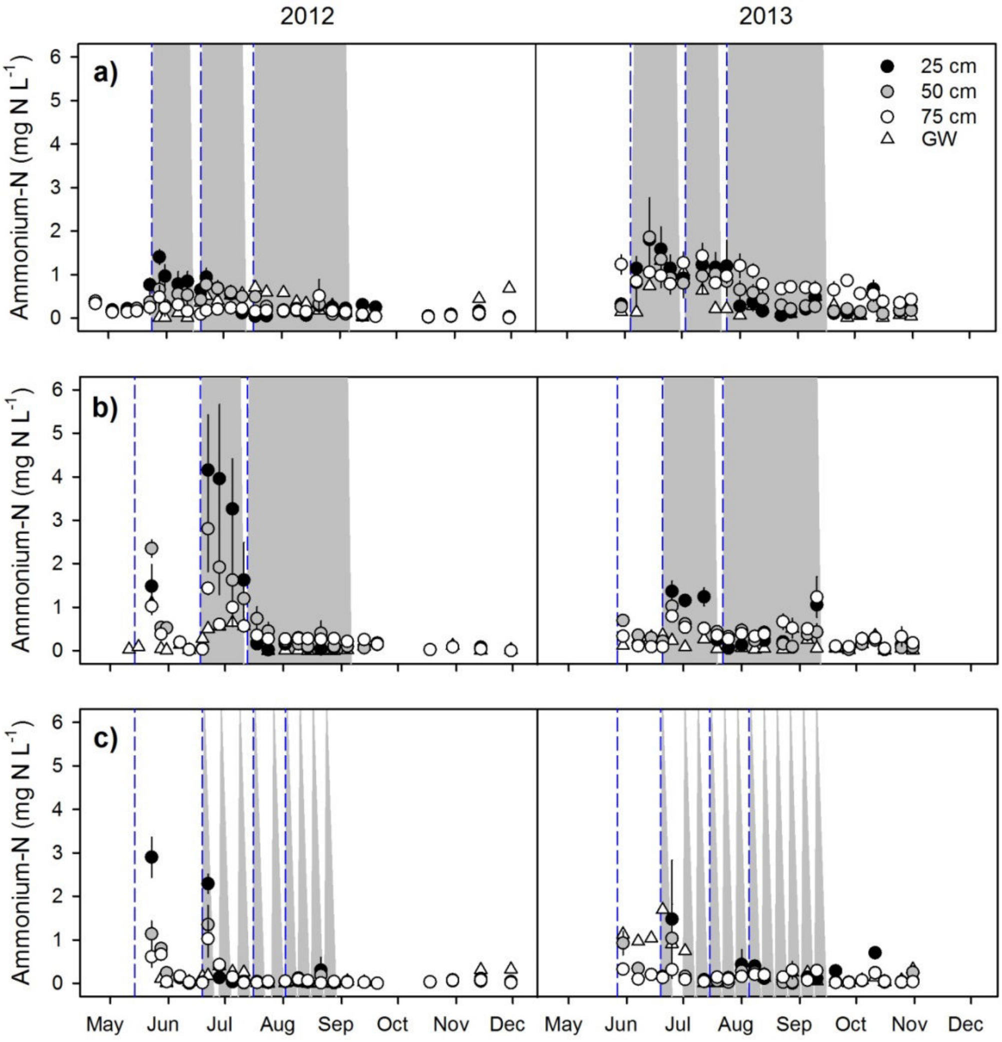

Figure 3: Variations in NH_4^+-N concentrations in soil solutions at 25, 50 and 75 cm depth and in groundwater (GW) in (a) water seeding and continuous flooding (WFL), (b) dry seeding and delayed flooding (DFL), and (c) dry seeding and intermittent irrigation (DIR) over the 2012 and 2013 cropping seasons. Shaded areas represent the presence of flood water or irrigation events, while dashed lines represent N fertilizer applications.

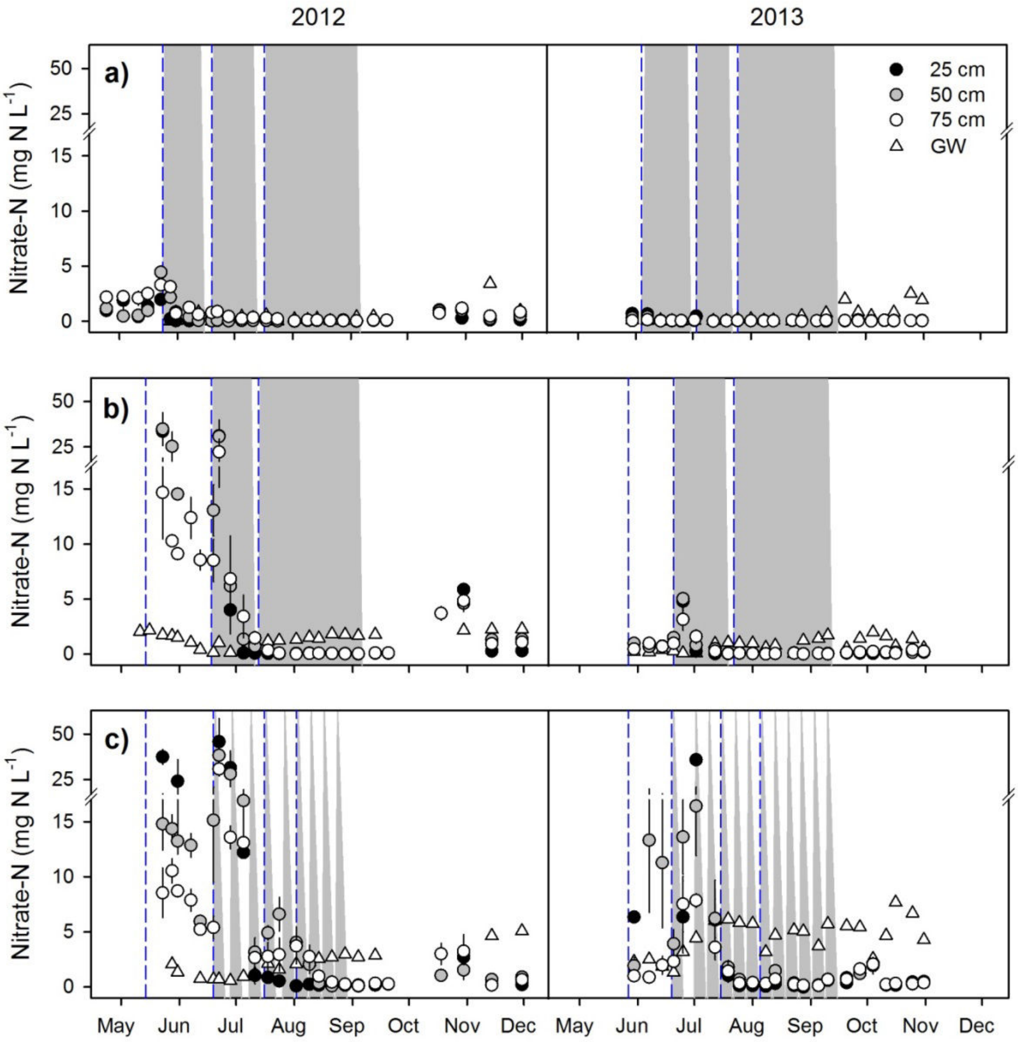

Figure 4: Variations in NO_3^--N concentrations in soil solutions at 25, 50 and 75 cm depth and in groundwater (GW) in (a) water seeding and continuous flooding (WFL), (b) dry seeding and delayed flooding (DFL), and (c) dry seeding and intermittent irrigation (DIR) over the 2012 and 2013 cropping seasons. Shaded areas represent the presence of flood water or irrigation events, while dashed lines represent urea applications.

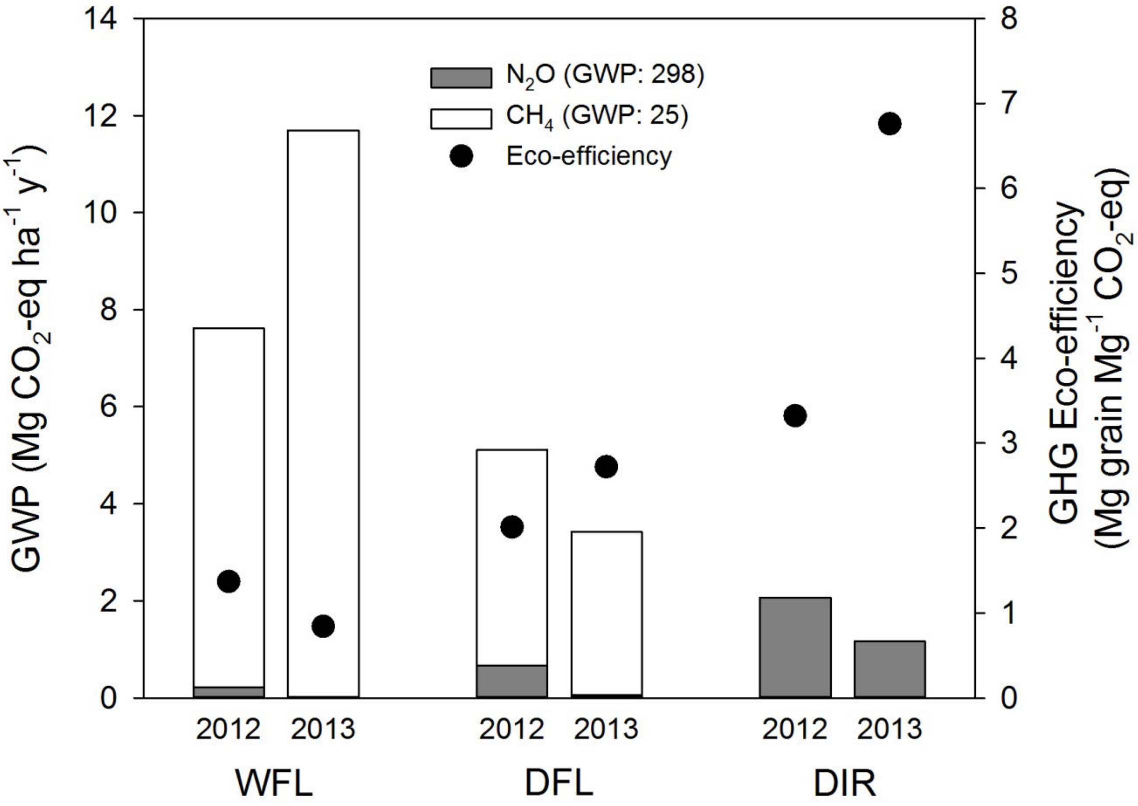

Figure 5: Yearly greenhouse gases emissions expressed in terms of Global Warming Potential (sum of N_2O and CH_4) and GHG Eco-Efficiency for the three water management practices in the 2012 and 2013 cropping seasons. Series "2012" includes values measured from 21 March 2012 to 20 March 2013, while series "2013" values from 21 March 2013 to 20 March 2014.

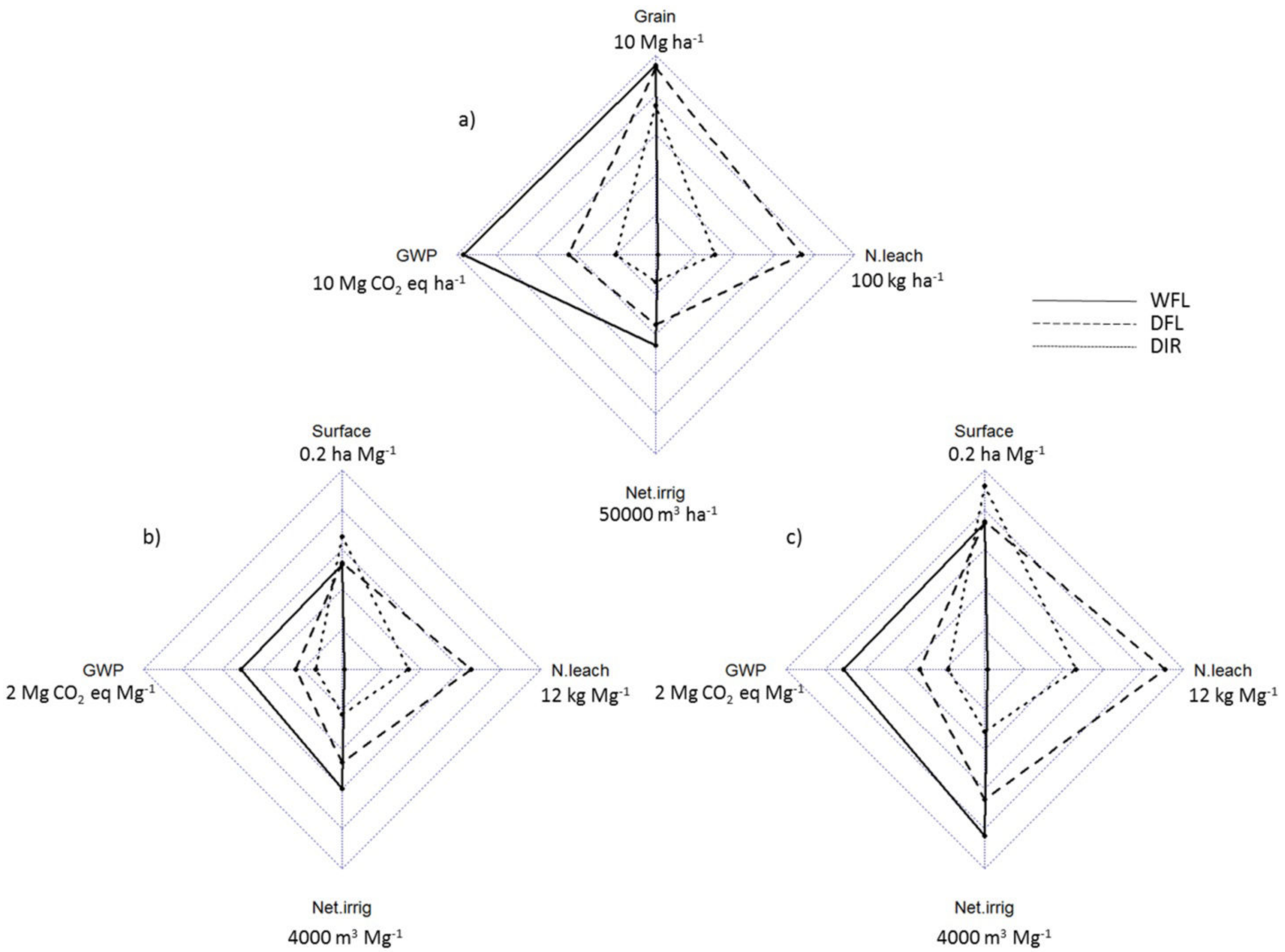

Figure 6: Agro-ecological indicators of the three water management practices reported on the basis of (a) cropping surface, (c) grain rice yield and (b) milled rice yield.

Table 1

Performance of the three water managements (WFL = water seeded and continuous flooding; DFL = dry seeded and delayed flooding; DIR = dry seeded and intermittent irrigation) alone or in interaction with the two years and with the four varieties in terms of grain yield, total and straw biomass, and harvest index, and significance of the different analyzed effects.

Year	Variety	Water management	Grain yield *(Mg ha^{-1})*	Total biomass *(Mg ha^{-1})*	Straw *(Mg ha^{-1})*	Harvest Index *(%)*
Average		WFL	9.5 a	18.7 a	9.2 a	50.8 b
		DFL	9.4 a	17.9 b	8.6 b	52.3 a
		DIR	7.5 b	14.3 c	6.8 c	52.2 a
2012		WFL	9.9 a	19.0	9.1	52.0
		DFL	9.9 a	18.8	8.9	52.8
		DIR	7.6 b	14.6	7.0	51.8
2013		WFL	9.1 a	18.4	9.3	49.6 b
		DFL	8.8 a	17.0	8.2	51.7 a
		DIR	7.3 b	14.0	6.6	52.7 a
Average	Gladio	WFL	10.1 a	19.8 a	9.7 a	51.1
		DFL	9.8 a	18.4 b	8.7 b	53.0
		DIR	7.3 b	13.7 c	6.4 c	53.5
	Baldo	WFL	8.8 a	17.7 a	8.9 a	49.6
		DFL	9.0 a	17.5 a	8.6 a	51.3
		DIR	6.7 b	13.0 b	6.4 b	51.1
	Selenio	WFL	10.4 a	20.4 a	9.9 a	51.1
		DFL	9.8 a	19.2 a	9.3 a	51.2
		DIR	8.4 b	16.3 b	7.9 b	51.4
	Loto	WFL	8.7 a	16.8 a	8.2 a	51.5
		DFL	8.8 a	16.5 a	7.6 a	53.6
		DIR	7.5 b	14.1 b	6.7 b	52.9

Sources	*P*(F) values			
water manag.	0.000	0.000	0.000	0.001
variety	0.000	0.000	0.000	0.000
year	0.000	0.000	0.045	0.018
water manag. × year	0.010	0.077	0.088	0.001
water manag. × variety	0.003	0.002	0.010	0.489
variety × year	0.006	0.133	0.075	0.000
x	0.073	0.095	0.205	0.892
y	0.119	0.042	0.039	0.209

Within a column for each year or for each variety, means followed by different letters are significantly different according to Bonferroni's post hoc test ($P<0.05$).Covariate was evaluated by determining x (N-S direction) and y (W-E direction) coordinates for each sub-plot (sub-plot center),

Table 2

Performance of the three water managements (WFL = water seeded and continuous flooding; DFL = dry seeded and delayed flooding; DIR = dry seeded and intermittent irrigations) alone or in interaction with the two years and with the four varieties in terms of yield components (panicle density, spikelets, 10^3 seeds weight and sterility) and tillering rate and significance of the different analysed effects.

Year	Variety	Water management	Panicle density *(m^{-2})*	Spikelets *($panicle^{-1}$)*	10^3 seeds weight *(g)*	Sterility *(%)*	Tillering rate
Average		WFL	615 a	85 b	32.4 a	13.0 a	2.1 ab
		DFL	436 b	112 a	32.2 a	10.0 b	2.2 a
		DIR	409 b	112 b	31.6 b	10.4 b	1.9 b
2012		WFL	581 a	88 c	32.7 a	7.2	1.8 b
		DFL	437 b	122 a	31.3 c	7.3	2.2 a
		DIR	416 b	113 b	31.9 b	6.9	1.9 b
2013		WFL	649 a	83 c	32.0 b	18.9 a	2.3 a
		DFL	435 b	102 b	33.0 a	12.7 b	2.1 ab
		DIR	401 b	111 a	31.2 c	13.9 b	1.9 b
Average	Gladio	WFL	791 a	74 c	25.7 a	12.2	2.2
		DFL	490 b	127 a	26.1 a	10.1	2.4
		DIR	504 b	115 b	25.1 b	11.3	2.3
	Baldo	WFL	374 a	100 b	42.8 a	12.1 a	1.7 b
		DFL	304 b	119 a	41.9 b	11.7 a	2.4 a
		DIR	253 b	121 a	41.2 b	7.5 b	1.8 b
	Selenio	WFL	723 a	87 b	26.2	12.2 a	2.3
		DFL	517 b	110 a	25.5	8.5 b	2.2
		DIR	468 b	120 a	25.5	15.7 a	2.0
	Loto	WFL	572 a	81 b	34.9	15.5 a	1.9 a
		DFL	432 b	92 a	35.2	9.8 b	1.6 ab
		DIR	410 b	90 ab	34.4	7.2 b	1.4 b

Sources			*P* (F) values		
water manag.	0.000	0.000	0.000	0.000	0.005
variety	0.000	0.000	0.000	0.244	0.000
year	0.081	0.000	0.425	0.000	0.096
water manag. × year	0.001	0.000	0.000	0.000	0.000
water manag. × variety	0.000	0.000	0.005	0.000	0.001
variety × year	0.215	0.003	0.000	0.018	0.000
x	0.000	0.887	0.053	0.781	0.622
y	0.563	0.239	0.142	0.977	0.160

Within a column for each year or for each variety, means followed by different letters are significantly different according to Bonferroni's post hoc test (P<0.05).Covariate was evaluated by determining x (N-S direction) and y (W-E direction) coordinates for each sub-plot (sub-plot center),

Table 3

Performance of the three water managements (WFL = water seeded and continuous flooding; DFL = dry seeded and delayed flooding; DIR = dry seeded and intermittent irrigation) alone or in interaction with the two years and with the four varieties in terms of milled rice yield, head rice yield, damaged kernels and chalkiness, and significance of the different analysed effects.

Year	Variety	Water management	Milled rice yield *(%)*	Head rice yield *(%)*	Damaged kernels *(%)*	Chalkiness *(%)*
Average		WFL	71.7 b	57.1 b	1.7 ab	2.7 a
		DFL	71.6 b	59.3 a	1.9 a	2.6 a
		DIR	72.4 a	56.9 b	1.4 b	1.2 b
2012		WFL	71.6 b	56.9 b	1.7	2.5 a
		DFL	71.8 b	60.5 a	2.1	2.9 a
		DIR	72.5 a	59.4 a	1.6	1.3 b
2013		WFL	71.9 b	57.2 a	1.7	2.9 a
		DFL	71.4 c	58.2 a	1.8	2.2 b
		DIR	72.4 a	54.4 b	1.3	1.1 c
Average	Gladio	WFL	70.4 b	63.9	1.0	0.8
		DFL	71.0 a	64.9	1.5	1.1
		DIR	71.1 a	63.8	1.1	0.7
	Baldo	WFL	72.9 a	47.8 b	1.3	3.0 a
		DFL	72.2 b	53.5 a	1.5	2.5 a
		DIR	73.3 a	47.4 b	0.9	0.7 b
	Selenio	WFL	72.1 b	60.9	2.3	2.6 a
		DFL	71.6 c	59.2	2.3	3.1 a
		DIR	73.0 a	58.3	1.7	1.3 b
	Loto	WFL	71.5 b	55.6 b	2.1	4.4 a
		DFL	71.5 b	59.7 a	2.5	3.5 b
		DIR	72.4 a	58.1 ab	2.0	2.2 c

Sources	*P* (F) values			
water manag.	0.000	0.001	0.000	0.000
variety	0.000	0.000	0.000	0.000
year	0.099	0.000	0.063	0.240
water manag. × year	0.003	0.002	0.269	0.004
water manag. × variety	0.000	0.004	0.525	0.000
variety × year	0.000	0.000	0.000	0.004
x	0.702	0.394	0.123	0.451
y	0.000	0.478	0.327	0.795

Within a column for each year or for each variety, means followed by different letters are significantly different according to Bonferroni's post hoc test ($P<0.05$).Covariate was evaluated by determining x (N-S direction) and y (W-E direction) coordinates for each sub-plot (sub-plot center),

Table 4

Performance of the three water managements (WFL = water seeded and continuous flooding; DFL = dry seeded and delayed flooding; DIR = dry seeded and intermittent irrigations) alone or in interaction with the two years and with the four varieties in terms of grain and straw N contents, total N uptake in fertilized and control plots, and apparent N recovery, and significance of the different analyzed effects.

Year	Variety	Water management	Grain N content *(%)*	Straw N content *(%)*	Total N uptake *(kg ha^{-1})* Fertilized	Control	Apparent N recovery *(%)*
Average		WFL	0.94 b	0.64	148.0 a	79.1 a	49.7 a
		DFL	1.00 a	0.64	148.6 a	80.7 a	49.2 a
		DIR	1.00 a	0.63	118.0 b	57.6 b	44.0 b
2012		WFL	1.01 c	0.80	172.6 a	95.4 a	55.4
		DFL	1.08 b	0.82	179.9 a	100.6 a	57.5
		DIR	1.13 a	0.80	141.4 b	71.8 b	50.9
2013		WFL	0.88	0.48	123.5 a	62.7 a	44.0
		DFL	0.91	0.46	117.2 a	60.7 a	40.9
		DIR	0.87	0.47	94.6 b	43.3 b	37.2
Average	Gladio	WFL	0.96	0.72	168.3 a	82.0	53.9
		DFL	1.02	0.70	160.8 a	80.9	49.9
		DIR	1.04	0.70	120.3 b	58.6	38.5
	Baldo	WFL	0.91	0.58	130.4 a	80.6	41.5
		DFL	0.97	0.55	135.0 a	82.0	44.1
		DIR	0.95	0.59	101.1 b	55.5	38.0
	Selenio	WFL	0.89	0.62	156.1 a	79.6	54.6
		DFL	0.90	0.65	150.1 a	76.1	52.9
		DIR	0.96	0.62	130.1 b	58.6	51.0
	Loto	WFL	1.00	0.63	137.3 a	74.0	48.7
		DFL	1.09	0.66	148.4 a	83.6	49.9
		DIR	1.06	0.61	120.7 b	57.6	48.6

Sources	*P* (F) values				
water manag.	0.000	0.825	0.000	0.000	0.034
variety	0.000	0.000	0.000	0.743	0.001
year	0.000	0.000	0.000	0.000	0.000
water manag. × year	0.000	0.471	0.030	0.017	0.546
water manag. × variety	0.128	0.509	0.018	0.229	0.348
variety × year	0.083	0.218	0.002	0.532	0.018
x	0.701	0.053	0.497	0.774	0.304
y	0.132	0.832	0.363	0.904	0.282

Within a column for each year or for each variety, means followed by different letters are significantly different according to Bonferroni's post hoc test (*P*<0.05).Covariate was evaluated by determining x (N-S direction) and y (W-E direction) coordinates for each sub-plots (sub-plot center),

Table 5

Cumulative NO_3^- fluxes and flow-weighted NO_3^- concentrations in inflow, outflow and percolation waters over the two cropping seasons (seeding to harvest) as a function of water management (WFL = water seeded and continuous flooding; DFL = dry seeded and delayed flooding; DIR = dry seeded and intermittent irrigation).

	Cumulative NO_3^- fluxes (kg N ha^{-1})						Flow-weighted NO_3^- concentrations (mg N l^{-1})					
	WFL		DFL		DIR		WFL		DFL		DIR	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Inflow	70.9	35.7	59.0	26.4	7.0	10.7	0.73	0.82	0.69	0.76	0.68	0.76
Outflow	10.4	5.1	15.5	1.7	3.1	7.9	0.15	0.18	0.24	0.08	0.76	1.20
Percolation	1.2	1.1	139.0	7.9	42.8	17.1	0.05	0.09	7.62	0.82	14.03	3.93
0-30 DAS[a]	0.6	0.8	11.8	6.1	5.4	4.4	0.06	0.17	22.59	2.68	12.71	9.09
31-60 DAS[a]	0.3	0.1	126.1	1.5	34.5	11.1	0.05	0.04	15.31	0.84	25.38	7.43
61-90 DAS[a]	0.3	0.1	0.9	0.2	2.8	0.9	0.19	0.04	0.05	0.06	4.23	0.65
91-120 DAS[a]	0.1	0.1	0.2	0.1	0.1	0.4	0.02	0.03	0.04	0.04	0.20	0.46

[a] 30-day cumulative data for percolation flows; DAS, days after seeding.