Agriculture, Ecosystems and Environment 249 (2017) 91–100

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

Yao He[a], Eva Lehndorff[a], Wulf Amelung[a], Reiner Wassmann[b,c], Ma. Carmelita Alberto[b], Georg von Unold[d], Jan Siemens[e,*]

[a] Institute of Crop Science and Resource Conservation (INRES) – Soil Science and Soil Ecology, University of Bonn, Nussallee 13, 53115 Bonn, Germany
[b] Crop and Environmental Sciences Division, International Rice Research Institute, Los Baños, Philippines
[c] Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research (IMK-IFU), Kreuzeckbahnstrasse 19, 82467 Garmisch-Partenkirchen, Germany
[d] METER Group AG, The European head office, Mettlacher Straße 8, 81379 Munich, Germany
[e] Institute of Soil Science and Soil Conservation, iFZ Research Centre for Biosystems, Land Use and Nutrition, Justus Liebig University Giessen, Heinrich-Buff-Ring 26-32, 35329 Giessen, Germany

ARTICLE INFO

Keywords:
Dissolved organic matter
Nitrate
Lysimeter
Hydrology
Water
Tropical rice
Upland crop

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)

* Corresponding author.
E-mail address: jan.siemens@umwelt.uni-giessen.de (J. Siemens).

http://dx.doi.org/10.1016/j.agee.2017.08.021
Received 1 March 2017; Received in revised form 14 August 2017; Accepted 16 August 2017

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.