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Deeper tillage and root growth in annual rice-upland cropping systems result in improved rice yield and economic profit relative to rice monoculture

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ABSTRACT

Continuous intensive monocultures of rice can lead to subsoil compaction, reduced topsoil quality and decline in rice yield. The objectives of this study were to evaluate the effect of rotating rice with upland crops on properties of an alluvial paddy clay soil, rice yield components, and economic profitability. A field experiment was established in the Vietnamese Mekong Delta for 10 years with a randomized complete block design including four rice based crop rotations and four replications: (i) rice–rice–rice (control, i.e., farmers' practice), (ii) rice–maize–rice, (iii) rice–mung bean–rice, and (iv) rice–mung bean–maize. Rice alternated with upland crops significantly improved physical quality of soil in terms of bulk density, soil porosity, soil aggregate stability, and soil penetration resistance compared to the traditional rice monoculture practice, especially in the 10–20 and 20–30 cm depth layers. As a consequence, also rice rooting depth and root mass density was strongly increased in all three rice upland crop rotations. This resulted in a higher plant height, total number of tillers and panicles, filled grain percentage and a rice yield that was 32–36% higher compared to the control, and farmer's profitability even increased 2.5–2.9 times. The reason for improved rice growth upon deeper root development should be investigated further, with specific attention to micronutrient availability.

1. Introduction

In riverine floodplain areas worldwide, rice monoculture is intensifying towards double or triple annual rice crops. Continuous intensive monocultures of rice can lead to subsoil compaction, reduced topsoil quality and decline in rice yield. Because of long-term submergence, continuous rice growing has been found to yield an adverse impact on soil nitrogen supply (Pulleman et al., 2000; Norman et al., 2003), which can negatively affect agricultural sustainability (Dobermann and Witt, 2000). A few studies employing ^{15}N NMR spectroscopy found prolonged anaerobic decomposition of crop residues to enhance N binding to lignin-derived phenols, which may inhibit its mineralization (Schmidt-Rohr et al., 2004; Olk et al., 2007, 2009).

Soil puddling under saturated conditions with machinery is the standard soil preparation in lowland rice cultivation. After prolonged rice cultivation a 10–50 cm plough layer (or hard pan) is thus formed below the puddle layer, preventing ponding water to drain further downward (Liu et al., 2001). While it limits water losses, subsoil compaction can be a major crop growth constraint in intensively cultivated paddy fields with clay soils being most susceptible (Gay et al., 2009). It limits rooting depth and root exploration (Rosolem et al., 2002), which might result in reduced uptake of water and nutrients (Bingham et al., 2010; Lipiec and Hatano, 2003).

In the Vietnamese Mekong Delta, where this study was conducted, soil quality for sustainable rice production is under considerable pressure, as in similar settings worldwide. Effects of different cropping systems with rotations of rice and upland crops like maize and mung bean on soil properties in the spring–summer season, i.e., the wet season when rice, maize, or mung bean are cultivated, have been previously reported (Linh et al., 2014, 2015) for the Mekong Delta. They showed an improvement of soil bulk density, soil strength, soil porosity, soil organic carbon, $C_{hydrolyzable}$ for cropping system with rotations of rice and mung bean and/or maize grown on temporary beds compared to intensive rice monoculture.

We hypothesize that growing upland crops as maize (*Zea mays* L.) and/or mung bean (*Vigna radiata* (L.) R. Wilczek) instead of rice

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(*Oryza sativa* L.) as in rice monocultures positively affect root growth and yield of rice grown in a subsequent season because of improved soil properties. The objective of this paper was to evaluate the effects of rotating rice with upland crops on soil properties at harvest in the winter–spring season, i.e., the dry rice season, and to investigate how this affects yield components and yield of rice. The combination of a shallow puddle layer and triple annual crop exports bears an explicit risk of nutrient deficiency due to shallow rice rooting, an important parameter most often overlooked. Deeper tillage common in upland crops like maize should loosen topsoil layers and allow for enhanced root growth and availability of nutrients, thus improving rice yield. At the same time, however, breaking up the plough pan of any paddy soil may result in irrigation water and dissolved nutrient losses, with on the opposite a detrimental effect on rice yields. The present study measured a suite of soil physical and chemical traits after completion of a 10 year field experiment in the Vietnamese Mekong Delta with rice monoculture and three rice upland crop rotations. We explicitly determined rice root biomass within depth increments to assess the impact thereupon of upland crop inclusion in paddy rice based rotations. Evidently, economic benefit would be an important criterion for shifting from rice monoculture to new crop rotation systems with upland crops, and therefore net return and benefit–cost ratio was investigated as well.

2. Material and methods

2.1. Site description and field experiment

A field experiment was conducted over a period of ten years at a farmer's field (10°22′51″N, 106°07′03″E, and 2 m above sea level) located in Cai Lay district, Tien Giang province, Mekong Delta, Vietnam. The historical cropping background was rice monoculture for over 30 years prior to establishment of the experiment in 2002. The area is characterized by a tropical monsoon climate with an annual mean temperature of 25–33 °C, and mean precipitation of 1800 mm per year, of which about 90% is concentrated between May and November (Fig. 1). The soil was classified as a Gleyic Fluvisol (FAO, 2014) or Typic Fluvaquent (Soil Survey Staff, 2010).

In 2002 at the onset of the experiment, the soil was slightly acidic (pH 5.5), had a topsoil (0–20 cm) organic carbon content of 21.5 g kg^{-1} and a cation exchange capacity (CEC) of 23–24 cmol kg^{-1}. The USDA soil textural class was clay, with a mean of 2% sand, 32% silt, and 66% clay.

The experimental setup consisted of a randomized complete block design with four treatments and four replicates. Rice (*O. sativa*), the main crop, was rotated with maize (*Zea may* L.) and mung bean (*V. radiata*) in different combinations in a three crops per year system (Fig. 2). Each year, the three cropping periods were November–February with only rice in all treatments, March–June with rice, maize or mung bean and July–October with rice or maize, resulting in four treatments: (i) rice–rice–rice (R–R–R) (control, i.e., the conventional system close to farmers' practice), (ii) rice–maize–rice (R–M–R), (iii) rice–mung bean–rice (R–Mb–R), (iv) rice–mung bean–maize (R–Mb–M). Crop rotations were repeated every year during ten years of experiment. NPK fertilizer (N–P_2O_5–K_2O) rates were 100–45–30, 140–50–30 and 40–30–60 kg ha^{-1} for rice, maize and mung bean, respectively. Fertilizers used for the experiment were urea (46% N), potassium chloride (60% K_2O) and super phosphate (13.5% P_2O_5).

Soil preparation was done 1–3 days before the rice was sown. For rice cropping, this involved chisel tillage (10–15 cm depth) followed by inundation and puddling with the aim of preparing a seedbed of fine aggregates. Before 2000, a heavy four-wheel tractor was used which was replaced by a handheld two-wheel tractor from 2000 onwards. The rice field plots were irrigated when 100–150 mm of standing water dropped below the soil surface throughout the rice cropping season till ten days prior to harvest. For soil preparation under maize and mung bean, temporary beds of 0.2 m height above the field surface and 0.4 m of width were manually prepared with a shovel hoe. This resulted in partly mixing soil from the original puddle layer and the underlying plough pan, creating furrows of about 0.3 m depth. The soil was leveled again after harvest when maize or mung bean cultivation was followed by rice. Prior to each growing season, the respective soil preparation was repeated.

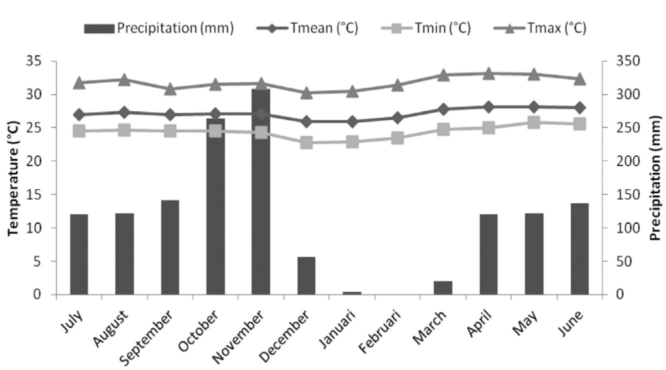

Fig. 1. Rainfall distribution and average temperature at the Cai Lay district experimental field for the year under study (July 2011–June 2012).

2.2. Soil sampling and field measurements

Soil sampling and field measurements took place after rice harvest at the end of the winter–spring cropping season of the tenth experimental year. Undisturbed soil cores were taken with 100 cm^3 rings at three depths from small pits (0–10 cm, 10–20 cm and 20–30 cm) following the procedure described by Dirksen (1999). Disturbed soil samples composed of ten subsamples per plot were taken at three depth intervals (0–10 cm, 10–20 cm and 20–30 cm) using a sampling tube type auger. Soil penetration resistance was measured with a handheld electronic penetrometer (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) directly in the field. This instrument was used to measure resistance of up to 10 MPa pressure to a depth of 80 cm in one centimeter intervals. These measurements were repeated three times in each of the four replicate plots per treatment and values were averaged per plot. Concurrently with soil strength measurements, soil moisture content was determined in 10 cm intervals until 80 cm depth.

At harvest, four subplots of 5 m^2 were harvested per cropping system and yield was standardized to tonnes ha^{-1} of total grain (14% moisture base) and straw dry matter yield. The grain yield relative to that of the R–R–R (control = 100%) treatment was calculated for each crop rotation treatment. The height of rice, thousand grain weight, filled grain, grain per panicle and panicle number were determined from plants harvested from a sample area of 0.5 m^2 per subplot. Maximum rooting depth was determined per subplot by digging out and uprooting a single plant near its base after which the length of the longest root was recorded. Root biomass was determined on soil cores. To this end, a 30 cm deep cylindrical core with 10 cm diameter was pushed into the soil to collect an undisturbed soil sample. These soil samples were separately washed and roots separated using a set of sieves with mesh sizes from 1 to 0.05 mm after they were cut once for 10 cm depth increment starting from the soil surface. Then roots were oven dried at 105 °C and their dry weight recorded.