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Compensatory mechanisms of litter decomposition under alternating moisture regimes in tropical rice fields

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ABSTRACT

A conversion from permanently flooded rice cropping systems to crop rotations that include non-flooded upland crops is heavily promoted in tropical regions to meet the challenges of sustainable food production while reducing water consumption and trace gas emissions. Shorter periods of flooding and manipulation of fertilizer inputs affect belowground community composition, biomass and functioning. However, there have been no previous studies of how such shifts in rice field management might affect soil biota and decomposition. Our objective was to examine how crop diversification, which demands different moisture regimes and nitrogen inputs, influences belowground invertebrate assemblages and their contribution to the decomposition of crop residues.

We conducted a litterbag experiment in lowland paddy fields at the experimental field sites of the DFG-ICON project (Laguna, the Philippines) that were either continuously flooded, had seasonally alternating wet and dry periods, or were continuously dry. Additionally, subplot treatments within these crop rotations included different N fertilizer management practices. At a total of 36 plots we used litterbags with two different mesh sizes to assess decomposition with and without fauna over a period of 72 days. Furthermore, we sampled soil microfauna and mesofauna in both the wet (rainy) and dry seasons.

Although we found no correlation between faunal abundance and the contribution by invertebrates to rice straw decomposition, we found that soil water content was the decisive factor determining the activity of decomposer invertebrates as well as the composition and abundance of the soil fauna in fields with alternating cropping regimes. The impact of invertebrates on rice straw decomposition was higher under anaerobic than aerobic soil conditions which compensated for reduced microbial decay rates during periods of flooding. In contrast, microbial decomposition rates were higher under aerobic conditions, whereas invertebrates had no apparent effects on the mass loss of rice straw despite their higher abundance in dry fields. Our results demonstrate that invertebrates are essential for the effective decay of rice straw residues under flooded soil conditions, and therefore play an important role in supplying nutrients to flooded rice.

1. Introduction

Flooded rice cultivation with two to three crops per year is the most predominant agricultural land use system in the lowland tropics and subtropics of Asia (Cassman and Pingali, 1995) and provides about 90 % of the global rice supply (FAOSTAT, 2008; USDA, 2007). Currently, the sustainability of producing rice in flooded fields has been questioned in regard to water use efficiency and greenhouse gas emissions (Bouman et al., 2007; Mueller et al., 2012). A range of management strategies have been developed to reduce water consumption and methane emissions from rice-based cropping systems while ensuring sufficient productivity (e.g. Wassmann and Vlek, 2004). One of the most promising approaches

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is the inclusion of non-flooded crops into rice-dominated systems (Bouman et al., 2005; Timsina et al., 2010, 2011). However, crop diversification in rice-based systems also bears the risk of depleting soil nutrients and reducing soil organic matter (Haefele et al., 2013; Witt et al., 2000).

A rich assemblage of organisms inhabits paddy rice soils (Bambaradeniya and Amarasinghe, 2003). These organisms significantly contribute to the decomposition of crop residues and element cycling (Lekha et al., 1989; Schmidt et al., 2015b; Widyastuti, 2002). The belowground community of conventionally managed paddy soils is dominated by aquatic and semi-aquatic oligochaetes and nematodes, whereas microarthropods are generally rare (Watanabe and Roger, 1985). Changes in water management by introducing upland crops together with consequent adjustments in fertilizer use are likely to adversely impact native assemblages of soil animals in rice fields. A reduced contribution by the soil fauna to decomposition processes could also diminish microbial activity and thus the mineralization of both carbon (Setälä et al., 1988) and nitrogen (Huhta et al., 1988). On the other hand, increased niche diversity over time due to crop diversification might stimulate the increase of abundance, richness and functional diversity of belowground fauna (Cancela da Fonseca and Sarkar, 1998) with positive implications for litter decomposition. For example, in continuously flooded fields soil mites and springtails have been shown to play a minor role in the decomposition of organic matter (Widyastuti, 2002), but under aerobic conditions their abundance rapidly increases (Widyastuti, 2002) which might enhance their contribution to the regulation of microflora-mediated decomposition.

Decomposition of soil organic matter is one of the most important ecological processes regulating nutrient cycling and energy flow in the soil (Lekha et al., 1989; Manzoni et al., 2008; Talbot and Treseder, 2011). It is highly interactive and involves a broad spectrum of micro-, meso- and macrofaunal groups (Anderson, 1995; Coleman and Crossley, 1996; Wolters, 1991) that generally have indirect effects on the decay of organic matter, e.g. by increasing the surface area and improving the quality of litter as a substrate for microbial colonization (Heath et al., 1964). Hence, microbial activity and biomass are strongly defined by higher trophic level interactions in soil food webs (Lekha et al., 1989; Singh et al., 2005). In addition, the rate of litter decomposition is triggered by several biotic and abiotic factors such as soil properties (e.g. soil moisture and soil texture; Amato and Ladd, 1992; Clark and Gilmour, 1983; Merckx et al., 1985; Steinberger and Whitford, 1988) and the biochemical composition of the plant residues (e.g. N availability and lignin concentration; Bollen, 1953; García-Palacios et al., 2013; Singh et al., 2005; Tian et al., 1993). Decomposer invertebrates are likely to increase the effectiveness of litter decomposition in flooded rice fields (Schmidt et al., 2015a) where microbial activity is hampered by the high C/N ratios and lignin contents of rice straw as well as the anaerobic conditions of flooded fields (Acharya, 1935; Koegel-Knabner et al., 2010; Schmidt et al., 2015b; Vigil and Kissel, 1991).

Different management practices can have a large impact on the organic C and N balance in the soils of continuous rice cropping and rice-maize rotation systems (Witt et al., 2000). Furthermore, the abundance and composition of soil fauna assemblages are influenced by crop type (Wardle et al., 1999). However, previous studies have not considered how shifts in soil conditions during crop rotations and consequent effects on the composition of soil animal assemblages might affect decomposition and soil nutrient dynamics. Recently, Handa et al. (2014) reported that a reduction in the functional diversity of decomposer organisms slows down the cycling of litter derived C and N across a range of terrestrial and aquatic ecosystems. Furthermore, an increase in plant species richness after the introduction of crop rotations affects the biomass of microbes and soil animals (Wardle et al., 1999) which in turn might alter the rate of nutrient cycling in the soil. A better understanding of soil-dwelling animals and their impact on the dynamics of decomposition processes in rice-based agroecosystems will be essential for evaluating the benefits and risks associated with the introduction of non-flooded crops into these systems, and hence, for developing effective management strategies for the soils of rice producing regions.

The present study was conducted at the experimental field sites of the ICON (*"Introducing Non-Flooded Crops in Rice-Dominated Landscapes: Impact on Carbon, Nitrogen and Water Cycles"*) research group located in Los Baños (the Philippines). We examined how introducing non-flooded upland crops with different fertilization regimes into the cropping cycles of continuously flooded rice fields alters the assemblages of soil animals and the invertebrate-driven decomposition of rice straw. We addressed the following hypotheses:

Compared to non-flooded fields, microbial litter decomposition in flooded rice fields will decrease due to anaerobic soil conditions, which increases the relative importance of decomposer invertebrates.

The conversion from wet to dry conditions during crop rotation alters the structure of soil invertebrate assemblages. We expect macro- and microarthropod groups to be more abundant under aerobic field conditions.

The lack of aquatic invertebrates and their contribution to decomposition processes in soils of non-flooded fields is compensated by a more abundant and active terrestrial mesofauna.

2. Materials and methods

2.1. Study site

Experiments were conducted at the International Rice Research Institute (IRRI) about 66 km south of Manila (Laguna, the Philippines; elevation: approx. 20 m above sea level; coordinates: lat 14.2, lon 121.4 WGS84 decimal degrees). In this region lowland flooded rice is primarily cultivated in two crop cycles per year, one in the dry season (December–May) and one in the wet season (June–November). Our study was carried out during both seasons in 2013. The site had been used for paddy rice cultivation for several decades prior to the establishment of the field experiment by the ICON group.

Average minimum, mean and maximum temperatures during the time of our experiment (2012/12–2013/11) were 24.0, 27.7 and 31.5 °C. The climate is characterized by a high intra-annual variation of precipitation. The average rainfall per month during the dry season (2012/12–2013/05) was 87.4 mm and average monthly rainfall during the wet season (2013/06–2013/11) was 343.0 mm.

The soil is of volcanic origin and clay-dominated. It is classified as Andaqueptic Haplaquoll (USDA classification) with 54.2 % clay, 32.8 % silt and 13 % sand. The bulk density of the topsoil (0–0.1 m) is 1.0 kg dm^{-3}, the average pH is 6.1 and the organic C content is about 1.8 %.

2.2. Study design

Fieldwork was conducted at the experimental site (36 plots; 4 crop rotations × 3 fertilizer treatments × 3 replicates) of the ICON project (*"Introducing Non-Flooded Crops in Rice-Dominated Landscapes: Impact on Carbon, Nitrogen and Water Cycles"*). The 12 core fields (530–549 m^2 each, total area of about 150 × 100 m) are arranged in two rows with six fields in each row (see Fig. 1 for the core field design). The fields were separated by field bunds and encompassed by grass verges (5 m in diameter). Since the dry