agronomy

MDPI

Article

Influence of Water Management Farming Practices on Soil Organic Carbon and Nutrients: A Case Study of Rice Farming in Kilombero Valley, Tanzania

Edmond Alavaisha [1,2,*], Madaka Tumbo [3], Jacqueline Senyangwa [4,5] and Sixbert Mourice [6]

1 Institute of Resource Assessment, University of Dar es Salaam, Dar es Salaam P.O. Box 35097, Tanzania
2 Bolin Centre for Climate Research, 106 91 Stockholm, Sweden
3 Water Institute, Dar es Salaam P.O. Box 35059, Tanzania; madaka.tumbo@gmail.com
4 Department of Chemical Engineering, University of Cape Town, Rondebosch, Cape Town 7700, South Africa; nikusenyagwa@gmail.com
5 Stockholm Environment Institute-Africa Centre, World Agroforestry Centre, United Nations Avenue, Giri, P.O. Box 30677, Nairobi 00100, Kenya
6 Department of Crop Science and Horticulture, Sokoine University of Agriculture, Morogoro P.O. Box 3005, Tanzania; sixbert.mourice@gmail.com
* Correspondence: edmondalavaish@yahoo.com; Tel.: +255-719-964-870

Abstract: Water scarcity and nutrient availability for rice farming have become great matters of concern in the contexts of climate change and land use change globally. Both interact and contribute to crop productivity at the expense of nutrients and future water sustainability. The objective of this study was to understand the on-farm potential response of soil organic carbon (SOC), total nitrogen (TN), and total phosphorous (TP) to water management practices in rice farming within the Kilombero Valley, Tanzania. Soil samples were collected from three villages in the study area at four depths: 0–20, 20–30, 30–40, and 40–50 cm. Four water management regimes, namely: A = traditional flooding (rainfed) without intensification of rice farming; B = traditional flooding (rainfed) involving a system of rice intensification (SRI); C = alternative wetting and drying (AWD) involving SRI for one cropping season; D = abandoned fields (fallow); and E = AWD involving SRI for two cropping seasons, were investigated as regards their impact on SOC, TN, and TP. There were significant ($p < 0.05$) effects of water management regimes on SOC, TN, and TP. AWD involving SRI for one cropping season indicated a positive effect on SOC and TN across all depths as compared to other practices. We conclude that water management practice that involves AWD with SRI for one cropping season is a plausible approach to maintaining high SOC and TN, with the potential for increasing crop production while minimizing water consumption.

Keywords: rice; soil nutrients; farming management practice; irrigation; alternative wetting and drying (AWD); system of rice intensification (SRI)

Citation: Alavaisha, E.; Tumbo, M.; Senyangwa, J.; Mourice, S. Influence of Water Management Farming Practices on Soil Organic Carbon and Nutrients: A Case Study of Rice Farming in Kilombero Valley, Tanzania. *Agronomy* **2022**, *12*, 1148. https://doi.org/10.3390/agronomy12051148

Academic Editor: Stefano Marino

Received: 22 February 2022
Accepted: 6 April 2022
Published: 10 May 2022

1. Introduction

Rice (*Oryza sativa* L.) farming is one of the main activities and sources of income for people and is the most widely cultivated crop worldwide [1,2]. It is a major staple crop which sustains about 3 billion people [3], with about two-thirds of the total rice production grown under irrigation [2,4]. To achieve high yields, soils in rice fields need to be saturated [5,6], which requires large amounts of freshwater to be available. It is thus not surprising that the rice water productivity (yield per unit water used) averages as low as 0.4 kg of grain per cubic meter of water, or about half the water productivity of wheat [3]. Irrigation of rice grown during the dry season encompasses nearly 30% of global freshwater withdrawals. Considering the current 2.4% per year increase in rice demand [7], the need for more rice with less water is crucial for food security, and irrigation plays a greater role in meeting future food needs under climate change and land use change—driven by human population growth.

In the context of climate change and population growth, more efficient water management practices are required to meet food demand in an era of increasing water scarcity. One important water-saving practice in the rice field is alternative wetting and drying (AWD) that is conducted at varying frequencies and intensities during crop production [8,9]. The practice deliberately saves water and enhances the crop's water use efficiency. For example, [8,10] reported reducing water use by 23–30% compared to flooding practice. The use of irrigation water for producing rice can potentially be reduced by lowering the depth and duration (time) of standing water and by allowing the soil surface to dry before the next application of irrigation water. The practice ensures a supply of moisture at a level where rice roots can access the water in the subsurface soil, which remains saturated. It is also used for enhancing minimum use fertilizer as it minimizes leaching effects below the soil surface of farmland [5,11].

The duration, regularity, and predictability of rice field flooding have effects on the temporal variation of the water depth (volume), chemistry, microbial activity, and soil fertility [12–15]. AWD can improve crop nutrition, and re-wetting dry soil provokes both physical and biological changes that affect soil nutrient availability. Whether this alters crop nutrient uptake depends on competition between plants and microbes for nutrients, with the rate of re-wetting determining microbial dynamics. The practice creates aerobic and anaerobic conditions in the soil; the aerobic favoring soil microbial metabolism, fostering the degradation of soil organic carbon (SOC) [16], and releasing nutrients [17]. Under anaerobic conditions typical of flooded paddy fields, SOC can accumulate at a rate of 0.5 t/ha/y [18,19], but under more aerobic conditions, much of SOC is lost [20,21].

Soils in rice monoculture are susceptible to either loss or built-up SOC and nutrients when converted to the production of aerobic rice. Globally, SOC losses due to shifts to aerobic conditions could amount to about 1.2 Gt (about 20% of anthropogenic SOC emissions over one year), with agriculture accounting for a large portion, suggesting that AWD may reduce the global carbon sink of rice land in the long run; submergence of rice soils helps maintain SOC, even with intensive rice cropping [22]. This maintenance of SOC ensures that C remains sequestered in the soil. Soil submergence also promotes biological nitrogen fixation [23,24], and submerged soils can reduce microbial biological activity in long-term experiments.

SOC concentrations correlate with agricultural productivity and resource use efficiency [25]. When SOC is lost, nutrients in organic form—specifically N and P—are mineralized because they are chemically bound to organic C in relatively fixed proportions [17,26]. In contrast to relatively stable organic N and P, mineralized products can be leached, especially in the humid conditions typical of rice growing areas [3]. Thus, reducing the duration of soil saturation will increase water savings and minimize farm nutrient loss. Fertilizer requirements for rice production could be higher for aerobic soil than submerged soil. A higher need for fertilizer can arise from a lower natural N supply due to lower fixation nutrients (N) and possible lower net N mineralization in aerobic soil. A higher need for fertilizer P can arise from the reduced availability of soil P in aerobic soil. The crop management practice of using water-efficient practices is being promoted as a water-saving irrigation practice in the current population expansion and climate change era. Management of water by drying and wetting substantially affects yield and investment cost. However, there is still a need for more experiments to understand the influence of practice on the dynamics of nutrients, particularly in small-to-medium-scale rice farmers in developing countries where most have limited capital to access fertilizers and agrochemicals. Therefore, this study aims to evaluate the performance of various rice farming water management practices on enhancing soil organic carbon and nutrients using the Kilombero Valley in Tanzania as a case study.

2. Materials and Methods

2.1. Study Area

The was conducted in the Kilombero Valley, located in the southern central part of Tanzania (Figure 1). In situ experimental design was used in three selected villages, namely: Njage, Mkangawalo, which are located in the north, and Mkula, in the south-west of Ifakara town. The valley covers an area of approximately 39,000 km^2, with elevation ranges of 200 and 2500 m.a.s.l extending from Usangu to lower Rufiji [27]. The valley forms a broad floodplain bordered by a series of Udzungwa mountains in the north-west and the Mahenge highlands in the south-east.

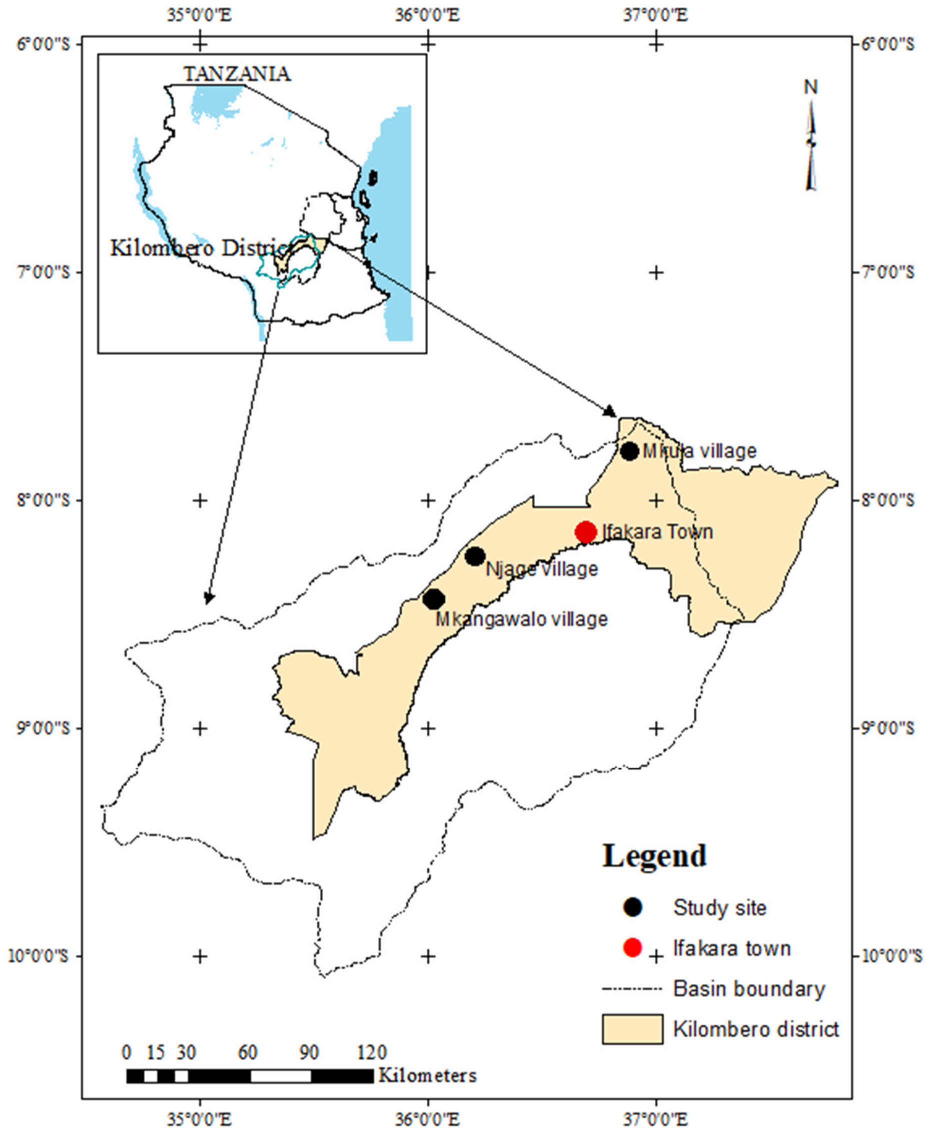

Figure 1. Map of Kilombero District and basin (Tanzania—inset) showing sampling villages in black circles.

The climatic condition of the valley is typical of the humid tropics, with an annual average rainfall of 1200–1400 mm. The valley is characterized by bimodal rainfall. The long-rain season is between March and May, and the short-rain season is between November and January. Despite uniform rainfall, the discharge of the rivers changes year to year due to variability and siltation. The daily mean temperature is between 22 and 23 °C. However, it varies with topography, where forested mountain areas are cooler compared to open flood plain areas [27]. The vegetation in the valley follows the gradient from high altitude, where there are higher plants comprised of miombo and evergreen forest, to the lower part of the valley, with shrubs and grassland. The lower part is used for farming, unlike the upper part of the valley, which is a reserve and a national park with small patches converted to small cultivated farms. The soils of the Kilombero Valley floodplain are classified as cambisols (inceptisols) on the upper slopes, fluvisols (entisols) in the valleys, and leptosols (entisols) on the lower slopes, and they hold water for long periods of time [28].

The valley is among important agro-investment sites in the *Kilimo kwanza* (Agriculture First) initiative, under the Southern Agricultural Growth Corridor of Tanzania (SAGCOT) project. Common crops are rice, maize, and banana for both food and commercial purposes. Other crops are cocoa, sugarcane, sesame, and sunflower, which are strictly commercial [12]. Farmers range from the majority of small-scale to medium-scale and large-scale. Over 80% are smallholders participating in irrigated and rainfed farming [29,30]. At Njage and Mkula, they depend both on irrigation schemes and rainfed farming for up to two rice farming seasons; unlike at Mkangawalo, where they only depend on rainfed farming for one farming season. Within irrigation farming practices there are different water management and farming techniques, both with goal of minimizing water usage, prolonging farming seasons, and increasing production. In most irrigation schemes of Kilombero, farmers adopted systems of rice intensification to increase crop yield with minimum agro-input and water. The practices include various AWD techniques (with either one or two cropping seasons) and organic amendment to conserve soil moisture. Rice farming practices in the Kilombero Valley are mainly traditional flooded irrigation that depends on rainfall, or irrigation using stream water diverted to irrigation canals. Under traditional flooding, farmers do not have control over ponding water in terms of quantity and residence time. However, the farming is either non-intensive or intensive, using agrochemicals to increase production. In sites with irrigation schemes or a reliable supply of water, systems of rice intensification (SRI) are common. The practice is water-efficient and uses improved seedlings singly spaced. Farming management and harvesting involve the use of agrochemicals, fertilizers, and simple machinery.

2.2. Sampling Design and Experimental Set up

Soil sampling methods were adopted and slightly modified from [12] (see flow chart in Figure 2). Soil sampling was conducted during the dry season, involving sites that were either already harvested or about to be prepared for another cropping season. Within each selected field and management practices, sampling plots were established with four to five replicated plots each. Five plots with a 10 m radius relative to the center of the farm were randomly distributed in each field under each of the following management practices: A = traditional flood irrigation (rainfed) without intensification of rice farming; B = traditional flooding (rainfed) with a system of rice intensification (SRI); C = alternative wetting and drying (AWD) farming practice involving SRI with one cropping season; D = abandoned fields (fallow) that had not been cultivated for approximately 7 years (reference sites); and E = AWD farming practice involving SRI with two cropping seasons. The selection of sites with different management practices was not random, but plots were randomly distributed to capture variations in farms during soil sampling work. The farming practices were locally adopted, yet have national and regional importance.

To estimate concentrations of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP), each plot in each field was sampled to 50 cm depth, including four soil layers: 0–20, 20–30, 30–40, and 40–50 cm. In each plot, five soil subsamples were taken using a soil auger (UNISON ENV. AB); one at the center and four others following a 90° sequence with respect to the center (Figure 3). Collected subsamples were mixed to obtain one homogenized sample per plot. Homogenized samples were stored in zip bags and taken to the laboratory for physical (texture) and chemical analyses (pH value, SOC, TN, TP). In addition, an undisturbed soil core was taken at the center of each plot for bulk density (BD) determination.

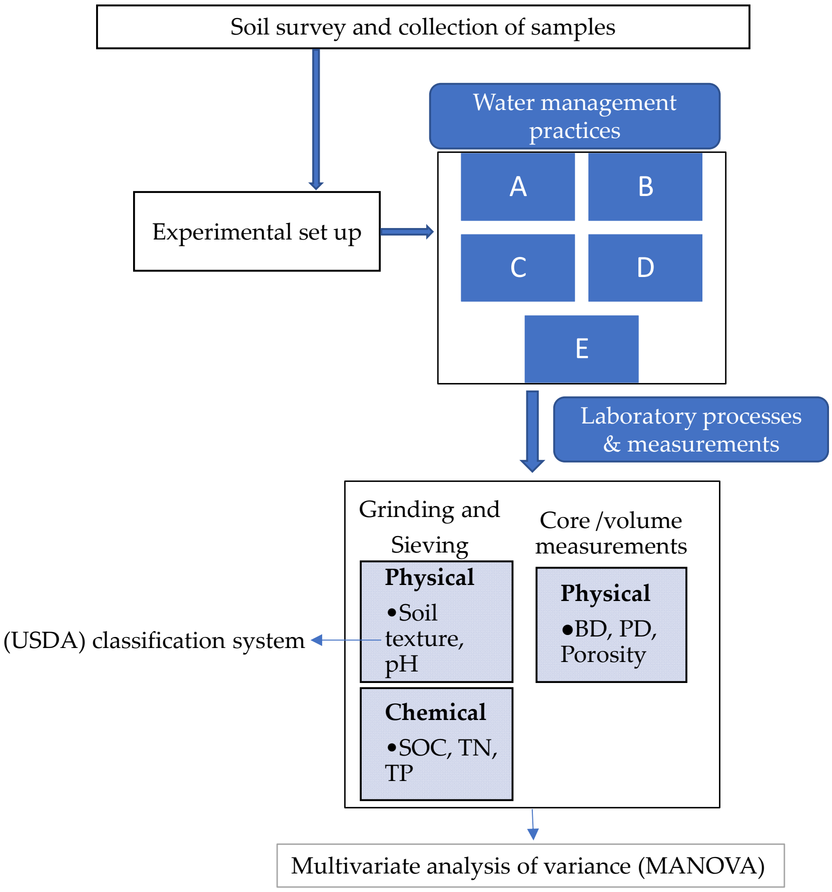

Figure 2. Flow chart for field experimental design and laboratory procedures and analyses. Letters A = traditional flood irrigation (rainfed) without intensification of rice farming, B = traditional flooding (rainfed) with rice intensification (SRI), C = AWD farming practice involving SRI with one cropping season, D = abandoned fields, and E = AWD farming practice involving SRI with two cropping seasons. BD—bulk density; PD—particle density; SOC—soil organic carbon; TN—total nitrogen; TP—total phosphorous.

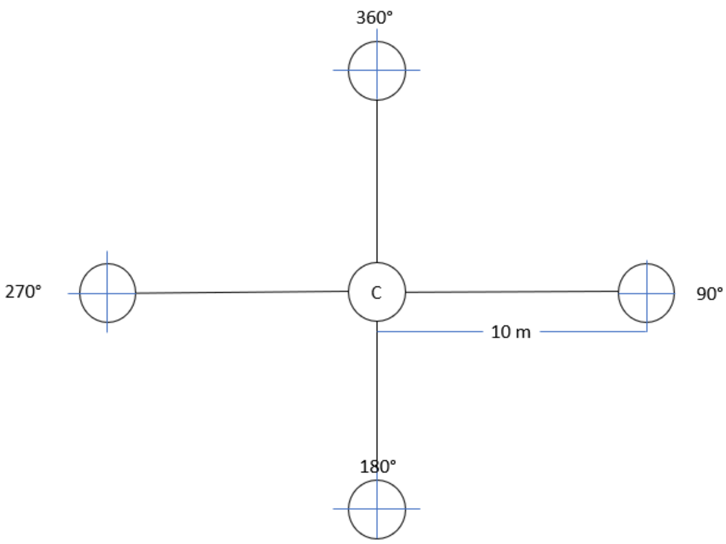

Figure 3. Illustration of sampling plot with composite subplots in different directions from the center.

2.3. Laboratory Analyses

Prior to laboratory analysis, the samples were oven dried at 50 °C (for 24 h), sorted to remove roots and litter debris, and grinded and sieved to obtain a homogenous mixture. Soil texture was analyzed using the hydrometer method [31,32], pH using supernatant suspension of 1:2.5 soil: 1 M KCL [32], bulk density (BD) using dry weight and volume of core (Equation (1)), particle density using mass of dry soil and volume (Equation (2)), and porosity using BD and particle density (Equation (3)). The determination of SOC concentrations was analyzed by the Walkley–Black procedures [31] where potassium dichromate ($K_2Cr_2O_2$) and concentrated sulfuric acid (H_2SO_4) were used. TN concentrations were completed following the Kjeldahl acid-digestion procedures [31,32], and TP was determined through perchloric acid digestion and then measured by calorimetry [32].

$$\text{Bulk Density (BD)} = \frac{\text{Dry weight (g)}}{\text{Volume of soil core (cm}^3\text{)}} \quad (1)$$

$$\text{Particle Density (PD)} = \frac{\text{Mass of dry soil (g)}}{\text{Volume of soil particle (cm}^3\text{)}} \quad (2)$$

$$\text{Porosity} = 1 - \left(\frac{\text{Bulk Density (BD)}}{\text{Particle Density (PD)}}\right) \quad (3)$$

2.4. Statistical Analyses

The data was tested and found to be normally distributed. Descriptive analyses were used to find variation in mean SOC, TN, and TP concentrations among farming practices and soil profiles. Textural characteristics of sampled soils were analyzed using the United States Department of Agriculture (USDA) classification system. Multivariate analysis of variance (MANOVA) was used for comparison of concentrations of SOC and TN and TP among different farming practices (A = traditional flood irrigation (rainfed) without intensification of rice farming; B = traditional flooding (rainfed) with intensification of rice farming; C = AWD farming practice involving SRI with one cropping season; D = abandoned fields; and E = AWD farming practice involving SRI with two cropping seasons), and depth (0–20, 20–30, 30–40, and 40–50 cm). A pairwise comparison using a post-hoc Tukey test was conducted to determine differences within management practices and depth intervals. Environmental factors (physical properties of soils) were also incorporated into the study. Because they are continuous variables, Pearson correlations were used to discover relationships between SOC and nutrient variation and soil physical and chemical characteristics (pH, soil texture, BD, and porosity). Analyses were carried out using Microsoft Excel 2016, Texture AutoLookup (TAL) Version 2.81 and IBM SPSS Version 26 statistical software. All statistical tests were considered statistically significant at $p < 0.05$ (95% confidence interval).

3. Results

3.1. Soil Texture

Soil texture was classified using both in the field and laboratory techniques to determine soil classes based on their physical texture. Soil texture (such as loam, sandy loam or clay) refers to the proportion of sand, silt, and clay sized particles that make up the mineral fraction of the soil. All sampling plots regardless of management practices and depth were similar, about 98% fall under silt loam texture (Figure 4). With this texture, roots are not restricted from growing and water holding and nutrient retention is fairly good.

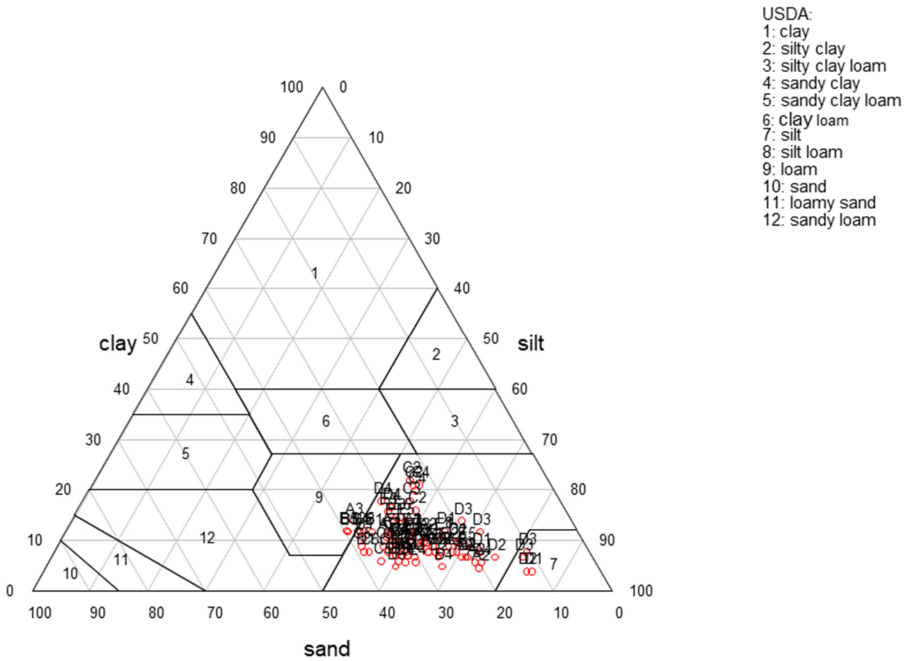

Figure 4. The soil textural triangle indicating the soil textures of sampled plots of different farming practices.

3.2. Variation in SOC and Nutrients across Farming Practices

We compared concentrations of SOC, TN, and TP between different water management farming practices. Alternative wetting and drying with one cropping season were found to have a higher mean concentration of SOC (21.94 4.45 g kg^{-1}) and TN (2.21 0.37 g kg^{-1}). In contrast, lower concentrations of SOC and TN were 7.45 1.26 and 1.08 0.90 g kg^{-1}, respectively, found in traditional rice flooding irrigation with intensification. SOC, TN, and TP concentrations were found to be affected by farming practices (Figure 5; Table S1). AWD farming practice involving SRI with one farming season had significantly higher SOC compared to traditional flooded with ($p = 0.000$) and without ($p = 0.001$) intensification. Similarly, TN was significantly higher in AWD farming practices involving SRI with one farming season compared to flooded irrigation farming practices. TP concentrations were significantly different ($p = 0.037$) between traditional flooding farming without intensification and AWD farming practice involving SRI with two seasons. Interestingly, AWD involving SRI with one cropping and abandoned field had relatively higher SOC and TN but lower bulk densities.

3.3. Effects of Farming Practices and Depths on BD, SOC, Soil pH, TN, and TP

SOC, TN, and TP concentrations varied from one farming practice to another, whereas BD increased with depth across the practices, as expected (Figure 6; Table S2). SOC was highly variable in AWD involving SRI for one cropping season as contrasted to traditional flooding, even though they had comparable quantities in top soil. TP was generally low across practices and depths, save for top soil layer in AWD involving SRI for one cropping season, fallow, and AWD involving SRI for two seasons. In all farming practices, higher mean concentrations of SOC, TN, and TP were found in the upper soil layers. SOC concentration (g kg^{-1}) decreased with depth in all farming practices except in fallow field, which were relatively constant (see Figure 6). SOC were higher in AWD farming practice involving SRI for one cropping season across soil depths. However, AWD farming practice involving SRI with two cropping seasons and fallow field had lower SOC in upper soil layers and significantly higher ($p < 0.05$) SOC and TP were in deep soil layers, 30–40 cm, and 40–50 cm. No significant difference ($p = 0.263$) of mean TP concentration with depth in farming in all farming practices was observed. Median soil pH was lower in top soil of

AWD farming practice involving SRI with one farming season and AWD farming practice involving SRI with two cropping seasons, compared to that of traditional flooding practices and in a fallow (Figure 6).

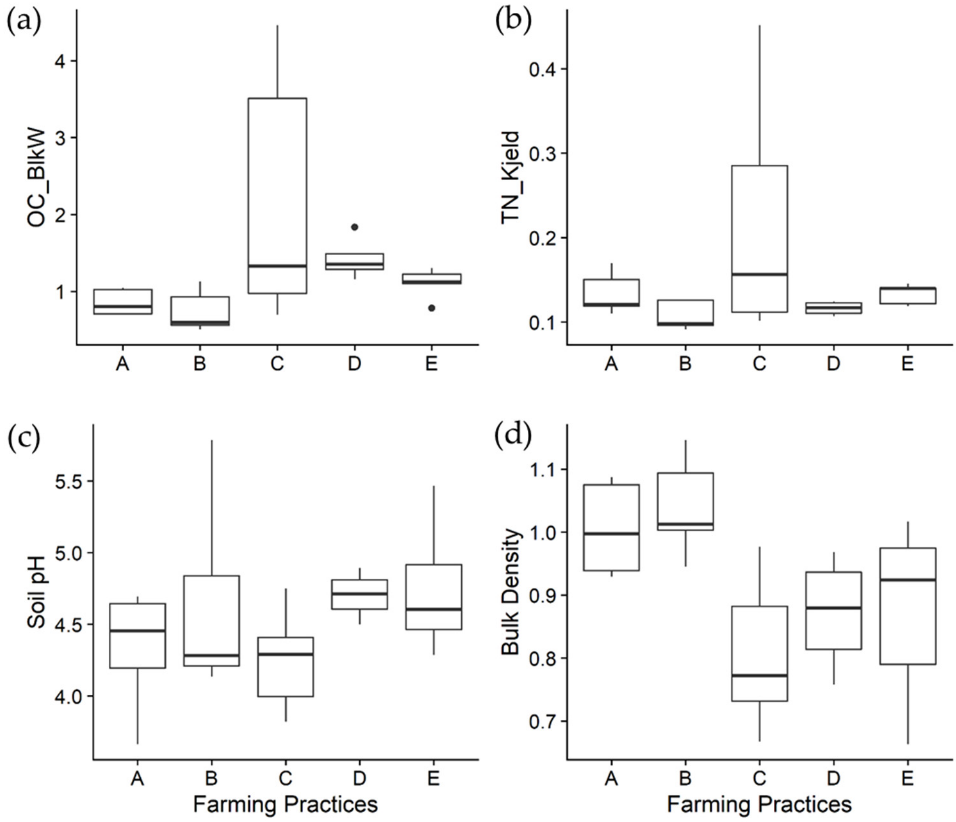

Figure 5. Boxplots for SOC (**a**), TN (**b**), soil pH (**c**), and BD (**d**) among different farming practices in Kilombero valley. Letters on the X-axis denote: A = traditional flood irrigation (rainfed) without intensification of rice farming; B = traditional flooding (rainfed) with rice intensification (SRI); C = AWD farming practice involving SRI with one cropping season; D = abandoned fields; and E = AWD farming practice involving SRI with two cropping seasons.

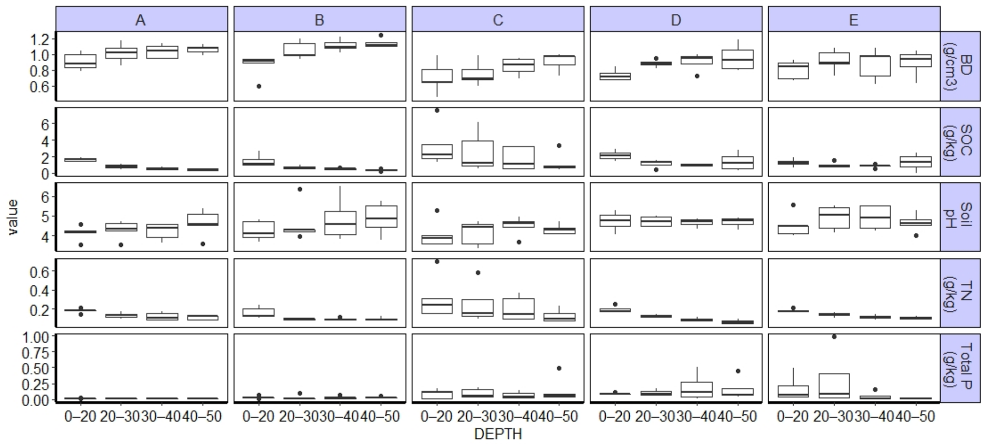

Figure 6. Boxplots for BD, SOC, soil pH, TN, and TP as regards farming practices A, B, C, D, and E and soil depth within the study area. A = traditional flood irrigation (rainfed) without intensification of rice farming; B = traditional flooding (rainfed) with rice intensification (SRI); C = AWD farming practice involving SRI with one cropping season; D = abandoned fields; and E = AWD farming practice involving SRI with two seasons.

3.4. Relationship among SOC, Nutrients (TN and TP), and Physical Characteristics of Soils

After examining the effect of farming practices with depth, we find a relationship of environmental variables with SOC, TN, and TP (Table 1). Pearson correlation indicated BD had a significant negative correlation with SOC, TN, and TP concentrations. Furthermore, porosity was positively correlated with mean SOC, TN, and TP, meaning increases in pore spaces increased accumulation of nutrients and lower bulk density. SOC, and TN and silt were significantly positive correlated and negative correlated with sand.

Table 1. Pearson correlation matrix between soil texture, pH, BD, porosity, SOC, TN, and TP in Kilombero Valley.

	% Clay	% Silt	% Sand	pH	BD g cm^{-3}	Porosity	SOC g kg^{-1}	TN g kg^{-1}	TP g kg^{-1}
%Clay	1	0.088	−0.869 **	−0.142	−0.070	0.051	0.009	0.081	−0.168
%Silt		1	−0.570 **	−0.073	−0.563 **	0.538 **	0.485 **	0.454 **	0.122
%Sand			1	0.153	0.338 **	−0.310 **	−0.248 *	−0.293 **	0.077
pH				1	0.216 *	−0.210 *	−0.254 *	−0.260 *	0.028
BD g cm^{-3}					1	−0.835 **	−0.685 **	−0.587 **	−0.221 *
Porosity						1	0.569 **	0.477 **	0.227 *
SOC g kg^{-1}							1	0.881**	0.137
TN g kg^{-1}								1	0.133
TP g kg^{-1}									1

** Correlation is significant at the 0.01 level and * at the 0.05 level.

4. Discussion

As the human population increases, more food will be required, and consequently, more pressure will be felt on land resources. The situation will worsen, especially in rice-growing areas where per capita land holding is decreasing. Soil fertility and quality are likely to suffer as a result of continuous cultivation and unsustainable soil and water management practices. Rice agriculture systems, on the other hand, are both causes (high potential for greenhouse gas emissions) and victims (increased water scarcity) of climate change. There is a pressing need to strike a balance between mitigating climate change and overcoming water scarcity and soil fertility challenges in rice agriculture.

4.1. Variation in SOC, TN, and TP with Management Practices

Farming management practices impact nutrient accessibility in agroecosystems [33,34]. Most farming practices are expected to improve soil quality, structure, and fertility, which are crucial for food production and global food security. In this study, mean concentrations of SOC, TN, and TP differed between water management farming practices. Alternative wetting and drying have been promoted as farming practices with the potential to reduce greenhouse gas emissions, especially methane [35,36]. The fact that AWD with SRI in one cropping season had a higher mean concentration of SOC and TN as compared with continuous flooding agrees with findings by other researchers [10,37,38]. In [39], the authors show that AWD fosters SOC and nitrogen accumulation as it halts anaerobic decomposition of organic matter in the soil, which results in methane and denitrification, which in turn emits N_2O [39]. Any practice that prevents carbon and nitrogen depletion in the soils under rice agriculture saves energy. Incorporation of crop residues requires tractor power, which should be derived from fossil fuel, while the production of nitrogen fertilizer demands energy too, right from the production process to transportation and application. In this regard, AWD may be an important farming practice in rice-cropping systems due to its low carbon footprint and hence a mitigation pathway as far as climate change is concerned. In addition, AWD can potentially save water, up to 23% compared to continuous flooding [8,10], suggesting that as precipitation drops and pressure on freshwater resources mounts, AWD practice should be taken seriously to overcome imminent challenges.

4.2. Influence of Management Practices and Depth on SOC, TN, and TP

As expected, depth had significant effects on soil quality and fertility with higher values at the top than deep layers across water management practices. This trend can be attributed to the fact that most operations are confined to the plough layer (0–20 cm depth) below which the exchange of materials becomes slow over time. For instance, the authors of [40–43] pointed to a decreasing trend of concentrations of SOC and TN with depth under irrigation and fertilizer application. The current study points to a similar pattern as well. However, AWD with one cropping season had higher mean concentration of SOC, TN across the soil profile compared to other practices, suggesting enhanced root penetration which contributes to SOC as a result of root decomposition, TN and TP as a result of increased root exudates and/or microbial activity. As for continuous flooding, anaerobic conditions may not necessarily contribute to SOC since the organic matter decomposing anaerobically forms methane which is released to the atmosphere. Thus, less organic carbon may be left in lower soil layers, and hence low SOC reported in the current study. The concentrations of SOC, TN, and TP were decreasing with increasing depth. In all farming management, higher SOC, TN, and TP concentrations were found in the upper soil layers. SOC concentration decreased with depth in all farming practices except in abandoned field, which were relatively constant (Figure 6). Our findings are similar to those reported by [22,44,45], where higher nutrients were found in the top soil layer, because of water saturation and direct nutrient inputs. In cultivated land, higher concentration in the top layers can be explained by additional residuals and chemical fertilizers. The amount of available nutrients in soils also depends on microbial and decomposition rate of organic matter. Higher levels of moisture content brought about by irrigation management can create anaerobic conditions that reduce decomposition and mediate nutrient accumulation [10,16]. AWD with SRI in one cropping results in the accumulation of SOC and TN in the upper-most layer that is saturated with water. These findings concur with [16,45], who noted that moisture above threshold level lowers microbial activities resulting in accumulation of nutrients. In addition, AWD with intensification accompanied with fertilization that has a positive impact on the SOC and TN concentrations in the upper soil layers [37,38], unless exposed to leaching.

Although AWD associated with SRI involves the use of both organic amendments and inorganic fertilizers [46], low quantities of TN may be due to less application of N fertilizers typical of low input farming or less water volumes used. The authors of [47] and [12] found higher TN concentrations in deep soil layers in organic amendment and irrigation. In continuous flooding practice where TN was expected to be higher in lower layers than AWD with SRI due to leaching, because of a large water volume used [48], it was not the case. This suggests that the nitrogen supply might have just been enough to cater for plant demand for the respective growing season. For instance, in [40,49] the authors pointed out that excess irrigation and fertilization contributed to higher nutrients in deep soil layers and deprived nutrients in the top soil layer; however, the degree of irrigation dominated the effect. The irrigation frequency also determines the leaching potential. Maintaining the moisture threshold improves agronomic conditions through mitigation of the impacts of excessive water use on crop yields [5,50].

Concentrations of TP were not significantly different among all farming practices across the depths. These results contrasted with other large-scale studies reporting increased phosphorous availability following soil drying and rewetting under both aerobic and anaerobic conditions. For example, AWD causes destruction of aggregates unlike continuous wetting [44]. Our findings may be attributed to the fact that the time frame for management practices was short, unlike in most large-scale farms, insufficient to notice changes in concentration of TP with depth [12,14,51]; unlike SOC and TN which respond quickly to microbial dynamics triggered by moisture content with depth. This might be the case in the Kilombero where soil is wetter; the addition AWD is more likely to cause accumulation SOC and TN, quicker than TP.

4.3. Environmental Factors and SOC and Nutrient Dynamics

Physical properties of soils were correlated with SOC, TN, and TP concentrations. BD was negatively correlated with SOC, TN, and TP, while porosity was positively correlated with SOC, TN, and TP. SOC and TN were positively correlated and were positively associated with the silt content and negatively with sand. High SOC and TN in the topsoil layer are associated with low bulk density and high porosity, all of which lead to increased water holding capacity [8,10,52]. Aggregates due to low bulk density allow water and nutrients to percolate to deeper soil layers, contributing to higher concentrations in deep soil layers reported in AWD practices involving SRI. Interestingly, high nutrients in traditional flooded areas with and without intensification may be associated with soil colloidal systems which enhance nutrient holding capacity and hence show a positive correlation with TN. This also points to the possibility of increasing N availability under AWD [5,10].

Soil texture affects plant growth and nutrient uptake because it alters the availability of water in the soil. The soils in AWD practice involving SRI had higher silt and clay content, subsequently SOC. The authors of [53] reported similar results, finding that soils in lacustrine accumulate SOC and favor less movement of water, which can influence root growth and crop production [3,52,54]. Soils with clay and silt contents have small to moderate pore spaces, thus lower rates of water diffusion, further compounded by absorption of water. This is an interesting fact that has practical application, especially for selection of crops; for examples, crops with small roots perform well in organic rich soil with less BD in upper soil layers. Further, the authors of [14,53] noted irrigation management that improves bulk density and soil texture associated with irrigation water saving, nutrient accumulation, and high crop yields. In contrast, irrigation practices lacking the soil and water conservation practices cause infiltration problems and loss of soil nutrients.

5. Conclusions

Water use management in rice farming is very important, particularly because of increasing water scarcity and the need to reduce greenhouse gas emissions to mitigate climate change challenges. We conclude that water management practice that involves AWD with SRI for one cropping season is a plausible approach for maintaining high SOC and TN in small-scale rice farming systems. This not only limits CO_2 emissions and nitrogen leaching, but also saves water. More research is required to understand the rates at which greenhouse gases can be reduced by this approach, the thresholds beyond which nitrogen leaching may become problematic, as well as water application rates that maintain higher yields in the Kilombero valley.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12051148/s1, Table S1: Multivariate analysis of variance (MANOVA) to show differences in SOC, nutrient, and physical properties of soil among farming management practices and depth at Kilombero Valley; Table S2: Post hoc Turkey test results to show direction of variation in soil properties and nutrients among farming practices and depth at Kilombero Valley.

Author Contributions: Conceptualization, E.A. and M.T.; methodology, E.A. and M.T.; software, E.A.; validation, E.A., M.T. and S.M.; formal analysis, E.A. and S.M.; investigation, E.A.; writing—original draft preparation, E.A. and S.M.; writing—review and editing, E.A., M.T., S.M., J.S.; visualization, E.A., M.T. and S.M.; project administration, M.T.; funding acquisition, M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was fully funded by the African Academy of Science (AAS) through CR4D project, grant number CR4D-19-07. Edmond Alavaisha also acknowledges the support from the Sida Grant SWE-2011-066 and Sida Decision 2015-000032 Contribution 51170071 Sub-project 2239.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Datasets generated during and/or analyzed during the study are available from corresponding author on fair request.

Acknowledgments: Assistance and cooperation provided by village leaders and communities of Njage, Mkangawalo, and Mkula is highly appreciated. We thank all farmers that allowed their pieces of land to be used in this research. Further, we extend our appreciation to staff of the Department of Soil and Geological Science, Sokoine University, Morogoro for laboratory analyses.

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

References

1. FAO. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW)–Managing Systems at Risk*; Food and Agriculture Organization of the United Nations: Rome, Italy; Earthscan: London, UK, 2011; ISBN 9780203142837.
2. Chauhan, B.S.; Jabran, K.; Mahajan, G. *Rice Production Worldwide*; Springer International Publishing: Berlin/Heidelberg, Germany, 2017; ISBN 9783319475165.
3. Bouman, B.; Lampayan, R.M.; Tuong, T.P. *Water Management in Irrigated Rice: Coping with Water Scarcity*; International Rice Research Institute: Los Banos, Philippines, 2007; ISBN 9789712202193.
4. Maclean, J.L.; Dawe, D.C.; Hardy, B.; Hettel, G.P. *Rice Almanac*, 3rd ed.; CABI Publishing: Wallingford, UK, 2003; Volume 92.
5. Cao, X.; Wu, L.; Lu, R.; Zhu, L.; Zhang, J.; Jin, Q. Irrigation and fertilization management to optimize rice yield, water productivity and nitrogen recovery efficiency. *Irrig. Sci.* **2021**, *39*, 235–249. [CrossRef]
6. Guo, J.; Fan, J.; Xiang, Y.; Zhang, F.; Yan, S.; Zhang, X.; Zheng, J.; Lii, Y.; Tang, Z.; Li, Z. Coupling effects of irrigation amount and nitrogen fertilizer type on grain yield, water productivity and nitrogen use efficiency of drip-irrigated maize. *Agric. Water Manag.* **2022**, *261*, 107389. [CrossRef]
7. Linquist, B.A.; Anders, M.M.; Adviento-Borbe, M.A.A.; Chaney, R.L.; Nalley, L.L.; da Rosa, E.F.F.; van Kessel, C. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Glob. Chang. Biol.* **2015**, *21*, 407–417. [CrossRef] [PubMed]
8. Mote, K.; Rao, V.P.; Avil, V.R.K.; Uma, K.M. Performance of rice (*Oryza sativa* (L.)) under AWD irrigation practice—A brief review. *Paddy Water Environ.* **2021**, *20*, 5–15. [CrossRef]
9. Rejesus, R.M.; Palis, F.G.; Rodriguez, D.G.P.; Lampayan, R.M.; Bouman, B.A.M. Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: Evidence from rice producers in the Philippines. *Food Policy* **2011**, *36*, 280–288. [CrossRef]
10. Carrijo, D.R.; Lundy, M.E.; Linquist, B.A. Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crop. Res.* **2017**, *203*, 173–180. [CrossRef]
11. Islam, M.; Rahman, M.; Mian, M.; Ali, M. Effect of Fertilizer Management on NPKS Leaching Loss from Sandy Loam Soil under Alternate Wetting and Drying Condition. *Bangladesh Rice J.* **2016**, *20*, 59–64. [CrossRef]
12. Alavaisha, E.; Manzoni, S.; Lindborg, R. Different agricultural practices affect soil carbon, nitrogen and phosphorous in Kilombero-Tanzania. *J. Environ. Manage.* **2019**, *234*, 159–166. [CrossRef] [PubMed]
13. Li, Y.; Barker, R. Increasing water productivity for paddy irrigation in China. *Paddy Water Environ.* **2004**, *2*, 187–193. [CrossRef]
14. Livsey, J.; Alavaisha, E.; Tumbo, M.; Lyon, S.W.; Canale, A.; Cecotti, M.; Lindborg, R.; Manzoni, S. Soil Carbon, Nitrogen and Phosphorus Contents along a Gradient of Agricultural Intensity in the Kilombero Valley, Tanzania. *Land* **2020**, *9*, 121. [CrossRef]
15. Alavaisha, E.; Lyon, S.W.; Lindborg, R. Assessment of water quality across irrigation schemes: A case study ofwetland agriculture impacts in Kilombero Valley, Tanzania. *Water* **2019**, *11*, 671. [CrossRef]
16. Moyano, F.E.; Manzoni, S.; Chenu, C. Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models. *Soil Biol. Biochem.* **2013**, *59*, 72–85. [CrossRef]
17. Manzoni, S.; Jackson, R.B.; Trofymow, J.A.; Porporato, A. The global stoichiometry of litter nitrogen mineralization. *Science* **2008**, *321*, 684–686. [CrossRef] [PubMed]
18. Pan, G.; Smith, P.; Pan, W. The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. *Agric. Ecosyst. Environ.* **2009**, *129*, 344–348. [CrossRef]
19. Wu, J. Carbon accumulation in paddy ecosystems in subtropical China: Evidence from landscape studies. *Eur. J. Soil Sci.* **2011**, *62*, 29–34. [CrossRef]
20. Chiti, T.; Gardin, L.; Perugini, L.; Quaratino, R.; Vaccari, F.P.; Miglietta, F.; Valentini, R. Soil organic carbon stock assessment for the different cropland land uses in Italy. *Biol. Fertil. Soils* **2012**, *48*, 9–17. [CrossRef]
21. Witt, C.; Cassman, K.G.; Olk, D.C.; Biker, U.; Liboon, S.P.; Samson, M.I.; Ottow, J.C.G. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant Soil* **2000**, *225*, 263–278. [CrossRef]
22. Pampolino, M.F.; Laureles, E.V.; Gines, H.C.; Buresh, R.J. Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. *Soil Sci. Soc. Am. J.* **2008**, *72*, 798–807. [CrossRef]
23. Buresh, R.J.; Reddy, K.R.; van Kessel, C.; Schepers, J.S.; Raun, W.R. Nitrogen Transformations in Submerged Soils. In *Nitrogen in Agricultural Systems*; American Society of Agronomy: Madison, WI, USA, 2008. Available online: https://pdfs.semanticscholar.org/1b1f/607ab0e90ce820e583234ff01525e6623c42.pdf (accessed on 21 October 2019).

24. Wei, L.; Ge, T.; Zhu, Z.; Ye, R.; Peñuelas, J.; Li, Y.; Lynn, T.M.; Jones, D.L.; Wu, J.; Kuzyakov, Y. Paddy soils have a much higher microbial biomass content than upland soils: A review of the origin, mechanisms, and drivers. *Agric. Ecosyst. Environ.* **2022**, *326*, 107798. [CrossRef]
25. Lal, R. Enhancing eco-efficiency in agro-ecosystems through soil carbon sequestration. *Crop Sci.* **2010**, *50*, S120–S131. [CrossRef]
26. Cleveland, C.C.; Liptzin, D. C:N:P stoichiometry in soil: Is there a "Redfield ratio" for the microbial biomass? *Biogeochemistry* **2007**, *85*, 235–252. [CrossRef]
27. RAMSAR. Information Sheet on Ramsar Wetland: The Kilombero Valley Floodplain. 2002, pp. 1–17. Available online: https://doi.org/1173RIS.pdf (accessed on 8 November 2018).
28. Massawe, B.H.J. *Digital Soil Mapping and GIS-Based Land Evaluation for Rice Suitability in Kilombero Valley, Tanzania*; The Ohio State University: Columbus, OH, USA, 2015.
29. Nindi, S.J.; Maliti, H.; Bakari, S.; Kija, H.; Machoke, M. Conflicts Over Land and Water Resources in the Kilombero Valley Floodplain, Tanzania. *Rev. Afr. Polit. Econ.* **2014**, *50*, 173–190. [CrossRef]
30. Alavaisha, E. *Agricultural Expansion Impacts on Wetland Ecosystem Services from Kilombero Valley, Tanzania*; Stockholm University: Stockholm, Sweden, 2020.
31. Klute, A.; Danielson, R.E.; Sutherland, P.L. *Methods of Soil Analysis*, 2nd ed.; American Society of Agronomy: Madison, WI, USA, 1986. [CrossRef]
32. Van Reeuwijk, L.P. *Technical Paper 9*; ISRIC: Wageningen, The Netherlands, 2002; ISBN 9066720441.
33. Lemly, A.D.; Kingsford, R.T.; Thompson, J.R. Irrigated agriculture and wildlife conservation: Conflict on a global scale. *Environ. Manag.* **2000**, *25*, 485–512. [CrossRef] [PubMed]
34. Vandermeer, J.; van Noordwijk, M.; Anderson, J.; Ong, C.; Perfecto, I. Global change and multi-species agroecosystems: Concepts and issues. *Agric. Ecosyst. Environ.* **1998**, *67*, 1–22. [CrossRef]
35. Haque, M.; Biswas, J.C.; Kim, S.Y.; Kim, P.J. Intermittent drainage in paddy soil: Ecosystem carbon budget and global warming potential. *Paddy Water Environ.* **2017**, *15*, 403–411. [CrossRef]
36. Setyanto, P.; Pramono, A.; Adriany, T.A.; Susilawati, H.L.; Tokida, T.; Padre, A.T.; Minamikawa, K. Soil Science and Plant Nutrition Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. *Soil Sci. Plant Nutr.* **2018**, *64*, 23–30. [CrossRef]
37. Adhya, T.K.; Linquist, B.; Searchinger, T.; Wassmann, R.; Yan, X. *Wetting and Drying: Reducing Greenhouse Gas Emissions and Saving Water from Rice Production*; Working Paper, Installment 8 of Creating a Sustainable Food Future; World Resources Institute: Washington, DC, USA, 2014; pp. 1–28.
38. Ye, Y.; Liang, X.; Chen, Y.; Liu, J.; Gu, J.; Guo, R.; Li, L. Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice. Effects on dry matter accumulation, yield, water and nitrogen use. *Field Crop. Res.* **2013**, *144*, 212–224. [CrossRef]
39. Ranatungaa, T.; Hiramatsub, K.; Onishib, T.; Ishiguro, Y. Process of Denitrification in Flooded Rice Soils. *Rev. Agric. Sci.* **2018**, *6*, 21–33. [CrossRef]
40. Li, Q.; Allen, E.L.; Wollum, A.G. Effects of Irrigation and Fertilization on Soil Microbial Biomass and Functional Diversity. *J. Sustain. For.* **2005**, *20*, 17–35. [CrossRef]
41. Kukal, S.S.; Benbi, D.K. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil Tillage Res.* **2009**, *102*, 87–92. [CrossRef]
42. Poirier, V.; Angers, D.A.; Rochette, P.; Chantigny, M.H.; Ziadi, N.; Tremblay, G.; Fortin, J. Interactive Effects of Tillage and Mineral Fertilization on Soil Carbon Profiles. *Soil Sci. Soc. Am. J.* **2009**, *73*, 255. [CrossRef]
43. Jobbágy, E.G.; Jackson, R.B. The Vertical Distribution of Soil Organic Carbon and Its Relation to Climate and Vegetation. *Ecol. Appl.* **2000**, *10*, 423–436. [CrossRef]
44. Wright, H.R. *Soil Drying and Re-Wetting Effects on Phosphorus Availability and Plant Yields*; Lancaster University: Lancaster, UK, 2018.
45. Entry, J.A.; Sojka, R.E.; Shewmaker, G.E. Management of Irrigated Agriculture to Increase Organic Carbon Storage in Soils. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1957. [CrossRef]
46. Liu, Z.; Rong, Q.; Zhou, W.; Liang, G. Effects of inorganic and organic amendment on soil chemical properties, enzyme activities, microbial community and soil quality in yellow clayey soil. *PLoS ONE* **2017**, *12*, e0172767. [CrossRef] [PubMed]
47. Angst, G.; John, S.; Mueller, C.W.; Kögel-Knabner, I.; Rethemeyer, J. Tracing the sources and spatial distribution of organic carbon in subsoils using a multi-biomarker approach. *Sci. Rep.* **2016**, *6*, 29478. [CrossRef]
48. Zheng, C.; Zhang, Z.; Wu, Y.; Mwiya, R. Response of Vertical Migration and Leaching of Nitrogen in Percolation Water of Paddy Fields. *Water* **2019**, *11*, 868. [CrossRef]
49. Kamoni, P.T.; Mburu, M.W.K.; Gachene, C.K.K. Influence of Irrigation and Nitrogen Fertiliser on Maize Growth, Nitrogen Uptake and Yield in a Semiarid Kenyan Environment. *East Afr. Agric. For. J.* **2003**, *69*, 99–108. [CrossRef]
50. Dodd, I.C.; Puértolas, J.; Huber, K.; Pérez-Pérez, J.G.; Wright, H.R.; Blackwell, M.S.A. The importance of soil drying and re-wetting in crop phytohormonal and nutritional responses to deficit irrigation. *J. Exp. Bot.* **2015**, *66*, 2239–2252. [CrossRef]
51. Dalai, R.C. Soil Organic Phosphorus. *Adv. Agron.* **1977**, *29*, 83–117. [CrossRef]
52. Murphy, B.W. *Soil Organic Matter and Soil Function–Review of the Literature and Underlying Data*; Department of the Environment: Canberra, Australia, 2014.

53. Rondon, T.; Hernandez, R.M.; Guzman, M. Soil organic carbon, physical fractions of the macro-organic matter, and soil stability relationship in lacustrine soils under banana crop. *PLoS ONE* **2021**, *16*, e0254121. [CrossRef]
54. Olivares, B.O.; Calero, J.; Rey, J.C.; Lobo, D.; Landa, B.B.; Gómez, J.A. Correlation of banana productivity levels and soil morphological properties using regularized optimal scaling regression. *Catena* **2022**, *208*, 105280. [CrossRef]