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Effects of Rotating Rice with Upland Crops and Adding Organic Amendments, and of Related Soil Quality on Rice Yield in the Vietnamese Mekong Delta

Nguyen Van Qui [1,2,*], Le Van Khoa [2], Nguyen Minh Phuong [2], Duong Minh Vien [2], Tran Van Dung [2], Tran Ba Linh [2], Tran Huynh Khanh [2], Bui Trieu Thuong [2], Vo Thi Thu Tran [2], Nguyen Khoi Nghia [2], Tran Minh Tien [2], Emmanuel Abatih [3], Ann Verdoodt [1], Steven Sleutel [1] and Wim Cornelis [1,*]

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Abstract: In the Vietnamese Mekong delta, soil quality and crop yield are steadily declining under rice monocultures with three crops per year. The objective of this study was to evaluate the medium-term effects of rotating rice with upland crops and adding organic amendments on rice yield and relate it to soil quality. A field trial with split-plot design including two factors and three replicates was carried out from 2017 to 2020, over the course of nine consecutive cropping seasons. Crop rotations and organic amendments were applied as main-plot and subplot factors, respectively. The rotations were: 1) rice–rice–rice (R–R–R), 2) soybean–rice–rice (So–R–R), and 3) sesame–rice–rice (Se–R–R), while organic amendment treatments included: i) no amendment (NO-AM); ii) compost of rice straw and cow manure (RS+CM), and iii) sugarcane compost (SGC); the composts were applied at a rate of 2.0 t ha^{-1}. The rotation cycle started with the so-called spring–summer (SS), followed by summer–autumn (SA) and ended with the winter–spring (WS) season. Rice yield significantly ($P < 0.05$) increased by organic amendments after nine growing seasons (2019–2020 WS), with an increment of 5.1% for RS+CM (7.07 ton/ha) and 6.1% for SGC (7.14 ton/ha). Contrary to our expectation, rotations with upland crops did not significantly increase rice yield. Rice yield significantly and positively correlated with an integrated soil quality index SQI ($r = 0.86$) for the topsoil (0–15 cm), but not for the subsoil (15–30 cm). The increased availability of soil nutrients (Si and marginally also P) and improved soil physical properties probably induced by organic amendments, along with other soil properties under study, cumulatively attributed to enhanced rice yield. Use of a SQI involving several soil quality indicators enables to overall quantify the importance of soil fertility for rice yield versus other factors and it provides an effective means of quantifying the integrated effect of improved management. Moreover, integrating a wide range of soil quality indicators in a SQI ensures its applicability across diverse settings, including different crop rotations and various soil types.

Keywords: crop rotation; organic amendment; rice yield; soil quality index; Mekong delta

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1. Introduction

Rice is a staple food in the Vietnamese Mekong delta - the third largest delta of the world [4]. The delta contributes to approximately 50% of the national rice production and is the largest rice exporting region of the country [3]. Irrigated triple rice is the dominant farming system [5,6] and resulted from the intensification of rice production to meet domestic consumption and export demand [3,25]. However, the sustainability of this system has been threatened.

Over the past decades, rice yield decline in the Mekong delta has been reported [72], and this could be due to soil quality deterioration [50,73,75,76,123]. Elsewhere yield of long-term rice monoculture systems was likewise found to decline [18,40,41], or stagnate [44,97]. Various reasons have been given to explain these declining or stagnating yield trends, and they were mainly soil related. Firstly, nutrient deficiency resulting from cumulative imbalanced use of fertilizer have been identified as reasons for rice yield decline, including macro-nutrients such as P, S and micro-nutrients such as Zn and Cu [40]. Likewise, Hoa et al. [50] reported improper use of fertilizers to result in a negative balance of K in the Mekong delta. On top, burning residues or removal of rice straw after harvest for various purposes, such as mushroom cultivation and for cattle fodder, are popular practices in the delta [113] that contribute to reduced nutrient recycling [9,124]. Provision of nitrogen (N) to rice in paddy fields should be regarded somewhat separately from other nutrients as it is often sufficiently or even oversupplied by farmers, but may still be deficient. A low nitrogen use efficiency (NUE) has been frequently reported for continuous lowland rice cropping systems despite the overuse of N fertilizers [20,23,45]. Cassman et al. [18] suggested that the declining yield trends in long-term triple rice cultivation systems may mainly be attributed to a particularly low N supplying capacity of the soils in these systems. Similar problems for the intensive rice systems have been recognized in the Mekong delta [50,109].

In addition to nutrient shortages, several other negative consequences of monoculture rice on soil quality have been documented by Fragria et al. [37], including iron and aluminum toxicity. On the other hand, soil structural degradation in the form of soil compaction caused by intensive agricultural production hampers root access to deeper nutrients therefore contributing to their deficiency [76].

In recent years, efforts have been made to improve or sustain soil health and rice yield, such as by the introduction of crop rotations and use of organic amendments. Crop rotations are applied and their benefit over monocultures have been widely reported in different agroecological areas [1,8,29]. For lowland rice production in particular, the inclusion of upland crops into the rotation could substantially alter soil into a more beneficial environment for the subsequent crop [12,29,80,95,122]. Variation in crop types may not only result in improved chemical, physical and biological soil properties, and ultimately in improved crop yield, and reduced greenhouse gas emissions [8,14,122], it can also bring about economic efficiency, compared to monocropping, by reduced water use and use of agrochemicals [72,95]. Positive effects of crop rotation on soil fertility may include increased total soil N and enhanced microbial activity [21,73,80], although effects are largely dependent on the agroecological area. Physically, crop rotations help improve aggregate stability and water holding capacity, decrease bulk density and reduce soil compaction [80], and such improvements have been observed for the Mekong delta as well with alongside beneficial effects on rice yield [72,74—76]. A farm household survey by Linh et al. [72] among 109 farmers suggested that crop rotations increased on-farm rice yield by 6% to 9%, depending on rotation sequence and cropping season.

Use of organic amendments has been found to be an effective practice to improve soil fertility and crop yields since these replenish soil organic matter and essential nutrients for plants [34,53,68,81,103]. In the Mekong delta in particular, studies of Watanabe et al. [118] and Watanabe et al. [119] revealed that addition of rice straw compost could improve rice yield and soil physical properties, such as penetration resistance.

Although including upland crops and organic amendments have been widely realized as alternative cropping practices to rice monoculture, these systems also can present constraints in terms of sustainability. For instance, Witt et al. [121] reported that the sequestration of soil N and C declined when rice was rotated with upland crops such as maize. This was due to a higher rate of mineralization of C under crop rotation conditions than under continuous rice cropping conditions. Linh et al. [72] reported that crop rotation significantly decreased SOC content of the topsoil (0–10 cm) as compared to the continuous rice cropping system in the Mekong delta. According to Cass et al. [17], long-term (21 years) rotation of rice with soybean resulted in a significant increase in soil bulk density and soil strength, while air-filled porosity was found to be significantly decreased. Meanwhile, Haynes and Naidu [48] reported that organic amendments at high rates in the long term might result in some detrimental effects on soil structure caused by excessive accumulation of monovalent cations such as Na^+ and K^+. Likewise, sequestration of C brought forth by use of organic amendments does not always result in improved N availability, as for instance Cassman et al. [19] found N supply to stagnate in locations where soil organic carbon (SOC) increased. Overall, rice cropping systems that include upland crops and use of organic amendments have shown beneficial effects on rice production as a result of changes in soil quality, but its effects in terms of sustainability remain questionable.

A new field experiment was thus set up to assess the potential of these cropping systems in the Vietnamese Mekong delta, by evaluating the effects of the combined application of crop rotations and organic amendments on rice yield, while using a recommended inorganic fertilizer rate and a moderate dose of organic fertilizers. The specific objectives of this paper were to (i) test whether the introduction of one upland crop season in a triple rice rotation and the application of organic soil amendments could beneficially affect rice growth, and (ii) if so, to test whether yield increases could be linked to improved soil quality. As upland crops, soybean and sesame were tested, as they are economically valuable for and acceptable by Mekong delta farmers. Inclusion of both crops has, moreover, been shown to potentially improve soil quality in previous studies [16,120]. As soil amendments, sugarcane compost and rice-straw mixed with cattle manure as both are relatively readily available to local farmers. Sugarcane is widely grown in the Mekong Delta and a compost made of it is commercially available at the local market. Rice straw with cattle manure is a by-product of farmers' households that can be easily composted can be made on-farm [88]. We hypothesize that already in the short term, after three years or nine growing seasons, the application of soil amendments and the introduction of one upland crop tends to positively affect rice growth, and that this relates to improved soil quality.

2. Materials and Methods

2.1. Description of the Study Site

The field experiment was set up in the My Loi hamlet, Thien My commune, Tra On district, Vinh Long province (9°57′13.6″ N, 105°55′58.6″ E), in the Vietnamese Mekong delta. The concerned field had been under rice for 40 years before initiation of the experiment in 2017. The area has a tropical monsoon climate with two distinct dry and rainy seasons. The dry season lasts from late October to May, while the rainy season lasts from June till late October. During the complete experimental period, the average annual precipitation was 1345 mm, and the monthly average air humidity, air temperature, and solar radiation were 87.9%, 27.1 °C, and 16.2 MJ m^{-2}, respectively. Monthly weather data, from January 2017 to January 2020, measured on the spot with a WS-GP2 automatic weather station (Delta-T Devices Ltd.) are shown in Figure S1 (Supplementary materials).

The soil in the experimental field is classified as Rhodi-Gleyic Luvisol [58], and is characterized by its high clay content (> 45%) with silty clay texture [108] and it is strongly acidic (pH_{KCl} < 3.0 in the puddle layer). The plow layer had a low CEC (< 14.0 meq(+) 100 g^{-1}) [66] in spite of its elevated organic matter content (55 g kg^{-1}), which however was much very low in the subsoil layers (about 6 g kg^{-1}) [83]. Background values of the soil properties by horizon, measured to a depth of 180 cm before starting the field experiment, are shown in Table.1. The analysis methods are presented in section 2.3.

Table 1. Physico-chemical characteristics of the soil profile before the commencement of the field experiment.

Soil properties	Depth interval			
	0–15 cm	15–45 cm	45–100 cm	100–180 cm
pH_{H2O} (1:2.5)	4.63	5.71	5.22	5.80
pH_{KCl} (1:2.5)	3.0	4.23	4.21	4.03
H+ (meq 100 g^{-1})	0.24	0.01	0.01	0.02
K+ (meq 100 g^{-1})	0.23	0.25	0.32	0.47
Na+ (meq 100 g^{-1})	1.17	1.10	1.22	1.87
Ca^{2+} (meq 100 g^{-1})	7.46	9.06	8.46	6.80
Mg^{2+} (meq 100 g^{-1})	3.83	6.21	6.86	7.66
CEC (meq 100 g^{-1})	12.93	16.63	16.87	16.82
Organic matter (g kg^{-1})	55.2	6.0	6.0	9.4
Sand (g kg^{-1})	14	9	11	11
Silt (g kg^{-1})	535	484	457	453
Clay (g kg^{-1})	451	507	532	536
Texture	Silty clay	Silty clay	Silty clay	Silty clay
Bulk density (g cm^{-3})	1.04	1.43	1.36	1.27

2.2. Treatments and Experimental Design

In this study, a 3-year field trial was carried out from 2017 to 2020, spanning nine growing seasons (Figure 1). The trial was laid out in a split-plot design including two factors, with crop rotations and organic amendments as main-plot and subplot factors, respectively. The crop rotations were: 1) rice–rice–rice (R–R–R); 2) sesame–rice–rice (Se–R–R); and 3) soybean–rice–rice (So–R–R). The organic amendment treatments included: i) no amendment (NO-AM); ii) compost of rice straw and cow manure (RS+CM); and iii) sugarcane compost (SGC) – a commercial organic product. The treatments were replicated three times, resulting in a total of 27 experimental plots (Figure 1). The rotation cycle started with the so-called spring–summer season (SS, February–May), followed by the summer–autumn season (SA, June–September) and ended with the winter–spring season (WS, October–January). For the crop rotations, sesame (*Sesamum indicum* L.) and soybean (*Glycine max* L.) were grown in the SS season, followed by two rice crops (*Oryza sativa* L.) in the SA and WS seasons. The main plots of 17.5 m x 5.5 m (96.25 m^2) were separated by bunds of 60 cm x 40 cm (width x height). Subplots of 5.5 m x 5.5 m (30.25 m^2) were separated by bunds of 40 cm x 30 cm. Plastic sheets were inserted to a depth of 40 cm along the bunds to prevent lateral movement of water between adjacent plots.

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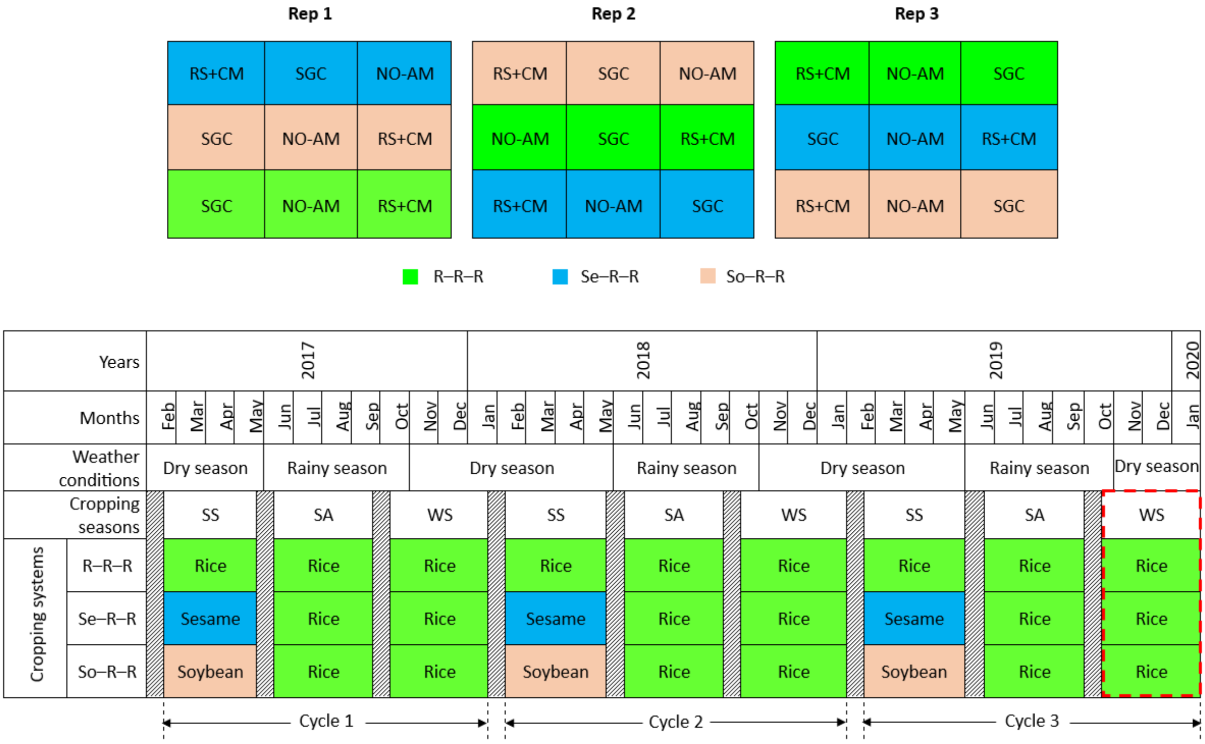

Figure 1. Illustration of the field layout (upper part) and cropping schedule (lower part) during a 3-year experiment at Tra On district, Vinh Long province, Mekong delta. R–R–R, Se–R–R, and Se–R–R refer to rice–rice–rice, sesame–rice–rice, and soybean–rice–rice, respectively. NO-AM, RS+CM, and SGC refer to no organic amendments, rice straw + cow manure compost, and sugarcane compost, respectively. SS, SA, and WS refer to spring–summer, summer–autumn, and winter–spring seasons, respectively. The diagonal parts indicate the fallow period between cropping seasons. The dashed rectangle indicates the season analyzed in this study.

For the rice crop, land preparation involved turning up the topsoil layer (0–15 cm) and breaking up the soil clods with a hoe. Next, puddling was performed under wet conditions to create a seedbed. Just before sowing, field water was drained, and the soil was levelled with a banana trunk. Pregerminated seeds were sown by broadcasting at a rate of 200 kg ha^{-1}, using a short-duration rice variety (IR50404) of 85–90 days. The upland crops, sesame (variety Me Den, 75–80 days) and soybean (variety MTD-748, 85–95 days) were sown in rows at a depth of about 4.0 cm and a planting density of 333.333 plants ha^{-1} (20 cm x 30 cm spacing). No land preparation was performed in the upland crops. After rice and upland crops were harvested, stubbles and plant residues were manually removed from the field.

Compost was applied at a rate of 2.0 t ha^{-1} crop^{-1}. Chemical fertilizers were applied to rice, sesame, and soybean at rates of 100/80N-20P-25K, 60N-26P-37K, and 30N-26P-25K kg ha^{-1}, respectively. For rice, N was applied at a rate of 100 kg ha^{-1} in winter-spring, while a lower rate (80 kg ha^{-1}) was applied in spring–summer and summer–autumn. N, P, and K were applied as urea (46%N), superphosphate (16% P_2O_5), and potassium chloride (60% K_2O), respectively. Compost and P fertilizer were applied immediately before sowing of rice, sesame, and soybean. For rice, N fertilizer was split into three doses and 20% was applied 7–10 days after sowing (DAS), 40% at 20–25 DAS, and 40% at 40–45 DAS. K fertilizer was split into two equal doses and applied at 20–25 DAS and 40–45 DAS. For sesame and soybean, N and K fertilizer were split into two equal doses, applied at 15–20 DAS and 30–35 DAS.

Rice plots were flooded over almost the entire cropping season, with field water being drained ~10 days before harvest. The water level was maintained at 1 to 5 cm above surface. Soybean and sesame plots were irrigated periodically, so that the soil was under moist conditions and the irrigation amount varied with the plant's age. Weeds were removed manually, while pests and diseases were controlled by pesticides when necessary.

2.3. Sampling and Analysis of Compost and Soil during the Experiment

2.3.1. Compost Analysis

Chemical compost properties, including pH, EC, organic matter (OM), total N, P, K, Ca and Mg (Table 2) were determined before each application in case of compost of rice straw and cow manure (RS+CM), while sugarcane compost (SGC), a commercial product, was only analyzed once.

Table 2. Chemical properties of rice straw + cow manure (RS+CM) and sugarcane (SGC) composts used in the field experiment (2017–2020).

Parameters	RS+CM [l]	SGC
Organic matter (g kg^{-1}) [a]	546	307
pH_{H2O} (1:2.5) [b]	8.0	5.0
EC_{H2O} (1:2.5) (mS cm^{-1}) [c]	3.1	–
N (g kg^{-1}) [d]	24.1	22.9
P (g kg^{-1}) [e]	10.0	15.6
K (g kg^{-1}) [f]	23.9	18.2
Ca (g kg^{-1}) [g]	17.5	76.1
Mg (g kg^{-1}) [h]	12.1	0.8
C:N ratio [k]	11.8	6.7

[a] Walkley and Black [116]; [b & c] 1:2.5 ratio soil:water extracts, measured with a glass electrode pH meter (model HI 8314) and EC meter (model Schott Lab 960), respectively; [d] Kjeldahl apparatus [52]; [e–h] acidic digestion [115]: [e] determined with a spectrophotometer (Shimazu UV-1800), [f–h] determined with an atomic absorption spectrometer (Thermo Scientific, iCE 3000 Series); [k] the C-content, estimated as 50% of the OM content [96]; [l] averages from nine cropping seasons.

2.3.2. Soil Sampling and Analysis

Soil sampling was done in the 2019–2020 WS, i.e., after nine cropping seasons. After the harvest, both undisturbed and disturbed soil samples were taken within two depth intervals (0–15 cm, 15–30 cm) to determine physical and chemical properties. The undisturbed soil cores were taken in standard sharpened steel 100-cm^3 cylinders with a dedicated auger in three replicates per plot, while the disturbed samples were collected from a mixture of three replicates per plot.

Disturbed soil samples were firstly air-dried, ground and passed through a 2-mm sieve. The soil particle size distribution (sand, silt, and clay content) was analyzed on the disturbed samples by the pipette-sieve method [42] and soil texture class was then determined based on the USDA texture triangle [108].

Bulk density (ρ_b) was determined as dry soil mass per bulk volume of soil core [126], with dry mass being obtained at 105 °C for 24 hours. Particle density (ρ_p) was determined as dry soil mass per volume of soil particles using the pycnometer apparatus [11]. Then, porosity (ϕ) was determined from bulk density and particle density [98].

Saturated hydraulic conductivity (K_S) was measured on pre-saturated intact soil cores with a KSAT meter (METER Group, USA) in falling head mode, based on Darcy's law [108]. The SWRC was determined with a HYPROP system (METER Group, USA) using pre-saturated soil cores and METER Group ring adapter [91]. The measured data points were fitted with the PDI-variant of the unconstrained van Genuchten model [55,92]. Volumetric water content at field capacity (–10 kPa) [63] and permanent wilting point (–1500 kPa) were extracted from the SWRC. Plant available water capacity (PAWC) was determined as the amount of water held between field capacity and permanent wilting point [98,99], air capacity (AC) as the pore volume corresponding to the volumetric water content between saturation and field capacity [98], and relative water capacity (RWC) as the ratio of field capacity to saturation water content [99]. The pore size distribution was determined according to the classification by Brewer [13]. Pores with equivalent diameter > 75 μm were classified as macropores, with diameter of 30–75 μm as mesopores, and with diameter of 5–30 μm as micropores. Macro-, meso-, microporosity were then determined from the water contents at matric potentials between 0 and –4 kPa, –4 and –10 kPa, –10 and –60 kPa, respectively, based on the capillary equation [99].

Soil penetration resistance (PR) was measured to a depth of 80 cm with 1.0-cm depth intervals using a hand-held electronic penetrologger (Royal Eijkelkamp). A cone of 30°-top angle and 2.0 cm^2-base area was used. Measurements were replicated five times per plot. The measured data were then averaged for two 15-cm depth intervals to a depth of 30 cm. At the measurement of penetration resistance, soil moisture was determined at 10-cm depth intervals to a depth of 80 cm to assure that the PR was measured near field capacity conditions. The percentage of water stable aggregates (WSA) was measured by wet sieving apparatus using a single sieve (250 μm) (Royal Eijkelkamp) according to Kemper and Rosenau [62].

Soil pH was determined on soil:distilled water and 1M KCl suspensions (1:2.5 ratio). Electric conductivity was determined on a saturated paste extract (ECe) with distilled water. pH and EC were measured with pH and EC meters, respectively. Soil organic matter (OM) content was obtained by the Walley-Black method [116]. Soil cation contents in exchangeable form (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were measured by the $BaCl_2$-compulsive exchange method [110], and the extracts were analyzed by an atomic absorption spectrometer (Thermo Scientific, iCE 3000 Series). The content of H^+ on the exchange complex was estimated from the difference between the total acidity (pH_{KCl}) and actual acidity (pH_{H2O}). The cation exchange capacity (CEC) was then estimated as the sum of all measured exchangeable cations. For the samples taken after the harvest, total C and total N were measured by a Leco CN analyser. Since the soil was acidic with pH_{H20} values ranging from 5.0 to 6.8 and free of inorganic carbonates, total C was assumed to be equal to total OC (TOC). Available P and exchangeable cations (K, Ca, Mg, Fe, Mn, Cu, Zn, and Si) were extracted with NH_4-Acetate EDTA (pH 4.65) [27] and measured with an ICP-OES Spectrometer (Thermo Scientific, iCAP 6000 Series).

2.3.3. Grain Yield, Above-Ground Biomass, and Yield Components

Final rice grain yield and above-ground biomass were determined from a 5-m^2 area in the center of the plots. The rice plants were harvested, and grains were separated manually. The grains and straw were weighed, and sub-samples (100 g) were taken. The sub-samples were oven-dried at 70°C for 48 hours to determine moisture content. The grain yield was calculated based on a standard moisture content of 14%. The total above-ground biomass was calculated as the sum of the dry weights of grain and straw.

To determine the yield components of rice, plants were collected from an area of 0.25 m^2 with two replicates per plot. The samples were then treated to determine yield components including panicle number, total grain number, filled and unfilled grain number, 1000-grain weight, and filled grain percentage. The 1000-grain weight is reported at a moisture content of 14%, which was determined using a grain moisture meter (GMK-303).

2.3.4. Soil Quality Index

A soil quality index (SQI) was established using the above 23 soil properties, measured at both sampling depths, according to the procedure outlined by Andrews et al. [2]. Saturated hydraulic conductivity Ks was not included in the index given the high variation in the data, which could be attributed to the limited number of replicated within-plot samples in our study. We used the entire dataset to derive a SQI as this is suggested to be the better approach [69] compared with using a minimum data set derived from statistical techniques such as principal component analysis. Also, Vasu et al. [114] reported that an SQI based on expert opinion showed a better correlation with crop yield than one derived from an unsupervised variable selection and weighing method. Next, the soil quality indicator values were transformed to unitless scores and integrated into an index. For scoring the soil quality indicators, three scoring functions were applied: "more is better", "less is better", or "optimum" with reference to maximizing rice yield. "More is better" is applied to soil quality indicators which are considered "good" when their value increases (e.g., available K). Conversely, "less is better" is applied to soil quality indicators that are considered "bad" when their value increases (e.g., penetration resistance). "Optimum" is assigned to those considered "best" at a certain value or range (e.g., pH), beyond which "more is better" or "less is better" is applied.

A sigmoid non-linear function was applied to transform soil quality indicator values into a unitless soil quality indicator score [7,106,128] S, ranging from 0 to 1:

$$S = \frac{a}{\left(1 + \left(\frac{x}{x_0}\right)^b\right)}$$

where, a is the maximum score (= 1.0); x is soil quality indicator value, x_0 is the mean value of the soil quality indicator, as observed in the collected dataset; and b is the slope which holds –2.5 for "more is better" and +2.5 for "less is better" [7]. The functions of the soil indicators are shown in Table S1 (Supplementary materials).

The scores were then integrated into a non-weighted additive SQI [7,26]:

$$SQI = \sum_{i=1}^{n} S_i/n$$

where, S_i is the indicator score; n is the number of soil quality indicators integrated into SQI. A preliminary study using our data and various transformation functions showed that this non-weighted additive SQI combined with a sigmoid non-linear transformation showed the strongest correlation to rice yield and was retained as the best-suited approach.

2.4. Statistical Analysis

Statistical analyses of the data were performed using RStudio software (version 2022.12.0). The splitplot function from the Doebioresearch package (Analysis of Design of Experiments for Biological Research) [94] was used to perform analysis of variance (ANOVA). In case of significant treatment effects, an LSD test was used to compare treatment means at a significance level of 5%. Pearson's correlation coefficients were calculated between rice yield and soil properties, as well as rice yield and soil quality index (SQI).

3. Results

3.1. Yield Components

Yield components of rice (Figure 2) displayed some variation after the nine growing seasons, covering three rotational cycles, with panicle number 515–603 panicles/m^2, total grain number 54.7–63.4 grains/panicle, filled grain number 48.2–55.7 grains/panicle, unfilled grain number 6.0–7.7 grains/panicle and filled grain percentage 88.1–90.7%. However, neither the factors crop rotation nor organic amendments alone ($P > 0.05$) affected any of these yield components, except for a marginal ($P = 0.096$) effect of organic amendments on the filled grain number. Although insignificant, inclusion of an upland crop in the rotation tended to increase panicle number/m^2 (4.7–7.0%), total grain number/panicle (0.9–5.1%), and filled grain number/panicle (0.8–4.2%) as compared to the rice monoculture cropping system. Likewise, use of organic amendments tended to increase total grain number (4.1–6.7%) and filled grain number (4.1–8.3%), but only a marginal ($P < 0.1$) increase in filled grain number was observed with the addition of SGC over the no amendment treatment.

Combined inclusion of upland crops in the rotation and organic amendments did ($P < 0.001$) affect the 1000-grain weight of rice, even though differences between treatments were small. Moreover, use of organic amendments likewise did, across the cropping systems, significantly ($P = 0.022$) affect the 1000-grain weight (SGC 28.1 and RS+CM 27.9 g vs. 27.8 g of 1000 grains), while introduction of upland crops in the rotations did not (Figure 2). The 1000-grain weight was highest

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under Se–R–R and NO-AM (28.3 g), followed by Se–R–R and SGC (28.1 g), while lowest under R–R–R and NO-AM (27.6 g).

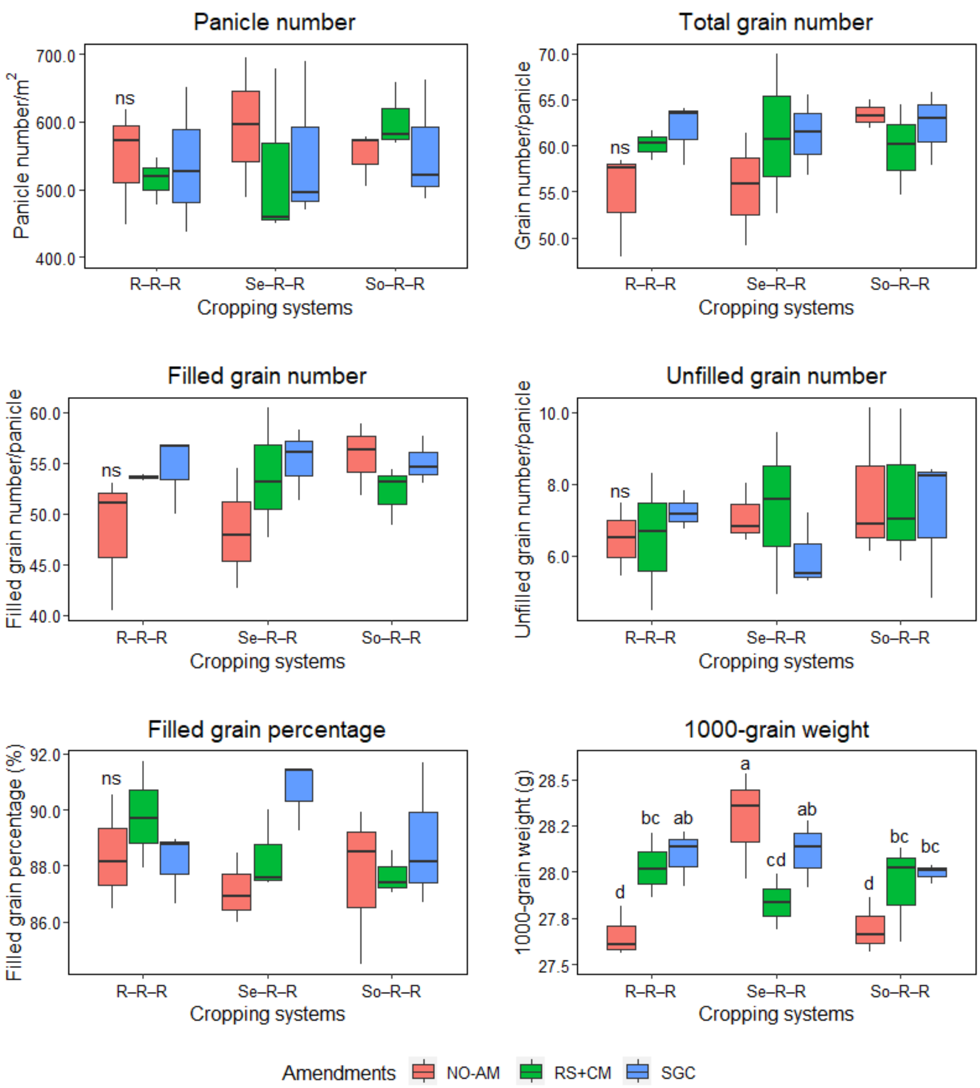

Figure 2. Yield components of rice under different crop rotation x organic amendment treatment combinations after nine growing seasons, i.e. in the 2019–2020 WS season. Treatment means with the same letter are not different at a significance level of 0.05 according to ANOVA and the LSD post-hoc test; ns: non-significant. R–R–R, Se–R–R, and So–R–R refer to rice–rice–rice, sesame–rice–rice, and soybean–rice–rice, respectively; NO-AM, RS+CM, and SGC refer to no amendment, rice straw + cow manure compost, and sugarcane compost, respectively.

3.2. Grain Yield and Above-Ground Biomass

Rice grain yield ranged from 6.55 to 7.30 t ha^{-1}, with the highest yield observed for Se–R–R combined with SGC and the lowest from R–R–R without any amendment (NO-AM) (Table 3). Use of organic amendments did ($P < 0.05$) raise grain yield by 5–6% with 7.07 t ha^{-1} for RS+CM and 7.14 t ha^{-1} for SGC, which was significantly higher than 6.73 t ha^{-1} in case no amendments were applied. Averaged across amendment treatments, the rotations tended to have higher rice yield than the R–R–R monoculture, with the average values in the order of Se–R–R (7.01 t ha^{-1}), So–R–R (6.99 t ha^{-1}), compared to 6.93 t ha^{-1} in R–R–R. Rotations of rice with sesame and soybean therefore increased average rice yield by 0.8–1.1% as compared to the R–R–R monoculture, respectively (Table 3), but these differences were not significant.

Above-ground biomass dry matter ranged from 10.4 (R–R–R without amendment) to 12.38 t ha^{-1} (Se–R–R plus SGC) (Table 3). As for rice yield, crop rotation alone or in interaction with use of organic amendments did not significantly ($P > 0.05$) affect the above-ground biomass, while organic amendments did. Application of SGC significantly ($P < 0.05$) increased the above-ground biomass by 5.6% compared to the NO-AM treatment (Table 3).

Table 3. Rice yield and above-ground biomass after nine growing seasons (three rotation cycles; 2019–2020 WS season).

Cropping system	Amendment	Grain yield (t ha^{-1})	Above-ground biomass (t ha^{-1})
R–R–R	NO-AM	6.55 ± 0.11	10.40 ± 0.35
	RS+CM	7.25 ± 0.04	11.48 ± 0.18
	SGC	7.00 ± 0.26	11.51 ± 0.42
Se–R–R	NO-AM	6.86 ± 0.15	11.71 ± 0.82
	RS+CM	6.87 ± 0.93	11.33 ± 1.54
	SGC	7.30 ± 0.46	12.38 ± 1.15
So–R–R	NO-AM	6.77 ± 0.40	11.65 ± 0.11
	RS+CM	7.08 ± 0.14	11.50 ± 0.31
	SGC	7.11 ± 0.41	11.76 ± 0.46
Cropping system			
R–R–R		6.93	11.13
Se–R–R		7.01	11.81
So–R–R		6.99	11.64
Amendment			
NO-AM		6.73 b	11.25 b
RS+CM		7.07 a	11.44 ab
SGC		7.14 a	11.88 a
$LSD_{0.05}$			
Cropping system		ns	ns
Amendment		0.29*	0.49*
Cropping system x Amendment		ns	ns

* indicates significance at $P < 0.05$; ns: non-significant. Means followed by a common letter are not significantly different at 5% level (LSD test). The figures following ± signs are standard deviation (n = 3). R–R–R, Se–R–R, and So–R–R refer to rice–rice–rice, sesame–rice–rice, and soybean–rice–rice, respectively; NO-AM, RS+CM, and SGC refer to no amendment, rice straw + cow manure compost, and sugarcane compost, respectively.

3.3. Yield vs. Soil Properties

Rice yield correlated ($P < 0.05$) negatively with the 0–15 cm soil bulk density and penetration resistance, and positively with porosity, air capacity, macroporosity, mesoporosity, and microporosity (Figure 3). Additionally, rice yield was found to marginally ($P < 0.1$) positive and negative correlate with the plant available water capacity and EC, respectively. Regarding soil chemical properties, rice yield marginally ($P < 0.1$) and positively correlated with available P content and significantly ($P < 0.05$) and positively with Mn and Si contents (Figure 3). Similar relations were not found between rice yield and properties of the 15–30 cm depth layer.

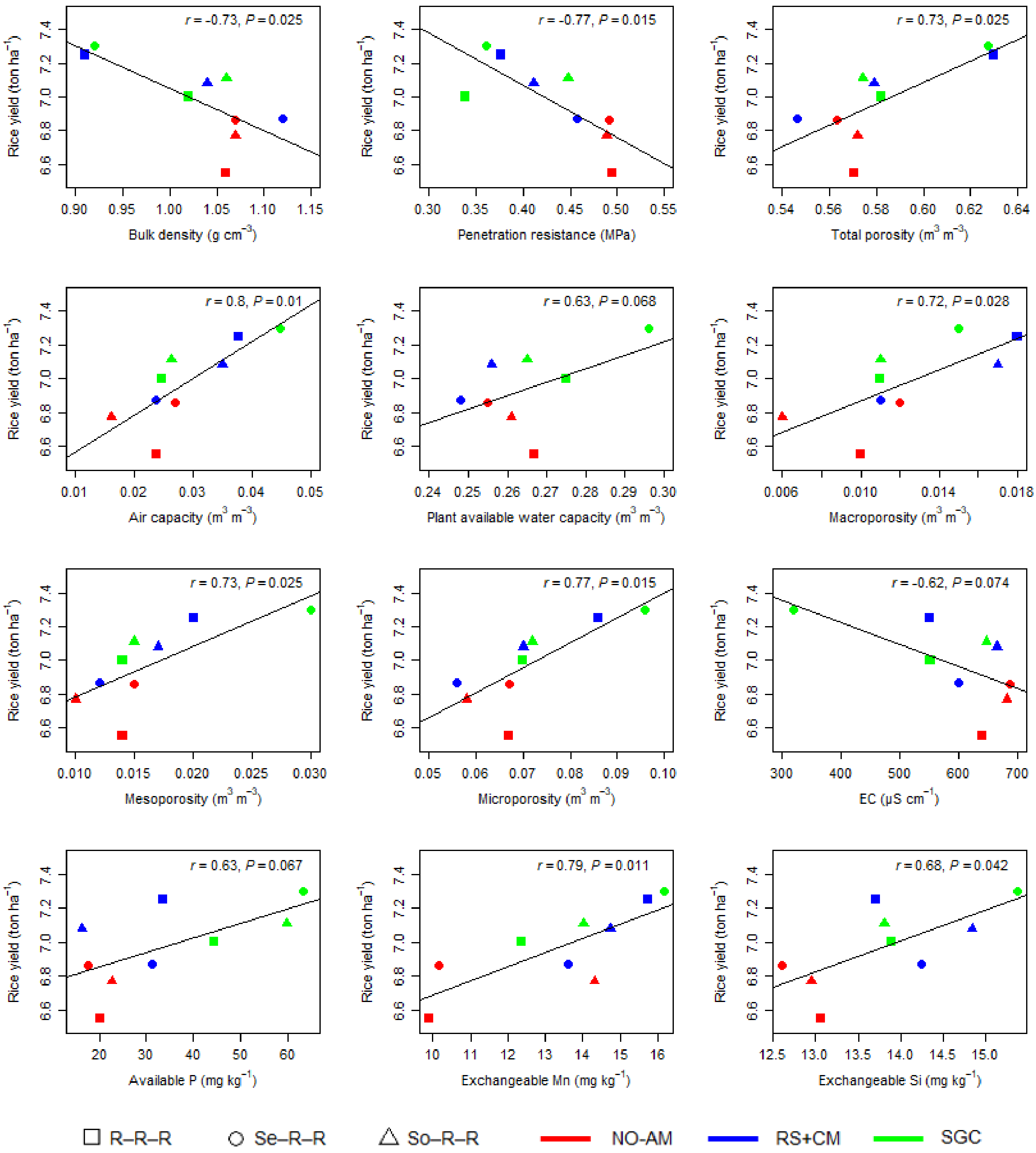

Figure 3. Rice yield related to soil physical and chemical indicators (0–15 cm) after nine growing seasons (three rotation cycles; 2019–2020 WS season) (n = 9). R–R–R, Se–R–R, and So–R–R refer to rice–rice–rice, sesame–rice–rice, and soybean–rice–rice, respectively. NO-AM, RS+CM, and SGC refer to no amendment, rice straw + cow manure compost, and sugarcane compost, respectively. *P* is the significance level of the linear regression and *r* the correlation coefficient between the shown variables.

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3.4. Rice Yield vs. SQI

The relationship between rice yield after nine growing seasons and SQI (three rotation cycles) is presented in Figure 4. Rice yield was significantly ($P < 0.01$) and positively related with SQI of the topsoil (0–15 cm) ($r = 0.86$). No such relation existed for the subsoil (15–30 cm).

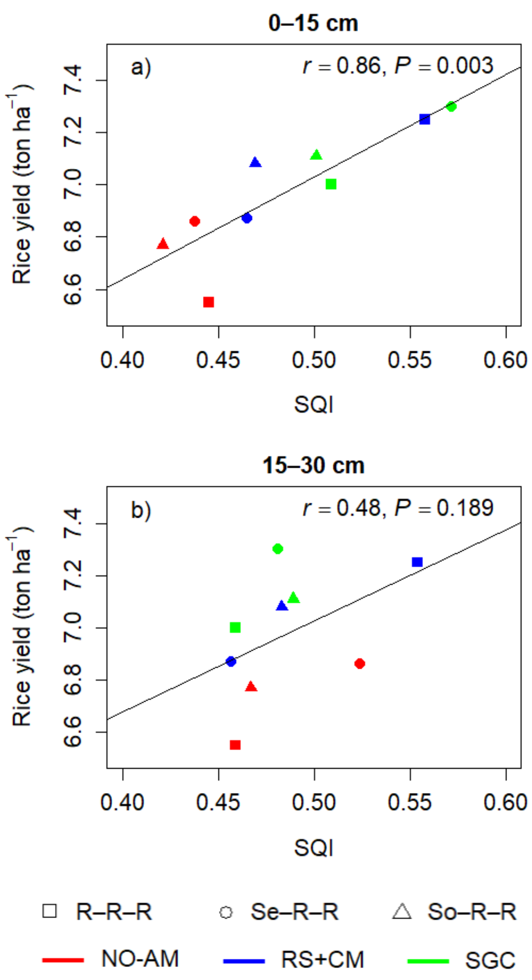

Figure 4. Relation between 2019–2020 WS season rice yield and a soil quality index (SQI) for two depth intervals (n = 9). R–R–R, Se–R–R, and So–R–R refer to rice–rice–rice, sesame–rice–rice, and soybean–rice–rice rotations, respectively. NO-AM, RS+CM, and SGC refer to no amendment, rice straw + cow manure compost, and sugarcane compost, respectively.

4. Discussion

4.1. Soil Amendments and Crop Rotations Effect on Rice Growth

Rice yield may be determined by yield components including panicle number per m^2, grain number per panicle, filled grain number, filled grain percentage, and 1000-grain weight [127]. In the present study, inclusion of a crop rotation and use of organic amendments had a significant combined positive effect on the 1000-grain weight of rice after three rotation cycles. In addition, use of organic amendments alone, as well marginally favored the filled grain number per panicle, though only marginally. Inclusion of an upland crop in the rotations on its own had no significant effect on crop growth after these three rotation cycles. Our findings are thus not entirely in accordance with those by Linh [71] who reported that crop rotation after 10 cycles (30 cropping seasons) significantly increased panicle numbers per m^2 and grain number per panicle of rice. This contrast is probably due to the shorter duration of our experiment, as both yield components did tend to improve with the introduction of crop rotations.

In this study, organic amendments significantly increased 1000-grain weight of rice both in the So–R–R and R–R–R systems, while a reverse trend was observed under the Se–R–R system. The beneficial effects of organic amendments on 1000-grain weight of rice were reported by previous studies [47,65,124]. This can be attributable to higher N availability at the heading stage as reported by De Datta [30] or all-around improvement of soil N supply [35,37,38]. Also, Litardo et al. [78] saw beneficial effects of organic amendments on other rice yield components with combined application of chemical fertilizer and compost increasing panicle length, grain number per panicle, and filled grain percentage as compared to the chemical fertilizer application alone. In line with the improved yield components, organic amendments also increased rice yield and above-ground dry biomass after three rotation cycles with upland crops (Table 3). Though rotations as such did not significantly affect rice yield and biomass, there was an increasing tendency in their increase when rotating rice with one upland crop. It was likely that a significant effect of rotation on rice yield may be expected with a long-term introduction. In a 10-year rotation experiment of rice with various upland crops, Chen et al. [21] reported that rice yield was significantly increased in all rotation systems, which was attributed to the improvement in soil organic matter and total N content by rotations. Likewise, it was confirmed by previous studies in the Mekong delta that inclusion of upland crops after 10 years helped significantly improve rice yield, resulting from improvement in soil physical and chemical properties, especially the subsoils (within 10–30 cm), and expansion of the rooting depth [74]. Wang et al. [117] reported that rotation of rice with upland crops increased rice yield and above-ground biomass by improving C and N stocks, and N availability of the subsoil (20–30 cm). To further interpret these effects, we investigate the overall effect of crop rotation and use of organic amendments on soil quality and its relation with rice productivity in section 4.2 below.

4.2. Soil Quality Index as a Predictor of Rice Yield

Sustainable management practices to improve rice production, such as use of crop rotations and organic amendments, need to be assessed in terms of their overall effect on soil quality [32]. To provide an integrated assessment of such effects, a soil quality index (SQI) that integrates various soil properties used as indicators of soil quality has been forwarded as an effective means for evaluation [105,107]. In the current study, rice yield after nine experimental cropping seasons (2019–2020 WS) was found to significantly and positively relate (r = 0.86) with our topsoil SQI (0–15 cm) (Figure 4). Liu et al. [79] reported a significant correlation between rice yield and SQI, which explained 69% in rice yield. Similar results have been reported in several studies, where other SQIs could predict 71–80% [10], 47–57% [67], and 50% [49] of the variation in rice yield across soils. In our study, the SQI (0–15 cm) explained 74% of the variation in rice yield (Figure 4) confirming SQI to be an effective tool to predict variation in rice production across different rice-based crop rotations combined with or without use of organic amendments. However, an SQI does not necessarily positively correlate with rice yield, as several previous studies found no [70] or even a negative [86] correlation between a derived SQI and rice yield. Lima et al. [70] suggested that such poor relations could be due to the fact that rice yield not only depends on soil quality, but also on other factors such as seed quality and irrigation. Obviously, variation in such factors was ruled out in our field experiment. Another explanation for the variable prediction of rice yield by SQIs reported in literature is the large existent diversity in indexing methods applied [102].

In the current study, rice yield did not correlate to our subsoil SQI (15–30 cm). This suggests that the effects of the applied cropping practices on subsoil quality were either not pronounced enough to impact crop productivity or of lesser importance to rice growth than effects on topsoil quality. Previous studies have reported a better correlation between rice yield and SQI in the topsoil (0–15 cm) than that averaged from top and subsoil (over 0–30 cm) (e.g., Lenka et al. [67]).

4.3. Rice Yield as Affected by the Cumulative Effects of Soil Properties

We suppose that the improvement in rice yield results from the enhancement in soil quality which can be attributed to improvement in the studied soil properties induced primarily by organic amendments and to a much lesser extent by crop rotations. These improvements are indicated by

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their positive and negative relationships between various soil properties with rice yield (Figure 3) as discussed further below.

Organic amendments have been widely reported to improve soil fertility and rice yield [59,84,90,93]. In the current study, it is accordingly plausible that the stimulatory effect of the organic amendments on rice yield and above-ground dry biomass resulted at least partly from the increased availability of plant nutrients. Such was indeed suggested by significant positive relations between rice yield and Mn (r = 0.79) and Si (r = 0.68), and P to a lesser extent as well (r = 0.63 but only at p = 0.067). On top, there was a marginally significant negative relation with EC (r = –0.6), indicating that lowered salt stress could have played a role also (Figure 3). The marginal relation with EC may have been coincidental or indirect as it was within the optimal range for rice growth (< 3 dS/cm) [111].

Mn is usually not considered a vital plant nutrient but it does play an important role in photosynthesis in rice plants [39]. The results suggested that increased Mn availability by organic amendments and rotations have stimulated rice growth. This seems a particularly plausible explanation as Fairhurst et al. [39] identified 12 mg Mn kg^{-1} as critical threshold for Mn deficiency, which was surpassed by use of RS+CM or SGC (Figure 3). The observed positive correlation between rice yield and exchangeable Si content (0–15 cm) (Figure 3) likewise may indicate that Si was limiting plant growth. Rice is well-known to be a Si-demanding crop [28,82,104] and Linh et al. [71] reported that in Mekong delta soils available soil Si was below the deficiency threshold (40 mg kg^{-1}) for rice, as a consequence of repeated removal of rice straw in rice monoculture systems. The use of OM amendments improved soil Si availability here, in line with Watanabe et al. [119] who reported an increase in available Si and rice yield with application of rice straw compost (6 ton ha^{-1}) after 25 rice cropping seasons. There may further be a link between Si and P availability as recently Schaller et al. [104] demonstrated that improved Si availability also results in enhanced P availability in paddy soils by the replacement of P with Si at the surface of amorphous and crystalline Fe complexes. An increase in P availability resulting from organic amendments has been often associated with increased P uptake in plants and grains [59], and therefore increased rice yield [78]. However, the limited strength of the here observed relation between yield and P suggests that other soil properties were more important. This seems a likely explanation as doubled or even tripled P-availability after use of SGC apparently did not drastically improve rice yield.

Rice yield was found to correlate to several soil physical properties, aligning with several previous reports of soil physical quality control on rice yield [51,89]. More specifically, Nwite et al. [89] reported a strong correlation between rice yield and bulk density, aggregate stability, saturated hydraulic conductivity, and aggregate size fraction, and all these properties were affected by organic amendments. After the nine seasons in our study, several of such soil physical properties were altered by the treatments although they appeared predominantly changed by the use of organic amendments rather than by implementing crop rotations (Figure 3). Reynolds et al. [101] also found that long-term application of composts helped to improve physical quality of fine textured soils, as evidenced by increased macro- and microporosity. Positive correlations of yield with topsoil macro-, meso- and microporosity indicated that overall enhanced porosity was beneficial for rice growth in our experiment. With soil pores playing an important role in providing living space to soil biota [64], and in storing and transporting air, water, and nutrients [56], it is logical that pore space architecture also in turn affects crop yield. According to Kar and Ghildyal [60], rice root tips can penetrate macropores as small as 75 µm, corresponding with the macropore size of > 75 µm considered in this study. Thus, enhanced macroporosity would potentially favor root growth, thereby improving nutrient and water uptake [46]. We also found a highly positive correlation ($P < 0.01$) between air capacity and rice yield (Figure 3). Although air capacity does not have much significance when rice fields are flooded and soils are saturated, farmers in the Vietnamese Mekong delta often implement surface drainage 2–3 times during the cropping season, thereby making air capacity a relevant factor. The practice aims at enhancing root anchoring and stimulating root growth, and reducing risks of toxicity (e.g., Fe^{2+}). Increased air capacity might thus favor diffusion of oxygen into soil and thus potentially bring about several benefits, such as increased soil microbial activity and nutrient availability [15,24], reduced iron toxicity [36], and finally enhanced rice yield [33]. Indeed, several studies have evidenced the important role of soil aeration to rice growth, even though rice plants have the capacity to conduct oxygen from the atmosphere to their roots through their stem for respiration [57,127,130]. For instance, Zhu et al. [130] found that provision of oxygen to soil via aerated irrigation resulted in a significant increase in effective panicles, seed setting rate, and grain yield and improved root function of rice. On the other hand, rice yield decreased with increasing bulk density of the topsoil, and this decrease appeared linear between the lowest (0.91 g cm^{-3}) and highest (1.12 g cm^{-3}) observed bulk density (Figure 3). Nwite et al. [89] also reported that rice yield decreased (r^2 = 0.763) as bulk density started to increase above 1.05 g cm^{-3}, though in their case quadratically. Likewise, Linh et al. [77] observed in the Mekong delta negative effects on rice yield from increased soil bulk density and decreased macroporosity of the puddled layer during later growth stages, which might be attributed to the settlement of soil particles during the cropping season [129]. It should be noted that in conventional rice cultivation, puddling, which results in increased bulk density and microporosity [69], is a common practice that facilitates crop establishment and growth [85].

In addition, there was a positive correlation between rice yield and penetration resistance ($r = -0.77$) (Figure 3), in line with Mohanty et al. [86] who reported a likewise relationship, and a remarkable decrease in rice yield when it reached 0.75 MPa. As topsoil penetration resistance was in all treatments above this threshold, it is not entirely clear if the relation to rice yield we found was direct or just via mutually correlating variables.

In sum, the SQI derived in the current study integrates 23 soil quality indicators and related stronger to rice yield than any of these individual indicators. Thus, as could be expected, higher rice yield appeared to result from the cumulative effect of improved soil fertility overall, rather than from the enhancement of one or a few single soil quality indicators. In assessing the effectiveness of soil quality improving management, it thus seems advisable to integrate effects on individual soil properties into a wide SQI that encompasses both chemical as well as physical soil properties. While the observed improvement in SQI after nine growing seasons is encouraging, care should be taken before extrapolating these short-term gains to the longer term. For example, the efficacy of applying composts at a rate of 2 t ha^{-1}, as investigated here, on offsetting the anticipated loss of SOC resulting from the inclusion of upland crops in the rice-based rotation as reported by previous studies (e.g., Linh et al. [72]; Witt et al. [121]; Cass et al. [17]), warrants careful consideration. Some effects of implementing adjusted farming management may only significantly affect soil quality and rice yield on the longer term.

5. Conclusions

After nine cropping seasons with three rotation cycles, rice yield significantly increased by use of organic amendments, but not by implementing crop rotations, although an increasing tendency in yield was observed. Rice yield was significantly and positively correlated with a derived SQI of the topsoil (0–15 cm), which predicted 74% of overall rice yield. Conspicuously, there was no relation between an SQI of the 15–30 cm layer and rice yield, although possibly the duration of our experiment may have been too short to obtain sufficient variation in subsoil properties critical for rice growth. The relation between the topsoil SQI and yield was suggested to result from the increased availability of nutrients (Si and possibly also P), alleviated soil compaction, and improved aeration and porosity primarily by organic amendments. Probably not only these, but also other soil properties as well, cumulatively determined rice yield. Even though the SQI used in this study proved a good predictor of rice yield, still some difficult to quantify, yet relevant soil functions, could still be considered to be included in the future to improve its predictive power. Actual crop availability of N for instance cannot be readily assessed from a simple soil test. Use of a SQI encompassing many soil properties indeed then precisely enables to overall quantify the importance of soil fertility for rice yield versus other factors and it provides an effective means of quantifying the integrated effect of new management. Including a wide range of properties (here 23) in a SQI moreover should secure its applicability across diverse settings, including different crop rotations and various soil types.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Figure S1: Monthly precipitation, and average humidity, air temperature and solar radiation from January 2017 to January 2020 (Data were recorded by a WS-GP2 automatic weather station, Delta-T Devices Ltd., installed adjacent to the field trial, except from January to August 2017 when data were obtained from the nearest meteorological station, Cang Long Meteorological Station, approximately 29.4 km from the field trial). Table S1: Functions assigned to the soil indicators.

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Conflicts of Interest: The authors declare that no conflicts of interest exist.

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