Agriculture, Ecosystems and Environment 258 (2018) 162–171

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Nitrogen fertilizer fate after introducing maize and upland-rice into continuous paddy rice cropping systems

Irabella Fuhrmann[a,e], Yao He[a], Eva Lehndorff[a], Nicolas Brüggemann[b], Wulf Amelung[a], Reiner Wassmann[c,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] Forschungszentrum Jülich GmbH, Institute for Bio- and Geosciences, Agrosphere (IBG-3), Wilhelm-Johnen-Straße, 52428 Jülich, Germany
[c] Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research Atmospheric Environmental Research (IMK-IFU), Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany
[d] Crop and Environmental Sciences Division, International Rice Research Institute, Los Baños, Philippines
[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:
^{15}N urea
Amino sugars
Fertilizer recovery
Hydragric Anthrosol
Paddy-upland crop rotation

ABSTRACT

Water scarcity and economic incentives favor the introduction of upland crops into permanent paddy rice systems during dry seasons. However, introducing upland crops into permanently flooded cropping systems temporarily changes soil conditions from anaerobic to aerobic, affecting nitrogen (N) dynamics profoundly. We hypothesized that under maize and dry rice, total fertilizer ^{15}N recovery in soil as well as the immobilization of fertilizer ^{15}N in microbial residues is reduced compared with continuous paddy rice cropping. Furthermore, we expected enhanced emissions of fertilizer ^{15}N in form of nitrous oxide (N_2O) under maize and dry rice. To test these hypotheses, we traced the fate of a ^{15}N-urea pulse in a field experiment in the Philippines with three different crop rotations: continuous paddy rice, paddy rice – dry rice, and paddy rice – maize for two years. Indeed, the ^{15}N recovery in the first 5 cm of bulk soil was lowest in the paddy rice – maize rotation (arithmetic mean with standard error: 19.2 ± 1.8% of applied ^{15}N), while twice as much was recovered in the first 5 cm of bulk soil of the continuous paddy rice cropping systems (37.8 ± 2.2% of applied ^{15}N) during the first dry season. The ^{15}N recovery in the plant biomass (shoots and roots) in the continuous paddy rice cropping was 13% larger than in the dry rice plant biomass and 5% larger than in the maize plant biomass during the first dry season. Fertilizer ^{15}N remained longest in paddy rice – maize (mean residence time = 90 ± 25 days) and in continuous paddy rice (mean residence time = 77 ± 30 days), compared with dry rice – paddy rice rotation (mean residence time = 16 ± 5 days). After 2 years, 10% (paddy rice – dry rice, paddy rice – maize) to 23% (continuous paddy rice) of the applied fertilizer ^{15}N were still stored in soil. The largest fraction of this ^{15}N was immobilized by soil microbes, which stored 3–4% of applied ^{15}N in the form of amino sugars as specific cell wall constituents, in all cropping systems. Nevertheless, introducing upland crops into continuous paddy rice systems likely increased N leaching losses and resulted in initial losses of urea- ^{15}N to N_2O, which thus has to be considered in climate smart mitigation strategies.

1. Introduction

Rice (*Oryza sativa* L.) is one of the three most important food crops next to wheat and maize (FAO, 2016a). Worldwide, almost 165 million hectares (FAO, 2017) are used for rice production and 88% of rice plants are grown under flooded conditions (IRRI, 2012). However, water scarcity is an important issue in rice production, even though the irrigation water is predominantly re-used (Steduto et al., 2012). Paddy rice systems are therefore under change. Non-flooded crops, such as dry rice (also upland rice or aerobic rice), wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), are more and more integrated into paddy rice cropping systems in dry seasons (Bouman et al., 2007; Timsina and Connor, 2001). Dry rice needs less water and nutrients compared to flooded rice (Gupta and O'Toole, 1986), but yields are comparably lower than those obtained with paddy rice (Belder et al., 2005). Maize, in turn, has the advantage that it also supplies livestock and poultry feed. In Southeast Asia, particularly the paddy rice − maize cropping system is thus increasingly used for food and fodder production

---

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

https://doi.org/10.1016/j.agee.2018.02.021
Received 28 December 2017; Received in revised form 10 February 2018; Accepted 13 February 2018

(Timsina et al., 2010). The rotation of maize and paddy rice has recently been taken as an example for the "Save and Grow" strategy of the FAO for the sustainable intensification of cereal production (FAO, 2016b). Worldwide, rice and maize both currently contribute to 42.5% of world's food calory supply (FAO, 2016b).

The usage of nitrogen (N) fertilizer in paddy rice production is intensive. In 2004 the rate of N fertilization of rice (226 kg N ha^{-1}, Ma et al., 2008) exceeded N fertilization of maize by 5% and N fertilization of wheat by 12%. However, the N use efficiency is less than half of the efficiency typically found in upland crops (Kögel-Knabner et al., 2010; Olk et al., 1996). With the introduction of maize, there is an additional risk of N losses, particularly due to crack formation in the first years after maize production (He et al., 2017). Yet, the same authors also stated that with prolonged cropping duration, the system adapts and additional N leaching losses caused by maize decrease. However, to our knowledge a full N balance after introducing an upland crop into permanent paddy rice is still lacking.

Cassman et al. (2002) compared several experiments with maize, rice or wheat cultivation and found largest average fertilizer N recoveries for maize (37%), followed by rice (36%) and wheat (32%). In experiments dealing with rice – wheat crop rotations, rice plants used more soil organic N than wheat, for example (Shinde et al., 1985). Other experiments dealing with dry rice found lower fertilizer recoveries in aerobic rice plants and in the soil than in the permanently flooded fields (Belder et al., 2005; Kadiyala et al., 2015). Kadiyala et al. (2015) found larger recoveries in soil of the flooded rice after the first season, so that the following crop (in this case maize) could take up a larger amount of residual fertilizer N, suggesting that the fate of N can be traced beyond one cropping season. Cao and Yin (2015) found a similar pattern in a permanently flooded rice system. In their experiment, the major fraction of applied ^{15}N was also recovered in plant biomass, followed by the recovery in soil (0–20 cm). The rest was either lost via ammonia (NH_3) emissions or unaccounted.

Zhao et al. (2009) found 6% of the applied N in form of NH_3 in rice and 1% in wheat in a rice-wheat crop rotation. Large rates of nitrous oxide (N_2O) emissions were measured for the wheat crop, but also during fallow periods of the paddy rice crop, when aerobic-anaerobic cycles occurred with elevated amounts of soluble nitrate (NO_3^-, Pathak et al., 2002). This amount can be reduced when nitrogen is immobilized by microorganisms (Olk et al., 1996; Pande and Becker, 2003). Part of this microbial N is bound in amino sugars, which are specific markers for the residues of bacteria and fungi (e.g. Amelung et al., 2008; Murugan and Kumar, 2013; Said-Pullicino et al., 2014). Although amino sugar-N represents only a small portion of the microbially bound N, it accounted for up to 3.7% of total N in paddy and non-paddy surface soils (Roth et al., 2011). The fate of amino sugars is influenced by the supply of available C sources and N transformation processes and responds, thus, to changes in soil management and the resulting changes in soil properties (Amelung et al., 2001a; Ding et al., 2011; Lauer et al., 2011). Overall, 26 amino sugars have been recognized in microorganisms, four of them are detectable in soil. Glucosamine (Glu) is primarily a component of the chitin in the fungal cell walls, though it also can be found in some bacteria. Muramic acid (MurA) originates uniquely from bacterial cell wall residues. The origin of galactosamine (Gal) and mannosamine (Man) is less clear. It has been suggested that Gal is derived from bacterial genera, but other evidence suggests that it may also be derived from fungi (Amelung et al., 2008; Glaser et al., 2004; Liang and Balser, 2010). Appuhn and Joergensen (2006) suggested that the concentration of amino sugars may even serve as a proxy for the content of living biomass, using a conversion factor of 9 for fungi and of 45 or higher for bacteria when assuming that fungi and bacteria contain 46% C. However, the response of microbial residues to land-use change will be slower than for living biomass, particularly with an expected mean residence time of amino sugars in the range of a few years (Derrien and Amelung, 2011). Combining ^{15}N-fertilization with compound-specific ^{15}N analysis of these amino sugars may provide a clue to the in-situ turnover and sequestration rate of fertilizer N into the residues of both bacteria and fungi (He et al., 2006; Liang and Balser, 2010).

Analyses of N_2O emission in combination with ^{15}N-fertilization may help to elucidate the overall environmental impact of introducing upland crops into paddy rice systems. Pathak et al. (2002) indicated that NO_3^- served as a substrate for N_2O production and was predominantly produced in soils with changing soil moisture conditions, where denitrification and nitrification processes occur simultaneously. Although the contribution of N_2O emissions to total N loss and thus the reduction of nitrogen use efficiency is comparatively low, these emissions are critical for the greenhouse gas balance of the cropping system.

The objective of our study was to compare the utilization of fertilizer N in three rice dominated cropping systems: double paddy rice (R-Wet), paddy rice – dry rice (R-Dry) and paddy rice − maize (M-Mix) using ^{15}N-labelled urea as fertilizer. We hypothesize that the introduction of maize or dry rice results in:

(i) reduced ^{15}N fertilizer recoveries in bulk soil and plants for maize and dry rice,
(ii) larger immobilization of fertilizer ^{15}N in microbial residues for permanent paddy rice,
(iii) and larger emissions of fertilizer ^{15}N in form of N_2O for maize and dry rice,

compared to double paddy rice.

2. Materials and methods

2.1. Study site and experiment design

The field experiment was conducted at the experimental station of the German Research Foundation (DFG) research unit 1701 ICON at the International Rice Research Institute (IRRI) in Los Baños, Philippines (14° 11′ N, 121° 15′ E). The average long-term temperature in this area is 25.2 °C (1976–2011). In 2012 to 2014, the mean temperature was 27.5 °C. Annual precipitations were 2270 mm, 2350 mm and 1550 mm in the years 2012, 2013, and 2014, respectively, thus varying over the long-term average of 2006 mm per year. Most of the precipitation (67–78%) fell during the wet season (June–November), 22–33% during the dry season (December-May), respectively. Climate data were documented by the climate unit at IRRI. Detailed rainfall and temperature data can be accessed in the Supplementary data (Fig. S1). Soil properties were determined before the experiment started. The soil was developed from fluvial sediments overlying volcanic tuff and classified as Hydragric Anthrosol with clay dominated soil texture (Table S1) according to World Reference Base (IUSS Working Group WRB, 2015). The studied area has been at least 50 years under continuous paddy rice cultivation before the experiment started in 2011.

Three cropping systems were investigated with three replicates each: continuous paddy rice (R-Wet), paddy rice – dry rice (R-Dry), and paddy rice – maize (M-Mix). In separate fields we installed nine PVC rings (Ø 113 cm, 55 cm height) down to 25 cm soil depth (plough pan) to avoid the lateral loss of N to the rest of the field. The upper rim of the PVC ring extended 30 cm above the soil surface to prevent lateral exchange of irrigation water with the surrounding field (Fig. S2). Land preparation, irrigation, groundwater regulation and the drainage in the PVC rings were done manually. Weeds were uprooted and placed on top of the soil inside the ring. According to IRRI crop management routine, our field was fertilized with solophos (18% P) and potash (60% K) before seeding. We applied N in form of urea (46% N). Rice (both paddy rice and dry rice) received a total fertilization of 130 kg N ha^{-1}, in three splits of 30, 50, 50 kg N ha^{-1} (3, 5, 5 g N $ring^{-1}$). Maize was fertilized with 60, 30, 60 kg N ha^{-1} (6, 3, 6 g N $ring^{-1}$). The ^{15}N labelling for the main experiment was conducted as the first N split in the 2012 dry season with ^{15}N-urea (95 atom-%, Campro Scientific GmbH,