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Drainage and leaching losses of nitrogen and dissolved organic carbon after introducing maize into a continuous paddy-rice crop rotation

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ABSTRACT

Farmers in South Asia increasingly switch from continuous paddy-rice cropping to rotations including non-flooded crops, such as growing maize in the dry season. We hypothesized that the introduction of maize into a permanent paddy-rice cropping system boosts drainage and leaching losses of nitrogen (N) and dissolved organic carbon (DOC) in the initial years of maize establishment, due to the disturbance of the equilibrated soil conditions established under continuous paddy cropping. We tested this hypothesis in a 3.5-year field experiment using monolith lysimeters cropped with either (i) single paddy rice in the wet season and maize in the dry season (maize-paddy rice, M-MIX), or (ii) double paddy rice (R-WET) as control. Expandable and compressible pads minimized the formation of a gap at the interface between soil monolith and lysimeter casing during shrinking and swelling of the clay soil. In the first year of introducing maize, drainage ($606\ l\ m^{-2}\ yr^{-1}$) and leaching of total nitrogen (TN, $6.8\ g\ N\ m^{-2}\ yr^{-1}$) and DOC ($2.7\ g\ m^{-2}\ yr^{-1}$) were significantly larger in M-MIX than in R-WET (water: $149\ l\ m^{-2}\ yr^{-1}$, TN: $0.1\ g\ m^{-2}\ yr^{-1}$, DOC: $0.7\ g\ m^{-2}\ yr^{-1}$). However, the additional losses of water, nitrogen, and DOC caused by the introduction of maize disappeared in the following years. In the last two dry seasons of our study, drainage and leaching losses of TN, and DOC were even significantly smaller in M-MIX than in R-WET. In the dry seasons of the 2nd to 4th year after introducing maize (2013–2015), M-MIX saved on average $388\ l\ m^{-2}$ of percolation water losses compared to R-WET and leaching losses of TN and DOC under maize were reduced on average by $0.6\ g\ m^{-2}$ and $1.6\ g\ m^{-2}$, respectively. We conclude that leaching losses of water and nutrients are only transiently boosted during the first year after introducing maize in perennial rice cropping systems, so that maize cropping in the dry season could save water and reduce nutrient leaching in comparison to continuous paddy-rice cropping in the long run. Long-term field trials are necessary to validate the lysimeter results.

1. Introduction

Rice (*Oryza sativa* L.) is the most important food crop globally (FAO, 2014). In Asia, paddy rice is typically grown either as a double-cropped monoculture or in rotations with upland crops such as wheat (*Triticum aestivum* L.), dry rice or maize (*Zea mays* L.) in the dry season (Timsina et al., 2010). In response to water scarcity, expanding human populations, and the increasing demand of fodder for livestock, the paddy-rice–maize cropping system is rapidly spreading in south Asia (Alberto et al., 2014; Timsina et al., 2011). This trend is also promoted by national policies reflecting increased concerns about the (low) profitability of traditional rice cultivation (Keyser et al., 2013). Shifting from a flooded to a non-flooded cropping in the dry season has beneficial effects on the environment such as reduced methane emissions (Kraus et al., 2016; Weller et al., 2015, 2016) and less water consumption (Timsina et al., 2011) compared to the continuous cropping of paddy-rice. However, the cropping of maize causes longer periods with dry soil compared to continuous paddy-rice cropping, which induces changes in biological, chemical, and physical soil properties (Linh et al., 2015; Zhou et al., 2014) and affects soil organic carbon (C) and nitrogen (N)

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cycling (Zhao et al., 2009; Nishimura et al., 2008; Buresh et al., 2008; Witt et al., 2000).

In paddy-rice cropping, the characteristic plough pan prevents water leaching and increases the plant-available water capacity in the puddled layer (Janssen and Lennartz, 2007). However, sometimes water losses are particularly high in paddy cropping when macropores like desiccation cracks are present that form in clayey soils during the dry and fallow period (Janssen et al., 2010; Lennartz et al., 2009; Sander and Gerke, 2006). In addition to water percolation through the plough pan, water losses may occur though bunds and (or) surface runoff (Zhang et al., 2014; Jannsen et al., 2010; Liu et al., 2003).

Maize plants need well-drained soils (FAO, 2015). Dry soil conditions during the maize cropping period causing desiccation cracks in soils, as well as maize roots can lead to a disintegration of the plough pan increasing percolation losses of water (Zhou et al., 2014). Deep maize root channels could remain until the following wet seasons and impede the establishment of a plough pan during puddling prior to paddy-rice transplanting.

Apart from water losses, paddy-rice cropping systems must usually cope with lower nitrogen-use efficiency than upland cropping systems (Wang et al., 2007; Kirk 2004; Dobermann et al., 2002). Olk et al. (1996) speculated that the low nitrogen-use efficiency of the paddy-rice cropping system could be linked to an increasing formation of phenolic moieties in soil organic matter with increasing duration of flooding, which react with ammonia and therewith reduce N-availability. An increased soil aeration caused by the cultivation of upland crops could therefore promote soil organic matter and organic nitrogen mineralization. On the one hand, this enhanced mineralization could improve the N-availability, but on the other hand it could increase nitrate leaching and the emission of N_2O (Weller et al., 2015, 2016; Kögel-Knaber et al., 2010).

Nitrogen losses under paddy-rice–wheat rotations have been well investigated (Song et al., 2015; Zhao et al., 2009; Wang et al., 2007; Pande and Becker, 2003). In principle, soil processes under paddy-rice–maize systems should be comparable to such paddy-rice–wheat systems (Timsina et al., 2010). However, the soil nutrient extraction and soil nutrient drawdown caused by paddy-rice–maize systems is likely greater than for paddy-rice–wheat systems (Witt et al., 2000). Furthermore, there is little information about the initial effects of introducing maize into paddy cropping on N leaching losses. After replacing paddy-rice with maize in the dry season, Witt et al. (2000) found that the total soil nitrogen stocks decreased by 51 and 57 kg N ha^{-1} after two years for non-fertilized and fertilized treatments, respectively. However, the N leaching losses were not determined.

Nitrogen is typically leached together with other substances contained in soil water, among them dissolved organic matter (DOM). The DOM is a quantitatively small, but important component in the cycling of organic matter in soils (Kaiser and Kalbitz, 2012; Bolan et al., 2011), since it acts as carrier of organically bound nutrients (e.g. dissolved organic nitrogen, DON, Siemens and Kaupenjohann, 2002) as well as carbon and energy source for subsurface microorganisms, including denitrifiers (Jahangir et al., 2012). The concentrations of DOM in soil water are controlled by the balance between its production, metabolic transformation or mineralization, leaching, sorption, and precipitation (Kaiser and Kalbitz, 2012). In paddy-rice soils the mineralization of DOM and its retention by sorption to iron (hydr)oxides is likely smaller than in most well-aerated, terrestrial soils, so that leaching may be a major DOM loss pathway. Katoh et al. (2004) reported leaching losses of 8.5–17.0 g of dissolved organic carbon (DOC) per m^2 from the plough layer of paddy fields over one cropping season of a wheat–paddy-rice rotation. Said-Pullicino et al. (2016) determined large DOC leaching losses of up to 51.1 g m^{-2} yr^{-1} from topsoils into subsoils for temperate paddy rice production systems in Italy. However, information on DOC leaching in paddy-rice–maize cropping systems is lacking. Based on our understanding of DOC dynamics in soils, one could expect that the introduction of maize decreases DOC concentrations in soil water, because of increased mineralization of soluble organic matter and increased formation of iron (hydr)oxides under aerobic soil conditions.

We hypothesized therefore that the introduction of maize promotes drainage and the leaching of N relative to continuous paddy rice cropping. In contrast, leaching losses of DOC could even decrease due to the formation of increasingly aerobic soil conditions under maize. We investigated how the introduction of maize as a crop for the dry season into a continuous paddy-rice cropping system affected drainage as well as concentrations and leaching losses of N, and DOC in 3.5-year monolith lysimeter experiment under field conditions.

2. Materials and methods

2.1. Study area

The lysimeter field experiment was conducted at the central field site (14°09′45″ N, 121°15′35″ E) of the German Research Foundation (DFG) Research unit 1701 "ICON" at the International Rice Research Institute (IRRI) in Los Baños, Philippines. The soil of the experimental field was classified as a Hydragric Anthrosol with clay-dominated soil texture (0–5 cm: 60.6% clay; 5–20 cm: 52.0% clay) (He et al., 2015). The details of soil properties were summarized in Table 1. The average annual rainfall in the last thirty years (1979–2010) at the site was 2006 mm. The long-term average rainfall for the dry season was 300 mm and 1706 mm for the wet season. The daily precipitation and pan evaporation data collected by IRRI climate unit for the study area and the calculated evaporation from the lysimeters for the periods from February 2012 until June 2015 are available as online Supplementary material (Figs. S1 and S2). Average annual Max/Min temperatures were 30.7 °C and 23.6 °C, respectively.

Two cropping systems were investigated with three replicates each: double paddy-rice cropping (R-WET) as control and a crop rotation of maize in the dry season and paddy-rice in the wet season (M-MIX). In the studied field, maize cropping was first introduced in February 2012. Prior to this date, the area was at least 50 years under permanent paddy-rice cultivation. The cropping period of dry seasons was from January or February to April or May; the cropping period of wet seasons from June or July to October. The exact dates of sowing, transplanting and harvest for the two cropping systems were given as Supplementary material (Table S1). The cropping of the lysimeters, including land preparation and irrigation, was done manually. Prior to the cultivation

Table 1
Soil properties.

Soil horizon		N (%)	C (%)	C/N	pH (H_2O)	Sand (%)	Silt (%)	Clay (%)	Bulk density[a] (g cm^{-3})
Ap	0–4 cm	0.2	2.4	11.1	6.5	7.4	29.2	60.6	–
Arp	4–15 cm	0.2	1.7	10.8	6.8	7.8	31.4	58.6	0.9
Ardp	15–24 cm	0.1	1.4	10.7	6.6	10.3	29.4	56.3	0.9
Bl1	24–33 cm	0.03	0.3	9.7	7.1	18.0	21.0	59.4	0.9
Bl2	33–55 cm	0.02	0.2	9.5	6.8	18.7	20.2	56.9	0.8

[a] Sampled when soil was wet.

of paddy-rice, the topsoil was digged over and puddled by hand. Prior to the cultivation of maize, the topsoil was digged over and raked to mimic harrowing.

2.2. Lysimeter setup

From December 2011 to February 2012, we installed six monolith lysimeters (Ø 113 cm, 80 cm height) down to 60 cm soil depth (He et al., 2015, Fig. S3, Supporting information). The vertical lysimeter casing was inserted around the soil monolith by digging a circular trench and pushing the casing downwards manually. The lysimeter bottom segment contained two porous silicium carbide cups (50 cm length of porous cup, with an equivalent pore size of approximately 2 µm; METER Group AG, Munich, Germany) that were embedded in washed quartz sand.

Inspired by the double-wall lysimeters that Berglund et al. (2010) used for swelling and shrinking peat soils, bypass flux of water along the interface of the soil monolith and the vertical lysimeter casing was minimized with an expandable and compressible polyvinyl-chloride pad at the inside of the lysimeter casing that compensated shrinkage and swelling of the clay soil monolith with changing soil moisture content (Fig. S3). During excavation, the flexible pad was compressed and fixed flat to the lysimeter steel casing by applying vacuum. After the lysimeter casing had been pushed around the soil monolith, we released the vacuum and the pad pressed with gentle force towards the soil monolith (Fig. S3).

When the groundwater level was deeper than the lysimeter bottom, drainage water was collected with suction cups at the lower boundary of the lysimeter at 60 cm soil depth. These suction cups were installed in a bottom layer of washed quartz sand and operated with a constant suction of 22 ± 2 hPa. When the groundwater level was above the lysimeter bottom, suction cups were switched off and groundwater was added into a piezometer (30 cm diameter) that was connected to the lysimeter with a tubing in order to mimic groundwater levels outside the lysimeters (He et al., 2015). The suction cups were connected to a KIPP 100 tipping gauge that was connected to a DT80 data logger for recording drainage volumes with high temporal resolution (METER Group AG, Munich, Germany). Additionally, the water volumes added to the lysimeters with irrigation or via the piezometers as well as the volumes of water leaving the lysimeters with drainage were recorded manually from March 2012 until June 2015. In order to control the volume of water added with irrigation, the upper rim of the lysimeters was connected to a flexible liner of polyvinyl-chloride tarp that extended above the surface of the irrigation water level (Fig. S3). The irrigation water was taken from the field hydrant that was connected to an open-air water reservoir about 100 m away from our field. The reservoir was filled with groundwater pumped onsite. The groundwater DOC and TN concentrations were 1.4 mg l^{-1} and 0.07 mg l^{-1}, respectively. It was negligible for the input of field DOC and TN concentrations. Irrigation water was added to the lysimeters cropped with paddy-rice until the water level inside the lysimeters equaled the water level outside around the lysimeters (approximately 3–5 cm ponding depth). The irrigation amount for growing maize was adjusted according to the water demand of the maize plants without flooding the soil.

After heavy precipitation, sometimes water had to be removed from the ponded lysimeter surface in order to adjust the water level to the level of the surrounding paddy rice fields. The volumes of water removed were also recorded manually. As the high-resolution outflow measurements with the tipping gauge did not cover the entire experimental period without data gaps, the manually recorded volumes were used to calculate the water balance of the lysimeters.

2.3. Fertilization and crop residue management

According to IRRI crop management routine, our field was fertilized with solophos (18% phosphorus) and potash (60% potassium) before seeding. We added N fertilizer in the form of urea for both rice and maize. Paddy-rice plots received a total of 130 kg N ha^{-1} per season in three splits: 30 kg, 50 kg and 50 kg N ha^{-1} (3 g, 5 g and 5 g N per lysimeter) at 14, 26 and 50 days after transplanting (DAT), respectively. Maize plots were fertilized with a total of 150 kg N ha^{-1}, again in three splits of 60 kg, 30 kg and 60 kg N ha^{-1} (6 g, 3 g and 6 g N per lysimeter) at 0, 24 and 45 days after seeding (DAS), respectively.

Above ground crop residues were removed from the field after harvest, both in M-MIX and R-WET treatments. Maize stubbles and rice stubbles were left in the lysimeters.

2.4. Water sampling for chemical analysis

We collected water samples from 60 cm soil depth every two weeks and additionally 0, 1, 2, 4 and 7 days after N fertilizations, and after irrigation or heavy rains. Since the water passed the porous cups that acted as filter, water samples were not filtered additionally prior to analysis.

Water samples were split into two aliquots: one aliquot was stored at 4 °C for nitrate and ammonium analyses at IRRI and a second aliquot was frozen at −18 °C immediately after sampling, and later transported to Germany for DOC and TN analyses.

2.5. Chemical sample analysis

Nitrate and ammonium concentrations were analyzed at IRRI by Analytical Services Laboratory (ASL). The reagents preparation and analyses were following their operating procedure protocol (ASL, IRRI, 2016). Briefly, nitrate in water samples was reduced to nitrite by hydrazine in alkaline solution, with copper catalyst, then reacted with sulfanilamide and NEDD to form a pink compound measured at 520 nm. To reduce the pH, phosphoric acid was added at the final stage. For ammonium analysis, samples were reacted with salicylate and dichloroisocyanuric acid to produce a blue compound measured at 660 nm. The limit of detection for nitrate and ammonium was 0.1 mg N l^{-1}. In Germany water samples were defrosted gently. Concentrations of TN and DOC were determined by a TOC-V_{CPH} analyzer combined with TN unit TNM-1 (Shimadzu Corp., Kyoto, Japan) with a detection limit smaller than 0.1 mg N l^{-1}. Concentrations of dissolved organic nitrogen (DON) were calculated by subtracting NO_3^--N and NH_4^+-N concentrations from TN concentrations.

2.6. Calculations

We derived the mass flux of leached N and C for each individual lysimeter for each sampling interval by multiplying the manually recorded drainage volumes of the lysimeter with measured concentrations of NO_3^--N, NH_4^+-N, TN and DOC in leachates of the respective lysimeter. Then we calculated arithmetic mean concentrations and water fluxes per season. Additionally, flow-weighted average concentrations were calculated (modified from Miniotti et al., 2016, Eq. (1)).

$$\text{Flow-weighted average concentration} = (C_1 \times V_1 + C_2 \times V_2 + C_3 \times V_3)/(V_1 + V_2 + V_3) \quad (1)$$

With C_1, C_2 and C_3 as concentrations of nitrogen or DOC from lysimeter 1, 2 and 3, respectively; V_1, V_2 and V_3 as drainage volumes of lysimeter 1; 2 and 3, respectively.

Since water samples could not be taken and analysed for each leaching event, concentration data were interpolated linearly between sampling dates using Eq. (2).

$$C(t) = C(t_{-1}) + [(C(t_{+1}) - C(t_{-1}))/(t_{+1}–t_{-1}) \times (t - t_{-1})] \quad (2)$$

With C(t) as concentration at time t, $C(t_{-1})$ as measured concentration at the preceding sampling, and $C(t_{+1})$ as measured concentration at the following sampling.

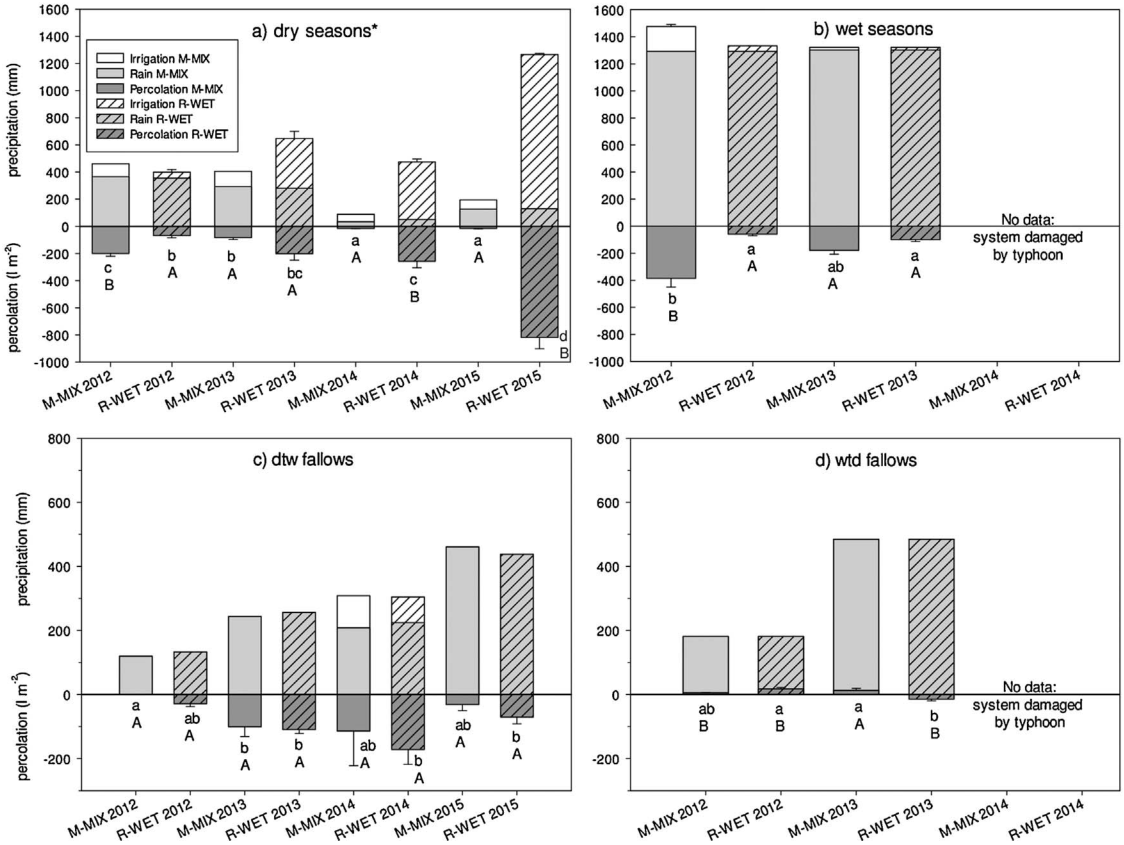

Fig. 1. Arithmetic means of irrigation, precipitation, and drainage in: (a) dry seasons from 2012 to 2015, (b) wet seasons from 2012 to 2014, (c) dtw (dry-to-wet) fallows from 2012 to 2015, and (d) wtd (wet-to-dry) fallows from 2012 to 2014; error bars represent the standard error (n ≤ 3). Statistical significance was tested using repeated measures ANOVA with subsequent Tukey HSD test with $p < 0.05$; *tested with log-transformed data; different small case letters indicate significant differences between the respective season of the experiment period across both crop managements; different capital letters indicate significant differences between crop managements within each season.

2.7. Statistical data evaluation

Data were statistically analyzed using a repeated measures analysis of variance (ANOVA). Additionally, a pair wise comparison of data and log-transformed data was undertaken using the Tukey HSD test and a non-parametric Mann-Whitney-*U* test. All statistical analyses were performed with the Statistica 8.0 software package (StatSoft, Hamburg, Germany).

3. Results

3.1. Water losses with drainage

Leached water volumes differed significantly between crop managements (tested with log-transformed data, $p = 0.0035$) and between seasons including fallow seasons ($p < 0.0001$, Fig. 1). Growing maize (M-MIX) induced significant larger leaching losses of water in comparison with R-WET cropping in the dry season and the wet season of the first year of the experiment (2012, $p = 0.0002$). In the dry season of 2012, the water drainage in M-MIX was 199 ± 21 $l\,m^{-2}$, which was three times as much as in R-WET cropping (68 ± 18 $l\,m^{-2}$, Fig. 1a). In the 2012 wet season, the drainage under the M-MIX crop rotation exceeded the drainage under the R-WET rotation almost by a factor of seven (385 ± 67 $l\,m^{-2}$ under M-MIX versus 58 ± 13 $l\,m^{-2}$ under R-WET). After 2012, the picture changed gradually. In 2013, water drainage did not differ significantly between R-WET and M-MIX (Fig. 1a–c). In the dry seasons of 2014 and 2015, the drainage in M-MIX were significantly smaller than in R-WET (Fig. 1a). In the 2015 dry season, only 15 ± 3 $l\,m^{-2}$ water were leached in M-MIX, while 819 ± 84 $l\,m^{-2}$ water drained in the R-WET crop rotation (Fig. 1a).

The duration of fallow seasons in our experiment was usually 1.5 to 3 months. The first dry-to-wet fallow in 2012 was shorter and had durations of two weeks for M-MIX and three weeks for R-WET, respectively, because of a delayed start of the dry season. The water drainage during dry-to-wet fallows were larger than leaching losses during the wet-to-dry fallow seasons (Fig. 1c,d). During the wet-to-dry fallow seasons, even negative net drainage was observed, because the volumes of water that had to be added to the piezometers in order to maintain an adequate groundwater level in the lysimeters exceeded the water volumes that were leached (Fig. 1d). Only for the R-WET rotation, a small net drainage of 14 $l\,m^{-2}$ was recorded in the wet-to-dry fallow period of 2013, which significantly exceeded the small net inflow of 13 $l\,m^{-2}$ of groundwater in M-MIX. (Fig. 1d).

3.2. Nitrogen losses with drainage water

The total nitrogen (TN) concentrations in drained water of M-MIX increased strongly after nitrogen applications, especially in the dry season of the first year (2012), when concentration levels of 20–60 $mg\,N\,l^{-1}$ were reached (Fig. 2). TN concentrations under the R-WET rotation increased less after N fertilization relative to the M-MIX rotation (Fig. 2). As a consequence, the mean TN concentrations under M-MIX were significantly larger than concentrations under R-WET in the dry and wet seasons of the first two years (Table 2). These differences were also observed between mean NO_3^- concentrations (Table 2).

The long-term average NH_4^+-N concentration under R-WET (0.3 ± 0.1 $mg\,N\,l^{-1}$) was similar to the long-term average NO_3^- concentration (0.5 ± 0.04 $mg\,N\,l^{-1}$, Table S2). In contrast, the long-term average concentration of NO_3^- (3.9 ± 1.3 $mg\,N\,l^{-1}$) for M-MIX

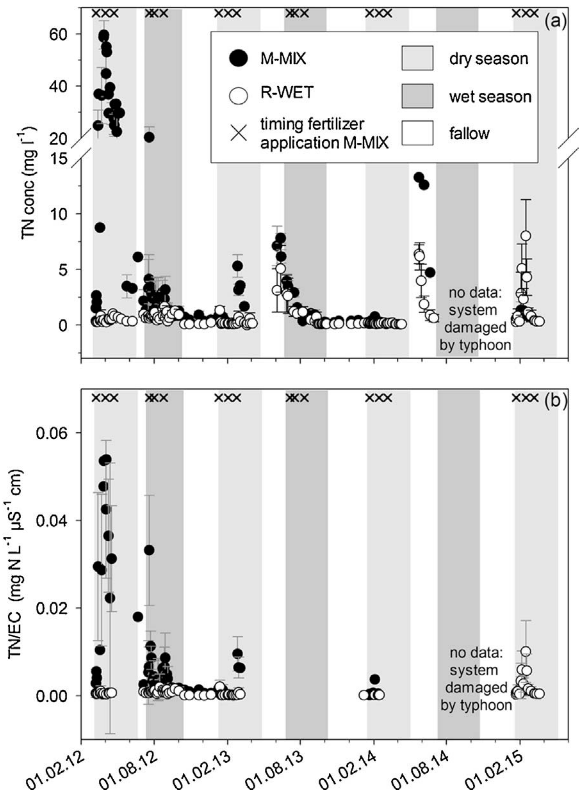

Fig. 2. Arithmetic mean concentrations of total nitrogen (mean TN, graph a) and arithmetic mean of TN concentrations normalized to electrical conductivity (mean TN/EC, graph b) in leachates from 2012 to 2015 at 60 cm sampling depth. Error bars represent the standard error (n ≤ 3).

was almost five times as high as the long-term average concentration of NH_4^+ (0.8 ± 0.2 mg N l^{-1}, Table S2). Average dissolved organic nitrogen (DON) concentrations equaled 0.1 ± 0.04 mg N l^{-1} for R-WET and 0.6 ± 0.01 mg N l^{-1} for M-MIX (Table S2). The TN long-term average concentration for M-MIX was also significantly larger than for R-WET (Table S2).

In line with larger TN concentrations, also leaching losses of TN under M-MIX significantly exceeded those under R-WET in the dry and the wet season of 2012 (Fig. 3a,b). Under M-MIX, the largest TN leaching loss of 5.3 ± 2.1 g m^{-2} was observed in the dry season of 2012 (Fig. 3a), which was equivalent to one third of the applied total urea N for one maize season. In 2013, differences between TN leaching losses under M-MIX and R-WET declined (Fig. 3). In the dry season of 2013, TN leaching losses under M-MIX and R-WET did not differ significantly (Fig. 3a). In the wet season of 2013, TN leaching losses were only slightly, yet significantly, larger under M-MIX (0.3 ± 0.04 g N m^{-2}) than under R-WET (0.1 ± 0.02 g N m^{-2}, Fig. 3b). In the dry seasons of 2014 and 2015, the TN leaching losses under R-WET exceeded TN losses under M-MIX, mainly because of the small volumes of water leached under M-MIX (Fig. 3a). The largest TN leaching loss in R-WET equaled 2.0 ± 0.8 g m^{-2} in the dry season of 2015, while a negligibly small mass of TN leached from M-MIX in this season (Fig. 3a).

During the fallow periods there were little if any differences between TN leaching losses of these two crop rotations, mostly insignificant (Fig. 3c,d). Only in the dry-to-wet fallow period in 2012, the small leaching losses under R-WET (0.02 ± 0.01 g N m^{-2}) significantly exceeded those under M-MIX, where no seepage was collected leading to zero leaching of N.

While in our experiment period NO_3^- and NH_4^+-N almost equally contributed to TN leaching from the R-WET plots (NO_3^-: 45%, NH_4^+: 31% of TN leaching), NO_3^- was the major N species leached under M-MIX (78% of TN leaching).

Table 2
Arithmetic mean concentrations of TN, NO_3^- and DOC in leachate water at 60 cm sampling depth in each season (± standard error n = 3, unless otherwise stated).

Year	Crop management	Dry season	Dry to wet	Wet season	Wet to dry
TN mg l^{-1}		+[1]	++[2]		++
2012	M-MIX	23.0 ± 5.3 cB[3]	–	2.7 ± 0.2 bB	0.6 ± 0.0 B
	R-WET	0.4 ± 0.1 abA	–	0.9 ± 0.1 aA	0.1 ± 0.0 A
2013	M-MIX	1.8 ± 0.3 bB	7.4 ± 1.0 B	1.0 ± 0.2 aA	0.3 ± 0.0 A
	R-WET	0.2 ± 0.03 aA	4.1 ± 1.5 A	0.7 ± 0.3 aA	0.1 ± 0.0 A
2014	M-MIX	0.3 ± 0.1 aA	4.3 ± 7.4[4] A	–	–
	R-WET	0.1 ± 0.02 aA	3.3 ± 0.8 A	–	–
2015	M-MIX	1.2 ± 0.6 abA	–	–	–
	R-WET	1.9 ± 0.7 bA	–	–	–
NO_3^- mg N l^{-1}		+			
2012	M-MIX	18.5 ± 5.0 dB	–	1.8 ± 0.3 bB	0.0 ± 0.0 aA
	R-WET	0.2 ± 0.1 abA	–	0.8 ± 0.2 aA	0.0 ± 0.0 aA
2013	M-MIX	2.8 ± 0.4 cB	0.4 ± 0.1 A	0.1 ± 0.0 aA	0.1 ± 0.0 bA
	R-WET	0.2 ± 0.01 abA	0.7 ± 0.1 A	0.1 ± 0.0 aA	0.1 ± 0.0 abA
2014	M-MIX	0.2 ± 0.1 aA	4.3 ± 7.4[4] A	–	–
	R-WET	0.1 ± 0.01 aA	3.3 ± 0.9 A	–	–
2015	M-MIX	1.0 ± 0.4 bcA	–	–	–
	R-WET	0.7 ± 0.1 bA	–	–	–
DOC mg l^{-1}		++			
2012	M-MIX	6.0 ± 0.3 B	–	3.9 ± 0.2 bA	3.7 ± 0.7 A
	R-WET	5.1 ± 0.2 A	–	4.2 ± 0.2 bA	2.8 ± 0.2 A
2013	M-MIX	3.6 ± 0.3 A	4.4 ± 0.3 A	2.5 ± 0.1 aA	2.5 ± 0.0 A
	R-WET	3.7 ± 0.5 A	6.9 ± 1.6 A	2.7 ± 0.2 aA	2.7 ± 0.2 A
2014	M-MIX	3.4 ± 0.7 A	1.4 ± 2.4[4] A	–	–
	R-WET	3.2 ± 0.1 A	3.8 ± 0.2 A	–	–
2015	M-MIX	4.6 ± 0.2 A	–	–	–
	R-WET	4.2 ± 0.3 A	–	–	–

[1] + tested with log-transformed data (repeated measures ANOVA with Tukey HSD test $p < 0.05$).
[2] ++ tested by *U* test $p < 0.05$.
[3] Different small case letters indicate significant differences between the respective season of the experiment period across both crop managements; different capital letters indicate significant differences between crop managements within each season (repeated measures ANOVA with Tukey HSD test $p < 0.05$).
[4] n < 3.

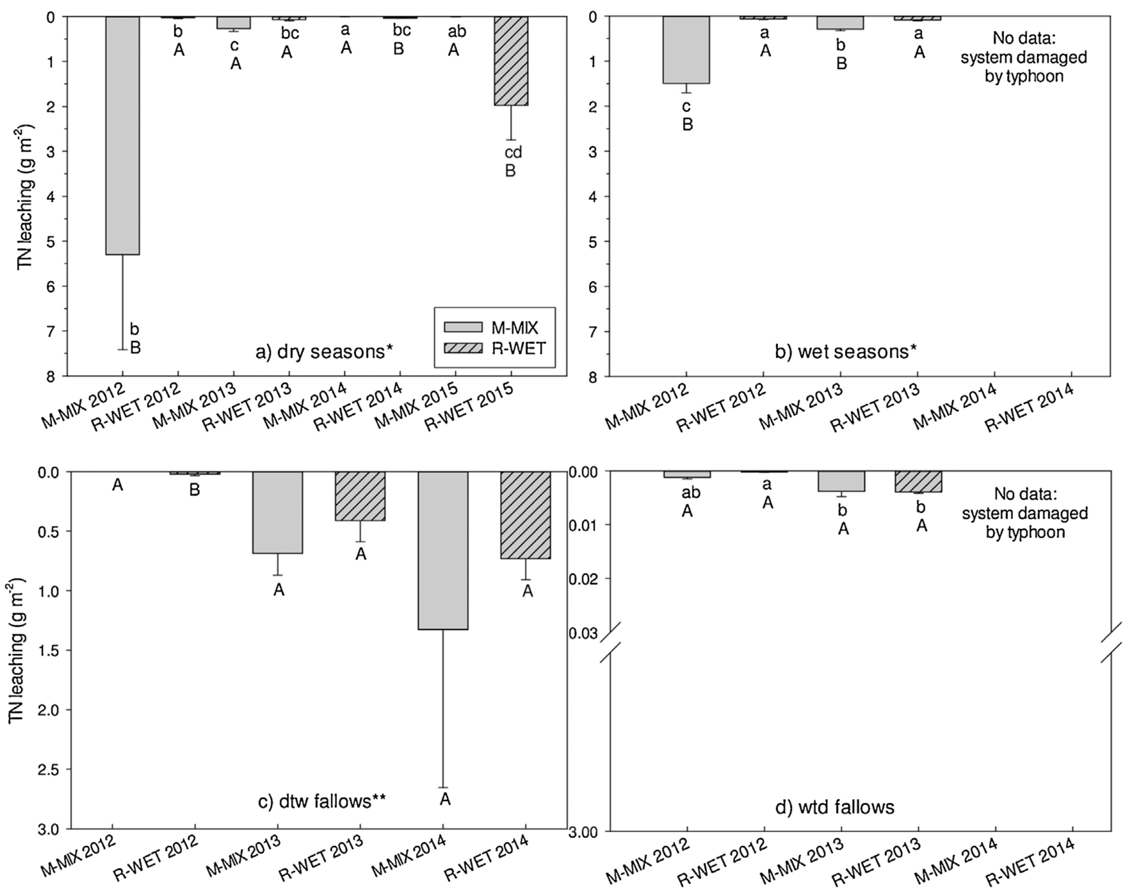

Fig. 3. Arithmetic mean total nitrogen leaching losses in (a) dry seasons from 2012 to 2015, (b) wet seasons from 2012 to 2014, (c) dtw (dry-to-wet) fallows from 2012 to 2014, and d) wtd (wet-to-dry) fallows from 2012 to 2014; error bars represent the standard error (n ≤ 3). Statistical significance was tested using repeated measures ANOVA with subsequent Tukey HSD test with $p < 0.05$, if not indicated otherwise; *tested with log-transformed data; **tested by *U* test $p < 0.05$; different small case letters indicate significant differences between the respective season of the experiment period across both crop managements; different capital letters indicate significant differences between crop managements within each season.

3.3. DOC leaching losses

Concentrations of DOC in drainage water ranged from 2 to 16 mg l^{-1} (Fig. 4). The introduction of maize (M-MIX) increased the mean DOC concentration only in the first dry season in 2012 in comparison to R-WET (Table 2). The mean DOC concentrations of 2012 and 2013 differed significantly ($p < 0.05$) between dry (4.6 mg l^{-1}) and wet seasons (3.3 mg l^{-1}), but not between crop rotations.

The fluxes of DOC with water leached from the lysimeters under the M-MIX crop rotation were larger than fluxes from lysimeters under R-WET during the dry season and the wet season 2012 (Fig. 5a,b). In the dry seasons of the following years 2013, 2014, and 2015, DOC leaching losses under M-MIX were significantly smaller than those under R-WET (Fig. 5a). Also in the dry-to-wet fallow 2012 and in the wet-to-dry fallow 2013, DOC leaching losses under R-WET significantly exceeded those under M-MIX (Fig. 5c,d). The largest leaching loss of DOC per season of 3.4 g m^{-2} was found under R-WET in the dry season 2015 (Fig. 5a).

4. Discussion

4.1. Water losses with drainage

Introducing maize into a continuous paddy-rice cropping system increased water drainage in the initial phase of our experiment significantly. The land preparation destroyed the plough pan, which effectively improved the aeration for maize cropping, but also increased the percolation in M-MIX in the dry season 2012. The conversion of the continuous rice cropping system into a maize–rice rotation also affected drainage during wet seasons under paddy-rice. Most likely, puddling after the maize crop was unable to re-establish a plough pan as tight as plough pans found under long-term continuous paddy rice cropping. Janssen and Lennartz (2007) showed that a field with three years paddy cultivation had no visible plough pan and showed much larger water percolation rates in comparison with soils that were under paddy rice cultivation for 20 years or 100 years. However, large water losses of the maize–rice rotation during the wet season could be partly compensated or even over-compensated by reduced drainage during the maize cropping period, as observed for example in the dry season of 2013 (Fig. 1a)

Drainage under R-WET was small in the first year of our experiment in 2012, but increased steadily in the dry seasons from 2013 to 2015 (Fig. 1a). We attributed these elevated water losses with drainage to the formation of desiccation cracks in the clayey soil during the fallow seasons of continuous rice cropping (Fig. S4, Supporting information). The paddy fields were also not flooded a few days after transplanting and two weeks before harvest during growing rice. Drying of the clayey and puddled soil causes unwanted water and solutes losses as a consequence of shrinkage and cracking (Janssen and Lennartz, 2007; Cabangon and Tuong, 2000; Bronswijk and Evers-Vermeer, 1990). Some of the cracks could reclose when fields were reflooded (Liu et al., 2003), but cracks may not necessarily close after rewetting and lead to high percolation, thus permanently increasing the drainage (Janssen et al., 2010; Tuong et al., 1996). Large drainage during the dry seasons of 2014 and particularly 2015 were also related to large volumes of irrigation, which in turn were perhaps caused by below average precipitation during the dry seasons of these years. Water availability in the dry season and irrigation costs are issues also in the Philippines.

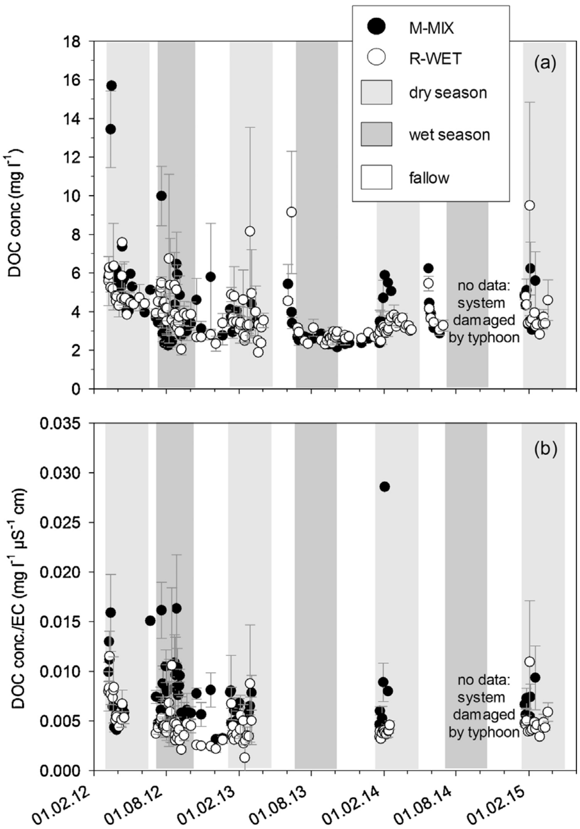

Fig. 4. Arithmetic mean concentrations of dissolved organic carbon (DOC, graph a) and DOC concentrations normalized to electrical conductivity (DOC conc./EC, graph b) in leachates from 2012 to 2015 at 60 cm sampling depth. Error bars represent the standard error (n ≤ 3).

Therefore, the large volumes of irrigation that were applied to the lysimeters and to the experimental fields to ensure optimal water levels might not necessarily reflect agricultural practice on large scale in all years.

On the other hand, water drainage under M-MIX decreased after 2012 with increasing time of the experiment in the dry seasons of 2013–2015 (Fig. 1a) and in the wet season 2013 (Fig. 1b). This decrease of water losses with drainage over time might have been caused by the clogging of cracks and macropores that were formed during the initial maize growing season with soil material from the Arp-horizon during the land preparation by puddling for the rice crop grown in wet seasons. As a consequence of decreasing water losses with drainage over the course of the experiment under M-MIX and increasing water losses under R-WET, the cropping of maize resulted in overall reductions of drainage already after a conversion period of two years.

Overall, it appeared that the development of soil cracks rather than the introduction of maize determined the medium to long-term water balance.

4.2. Nitrogen leaching

Nitrogen leaching losses commonly depend on water management, crop and crop residue management, as well as fertilizer management (Tian et al., 2007; Wang et al., 2007; Chowdary et al., 2004). Typically, N leaching from paddy-rice cropping systems is not pronounced and smaller than, for example, in paddy-rice − upland crop rotations (Zhao et al., 2009; Buresh et al., 2008; Zhu et al., 2000). However, some studies found larger leaching losses of N during paddy-rice cropping compared to upland crops due to larger water infiltration and percolation (Tian et al., 2007; Wang et al., 2007). We observed the largest TN concentrations and leaching losses in the first maize growing season (Figs. 2, 3a). Peak concentrations of TN in soil water can result from reduced N uptake by crops, from a net input of N, as well as from decreasing soil water contents due to evapotranspiration. Indeed, especially during the young development stage in the first dry season, maize plants grew not perfectly in the soils with large water content (largest precipitation in that dry season) reducing their N uptake, thus increasing TN concentrations in soil solution. Net inputs of N can occur e.g. as consequence of soil organic matter mineralization or fertilization. Larger DON concentrations under paddy-rice – maize cultivation compared to continuous paddy-rice cropping might indicate more intense mineralization of soil organic matter after the introduction of maize.

To differentiate between net inputs or removal of N in soil water and "concentration effects" due to changing soil water contents, we normalized the TN concentration to the electrical conductivity of the leachate samples (Fig. 2b). This normalization indicated that most peak concentrations were caused by net N inputs into leachates and not a consequence of concentration and dilution effects. Peak TN concentrations in March, July and August 2012 as well as February 2013 occurred simultaneously or shortly after fertilization, suggesting that quick leaching of applied N fertilizer contributed to the observed increase in TN concentrations in 60 cm depth (Fig. 2). Peak TN concentrations in the fallow periods in June 2013 and May 2014 could be related to mineralization of soil N that was not balanced by N uptake of crops (Fig. 2).

Similar to the dry season 2012, also in the wet seasons in 2012 and 2013, the TN leaching losses were larger under M-MIX cropping than under R-WET cropping, accounting for 12% and 2% of applied urea N in M-MIX, versus less than 1% of applied N in R-WET.

The turning point for a beneficial effect of maize cropping on N leaching was at two years after the first maize season. Losses of TN under M-MIX decreased strongly in the third and fourth dry seasons as well as in the wet season 2013, while TN losses in the dry and wet seasons continuously increased under R-WET (Fig. 3a,b). Although TN concentrations and the flow-weighted TN concentrations in drainage under M-MIX were either significantly larger or at least comparable to those observed under R-WET (Fig. 2, Table 2 and Tab S3), N leaching losses under M-MIX were frequently smaller than under R-WET because of smaller percolation rates (Figs. 1 and 3). It appeared that after the establishment of the maize − rice cropping system, the TN leaching losses declined with increasing time as a result of both, decreasing TN concentrations in leachate and decreasing volumes of drainage. Overall, the TN leaching loss we observed in our study (3.5 years) in relation to the amounts of applied fertilizer N was 11% under M-MIX cropping, which was larger than the leaching losses in paddy soil under rice-wheat rotation that Zhao et al. (2009) and Wang et al. (2007) reported. Also the TN leaching loss under R-WET cropping (4%) in our study was larger than the loss that Ji et al. (2011) found (0.7–2.3%) in a lysimeter experiment with three types of soils.

Similar to the observation of Tian et al. (2007), transient increases of TN concentrations in leachates following N fertilizer applications were larger for M-MIX than for R-WET. Our results also confirm the finding of previous studies that NO_3^- is the major form of nitrogen leached under upland crops (e.g., Siemens and Kaupenjohann, 2002) and in paddy-rice – upland cropping systems (Zhu et al., 2000). Leaching of NH_4^+ from the investigated soils was also limited by their large content of negatively charged clay (Aulakh and Singh, 1997). In the first maize season of our experiment, the mean NO_3-N concentration in drainage equaled 18.5 mg l^{-1}, which exceeds the limit set for NO_3^--N concentrations in drinking water by the World Health Organization (WHO, 2011). It appeared that the combination of an initial longer aerobic phase in soil after 50 years of continuous paddy-rice cropping triggering the mineralization of soil organic nitrogen, the application of 150 kg fertilizer N per ha, and facilitated drainage caused by the destruction of the plough pan boosted concentrations and leaching of nitrogen, especially NO_3^-.

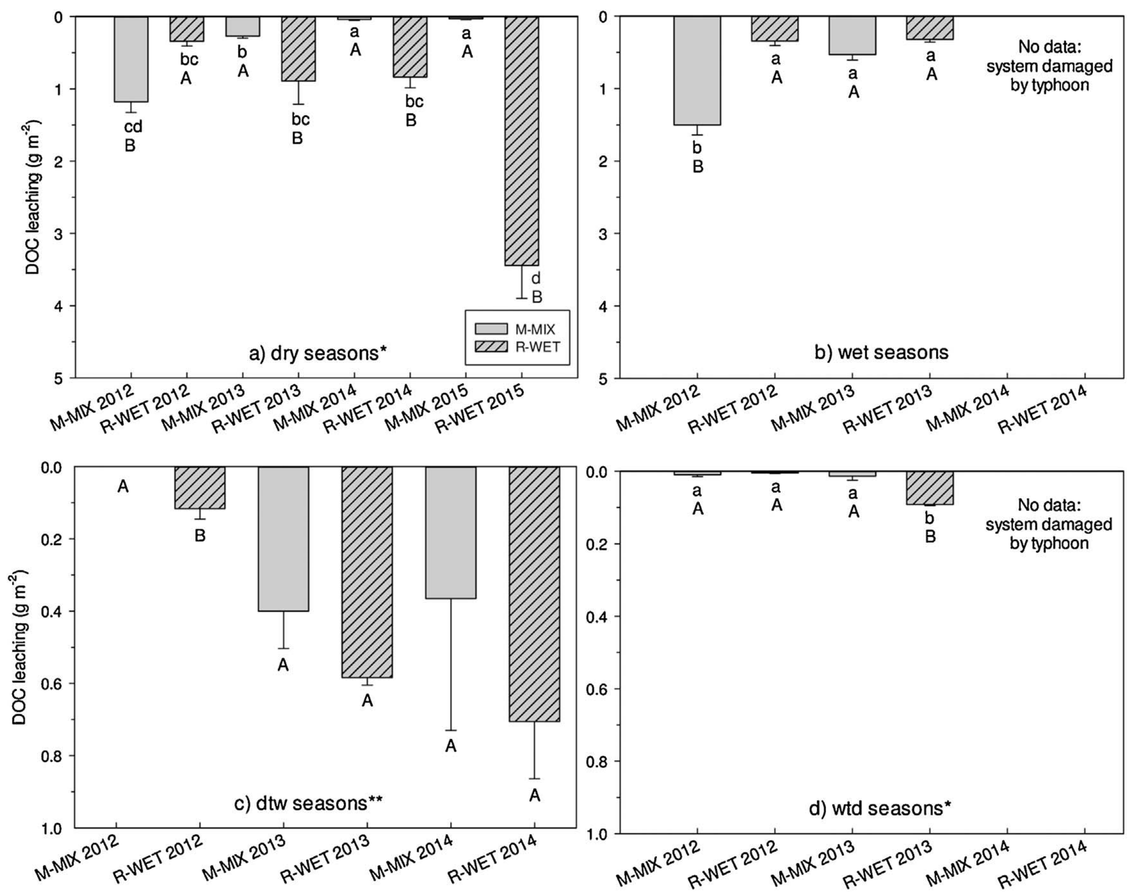

Fig. 5. Arithmetic mean DOC leaching losses in (a) dry seasons from 2012 to 2015, (b) wet seasons from 2012 to 2014, (c) dtw (dry-to-wet) fallows from 2012 to 2014, and (d) wtd (wet-to-dry) fallows from 2012 to 2014; error bars represent the standard error (n ≤ 3). Statistical significance was tested using repeated measures ANOVA with subsequent Tukey HSD test with $p < 0.05$, if not indicated otherwise; *tested with logarithmized data; **tested by *U* test $p < 0.05$; different small case letters indicate significant differences in the respective season of experiment period across both crop managements; different capital letters indicate significant differences between crop managements within each season.

The elevated concentrations of NH_4^+-N as quantitatively one of the most important TN forms under continuous rice cropping were in line with results of other studies (Zhao et al., 2009; Wang et al., 2007; Zhu et al., 2000). Ji et al. (2011) also report that TN leaching under paddy rice cultivation was mainly in the form of NH_4^+-N.

4.3. DOC concentrations and fluxes

We expected larger DOC concentrations under continuous rice cropping relative to the M-MIX rotation, because of more reducing soil conditions, leading to a slower degradation of solubilized organic matter and a mobilization of DOM due to the dissolution of iron (hydr) oxides (Said-Pullicino et al., 2016). Different from our expectation and from the results of Said-Pullicino et al. (2016), DOC concentrations at 60 cm below soil surface varied little between the two crop rotations. In the first maize season, DOC concentrations under M-MIX were even larger than those under R-WET (Table 2), most likely because of rapid transport of water through cracks minimizing DOM sorption. In addition, the degradation of soil organic matter under aerobic soil conditions could have increased DOC concentrations under maize especially during the first dry season. Also the temporal trend in DOC concentrations we observed differed from the trend that Said-Pullicino et al. (2016) observed in paddy-rice soils in Italy. While Said-Pullicino et al. (2016) found an increase in DOC concentrations under flooded conditions, concentrations tended to increase in the dry season and fallow season in our experiment (Fig. 4a). Larger DOC concentrations in leachates during dry seasons than during wet seasons (Fig. 4a) were not caused by a stronger dilution of mobilized organic carbon during wet seasons, since a normalization of DOC concentrations to electrical conductivity gave similar ratios for both seasons (Fig. 4b). This suggests that DOC concentrations were increased during the dry season by a net release of organic matter into soil water, e.g. by enhanced microbial oxidation of soil organic matter.

Due to similar DOC concentrations, differences between DOC leaching losses under the two crop rotations were related to differences between volumes of drainage. Average DOC leaching losses for years 2012 and 2013 equaled 1.3 ± 0.6 g C m^{-2} yr^{-1} under continuous rice cropping and 2.0 ± 0.7 g C m^{-2} yr^{-1} under M-MIX. These losses were smaller than the average flux of 4.1 ± 1.3 g C m^{-2} yr^{-1} that Kindler et al. (2011) reported for European croplands, smaller than the loss of 8–17 g C m^{-2} $season^{-1}$ that Katoh et al. (2004) estimated for a cropping season of a wheat-rice rotation with straw application in Japan, and much smaller than the loss of 3.7–51.1 g m^{-2} yr^{-1} that Said-Pullicino et al. (2016) calculated for paddy-rice systems in Italy. One reason for smaller leaching losses of DOC in our experiment compared to the experiments of Katoh et al. (2004) and Said-Pullicino et al. (2016) could be the relatively large sampling depth of 60 cm below soil surface. Dissolved organic carbon fluxes with drainage decrease exponentially with increasing soil depth, and Said-Pullicino et al. (2016) determined fluxes at 25 cm depth and Katoh et al. (2004) measured fluxes at 40 cm depth. Another reason for small DOC leaching losses in our experiment could be the large clay content of the soil at the IRRI experimental farm (around 60% weight, Table 1), which could reduce drainage volumes and promote DOM retention. For comparison, the soil in Italy studied by Said-Pullicino et al. (2016) had clay contents of 10–14% weight in the uppermost 90 cm.

5. Conclusions

We conclude that the introduction of maize cropping in the dry season of a continuous paddy-rice cropping system causes an initial increase of drainage and leaching losses of N and DOC. During this initial phase directly after the first maize cropping season, nitrate concentrations in leachates by far exceeded the limit of 50 mg l^{-1} for drinking water. These initially large N and DOC leaching losses after the introduction of maize seem to be linked to the decomposition of soil organic matter that accumulated during long-term paddy-rice cultivation. This decomposition of soil organic matter could also negatively affect the greenhouse gas balance of the paddy rice–maize cropping system. Hence, the large-scale conversion of paddy rice double cropping into a crop rotation including maize in the dry season within a short period of time is a risk for groundwater quality and atmosphere. However, since this increase of leaching losses under the maize − paddy rice rotation declined rapidly in the following years, the results of our study imply that the cropping of maize in the dry season can finally save irrigation water compared to continuous paddy rice cropping in the medium to long term, without inducing unacceptable N losses with drainage. Drainage and leaching losses of N and C are strongly controlled by the development of soil cracks depending on meteorological conditions. The formation of soil cracks especially triggered large percolation water losses during paddy rice cultivation in the dry season.

The assessment of drainage, leaching losses of N and C was made possible by using a novel lysimeter design that compensated for changes in soil volume with swelling and shrinking related to variations in soil water content.

It should be noted that the lysimeters used in our experiment excluded leaching losses through and under bunds, which may contribute significantly to total drainage, and leaching losses of N and DOC. Therefore, the results of our lysimeter experiment should be confirmed in long-term field scale studies, which comprise bunds between several fields. However, since leaching losses through the bunds are relevant for paddy-rice cropping only, long-term water saving under maize at field scale may eventually be even larger than reported here. These long-term field studies are also necessary to evaluate the losses of soil organic matter under a paddy rice–maize rotation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2017.08.021.

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