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Effect of Organic Amendments on the Productivity of Rainfed Lowland Rice in the Kilombero Floodplain of Tanzania

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Received: 29 June 2020; Accepted: 25 August 2020; Published: 29 August 2020

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Abstract: Organic amendments can reportedly sustain and increase lowland rice productivity in smallholder systems. Few studies have assessed locally-available substrates in hydrologically variable floodplain environments. We investigated the effects of green and farmyard manures on rice yields, and total soil C and N in the Kilombero floodplain, Tanzania. At both the fringe and the middle positions, five treatments were applied in 2016 and 2017, comprising (1) non-amended control, (2) farmyard manure, (3) pre-rice legumes, (4) post-rice legumes and (5) a combination of green and farmyard manures. Residual treatment effects were assessed in 2018 when rice plots were uniformly non-amended. Depending on the year and the position, organic amendments increased rice grain yields by 0.7–3.1 Mg ha^{-1} above the non-amended control. Sole green and farmyard manure applications had similar effects on grain yield, while a combination of green and farmyard manure led to a significant increase in grain yield above both the control and sole applications of organic amendments in both years. The contribution from biological N_2 fixation by legumes ranged from 4 to 61 kg N ha^{-1}. Despite partial N balances being mostly negative, we observed positive residual effects on the yield of the non-amended rice in the third year. Such effects reached up to 4 Mg ha^{-1} and were largest with post-rice legumes, sole or combined with farmyard manure. Irrespective of the position in the floodplain, manures significantly increased soil C and N contents after two years, hence enhancing soil fertility and resulting in increased rice grain yields. Comparable benefits may be obtained along the hydrological gradients of other large river floodplains of the region and beyond.

Keywords: *Lablab purpureus*; N_2-fixation; δ^{15}N natural abundance; *Oryza sativa*; *Stylosanthes guianensis*; *Vigna unguiculata*

1. Introduction

Tanzania is one of the largest rice producers in East Africa, accounting for about 50% of the total regional output [1]. Rice grain yields are generally low, ranging between 0.5 to 2.1 Mg ha^{-1} across all rice-growing environments [2]. Tanzania will need to double its current rice production by 2030 to meet the rapidly-growing domestic demand [3,4]. Most rice is produced in rainfed lowland floodplain environments and it is predominantly grown by smallholder farmers. With yields attainable by best farmers of >5 Mg ha^{-1}, the yield gap is large, reaching up to 3.4 Mg ha^{-1} [5,6]. Rice yields and total annual production in floodplains are highly variable, partly due to erratic rainfall and unpredictable soil submergence regimes but also because of low and variable soil fertility and poor management practices [7,8]. While mineral fertilizers are still considered being the primary option for soil fertility restoration [9], increasing the current low use of mineral N fertilizers will depend on their availability and affordability [10]. These latter conditions are rarely met in the remote rural villages of the Kilombero floodplain, which is one of the largest rice-growing areas of Tanzania and the focal environment of the present study.

Organic amendments, in contrast, have the potential to increase soil fertility without using external inputs. The effects of organic amendments on rice production have been widely studied. After the first review on historical uses of organic amendments in China, Korea and Japan by F.H. King in his book "Farmers of forty centuries" [11], the first scientific journal papers appeared in the 1950s. Since the mid-1980s, a large array of studies and later review papers on leguminous green and animal manures [12,13] and on food legume residues appeared [14]. In-situ or ex-situ (cut-and-carry) grown legume manures, sole or in combination with mineral fertilizers [15,16], have shown to increase rice grain yields on average by 35% and in some cases by >50% [17].

Apart from reported yield benefits, the incorporation of organic amendments has further been shown to improve aggregate stability [17] and other soil attributes by increasing total soil organic C and N, as well as available P, K, S, and Zn [16]. They also improve water infiltration, hydraulic conductivity and the soil's water-holding capacity [18], thus reducing negative effects of dry-spells and counteracting soil degradation [19]. In-situ-grown green manures during the pre-rice niche are additionally able to save nitrate from leaching and denitrification losses [20,21] and to reduce negative effects of iron toxicity [22], while promoting soil microbial and enzyme activities [23]. Organic amendments also can reduce plant pathogenic nematode communities and soil-borne diseases [24] and suppress weed growth [12]. There is evidence that locally-available organic amendments can be economically viable and resource-conserving alternatives to mineral fertilizers with a high promise to sustain and increase production in small-scale agriculture [25].

Despite beneficial effects, the adoption of organic fertilizer strategies in rice-based systems of Africa has remained low [9]. Besides labour limitations, farmers lack the knowledge of the benefits derived from organic amendments [26]. Other authors pinpointed the lack of both available farmyard manure and seeds of appropriate legume species as a hindrance to adopting strategies based on organic inputs [27]. Particularly in favourable irrigated lowland environments, the competitiveness of organic amendments with cheap and readily-available mineral fertilizer sources is reportedly low [12]. In addition, niches for growing green manure legumes are often non-existent in intensive irrigated production systems or too short or water-limited in extensive rainfed environments [12]. Most of these reported constraints to the use of organic amendment strategies refer to (irrigated) lowland rice in South and South-East Asia [12] and upland rice in West Africa [17] and are not, or only partially, applicable to rainfed floodplains in East Africa. Such floodplain environments are edaphically and hydrologically highly variable, and soil fertility is often low [28]. Consequently, the use efficiency of applied mineral N is highly variable and tends to be low [8]. In addition, mineral fertilizers are often unaffordable for smallholders or not available in a timely manner [29]. In the absence of mineral fertilizers, farmers have to rely largely on the native supplying capacity of minerals by the soil, often resulting in nutrient mining [30].

Organic amendments appear as a promising alternative strategy for soil fertility restoration and for increasing the yield of rainfed lowland rice, particularly in floodplains. Many farmers in the Kilombero floodplain own cattle and have thus the possibility to apply farmyard manure. One single crop of rainfed rice during the main rainy season [7] leaves available cropping niches for growing green manure, grain, or forage legumes either before rice planting (pre-rice niche) or after rice harvest (post-rice niche). The duration of these cropping niches depends on water availability for the establishment and the growth periods of green manure crops and thus on the onset of the rains for the pre-rice niche and on the soil moisture retention for the post-rice niche. These conditions of water availability differ spatially depending on the physical position of fields within the floodplain (distance from the central river) between the drought-prone fringe and wetter middle positions [31]. Due to severe submergence risks, the center positions closest to the river are largely unsuited for green manure growth, and even rice production is highly risky due to high production uncertainty and yield variability [7]. Conditions of water availability further vary temporally according to rainfall patterns within the season or between years [32]. Hence, the effectiveness of organic amendments in enhancing lowland rice performance in floodplains is expected to differ by amendment type, field position and year. We further assume that the repeated application of organic amendments can improve soil attributes with associated residual effects on subsequent non-amended crops.

To date, no studies have assessed the effects of different organic amendments on rainfed rice performance in the often remote rural floodplain environments of East Africa. We, therefore, quantified the effects of (a) sole farmyard manure application, (b) pre–rice green manure (c) post-rice green manure, and (d) of a combination of post-rice green and farmyard manure on rice grain yield (direct and residual effects), on soil C and N contents, and on partial N balances. The field experiments were conducted at the fringe and middle positions in the Kilombero floodplain between 2015 and 2018.

2. Materials and Methods

2.1. Edaphic and Climatic Conditions of the Experimental Sites

Field experiments were conducted in farmers' fields between 2015 and 2018 in two villages located near Ifakara town in the Kilombero District of Tanzania. The Kilombero floodplain is part of the Rufiji River Basin extending from 7.65° to 10.02° S latitude and from 34.56° to 37.79° E longitude and is the largest rice-growing environment of Tanzania. The floodplain is divided into three hydrological positions (fringe, middle and center) based on the origin of the water and submergence duration [31]. Only the fringe and middle positions were considered in this study after the complete submergence of the center position in 2015 [7]. The two test sites have been under continuous extensive rainfed rice production for >15 years. In Table 1, both sites had similar soil textural classes (silt loam) and a comparable soil pH (5.8–6.0). The soils of the fringe position contained more available P (48 mg kg^{-1}) than the middle position (16 mg kg^{-1}), but both were above the critical limit for rice growth of <8 mg P kg^{-1} and of plant-available (exchangeable) soil K of <60 mg K kg^{-1} according to Mehlich-3 soil extraction as earlier reported [7].

Table 1. Selected physical and chemical properties of the experimental topsoil (0–20 cm) in Kilombero floodplain at the onset of the experiment in November 2015.

Soil Characteristics	Fringe	Middle
Classification (WRB)	Fluvisol	Fluvisol
Soil texture	Silt Loam	Silt Loam
Clay (%)	14.3	26.6
Sand (%)	33.7	14.1
Silt (%)	52.0	59.3
Bulk density (g cm^{-3})	1.4	1.3
pH (H_2O)	6.0	5.8
Total C (g kg^{-1})	16.5	14.5
Total N (g kg^{-1})	0.9	0.9
Available P (mg kg^{-1}) *	47.5	16.0
Available K (mg kg^{-1}) *	71.4	79.2

* Mehlich-3. WRB-World Reference Base of the Food and Agriculture Organization of the United Nations (FAO). Presented values are means of n = 20 replicate samples.

The experimental site has a sub-humid tropical climate, with average annual temperatures of 22–23 °C and maximum and minimum peaks in December and July, respectively. Rainfall occurs in a pseudo-bimodal pattern with erratic rains between November and January and intensive rain between March and May. The dry season extends from June to October. Long-term average annual rainfall is 1100 mm. During the experimental period, rainfall varied between 632 mm (2018) and 1262 mm (2017) (Figure 1). Besides in-situ rainfall, the hydrology of the floodplain differs with the distance of fields from the central river. The hydrology in the middle position is determined mainly by overbank flow from the Kilombero River, while the fringe positions receive lateral subsurface flow contributions from adjacent mountain ranges [33]. Early rainfall events in November/December provide the moisture required for the growth of short-duration green manure crops before the establishment of the rice crop in March (pre-rice niche). Shallow groundwater and residual soil moisture after flood recession in June provide water for cultivating deep-rooted legumes during the dry season (post-rice niche), resulting in specific cropping sequences, and interactions of surface and groundwater determined the dynamics of water availability or submergence regimes (Figure 2).

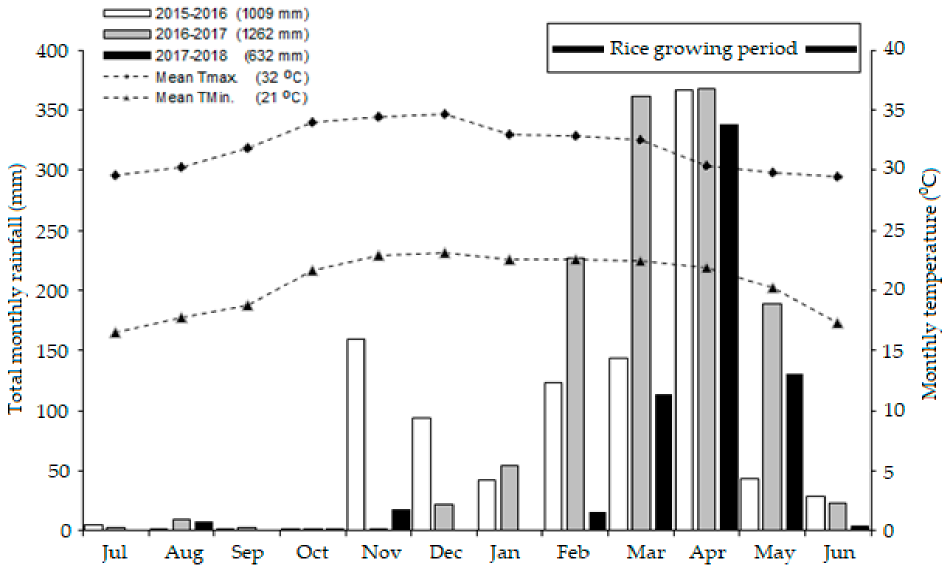

Figure 1. Monthly and total annual rainfall and mean minimum and maximum air temperature distribution during the three-year experimental period. Data were recorded at a weather station installed at Ifakara Health Institute research station, about 5 km West of Ifakara town.

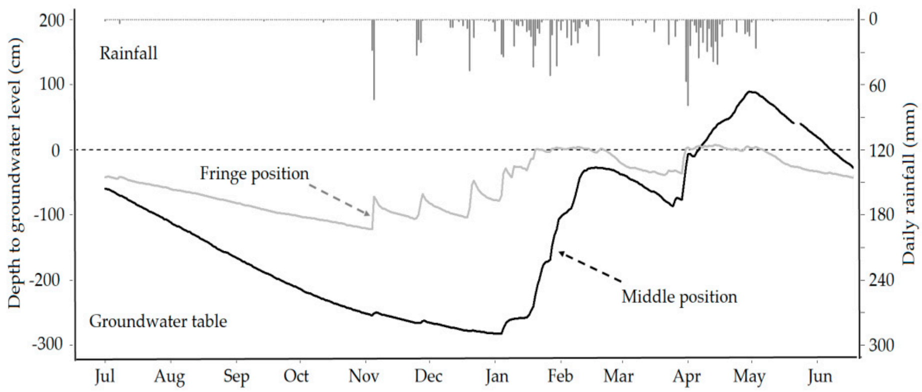

Figure 2. Depth to ground water level dynamics resulting from the surface water and groundwater interaction during dry, short- and long-rain season for the fringe and middle positions of the Kilombero floodplain, Tanzania from July 2015 to June 2016. Adapted from Gabiri et al. [33].

2.2. Experimental Design and Treatment Application

Four strategies using organic amendments were compared with a non-amended control in a randomized complete block design (RCBD) with four replications. The experiments were implemented at two contrasting locations within the floodplain (fringe and middle positions) and included: (i) farmyard manure, (ii) lablab (*Lablab purpureus* L.) as pre-rice green manure, (iii) stylosanthes (*Stylosanthes guianensis* L.) as post-rice green manure, (iv) a combination of cowpea (*Vigna unguiculata* L.) as post-rice green manure and farmyard manure application before rice planting and (v) the non-amended control treatment (Figure 3). The treatments were applied in the same plots for two consecutive years (2015 and 2016), their direct benefits were evaluated in 2016 and 2017, while the residual effect on a non-amended rice crop was assessed, with all plots being treated uniformly (no organic amendment) in 2018 (Figure 3). The trial were established at the two different hydrological positions using individual experimental plot sizes of 6 × 5 m (30 m^2). Plots were manually tilled to a depth of 15 cm, bunds of 50 cm height and 30 cm width were built and compacted around each plot to prevent lateral flows of water and nutrients. Additionally, one-meter-wide trenches were installed to separate the treatment blocks (replications). Field areas within the bunded plots were puddled and manually levelled.

Farmyard manure: Fresh cattle manure was obtained from one local farmer in the area. Subsamples were dried and analyzed for N content (Table 2). Fresh farmyard manure was homogenously applied at a rate equivalent to 60 kg N ha^{-1} and manually incorporated into the topsoil (0–15 cm) one week prior to soil puddling and rice transplanting. Depending on the N content, farmyard manure application rates varied by year between 5 and 6.7 Mg ha^{-1}.

Green manures: Three green manure species were selected, i.e., (i) lablab, (ii) stylosanthes and (iii) cowpea based on them being locally known and seeds being available. The choice of the specific genotypes used was informed by their multi-purpose use attributes. Besides being used as green manures, stylosanthes and the specific cowpea were forage types, and the grains of cowpea and lablab can potentially be used for human consumption. Such multi-purpose considerations have been pointed out being key factors for farmers' adoption of green manure technologies [12]. Legume seeds were obtained from the Agriculture Research Institute (ARI) in Ilonga, Tanzania (stylosanthes), and the National Semiarid Research Resources Institute (NaSARRI), Uganda (lablab and cowpea). Lablab was used as pre-rice green manure and established after the first rains in early or mid-December at a 40 × 40 cm spacing. Long-duration multi-purpose cowpea and the forage legume stylosanthes were established as post-rice green manures by dibble-seeding at a 20 × 10 (stylosanthes) or 20 × 40 cm spacing (cowpea) 2-5 days after rice harvest. The post-rice legumes grew on residual soil moisture for initially 2–3 months into the dry season, and re-greened and continued to grow for another 1–2 months after the onset of the short rains until the land preparation for rice in the subsequent year. No rhizobia inoculum was applied as all legumes nodulated spontaneously.

Biomass samples for weight, N content and the share of N derived from biological N_2 fixation were obtained from a 2 × 3 m harvest area in the middle of each plot at 45 (pre-rice legumes) and 150 days after seeding (post rice legumes). The biomass was chopped and incorporated manually into the topsoil (0–15 cm) two weeks before rice transplanting. Only in the cowpea treatment, farmyard manure was additionally applied at a rate of 60 kg N ha^{-1} and incorporated together with the fresh legume biomass two weeks prior to rice transplanting. In one corner of each legume plot, six maize plants were established at the time of legume seeding and were used as non-fixing references for $\delta^{15}N$ analysis after harvest at 45 days (pre-rice green manure) or 110 days (post-rice green manures). In the final experimental year (2018), rice was grown without any amendments to assess the residual effect of repeated manuring under ceteris paribus conditions (Figure 3).

Rice: Seeds of the high-yielding indica variety SARO-5 were obtained from the Tanzania Agriculture Research Institute (TARI) in Ifakara. Seeds were pre-soaked for 24 h, incubated for 48 h and sown in a nursery bed. Twenty-five days-old rice seedlings were transplanted into the puddled and levelled field plots at a 20 × 20 cm spacing at two seedlings per hill (25 hills m^{-2}) in late February or early March of each year, depending on the onset of the main rainy season. Plots were hand-weeded homogenously in all plots at 28 and 56 days after transplanting. Rice was harvested from 2 × 3 m sampling areas in the center of each plot in late May or early June. After manual threshing, measured with a digital grain moisture meter (Satake Moistex SS7) and adjusted to 14% grain moisture content. Additionally, 12 adjacent hills were cut at ground level to determine biomass accumulation and yield components, including the number of tillers and panicles m^{-2}, percentage filled grains, and 1000-g weight.

Table 2. Characterization of the organic amendments (biomass and N accumulation and the shares and amounts of N_2 fixed by legumes) applied at the fringe and the middle positions of Kilombero floodplain in 2016 and 2017.

Organic Amendment	2015						2016					
	Biomass (Mg dm ha^{-1})	N Content (%)	N Accum. (kg ha^{-1})	δ^{15}N (‰)	Nfda (%)	N Fixed (kg ha^{-1})	Biomass (Mg dm ha^{-1})	N Content (%)	N Accum. (kg ha^{-1})	δ^{15}N (‰)	Nfda (%)	N Fixed (kg ha^{-1})
Fringe												
Farmyard manure	5.0 ^{a}	1.2	60 ^{a}	-	-	-	6.7 ^{a}	0.9	60 ^{a}	-	-	-
Lablab	1.3 ^{c}	1.6	18 ^{b}	4.6	23	4 ^{c}	1.0 ^{c}	1.3	13 ^{b}	4.5	51	7 ^{c}
Stylosanthes	1.9 ^{bc}	1.9	36 ^{b}	4.4	25	9 ^{b}	5.2 ^{b}	1.4	73 ^{a}	5.9	39	28 ^{b}
Cowpea	2.1 ^{b}	3.6	76 ^{a}	3.0	39	30 ^{a}	2.5 ^{c}	3.1	78 ^{a}	3.1	59	46 ^{a}
Middle												
Farmyard manure	5.0 ^{a}	1.2	60 ^{b}	-	-	-	6.7 ^{a}	0.9	60 ^{b}	-	-	-
Lablab	1.8 ^{c}	1.8	18 ^{c}	4.6	27	5 ^{c}	1.1 ^{c}	1.9	21 ^{c}	4.4	29	6 ^{c}
Stylosanthes	2.5 ^{bc}	2.5	63 ^{bc}	4.3	29	18 ^{b}	3.1 ^{b}	2.0	62 ^{b}	4.4	28	17 ^{b}
Cowpea	3.8 ^{b}	3.4	122 ^{a}	4.2	29	35 ^{a}	3.8 ^{b}	3.2	122	2.3	50	61 ^{a}

%Nfda–Nitrogen derived from the atmosphere, δ^{15}N-atom per cent excess above 0.366% (atmosphere). Maize was used as a non-fixing reference crop with δ^{15}N values of 10.7‰, 6.4‰ for fringe and 6.7‰, 6.8‰ for middle position in 2015 and 2016, respectively. 'B–value' refers to isotopic discrimination in N-free medium and was applied as 1.36‰ for lablab [34], 1.76‰ for stylosanthes [35], and 2.20‰ for cowpea [36]. Different letters within a column denote significant differences at $p < 0.05$ according to Tukey Test. N accum= biomass × N content, N fixed = %Ndf × N accum.

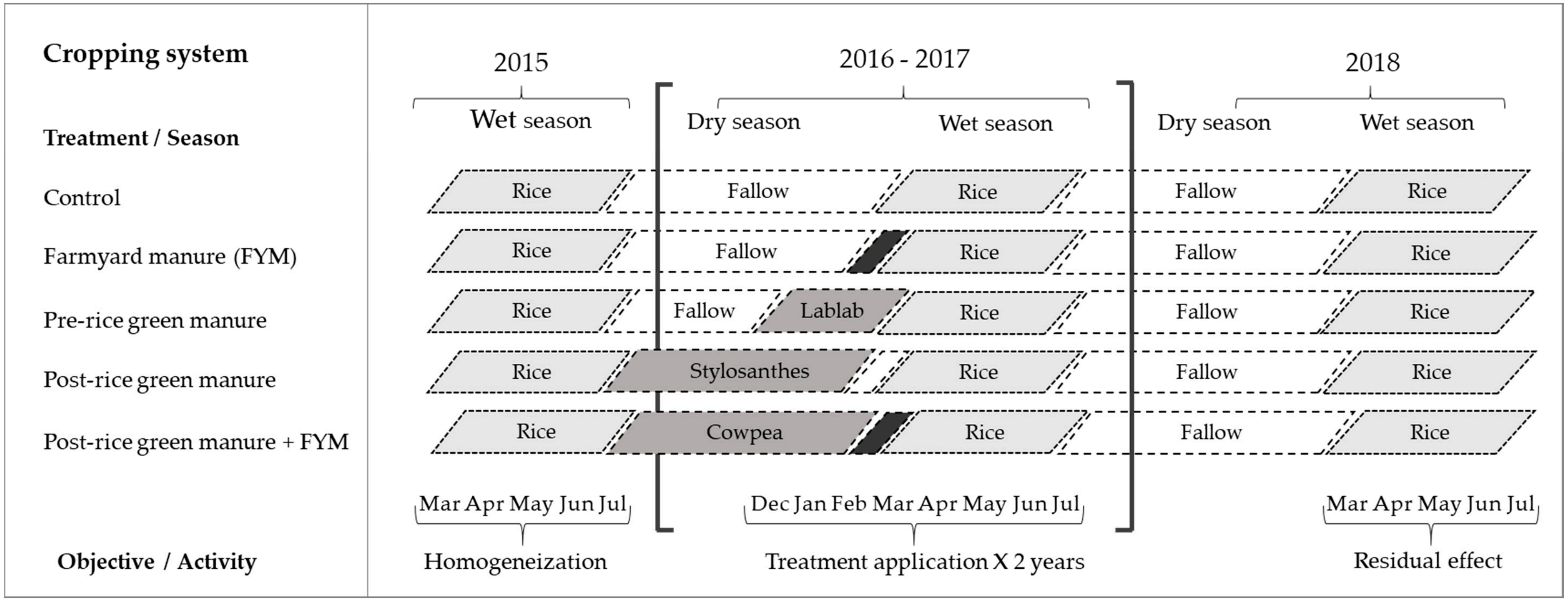

Figure 3. Characterization of the applied cropping systems, including crop species, i.e., rice, cowpea, lablab and stylosanthes, and their temporal sequence in Kilombero floodplain, Tanzania during the experimental period (2015–2018). Main rainy season extends from March to May, main dry season from July to February. Shaded black areas represent the period for farmyard manure (FYM) application.

2.3. Data Collection and Analyses of Plant Material and Soil

Samples of approximately 100 g of rice grain and straw, of farmyard manure and of legumes were oven-dried at 105 °C for ~48 h until constant weight. Sub-samples of about 1 g were fine ground and analyzed for their N content using an elemental analyzer (EURO EA Elemental Analyzer series 3000, EURO-EA Vector Pavia, Italy). The share on N derived from the atmosphere (%Ndfa) by legumes was estimated using the $\delta^{15}N$ natural abundance method. Above-ground plant parts were analyzed for N isotope ratios using a Europa Scientific Ltd. Geo 2020 mass spectrometer coupled to the ANCA-SL elemental analyzer (Welsh S. Sercon Ltd., Crewe, Cheshire, UK). The $\delta^{15}N$ signatures were calculated according to equation 1, with atmospheric N_2 serving as standard [20]. The shares of Ndfa (%) were assessed as shown in equation 2 [21]. The *B* value is the $\delta^{15}N$ share of the same N_2 fixing legume when grown with N_2 as sole N source (natural discrimination of the heavy ^{15}N isotope by the nitrogenase enzyme complex). The *B*-values were −1.36‰ for *Lablab purpureus* [22], −1.76‰ for *Stylosanthes guianensis* [23], and −2.2 for *Vigna unguiculata* [24]. All ^{15}N data were expressed as atom% in excess of the natural ^{15}N background abundance of the atmosphere of 0.3663%.

$$\delta^{15}N = \left[\left(\frac{^{15}\mathbf{N}}{^{14}\mathbf{N}}\mathbf{sample}/\frac{^{15}\mathbf{N}}{^{14}\mathbf{N}}\ \mathbf{standard}\right)1\right] \times 1000 \quad (1)$$

$$\%\mathbf{Ndfa} = \frac{\left(\delta^{15}\mathbf{N\ of\ reference\ crop} - \delta^{15}\mathbf{N\ of\ legume}\right)}{\left(\delta^{15}\mathbf{N\ of\ reference\ crop} - \mathbf{B}\right)} \times 100 \quad (2)$$

$$\mathbf{N\ accum.} = \mathbf{Biomass} \times \mathbf{N\ content} \quad (3)$$

$$\mathbf{N\ fixed} = \mathbf{N\ accum.} \times \%\mathbf{Ndfa} \quad (4)$$

Based on N contents and biomass accumulation, partial N balances were calculated for the different treatments as (N added by amendments)–(N removed with harvested grain) [20]. Nitrogen input by dry and wet deposition, N_2 fixation by free-living organisms or N losses by volatilization, denitrification and leaching were not considered.

Composite samples of seven topsoil cores per plot (0–20 cm) were collected before rice transplanting in 2015 and after rice harvest in 2017 to assess changes in soil C and N contents after two years of treatment application. The samples were air-dried, ground to pass through a 2 mm sieve, and analyzed for total N by dry combustion method at 950 °C using an Elemental Analyzer (vario-ELcube Elementar Analysesysteme GmbH, Langenselbold, Germany). Plant-available P and K were extracted from the initial soil samples (2015) using the Mehlich-3-extraction method [25]. Phosphorus was colourimetrically analyzed using molybdenum-blue complex (Specord 50Plus, Analytik Jena AG, Jena, Germany), while K was analyzed using ICP-OES (Spectro Arcos, Spectro Analytical Instruments GmbH, Kleve, Germany).

2.4. Statistical Analysis

A linear mixed model fit by Restricted Maximum Likelihood (ReML) variance components analysis was used for data on soil, yield, yield parameters and N uptake in each position. The fixed model included position, treatment and year, while replications were considered as a random factor. Descriptive statistics on means and standard errors of the means were calculated for main effects over years and for both hydrological positions. A two-way ANOVA was used for comparing soil nutrient concentrations and rice grain yield. Where applicable, mean separations were done using the Tukey test ($p < 0.05$).

3. Results

3.1. Nitrogen Accumulation and N_2 Fixation by Legumes

Above-ground biomass accumulation, N content, N accumulation and the amounts of N derived from biological N_2 fixation by green manures differed between legume species, position and cropping season (Table 2). The relatively more extended growth period during the post-rice niche compared to lablab, application of stylosanthes and cowpea produced higher biomass of 0.9–3.4 and 1.1–2.0 Mg ha^{-1} respectively. While, biomass accumulations by lablab and cowpea were comparable in both years and positions, the biomass of stylosanthes was much higher in 2016 (3.1–5.2 Mg ha^{-1}) than in 2015 (1.9–2.5 Mg ha^{-1}) and differed between positions. Also, the in-field variability (establishment and stand densities) was much higher with small-seeded stylosanthes than with the large-seeded legumes (data not shown).

The amount of N added by farmyard manure was fixed at 60 kg ha^{-1}. On the other hand, the amounts of N incorporated into the soil with legume biomass (N derived from both the soil and the atmosphere) varied widely between species and years. The highest N-accumulation was recorded in cowpea with 76-78 kg N ha^{-1} in the fringe and 122 kg N ha^{-1} in the wetter middle position. Similar to biomass, the N accumulation by stylosanthes was highly variable, ranging from 36-73 kg N ha^{-1}. The lowest N-accumulation range of 1.3–2.0 kg N ha^{-1} was recorded in lablab. The measured mean shares of N derived from N_2 fixation were higher in cowpea (44% Ndfa) than in lablab (32% Ndfa) or stylosanthes (30% Ndfa). Resulting amounts of N fixed differed between legumes, positions and years, ranging from 4 kg N ha^{-1} (lablab in the fringe position) to 61 kg N ha^{-1} (cowpea in the middle position). The amounts of N_2 fixed were higher in 2016 than in 2015, independent of the position.

3.2. Effect of Organic Amendments on Rice Grain Yield

Rice grain yields differed between treatments, positions and years (Table 3). The overall mean was 5.5 Mg ha^{-1} with higher average yields in the wet year of 2017 (6.1 Mg ha^{-1}) than in the relatively dry year of 2016 (4.8 Mg ha^{-1}). The yield of the non-amended control ranged from 3.6 (2016) to 4.9 Mg ha^{-1} (2017) and tended to be higher in the wet middle than the drier fringe positions, particularly during the dry year of 2016. Sole farmyard manure application at a rate of 60 kg ha^{-1} increased yields by 22% in the first and by 31% in the second years of treatment application. The rice yield response to green manure application showed a similar pattern (stronger response in 2017 than in 2016) and was significant in both years, irrespective of whether the legume was grown in the pre-rice (lablab) or the post-rice niche (stylosanthes). The N application rate was much lower with green manures compared to farmyard manure, pointing to a large N accumulation and fixation by the below ground biomass. The strongest yield response was observed in both years and positions with combined incorporation of the post-rice green manure (cowpea) and the application of farmyard manure, with yield increases of 86% in the dry (2015) and 45% in the wet year (2016).

ANOVA showed significant effects of treatment and year for most yield parameters (Table 4), while positions only affected the percentage of filled grains and thousand-grain weight. Significant interactions between treatments and years required a differentiated presentation of the findings by years (Table 3).

Panicle numbers ranged between 156 (2016) and 163 m^{-2} (2017), and in all cases, manuring resulted in significant increases. Panicle numbers tended to be higher (significant only in 2016) after incorporation of the post-rice green manure compared to pre-rice green manure or farmyard manure application. No treatment effect was observed regarding the percentage of filled grains and 1000-grain weights. However, the share of filled grains was higher in 2016 (94%) than in 2017 (80%). A combined application of green manure and farmyard manure in 2015 and 2016 not only provided highest yields but also resulted in highest N removal by the grain with 70 and 80 kg N ha^{-1} in 2016 and 2017, respectively.

Table 3. Effect of organic amendments on grain yield, N uptake and yield components of rainfed lowland rice in Kilombero floodplain, Tanzania in 2016 and 2017 (means across two positions).

Treatment	Rice Grain Yield (Mg ha^{-1})	Panicle Number (m^{-2})	Filled Grains (%)	1000 Grain Weight (g)	Grain N Removal (kg ha^{-1})
2016					
Control	3.6 ^{c}	103 ^{c}	92.3 ^{d}	30.0 ^{b}	35.7 ^{c}
Farmyard manure	4.4 ^{b}	146 ^{b}	93.4 ^{bc}	30.6 ^{a}	39.0 ^{b}
Pre-rice GM *	4.3 ^{b}	167 ^{b}	93.9 ^{b}	30.1 ^{b}	39.6 ^{b}
Post-rice GM *	4.3 ^{b}	186 ^{a}	92.7 ^{cd}	29.4 ^{b}	35.1 ^{c}
Post-rice GM + FYM #	6.7 ^{a}	181 ^{a}	94.5 ^{a}	30.8 ^{a}	70.4 ^{a}
Mean	**4.8**	**156**	**93.5**	**30.3**	**44.0**
2017					
Control	4.9 ^{d}	131 ^{b}	82.3 ^{a}	31.2 ^{a}	52.9 ^{d}
Farmyard manure	6.2 ^{bc}	162 ^{a}	79.8 ^{a}	31 ^{a}	68.4 ^{b}
Pre-rice GM	6.4 ^{b}	173 ^{a}	76.6 ^{a}	31.1 ^{a}	64.5 ^{b}
Post-rice GM *	5.7 ^{c}	167 ^{a}	79.4 ^{a}	30.7 ^{a}	59.2 ^{c}
Post-rice GM + FYM	7.1 ^{a}	174 ^{a}	81.1 ^{a}	30.7 ^{a}	80.0 ^{a}
Mean	**6.1**	**163**	**79.7**	**30.9**	**65.5**

* GM = green manure, # FYM = farmyard manure. Different letters within a column/year denote significant differences at $p < 0.05$ according to Tukey Test. Presented values are means of $n = 8$ replicates.

Table 4. Analysis of variance for grain yield, N uptake and yield components (means of the years 2016 and 2017).

Source of Variation	Rice Grain Yield (Mg ha^{-1})	Panicle Number (m^{-2})	Filled Grains (%)	1000 Grain Weight (g)	Grain N Removal (kg ha^{-1})	Total Crop N Uptake (kg ha^{-1})
Treatment	***	**	ns	**	**	**
Position	ns	ns	***	**	ns	*
Year	***	ns	**	**	**	**
Year x Treatment	**	*	***	ns	**	**
Position x Treatment	ns	ns	ns	***	ns	ns
Year x Position	ns	ns	ns	**	ns	ns
Treatment x Position x Year	ns	ns	ns	ns	ns	ns

Significant level '***' 0.001 '**' 0.01 '*' 0.05, ns—not significant.

3.3. Partial N Balances, Soil Attribute Changes and Residual Yield Effects

Partial N balances (N added from farmyard manure and legume Ndfa–N removed with harvested rice grain) varied widely between −59 and +38 kg N ha^{-1} (Table 5). While partial N balances were always negative in the non-amended control, they were negative to neutral with pre- and post-rice green manures and consistently positive across years and positions in the combined green and animal manure treatments with N surpluses of +22 to +38 kg N kg N ha^{-1}. These trends in the partial N balances are also reflected in changes of selected soil fertility attributes (Table 6). The soil C and N contents declined in control treatments by −4.4 to −1.1% between the start of the experiment in 2015 and the harvest of the rice crop in 2017. The application of organic amendments significantly improved the soils fertility status, increasing topsoil C contents (0–20 cm) by up to 29% in the fringe and up to 46% in the middle positions. Concomitant increases in soil N due to organic amendments were about 16% with lablab and ranged from 8-44% with stylosanthes across all positions.

In relative terms, a sustained application of sole farmyard manure in the fringe and middle increased soil C and N least compared to green manure legumes. However, the combination of post-rice green manure and farmyard manure showed strongest effects, increasing soil C from initially about 15 to up to 20 g kg^{-1} and soil N from about 0.9 to >1.3 g kg^{-1} after two years of treatment application.

The reported partial N balances (Table 5) and the changes in soil C and N contents following two years of organic amendments (Table 6) were associated with significant residual yield effects in the non-amended rice crop of 2018. Although the initial soil C contents were not significantly correlated with residual grain yields, there was a significant positive correlation between final total soil C content in June 2017 and rice grain yield in 2018 (Figure 4). While grain yields in the control treatment reached 4.4 Mg ha^{-1} in the fringe and 3.2 Mg ha^{-1} in the middle position, yields were significantly higher following pre-rice green manures in the middle (+34% yield-) and following post-rice green manure at both positions (+43% to >100% yield increase). No significant residual effects were detected with sole farmyard manure and pre-rice green manure application in the fringe position.

Table 5. Partial N balances of the lowland rice-based systems in Kilombero floodplain as affected by different organic amendments (2016–2017).

Treatment	2016			2017		
	N Input (kg ha^{-1})	N Removal (kg ha^{-1})	N Balance (kg ha^{-1})	N Input (kg ha^{-1})	N Removal (kg ha^{-1})	N Balance (kg ha^{-1})
Fringe						
Control	0.0	35.8 ^{b}	−35.8 ^{c}	0.0	54.8 ^{c}	−54.8 ^{d}
Farmyard manure (FYM)	60.0	35.6 ^{b}	24.4 ^{a}	60.0	65.7 ^{b}	−5.7 ^{b}
Pre-rice green manure (GM)	4.1	38.4 ^{b}	−34.3 ^{c}	6.7	60.7 ^{b}	−54.0 ^{d}
Post-rice GM	8.9	37.0 ^{b}	−59.1 ^{b}	28.1	54.5 ^{c}	−26.4 ^{c}
Post-rice GM + FYM	89.6	68.0 ^{a}	21.6 ^{a}	106.0	76.2 ^{a}	29.8 ^{a}
Control	0.0	35.6 ^{c}	−35.6 ^{d}	0.0	56.0 ^{d}	−56.0 ^{d}
Middle						
Farmyard manure (FYM)	60.0	42.4 ^{b}	17.6 ^{b}	60.0	71.1 ^{b}	−11.1 ^{b}
Pre-rice green manure (GM)	4.8	40.7 ^{b}	−35.9 ^{d}	6.0	68.3 ^{bc}	−62.3 ^{d}
Post-rice GM	18.1	33.2 ^{c}	−15.1 ^{c}	17.0	63.8 ^{c}	−46.8 ^{c}
Post-rice GM + FYM	95.4	72.8 ^{a}	22.6 ^{a}	121.9	83.9 ^{a}	38.0 ^{a}

N Input = Biomass × N content, N removal = rice grain yield × N content, N balance = N input- N removal. Legume N input = (N fixed (%Ndf × N accum.)) N removal = (grain N uptake (N harvested in the grain)), N balance = N input-N removal. Presented values are means of n = 4 replicates. Different letters within a column denote significant differences different at p < 0.05 according to Tukey test.

Table 6. Residual effect of treatment application on changes in topsoil (0–20 cm) concentration of total carbon and nitrogen before the start of the experiment in 2015 (initial) and after harvesting the third crop in 2017 (final) and on the grain yield of an unamended crop or rainfed lowland rice in 2018.

Position/Treatment	Total Soil Carbon (g kg^{-1})					Total Soil Nitrogen (g kg^{-1})					Rice Yield (Mg ha^{-1})	
	Initial		Final		%Δ	Initial		Final		%Δ		
Fringe												
Control	17.0	±1.07 ^{a}	16.6	±0.52 ^{b}	−2.4	0.92	±0.07 ^{a}	0.91	±0.00 ^{c}	−1.1	4.4	±0.57 ^{c}
Farmyard manure (FYM)	17.0	±1.48 ^{a}	17.6	±1.63 ^{b}	3.5	0.85	±0.07 ^{a}	0.98	±0.04 ^{b}	15.3	5.2	±0.56 ^{bc}
Pre-rice green manure (GM)	16.0	±1.07 ^{a}	18.1	±1.18 ^{ab}	13.1	0.87	±0.05 ^{a}	0.98	±0.05 ^{ab}	12.6	4.3	±0.41 ^{c}
Post-rice green manure	17.5	±2.27 ^{a}	18.7	±0.69 ^{a}	6.9	0.92	±0.09 ^{a}	0.99	±0.00 ^{a}	7.6	6.3	±0.45 ^{a}
Post-rice GM + FYM	15.1	±1.42 ^{a}	19.4	±0.94 ^{a}	28.5	0.81	±0.07 ^{a}	1.12	±0.08 ^{a}	38.3	6.0	±0.61 ^{ab}
Middle												
Control	13.7	±1.59 ^{a}	13.5	±1.09 ^{c}	−1.5	0.90	±0.12 ^{a}	0.86	±0.08 ^{c}	−4.4	3.2	±0.26 ^{c}
Farmyard manure (FYM)	14.8	±2.13 ^{a}	15.3	±2.56 ^{b}	3.4	0.92	±0.14 ^{a}	1.01	±0.18 ^{b}	9.8	4.7	±0.74 ^{b}
Pre-rice green manure (GM)	13.7	±3.42 ^{a}	15.5	±2.09 ^{ab}	13.1	0.89	±0.21 ^{a}	1.03	±0.13 ^{ab}	15.7	4.3	±0.23 ^{b}
Post-rice green manure	16.0	±1.00 ^{a}	21.3	±3.00 ^{a}	33.1	0.97	±0.00 ^{a}	1.40	±0.20 ^{a}	44.3	6.8	±0.22 ^{a}
Post-rice GM + FYM	14.3	±1.93 ^{a}	20.8	±1.69 ^{a}	45.5	0.97	±0.15 ^{a}	1.44	±0.09 ^{a}	48.5	7.2	±0.49 ^{a}
Source of variation												
Treatment	ns		*			ns		*			*	
Location	ns		ns			ns		ns			ns	
Location x Treatment	ns		ns			ns		ns			ns	

Residual response for the unamended rice crop in 2018. Values (means ± SE) followed by different letters within a column denote significant differences at p < 0.05 according to Tukey Test. Significant level '*' 0.05, ns—not significant.

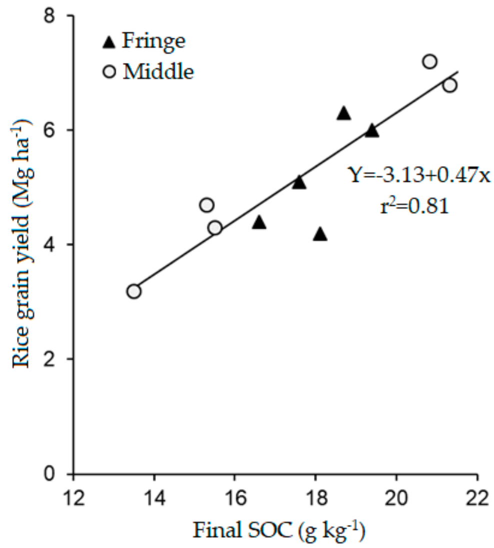

Figure 4. Relationship between final soil organic C and rice grain yield in 2018; y = −3.13 + 0.47x, adjusted $r^2 = 0.81$, df = 8, $p < 0.001$; there was no significant interaction between position and the relationship between soil organic carbon (SOC) and rice grain yield.

Averaged across treatments, the residual yield effects of previously applied organic amendments tended to be higher in the middle than in the fringe positions with 80% and 23% higher yields than in the non-amended control, respectively. N additions by dry and wet deposition or by free-living nitrogen fixation as well as removal by volatilization and denitrification and leaching are not considered.

4. Discussion

4.1. Niches for Organic Amendments

Despite the undisputed large potential of organic amendments for enhancing the productivity and sustainability the availability of farmyard manure is often limited for farmers who don't have animals or it has contested alternative uses, i.e., as amendment in home-gardens or as domestic fuel [37] and only few legumes species are used as green manures in Africa [38]. Thus, the rice-growing area under green manure legumes or receiving farmyard manure has declined from >20 Mio. in the 1980s to <5 Mio. ha in the early 2000s [39].

Such trends raise the question if organic amendments in general and leguminous green manures in particular have not loomed larger in scientists' minds than in those of farmers. In consequence, since the mid-1990s, scientists have analyzed the agronomic and socio-economic constraints to adopting organic amendments at farm level and tried to define niche environments where organic amendments outcompete mineral nutrient sources [40].

Such analyses point to legume seed availability, land limitations for legume growth and labour constraints for manure transport and incorporation to be the main culprits for low adoption rates [41]. Niche environments where green manures out-compete mineral N fertilizers were identified as rainfed systems with variable hydrology and sandy soil texture [12]. In consequence, the use of organic amendments is likely to have the largest impact in environments with little or no labour constraints (small field sizes in densely populated areas or availability of mechanical implements) and in hydrologically-variable environments with light-textured soils. These latter conditions negatively affect the use efficiency of applied mineral N fertilizer and favour the mineralization and effective N uptake by rainfed lowland rice from organic sources. Such social-ecological conditions are largely provided in Kilombero floodplain with land-holdings of <1 ha, the availability of tractor-based tillage implements [42]. In addition, the absence and the relatively high cost or the untimely availability of mineral N fertilizers [29], leave smallholder farmers in the Kilombero floodplain with organic amendments as the more attractive option to improve soil attributes, supply N and increase the performance of the prevailing low-input rainfed rice production systems.

Furthermore, hydrology is a major factor affecting the crop sequence and determining the integration of green manure legumes into rainfed rice production systems. The unreliable water availability associated with many rainfed situations also increases the riskiness of green manure use. Climate projections for Tanzania indicate increasing trends in rainfall amounts in the short (November-December) while decreasing in the long (March-May) rainy seasons [43]. While these projections are expected to favour the integration of legumes in the pre-rice niche, the delay in the onset of the main rainy season with more intense but short rainfall events may also attenuate the moisture deficit in the early dry season [32], thus favouring diverse crop options, including green manures in the post-rice niche. This situation was exemplified in the present study by a relatively better performance of both the pre- and the post-rice green manures in the wet middle position and during the wet year of 2017.

4.2. Direct Benefits of Organic Amendments

The present study considered the application of both farmyard manure and the in-situ growth of green manures as organic amendments for rainfed lowland rice in different floodplain environments of Kilombero (Figure 2). Depending on the position and the year, such strategies resulted in yield increases of 18-62% above the non-amended control. The positive effects from organic amendments can be attributed to the improvement in soil fertility compared to the low indigenous soil fertility in the control treatment. The extent of these yield-increasing effects was in a comparable order of magnitude as effects reported from annual green manure legumes in irrigated rice of the Philippines [44], of perennial legume residues in Zimbabwe [45], and of farmyard manure on rainfed rice in the Indian Punjab [46]. However, in these studies, application rates of organic N sources were either substantially higher than in the present study, or organic amendments were supplementing an application of mineral N [47]. Furthermore, beneficial effects of legume green manures were shown to occur in relatively fertile Gleysols in inland valley wetland with subsurface water and nutrient flow contributions from adjacent valley slopes in West Africa [48]. We show that relatively modest N application rates suffice to enhance the performance of lowland rice in floodplain environments with low soil fertility and additionally differentiated responses to both pre- and post-rice strategies in different hydrological positions. A similar trend was observed but with a larger magnitude of up to 133% yield increase when recommended rates of mineral fertilizer N were applied at the same experimental sites and in the same years [7]. The large, and compared to organic amendment relatively higher rice yield responses to mineral N, even at the moderate application rate of 60 kg ha^{-1} could be related to the low N status of the alluvial floodplain soils [28], where additionally small-scale farmers are not applying fertilizers and are hence mining the soil for nutrients [8]. Such soil fertility considerations are likely to affect particularly organic amendments that have to undergo microbial decomposition before nutrients become plant available. On the other hand, mineral N sources are often not available and rarely affordable by small-scale farmers [10].

Reported benefits from green manures are mainly related to the legumes' ability to accumulate sufficient biomass and to fix atmospheric N_2 during a short growing period. In our study, the amount of atmospheric N fixed in the above-ground green manure legume biomass contributed 4–61 kg N ha^{-1}, depending on the species, the production system, and the fields' position within the floodplain (Table 2). These amounts are substantially less than those reported from some studies in favourable irrigated systems [49] but within the range of works conducted in unfavourable rainfed lowlands in Cambodia [50] or North-East Thailand [51]. The share of N derived from the atmosphere (Ndfa) by biological N_2 fixation was assessed by the δ15N method as suggested by other authors [36] and ranged from 23% to 59%, depending on the species and the system (pre- vs. post-rice legumes). While the net N contributions from multi-purpose long-duration cowpea and from lablab were consistent with ranges reported from grain cowpea [52] or lablab in West Africa [53], the N contribution by stylosanthes grown as a post-rice forage species was much lower than that reported from rice-based systems in Madagascar [54] or from maize-based systems in Kenya [34]. Severe drought following the harvest of rice in 2015 combined with soil compaction after flood recession were likely to have affected legume establishment and stylosanthes growth during the dry season (Figure 2). Also, the small seed size of stylosanthes compared to lablab or cowpea may have negatively affected germination and crop establishment and increased performance variability between years and positions, but also within plots. A poor stand establishment with small-seeded legumes is related to imperfect land preparation and seed deposition at variable depths, from which large seeded legumes can more easily recover than small-seeded ones [55]. We conclude that long-duration multipurpose (forage and green manure) legumes will be required for the extended post-rice niche while short-duration and thus generally larger-seeded (grain and green manure) legumes may be preferred for the pre-rice niche in hydrologically variable floodplain environments.

4.3. Residual Benefits of Organic Amendments in Kilombero

Irrespective of the legume species, the system or the study year, sole growth of green manure legumes resulted in largely negative partial N balances. Only with the addition of farmyard manure N balances of the legume-based systems were positive (Table 5). However, these balance calculations disregarded below-ground biomass and N accumulation, which may have severely under-estimated the legumes' contributions to N balances, particularly in the case of stylosanthes with its extensive and deep root system. On the other hand, the N balances may be even more negative when gaseous N losses are accounted for [20]. Thus, some 15 kg N ha^{-1} are reportedly being lost by the process NH_3 volatilization in rice systems in Asia [56,57], while N losses by denitrification and nitrate leaching have been estimated at 32 kg ha^{-1} in non-amended rainfed rice in Nepal [20] and in Ghana [21]. However, long-term experiments have shown that most of the N added by organic amendments is contained in various organic fractions [58] and becomes only gradually plant available after microbial decomposition. Thus gaseous N losses are minimized and residual effects on subsequent crops can reportedly occur [59], as also observed in the present study where yield increases in previously legume-amended plots could reach 4 Mg ha^{-1} in 2018. (Table 6).

The slow mineralization of both farmyard and green manures compared to mineral N fertilizer [60] may have contributed to the observed build-up of soil organic C and N during the two years of continuous organic treatment application as suggested before [61], and thus have contributed to the reported residual benefits on soil C and N (Table 6), and presumably to higher water-holding capacity [62] and rice yield stability [63]. Similar residual benefits from sustained application of organic amendments have been reported from rainfed lowland rice systems in Asia, particularly on sandy soils with low inherent organic matter contents [64]. Such effects are however not uniform, and in the present case, they differed not only between amendment types and systems but also by the hydrological position of the field plots within the floodplain (Table 6). Thus, largest residual mean rice gain from previously amended plots was observed in the middle positions, while gains were less evident in floodplain fringes. This observation further stresses that the effects of organic amendments strategies are transferable in both hydrological positions but higher in the middle position of the Kilombero floodplain.

In summary, we assessed legume performance as well as direct and residual yield benefits from different organic amendments. The reported effects of manures on increasing rice grain yields, and soil C and N contents were confirmed for a floodplain wetland in East Africa by our work. We believe that comparable benefits may be obtained in other hydrologically variable floodplain environments of the region and beyond. However, given the large variability in hydrological situations both between positions and years, the effects of building soil organic matter for buffering hydrological extremes as well as the phyto-sanitary and weed suppression aspects warrant further research attention in the future.

5. Conclusions

This study highlights the importance of green and farmyard manure application in resource-poor smallholder rice farming systems. Repeated application of organic amendments can enhance soil C and N with associated effects on direct and residual rice yield increase in the Kilombero floodplain. With the prevalence of rainfed lowland systems with one single crop per year, there are available cropping niches for both pre- and post-rice green manure growth. In addition, the widespread cattle rearing in the area ensures the availability of farmyard manure. These organic amendments provide small-scale rainfed rice farmers with a promising alternative to poorly-available and generally non-affordable mineral N fertilizers for soil fertility restoration and enhanced sustainable food production in hydrologically variable floodplain environments.

Author Contributions: Conceptualization, M.B., D.N. and K.S.; methodology, J.K., D.N., K.S. and M.B.; validation, D.N. and M.B.; formal analysis, J.K., M.B.; investigation, J.K., K.S. and D.N.; resources, K.S., D.N. and M.B.; data curation, J.K., K.G.; writing—original draft preparation, J.K.; writing—review and editing J.K., K.G., D.N., K.S., T.F.D. and M.B.; visualization, J.K, D.N., T.F.D. and M.B.; supervision, D.N., K.S. and M.B.; project administration, D.N. and M.B.; funding acquisition, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry for Education and Research (BMBF) grant number FKZ 031A250 A-H, with additional funding provided by the German Federal Ministry of Economic Cooperation and Development.

Acknowledgments: The authors are grateful to Geoffrey Gabiri for the depth to ground water data and the field assistants for field establishment and management.

Conflicts of Interest: The authors declare no conflict of interest.

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