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Water Yam (*Dioscorea alata* L.) Growth and Tuber Yield as Affected by Rotation and Fertilization Regimes across an Environmental Gradient in West Africa

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Abstract: Yam (*Dioscorea* spp.) is a staple food crop and a source of income for millions of people in West Africa. Traditionally, in West Africa, yams are grown without any external inputs, leading to low tuber yields. The rapid decrease of tuber yield observed after the first yam cropping season has been ascribed to nutrient depletion and/or to the accumulation of yam-specific pests and diseases. This has led farmers to grow yam on new surfaces under fallow each year. Using a transdisciplinary approach, we identified different yam-based rotations and fertilization regimes that could stabilize yam production in rotational cropping systems and improve water yam (*D. alata*) productivity. These innovations were tested in researcher-managed field trials established along an environmental gradient crossing four yam growing zones spanning from the Humid Forest (Liliyo in Côte d'Ivoire) to the Derived Savanna/Forest Transition (Tiéningboué in Côte d'Ivoire), the Southern Guinean Savanna (Midebdo in Burkina Faso), and the Northern Guinean Savanna (Léo in Burkina Faso) between 2016 and 2018. The fertilization factor implemented at each site included a control with no fertilization (NON), sole mineral fertilization as NPK (MIN), combined organic and mineral fertilization (MINORG) and sole organic fertilization as manure (ORG), while the rotation factor included water yam in rotation with cereal (YamCer), legume (YamLeg), and white yam (YamYam). The average water yam tuber yields were 32.8, 20.3, 2.7, and 2.5 t fresh matter ha^{-1} in 2016, and 16.4, 10.7, 8.9, and 5.2 t fresh matter ha^{-1} in 2018 in Liliyo, Tiéningboué, Midebdo, and Léo, respectively. The most important determinants of tuber yields were the total amount of rainfall recorded during the yam growing period and between tuber initiation and maximum canopy development, and the soil carbon stocks in the 0–30-cm layer. We confirmed in this study that soil surface coverage measured between 70 and 98 days after planting was an early indicator of tuber yield. Fertilization impacted positively the soil surface cover but had a weak impact on tuber yields. Rotation had no impact on either the soil surface cover or tuber yields. This lack of observable impacts was partly due to the very large variability of tuber yields, to the variable rainfall, and to an anthracnose attack in two sites in 2018. The impacts of fertilization and rotation on yam yields should be studied over longer periods. This is, to our knowledge, the first publication showing the relative impacts of site-specific properties (rainfall and soil carbon stocks) versus management practices on water yam yield along an environmental gradient going across the West African yam belt.

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1. Introduction

Yams (*Dioscorea* spp.) are tuber crops cultivated throughout the tropics as a staple food and as a source of income for millions of people [1,2]. About 74 million tons of fresh yam tubers were produced worldwide in 2019 and up to 94% of these were harvested in West Africa [3]. In this region, the about-fivefold increase in yam tuber production observed within the last 50 years was not driven by a yield increase but by a sixfold increase in yam cultivated areas [3]. Traditionally, yam is grown with no external input, delivering low fresh tuber yields (on average 8.4 t ha^{-1} in 2019 [3]) which are far below the 40 to 50 t ha^{-1} that can be obtained on well-managed plots with high soil organic matter content [4,5]. The rapid decrease of tuber yields often observed after the first yam cropping season has been ascribed to a depletion in soil organic matter and nutrient contents and/or to the accumulation of yam-specific pests and diseases, leading farmers to grow yam each year on new fallow surfaces [1]. Given the increasing tuber demand due to the fast-growing population in West Africa and the increasing land scarcity, it is urgent to develop cropping practices to sustainably increase yam productivity in rotational cropping systems.

A survey conducted by Abdoulaye et al. [6] among experts classified the topic "improving soil fertility" as one of the most important challenges to be addressed for sustainable yam production. Carsky et al. [7], and Frossard et al. [8], recommended the implementation of integrated soil fertility management (ISFM) as a solution to improve yam yields sustainably. The concept of ISFM is defined as "a set of best practices, preferably used in combination, including the use of appropriate germplasm, the appropriate use of fertilizers and organic resources, good agronomic practices and considering the socio-economic context" [9]. Studies on the impact of ISFM on yam productivity are, however, scarce [7,8]. In West Africa, the few works conducted on this topic focused on specific geographic areas [10,11] and, therefore, could not consider the biophysical diversity (e.g., in terms of soils and climates) existing within the "yam belt" as defined by Asiedu and Sartie [12]. A study on the impact of various ISFM options conducted on very different sites (e.g., in terms of climates and soils) could help identify the most important parameters controlling tuber yield production and determine how cropping practices could then be adapted to sustainably increase productivity.

In the context of the "Swiss program for research on global issues for development", the YAMSYS project applied a transdisciplinary approach to develop efficient and acceptable practices to sustainably increase yam productivity in rotational cropping systems in West Africa [13,14]. Firstly, innovation platforms (IPs), as described by Davies et al. [15], were established in four yam growing zones spanning from the Humid Forest, to the Derived Savanna/Forest Transition, the Southern Guinean Savanna, and the Northern Guinean Savanna in West Africa [14]. The IPs identified and ranked the most important constraints for yam production and proposed solutions for each of them. Among other things, they proposed introducing crop rotation to alleviate the problem of land scarcity and fertilization and to solve the problem of soil fertility decline. The co-development of technologies also implied the use of preferred crops and varieties of the stakeholders, and locally available manure. These options were tested first in researcher-managed trials and then in farmer-managed trials. The results delivered by these trials were regularly discussed within the IPs during the three years of implementation. These discussions led to requests from the stakeholders to change fertilization rates and varieties during the trials. These requests were implemented to evaluate practices deemed acceptable by local farmers, resulting in changes in the researcher-managed trials during the field experiment [14].

This paper presents the results derived from the researcher-managed trials. The objective of this study was to evaluate how site-related characteristics such as rainfall

amount and distribution, soil carbon content, and locally adapted ISFM options (rotation and fertilization regimes) affect yam growth and yield. We hypothesized that tuber yield would increase with the increase of rainfall and with increasing soil carbon stocks. At the site level, we expected an increase in tuber yield with nutrient and organic matter inputs, while different rotations were assumed to have different results. A legume precrop was expected to increase water yam tuber yield because of additional N inputs through N_2 fixation; a cereal precrop was expected to have no impact on yam yield. Water yam yield was expected to decrease after a white yam precrop because of the accumulation of yam pests and diseases; moreover, non-fertilized water yam tuber yield was expected to decrease in a non-fertilized yam–yam rotation because of nutrient depletion.

2. Materials and Methods

2.1. Location, Climate, and Soil of the Field Experiments

The study was conducted in four sites representing four yam growing regions (Figure S1). The site of Liliyo in Côte d'Ivoire represented the Humid Forest, the site of Tiéningboué, also in Côte d'Ivoire, represented the Derived Savanna/Forest Transition. The site of Midebdo in Burkina Faso represented the Southern Guinean Savanna, and the site of Léo in Burkina Faso represented the Northern Guinean Savanna. A researcher-managed field experiment was installed in each site in 2016. The weather data were recorded during the yam growing seasons with a Campbell Scientific CR1000 station installed in each field trial, except for those of Tiéningboué in 2016, ranging from 14 days before planting to 42 days after planting, which were extracted from the $0.05 \times 0.05°$ raster of the Climate Hazards Group Infrared Precipitation with station data [16]. The distribution and cumulative amount of rainfall in 2016 and 2018 are presented on Figure 1. The soils were characterized by Schneider [17], based on the World Reference Base [18]. The long-term average of precipitations characterizing each site were taken from climate-data.org [19] (https://en.climate-data.org/ (accessed on 15 March 2021)).

The Liliyo site was characterized by an equatorial transitional climate with a long rainy season (February to July), and a short rainy season (September to November). The annual average precipitation is about 1300 mm. The field trial was installed in the village of Gnogboyo (5°51′ N 6°25′ W, 194 m above sea level) on an acric pisoplinthic Ferralsol. The Tiéningboué site had a tropical climate with one rainy season (March to October) and an annual average precipitation of about 1250 mm. The field trial was installed in the village of Dabakalatou (8°06′ N 5°42′ W, 350 m above sea level) on an acric plinthic Ferralsol. The Midebdo site was also characterized by a tropical climate with one rainy season (May to October). The annual average precipitation is about 910 mm. The field trial was installed in the village of Sinaperdouo (9°59′ N 3°08′ W, 304 m above sea level) on a pantofluvic Fluvisol. Finally, the Léo site had also a tropical climate with one rainy season (May to October) with an annual average precipitation of 800 mm. The field trial was installed in the village of Onliassan (11°03′ N 2°11′ W, 340 m above sea level) on a pisoplinthic Plinthosol.

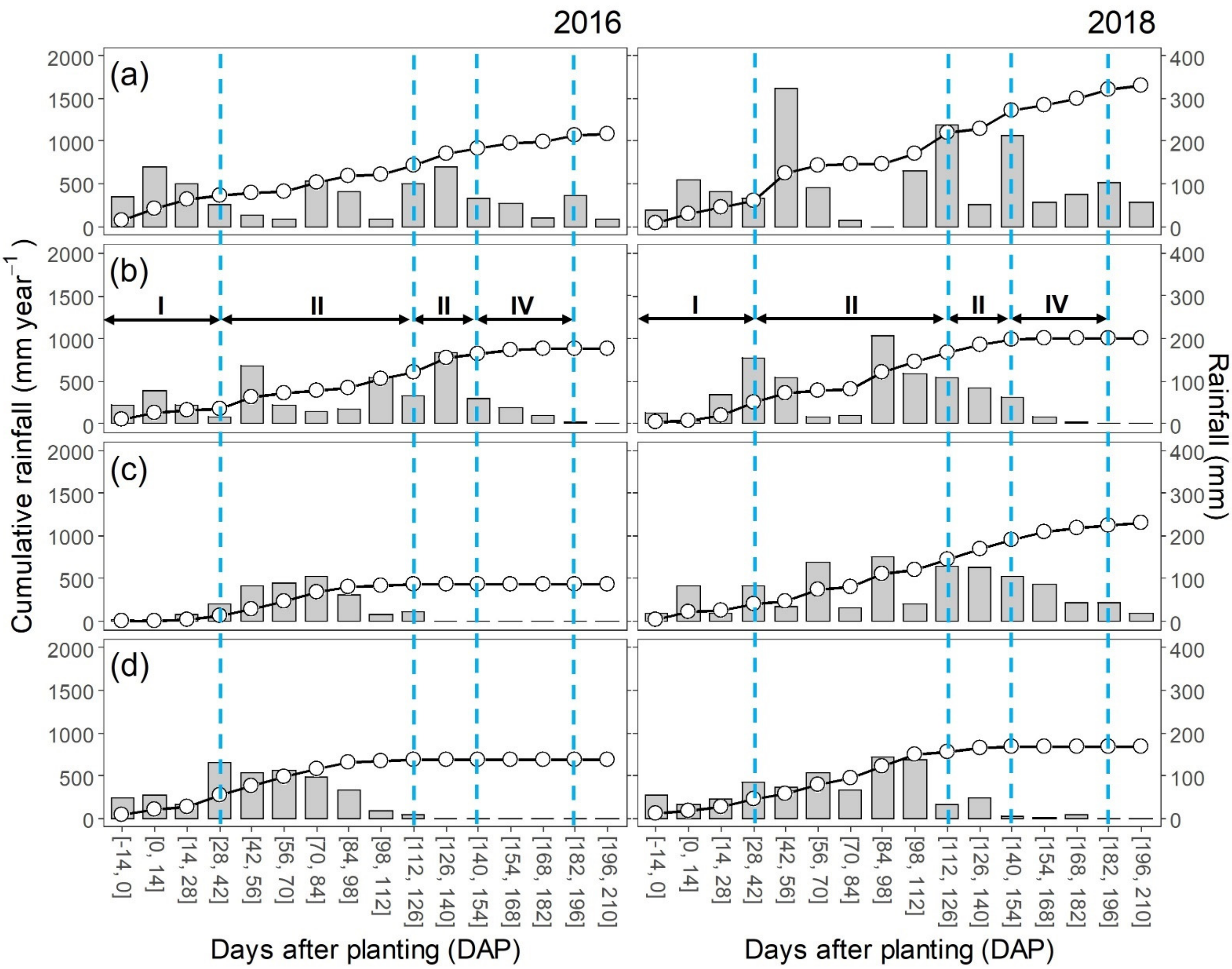

Figure 1. Rainfall recorded every two weeks (columns) and cumulative rainfall (lines) in Liliyo (**a**) and Tiéningboué (**b**), both located in Côte d'Ivoire, and in Midebdo (**c**) and Léo (**d**), both located in Burkina Faso, from 14 days before planting to vine senescence of yam in 2016 and 2018. Source: Campbell Scientific CR1000 weather station installed in each site. The data of Tiéningboué in 2016 (14 days before planting to 42 days after planting) are from 0.05 × 0.05° rasters of the Climate Hazards Group Infrared Precipitation with station data [16]. I, II, III, and IV indicate the different growth phases of water yam: phase I, starting 14 days before planting to emergence (SE) at 50 DAP (days after planting); phase II, from SE to tuber initiation (TI) at 112 DAP; phase III, from TI to maximum canopy development (MCD) at 140 DAP; and phase IV, from MCD to tuber maturity (TM) at 190 DAP.

2.2. Plant Materials

The crop species used in these experiments were water yam (*D. alata*), white yam (*D. rotundata*), maize (*Zea mays*), rice (*Oryza sativa*), and groundnut (*Arachis hypogaea*). In 2016, the improved water yam variety C18 [20] and the local water yam variety woroba were planted, respectively, in Liliyo and Tiéningboué, while the improved variety florido [21] was planted in Midebdo and Léo. These varieties were those preferred by local stakeholders [14]. In 2018, following results of the 2016 campaign and discussion with the stakeholders [14], the improved variety C18 was used in the four sites. The maize variety used in rotation in Liliyo, Midebdo, and Léo in 2017 was SR21 from the "Institut de l'Environnement et Recherches Agricoles, Burkina Faso" (INERA). A local rice variety was used in 2017 in Tiéningboué. Local groundnut varieties were used in Liliyo and Tiéningboué, while the improved variety CN94C (INERA) was used in Midebdo and Léo. In 2017, the improved

white yam variety R3 was planted in Liliyo, a local one named krenglê in Tiéningboué, and a local one named wassara in Midebdo and Léo.

2.3. Installation of the Field Experiments

The experiments were conducted from April to December in 2016, 2017, and 2018. The field experiment installed at each site was a split-plot, with four replicates (blocks) (Figure S2). The trials were installed in 2016 on lands that had been left in fallow for four years. The main plot concerned the type of crop rotation and the plots concerned the fertilization regimes. The type of crop rotation was randomly allocated within each block and the fertilization regimes randomly allocated within each rotation. The main plots within a given replicate were separated by a distance of 1.5 m, the plots within a given main plot by 1 m, and the replicates by 2 m. Each plot measured 20 m^2 (5 m by 4 m). In 2016, prior to the installation of the experiments, the land was cleared of vegetation manually and the large debris were removed without burning. The soil was ploughed at an average depth of 20 cm using an animal-drawn plough in Tiéningboué, Midebdo, and Léo, and manually using a hoe at a depth of 10 cm in the site of Liliyo. Then, topsoil was heaped into 50-cm high mounds with a hoe at a density of 1 mound m^{-2}. In 2017 and 2018, the soil was manually ploughed with a hoe at an approximate depth of 10 cm at the four sites. Yams were planted in the center of the mounds at about a 10-cm depth, while groundnut and maize or rice were directly sown after ploughing. In 2016, water yam planting was completed on 30 May in Liliyo, 17 May in Tiéningboué, 21 June in Midebdo, and 25 June in Léo. In 2018, the planting dates were 12 May, 29 May, 28 April, and 25 May in Liliyo, Tiéningboué, Midebdo, and Léo, respectively.

2.4. Crop Rotations and Fertilization Regimes

The three studied rotations were (i) water yam–cereal–water yam (YamCer), (ii) water yam–legume–water yam (YamLeg), and (iii) water yam–white yam–water yam (YamYam). Maize (*Zea mays*) was used as cereal in the site of Liliyo, Midebdo, and Léo, and rice (*Oryza sativa*) in Tiéningboué. The legume used in the four sites was groundnut (*Arachis hypogaea*). The four fertilization regimes applied to yam and cereals were: (i) no fertilization (NON); (ii) sole mineral fertilization as NPK (MIN); (iii) combined organic and mineral fertilization (MINORG); and (iv) sole organic fertilization as manure (ORG). The source of mineral fertilizer was urea for N, triple super phosphate for P, and potassium sulphate for K. The organic fertilizer was cow manure in Midebdo and Léo, while in Tiéningboué and Liliyo, it was poultry manure.

The amount of N added with the mineral fertilizers in the MIN treatment on water yam in 2016 was calculated based on the concentration of N in tuber of 5.2 kg t^{-1} of fresh tuber [22] for a fresh tuber yield of 25 t ha^{-1}. Considering this N concentration and the N:P and N:K ratio in fresh tuber of water yam reported by Frossard et al. [8], we estimated the concentration of P and K in tuber necessary to achieve the target yield of 25 t ha^{-1} which allowed us to calculate the quantity of nutrients to be added. The amounts of manure added in the ORG treatment in 2016 were based on the recommendations from the literature reported in Frossard et al. [8]. In Liliyo and Tiéningboué, 16 t fresh matter ha^{-1} of poultry manure was applied, and in Midebdo and Léo, 15 t fresh matter ha^{-1} of cow manure was applied. Note that the organic fertilizers used for the experimentations were taken in the vicinity of each site and therefore were different. In 2018, the targeted fresh yield was decreased to 10 t ha^{-1} after having realized that the amount of mineral and organic fertilizers were considered to be too high by the farmers. The amounts of N, P and K applied in the MIN treatment and the amounts of manure applied in the ORG treatments were decreased accordingly. In 2016 in Liliyo and Tiéningboué, 7.8 t fresh matter ha^{-1} of poultry manure was then applied, while in Midebdo and Léo, 10.5 t fresh matter ha^{-1} of cow manure was applied. MINORG received in 2016 and 2018 half of the NPK added in MIN as mineral fertilizer and half of the manure added in ORG. In MIN, half of the mineral fertilizer was broadcasted at emergence (about 60 days after planting), and the other half at

tuber initiation (about 120 days after planting). Mineral fertilizer was broadcasted at tuber initiation for MINORG. Manure was applied before mound preparation on MINORG and ORG. The N, P and K added by mineral fertilizers in MIN treatment in 2017 on white yam were calculated based on the same principles described for water yam for a targeted fresh tuber yield of 20 t ha^{-1} using the concentration reported in Frossard et al. [8]. The amounts of manure applied on white yam were 8 t fresh matter ha^{-1} in Liliyo and Tiéningboué, and 6 t fresh matter ha^{-1} in Midebdo and Léo in 2017. Maize received 21 t fresh matter ha^{-1} of poultry manure in Liliyo and 18 t fresh matter ha^{-1} of cow manure in Midebdo and Léo, while rice received 12 t fresh matter ha^{-1} of poultry manure in Tiéningboué. The amounts of mineral fertilizer added on maize and rice were those recommended by the extension services of Burkina Faso [23–25]. Groundnut was not fertilized. Rice and maize residues were removed from the plots at the harvest, while those of yam and groundnut were left on the plots and incorporated to the soil thereafter. Samples of manures, mineral fertilizers and plant residues of groundnut were taken and analyzed in the laboratory (see analyses in Section 2.6) in order to quantify the nutrients really added in the fields.

2.5. Crops Management

Soon after land preparation, yam tuber setts weighting about 200 g each were prepared by cutting whole, visually healthy tubers that had broken dormancy. To protect the yam planting materials against nematodes, fungi, and insects, the tuber setts were soaked in a liquid mixture of 3 g cypermethrin L^{-1} (insecticide), 1.2 g oxamyl L^{-1} (nematicide), and 8 g mancozeb L^{-1} (fungicide) in 2016 for 15 min. In 2018, the insecticide and nematicide were replaced by wood ash (15 g L^{-1}), following a discussion with the stakeholders [14]. After soaking, the setts were air-dried and planted one day after. The head parts of the tubers were used as planting material for the "sampling plants" to ensure a homogeneous germination, while other tuber parts were used for the border plants (Figure S2). No treatments were applied for maize, rice, and groundnut seeds before sowing.

During crop growth, weeding and treatments against pests were performed when required. Crops were not irrigated.

2.6. Fertilizers, Groundnut Straw, and Soil Sampling and Analyses

Manure, mineral fertilizers, and groundnut straw sampled each year and each site were analyzed for their total C, N, P, and K contents. Total C and N were analyzed using an elemental analyzer (vario PYRO cube, Elementar Analysensysteme GmbH, Germany). Total P and K contents were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, a Shimadzu Plasma Atomic Emission Spectrometer ICPE-9820) after microwave digestion in concentrated nitric acid (HNO_3), based on the method of Hoenig [26]. The total amounts of nutrients added on water yam with mineral and organic fertilizers are presented in Table 1, while the amounts of nutrients added on cereals (maize and rice) and white yam are presented in Table S1. The amounts of C, N, P, and K added by groundnut straw are presented in Table S2.

Soil samples were taken in May 2016 before the start of the field experiments and in December 2017 after two years of cropping in the 0–30-cm layer. Soil texture was measured following the method described by Robinson [27]. The total soil C and N contents were determined using an elemental analyzer (vario PYRO cube, Elementar Analysensysteme GmbH, Germany). Available phosphorus was extracted using resin membranes loaded with bicarbonate ions [28] and measured colorimetrically using the malachite green method [29]. Soil pH was measured in a suspension of 1 g of soil in 2 mL water (pH-H_2O) using a pH electrode (Benchtop pH/ISE meter model 720A, Orion Research Inc., Franklin, MA, USA). Cation exchange capacity and exchangeable bases were measured by ICP-OES after extraction in $BaCl_2$ [30]. Soil physical and chemical properties (0–30 cm) of the field trials are presented in Table 2. Soil total carbon content and pH in December 2017 are presented in Table S3. Table S4 presents the soil carbon stocks in the 0–30-cm layer in May 2016 and December 2017.

Table 1. Amount of C, N, P, and K added by mineral and/or organic fertilizers in 2016 and 2018 on water yam (*D. alata*) in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso).

Site	Fertilization	2016				2018			
		C	N	P	K	C	N	P	K
		kg ha^{-1}							
Liliyo	MIN	58.4	129.0	13.2	184.9	24.7	54.6	6.6	99.0
	MINORG [a]	1969.1	248.3	105.8	199.2	1135.9	89.1	32.1	103.6
	ORG	3879.8	367.5	198.4	213.5	2247.0	123.6	57.6	108.1
Tiéningboué	MIN	58.4	129.0	13.2	184.9	24.7	54.6	6.6	99.0
	MINORG [a]	1617.0	252.0	119.9	232.3	891.8	103.2	44.0	99.8
	ORG	3175.6	374.9	226.7	279.6	1758.8	151.7	81.4	100.6
Midebdo	MIN	58.4	129.0	13.2	184.9	24.7	54.6	6.6	99.0
	MINORG [a]	806.7	137.6	20.8	192.1	1520.3	116.8	20.4	148.0
	ORG	1555.0	146.2	28.4	199.3	3015.9	179.0	34.2	197.0
Léo	MIN	58.4	129.0	13.2	184.9	24.7	54.6	6.6	99.0
	MINORG [a]	940.7	131.4	19.2	159.5	764.3	67.5	9.8	92.8
	ORG	1823.1	133.8	25.3	134.0	1503.9	80.3	13.1	86.5

[a] MINORG received half of NPK added in MIN as mineral fertilizer and half of manure added in ORG as organic inputs. NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG combined organic and mineral fertilization), and ORG (sole organic fertilization as manure).

Table 2. Soil properties in the 0–30-cm layer of the field trials at the installation in 2016 in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso). Data are mean values ± standard errors.

Soil Properties	Liliyo	Tiéningboué	Midebdo	Léo
Bulk density (t m^{-3}) [a]	1.36 ± 0.07	1.39 ± 0.03	1.24 ± 0.02	1.48 ± 0.09
Clay (g kg^{-1} soil) [b]	79.8 ± 1.9	148 ± 3.8	56.3 ± 2.4	102.0 ± 5.0
Silt (g kg^{-1} soil) [b]	73.2 ± 3.0	105 ± 5.2	85.3 ± 11.9	197.0 ± 8.3
Sand (g kg^{-1} soil) [b]	847 ± 4.4	747 ± 6.4	858.0 ± 13.5	700.0 ± 12.3
Gravel (g kg^{-1} soil) [a]	317.9 ± 70.5	267.9 ± 30.5	45.1 ± 9.8	289.5 ± 84.5
pH, 1 g soil/2 mL H_2O	6.0 ± 0.1	5.5 ± 0.1	7.1 ± 0.1	5.3 ± 0.1
Total N (g kg^{-1} soil)	1.0 ± 0.03	1.0 ± 0.04	0.5 ± 0.02	0.4 ± 0.01
Total C (g kg^{-1} soil)	9.8 ± 0.45	11.7 ± 0.45	4.9 ± 0.23	4.6 ± 0.20
P content (Resin) (mg kg^{-1} soil)	10.2 ± 1.15	7.4 ± 0.57	3.6 ± 0.19	2.3 ± 0.09
Exchangeable K (cmol$^+$ kg^{-1} soil)	0.3 ± 0.02	0.4 ± 0.02	0.2 ± 0.01	0.4 ± 0.01
Cation exchange capacity (cmol$^+$ kg^{-1} soil)	6.7 ± 0.40	6.3 ± 0.35	3.1 ± 0.15	2.6 ± 0.17

[a]: Bulk density and gravel content, i.e., solid particles larger than 2 mm in diameter, were measured in December 2020 on eight soil pits opened in each site. Soil chemical properties presented correspond to the mean of 48 soil samples taken in May 2016 at each field trial and analyzed using the methods described above. [b]: Texture was measured on eight samples taken in December 2017 from the four blocks of each site (no fertilized plots of YamCer and YamLeg rotations).

2.7. Data Collection

Data were collected only from the six mounds located in the middle of each plot, i.e., where setts from the head parts of yam mother tubers had been planted (Figure S2).

Sett emergence was recorded weekly and visually, from the planting till 70 days after planting (DAP). The soil surface coverage by above-ground yam organs (SSC) was measured every two weeks, from 70 till 98 DAP in Liliyo and Tiéningboué in 2016, from 70 till 126 DAP in Midebdo and Léo in 2016, and from 70 till 168 DAP in the four sites in 2018. This was performed for four of the six "sampling plants" randomly identified at the beginning of the measurement (Figure S2). In 2016, the measurement of SSC was made using the method described by Burstall and Harris [31] and modified by Diby et al. [5]. For this purpose, a wooden frame of 1 m^2 divided into 100 meshes of 1 cm^2 was placed just

above the canopy, and the SSC was obtained by counting the number of meshes covered, by at least 50%, with above-ground organs. In 2018, in order to make the measurement more accurate and less laborious, we used the android program Canopeo [32] installed on a phone camera with an image size set to 1 m × 1 m to obtain square-shaped images. The wooden frame was placed on the four identified mounds mentioned above. Then, one image was taken at about 1.5 m above the canopy and the SSC was directly given by the program. In 2018, the SSC measurements were made from 70 DAP to 168 DAP in the site of Tiéningboué simultaneously with the two methods, so as to compare the results. The data showed a significant positive linear relationship ($r^2 = 0.78$) between the two methods of measurement (Figure S3). However, despite this good correlation, the wooden frame method overestimated the SSC by about 30%, compared to the Canopeo method (Figure S3).

In each plot, the six "sampling plants" were used for the assessment of the yam fresh tuber yields in 2016 and 2018 at the senescence of aboveground organs. The yam fresh tuber yields were calculated based on the total tuber weight recorded in the plot and the final emergence rate of tuber setts as follows (Equation (1)):

$$FTY\left(\mathrm{t\ ha^{-1}}\right) = \frac{TTW\ per\ plot\ (\mathrm{kg}) \times DP\left(\mathrm{mounds\ ha^{-1}}\right)}{N} \times \frac{1}{1000} \times Sprout\ emergence, \quad (1)$$

with FTY—fresh tuber yield; TTW—the total weight of yam tubers harvested at plot level; DP—the density of planting (10,000 mounds ha^{-1}); N—the number of mounds in a plot (six); and $Sprout\ emergence$—the final sprout emergence rate of yam tuber setts.

Rainfall use efficiency (RUE) by water yam was calculated as the ratio of the dry tuber yield (sample oven-dried at 70 °C to constant weight) to total amount of rainfall recorded during water yam growing period in 2016 and 2018 [33] as follows (Equation (2)):

$$RUE\left(\mathrm{kg\ ha^{-1}\ mm^{-1}}\right) = \frac{DTY\left(\mathrm{kg\ ha^{-1}}\right)}{Rainfall\ (\mathrm{mm})}, \quad (2)$$

with DTY—dry tuber yield and $Rainfall$—the total amount of rainfall recorded during the growing period of water yam.

2.8. Data Processing and Statistical Analyses

Statistical analyses were performed using the R statistical computing language, version 4.0.5 [34], with the environment RStudio version 1.3.1056 [35]. The significance level of the tests was set at $p = 0.05$. The mean standard error (se) is preceded by the sign ± in the text and tables. Graphical output was created with the ggplot2 package version 3.3.3 [36].

First, data of each year were analyzed to determine the effect of the site on yam growth, mean tuber weight, number of tubers, and yield. Then, given the strong effect of the site, data were analyzed separately for each site and each year to determine the effects of treatments and their interactions on yam growth parameters, mean tuber weight, number of tubers, and yield. Yield and soil carbon stock (SOCs) data were averaged irrespective to treatments on one hand, and considering rotation and fertilization regimes on the other hand for each site and each year. Some correlation analyses were carried out using the data of both years to determine the impact of rainfall and its distribution on yam fresh tuber yields. For the distribution of rainfall, we considered the cumulative amount recorded during the water yam growth phases, based on Craufurd et al. [37] and our personal observations during the growing seasons. We distinguished four phases: phase I, starting 14 days before planting to emergence (SE) at 50 DAP; phase II, from SE to tuber initiation (TI) at 112 DAP; phase III, from TI to maximum canopy development (MCD) at 140 DAP; and phase IV, from MCD to tuber maturity (TM) at 190 DAP. The impact of SOCs on yam fresh tuber yields (data averaged considering rotation and fertilization regimes) was also assessed using correlation analyses. Soil properties (SOCs and pH), growth parameters,

and yam fresh tuber yield of each year, selected based on results reported in the literature and the results of the correlation analyses performed in this study, were used to perform a principal component analysis (PCA). Soil pH was included as a proxy for soil classification and because of its relative impact on nutrient uptake by plant and SOCs as an important driver of soil fertility and its relation to yam productivity. The PCA was performed to evaluate the links between variables and to determine which variables best distinguished the between-ISFM variabilities. Finally, we applied a hierarchical clustering of principal components (HCPC) [38] to identify similarities between ISFM options in order to form clusters. In this paper, we term ISFM as a site-adapted fertilization regime or a combination of rotation and fertilization regimes.

The split-plot design implies spatial pseudo-replicates because the fertilization regimes are nested in the rotation. In addition, the SSC were repeated data with temporal pseudo-replicates. Therefore, linear mixed models [39] were used to assess the effect of crops rotation and fertilization regimes on yam growth, mean tuber weight, number of tubers, and fresh tuber yield. Equation (3) describes the mathematical structure of a linear mixed effect model:

$$y_{ij} = \beta_1 x_{1ij} + \beta_2 x_{2ij} \ldots \beta_n x_{nij} + \alpha_{i1} z_{1ij} + \alpha_{i2} z_{2ij} \ldots \alpha_{in} z_{nij} + \varepsilon_{ij}, \quad (3)$$

where y_{ij} is the value of the outcome variable for a particular ij case, β_1 through β_n are the fixed effect coefficients, x_{1ij} through x_{nij} are the fixed effect variables (predictors) for observation i in group i (usually the first is reserved for the intercept/constant; $x_{1ij} = 1$), α_{i1} through α_{in} are the random effect coefficients which are assumed to be multivariate normally distributed, z_{1ij} through z_{nij} are the random effect variables (predictors), and ε_{ij} is the error for case j in group i where each group's error is assumed to be multivariate normally distributed.

When assessing the effect of the site using all the data, site, fertilization, and DAP for SSC in 2016 and site, rotation, fertilization, and DAP for SSC in 2018 were considered as fixed factors. Given the temporal (SSC data) and spatial pseudo-replicates (split plot), block, rotation, and fertilization were considered as random factors. In 2016, the data on yam emergence were collected before applying mineral fertilizers, and analyses were performed based on three fertilization regimes, control (NON and MIN), half-dose of organic fertilization (MINORG), and sole organic fertilization (ORG). At the site level, the SSC data were analyzed considering fertilization regimes and DAP in 2016 and rotation, fertilization regimes, and DAP in 2018 as fixed factors, and block and rotation as random factors for the two years [40]. Sprout emergence of tuber setts, mean tuber weight, number of tubers, and tuber yield data of each site were analyzed considering fertilization (2016), rotation, and fertilization (2018) as fixed factors and block and rotation as random factors in 2016 and 2018 [40]. The analyses were carried out using the function *lme* of the package nlme version 3.1-152 [41]. Assumptions were visually checked [40], and transformations were performed in case of serious violation. The model was progressively simplified by removing non-significant fixed factors and interactions in order to get the appropriate p-values [40]. When a factor effect or interactions between factors were significant, Tukey post hoc tests were performed using the function emmeans of the package emmeans [42].

In order to assess year effect, data of the two years were divided in all possible combinations of treatments. Then, a t-test was conducted on each subset to assess the difference between the years.

The packages FactoMineR version 2.4 [43] and factoextra version 1.0.7 [44] were used for the PCA and HCPC analyses. The significance of this discrimination was obtained using the function *dimdesc* of the package factoextra. Results were considered significant at $p < 0.05$.

3. Results

3.1. Yam Emergence and Soil Surface Coverage by Water Yam Above-Ground Organs

Neither parameters related to the sites (rainfall and soil properties) nor ISFM options (fertilization and rotation) affected yam emergence in 2016 (Table S5). The cumulative average emergence rate at 49 DAP in this year were at least 93% (Table 3). In 2018, the cumulative average emergence rates at 49 DAP in Liliyo and Tiéniningboué were significantly higher than those of Midebdo and Léo, with no effect of treatments (Tables 3 and S5).

Table 3. Cumulative rate of water yam sprout emergence at 49 DAP, according to fertilization regimes in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016 and 2018. In 2018, yam variety C18 was cultivated in the four sites, after either a cereal, a legume, or a yam for each fertilization regime.

		Cumulative Rate of Water Yam Tuber Setts Sprout Emergence at 49 DAP			
Year	**Fertilization**	**Liliyo**	**Tiéningboué**	**Midebdo**	**Léo**
2016	NON	97.1 ± 0.96	96.8 ± 1.55	92.1 ± 2.57	98.8 ± 1.09
	MINORG	96.7 ± 1.12	99.2 ± 0.56	92.9 ± 1.79	96.8 ± 1.94
	ORG	96.7 ± 1.67	98.8 ± 0.90	94.6 ± 1.14	99.5 ± 0.45
	Mean	96.8 ± 0.72 ^{a}	98.3 ± 0.61 ^{a}	93.2 ± 1.09 ^{a}	98.4 ± 0.75 ^{a}
2018	NON	97.2 ± 1.87	93.9 ± 2.53	75.2 ± 7.26	88.9 ± 5.96
	MIN	98.6 ± 1.39	98.6 ± 1.39	86.1 ± 4.96	94.4 ± 3.21
	MINORG	95.8 ± 2.99	96.8 ± 2.17	73.6 ± 7.25	75.9 ± 7.93
	ORG	96.6 ± 1.39	94.4 ± 3.13	65.4 ± 6.95	83.3 ± 6.63
	Mean	97.6 ± 0.99 ^{a}	95.7 ± 1.18 ^{ab}	75.1 ± 3.40 ^{c}	85.6 ± 2.99 ^{b}

Each value of cumulative sprout emergence rate at 49 DAP represents a mean of 12 replicates. In 2016, sprout emergence data were collected before application of mineral fertilizer. In 2016, C18 (improved variety), Woroba (traditional variety) and Florido (improved variety) were cultivated in Liliyo, Tiéningboué and Léo/Midebdo, respectively, while in 2018, C18 was cultivated in the four sites. Different letters for each year denote significant differences between sites calculated by the Tukey test at p-level ≤ 0.05 (n = 48 replicates per treatment). NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG (combined organic and mineral fertilization), and ORG (sole organic fertilization as manure).

The soil surface coverage (SSC) by water yam above-ground organs in 2016 and 2018 was significantly affected by rainfall and soil properties and weakly by fertilization. The changes with time of SSC in the four sites in 2016 are presented in Figure 2. These values were significantly higher in Liliyo compared to the three others site at 70 DAP (Table S6). At 84 and 98 DAP, no significant difference was observed between Liliyo and Tiéningboué but the SSC in these two sites were significantly higher compared to Midebdo and Léo (Table S6). The SSC observed in Midebdo and Léo from 70 to 126 DAP were similar. No significant effect of fertilization was observed in Liliyo and Tiéningboué during the period of measurement, while MIN statistically increased the SSC compared to NON between 84 and 112 DAP in Midebdo, and 84 and 126 DAP in Léo (Figure 2).

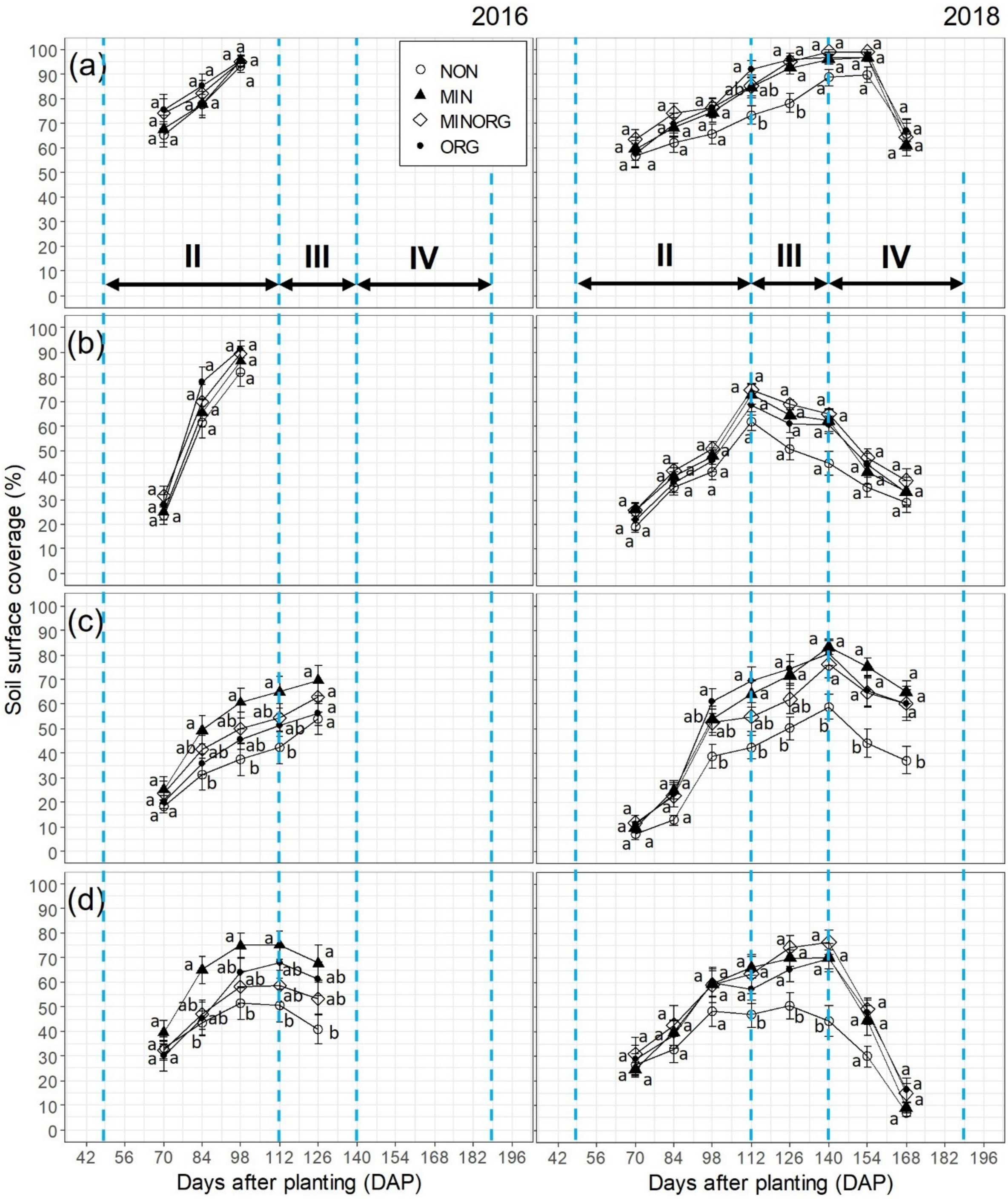

Figure 2. Effect of fertilization regimes on soil surface coverage by water yam above-ground organs in Liliyo (**a**) and Tiéningboué (**b**), both located in Côte d'Ivoire, and Midebdo (**c**) and Léo (**d**), both located in Burkina Faso, in 2016 and 2018. In 2016, SSC was measured using a wooden frame [32] modified by Diby et al. [5], while in 2018, it was measured using Canopeo (Patrignani and Ochsner, 2015). In 2016, the cultivars of water yam were C18 in Liliyo, woroba in Tiéningboué, and florido in Midebdo and Léo, while in 2018, C18 was cultivated in the four sites. Water yam was cultivated in 2018 in the four sites after either a cereal, a legume, or a white yam within a given fertilization regime. For each site and each DAP, different letters denote significant differences between treatments calculated by the Tukey test at p-level ≤ 0.05 (n = 12 replicates per treatment). II, III, and IV indicate the different growth phases of water yam: phase II from emergence (SE) at 50 DAP to tuber initiation (TI) at 112 DAP; phase III from TI to maximum canopy development (MCD) at 140 DAP; and phase

IV from MCD to tuber maturity (TM) at 190 DAP. NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG combined organic and mineral fertilization), and ORG (sole organic fertilization as manure).

In 2018, we observed an increase of SSC from 70 to 154 DAP in Liliyo, 70 to 112 DAP in Tiéningboué, 70 to 140 DAP in Midebdo, and 70 to 126–140 DAP in Léo, and then a decrease until 168 DAP in the four sites (Figure 2). Irrespective of rotation and fertilization regimes, the SSC values were significantly higher in Liliyo compared to the three other sites, from 70 to 168 DAP, while no difference was observed between Tiéningboué, Midebdo, and Léo (Tables S7 and S8). The ORG treatment significantly increased SSC at 112 and 126 DAP in Liliyo, compared to NON. In Midebdo, from 112 to 168 DAP, MINORG and ORG significantly increased SSC compared to NON. The SSC in Léo was significantly higher, from 112 to 140 DAP, for all fertilized treatments, compared to NON. Anthracnose (*Colletotrichum gloeosporioides*) symptoms were observed on 40% of the foliage in Tiéningboué and on 30% of the foliage in Léo during phases II and III of the water yam growing period, irrespective of rotation and fertilization regimes. Except for these anthracnose symptoms, no other symptoms of fungal, insect, or virus attacks were observed during these field experiments.

Both in 2016 and 2018, irrespective of rotation and fertilization regimes, the SSC data showed high variability (Table S9).

3.2. Mean Tuber Weight, Number of Tubers, and Fresh Tuber Yield of Water Yam

During the two years (2016 and 2018), the harvested tubers did not present any visible symptoms of diseases or insect damages.

Parameters related to the sites and fertilization regimes influenced the mean tuber weight and number of tubers during the two years. In 2016, mean tuber weights of 1.8 and 1.7 kg tuber^{-1} observed in Liliyo and Tiéningboué, respectively, which, were significantly higher compared to those of 0.13 and 0.14 kg tuber^{-1} observed in Midebdo and Léo, respectively (Figure S4). In 2018, mean tuber weights of 0.55 and 0.46 kg tuber^{-1} in Tiéningboué and Midebdo, respectively, were statistically lower compared to that of 0.99 kg tuber^{-1} observed in Liliyo, and significantly higher compared to that of 0.24 kg tuber^{-1} in Léo (Figure S4). In 2016, the number of tubers, namely, 16,510 and 18,980 tubers ha^{-1} harvested in Liliyo and Léo, respectively, were significantly lower compared to that of the 24,470 tubers ha^{-1} harvested in Midebdo, and statistically higher in comparison to that of the 12,830 tubers ha^{-1} harvested in Tiéningboué (Figure S4). Except in Liliyo (2016), where MINORG significantly increased mean tuber weight compared to MIN, neither rotation nor fertilization affected mean tuber weight and number of tubers in 2016 and 2018 (Figure S4). The mean tuber weights were significantly lower in 2018 in Liliyo and Tiéningboué and significantly higher in Midebdo and Léo compared to 2016 (Figure S4). The number of tubers harvested in 2018 was significantly higher in Tiéningboué (all fertilization regimes) and Léo (only NON treatment), and significantly lower in Midebdo (ORG treatment), compared to those of 2016 (Figure S4).

The impact of sites and fertilization regimes on the fresh tuber yields of water yam measured in 2016 and 2018 is presented in Figure 3 and Table S10. Fresh tuber yields showed very variable coefficients of variation, ranging between 12 and 100% (Table S6). The effect of rotations on tuber yield in 2018 is not shown because neither rotation main effects nor their interaction with fertilization regimes affected yam fresh tuber yields.

In 2016, irrespective of the fertilization regimes, the mean fresh tuber yields of 32.8 t ha^{-1} harvested in Liliyo with C18 were significantly higher compared to those of 20.3, 2.7, and 2.5 t ha^{-1} in Tiéningboué with Woroba, Midebdo, and Léo, both with Florido, respectively (Figure 3 and Table S10). The fresh tuber yields of Midebdo and Léo were statistically similar but both significantly lower compared to the one of Tiéningboué. In 2018, the mean fresh tuber yields of 10.7 and 8.9 t ha^{-1} in Tiéningboué and Midebdo were statistically similar but significantly lower compared to the one of 16.4 t ha^{-1} in Liliyo, and significantly higher compared to the mean of 5.2 t ha^{-1} harvested in Léo (Table S10).

Fertilization had little significant effect on yield. In 2016, ORG yielded significantly better than NON in Tiéningboué and Léo, while MIN had a significantly higher yield than ORG in Midebdo (Table S11). Rotation had no significant impact on yields (Table S12).

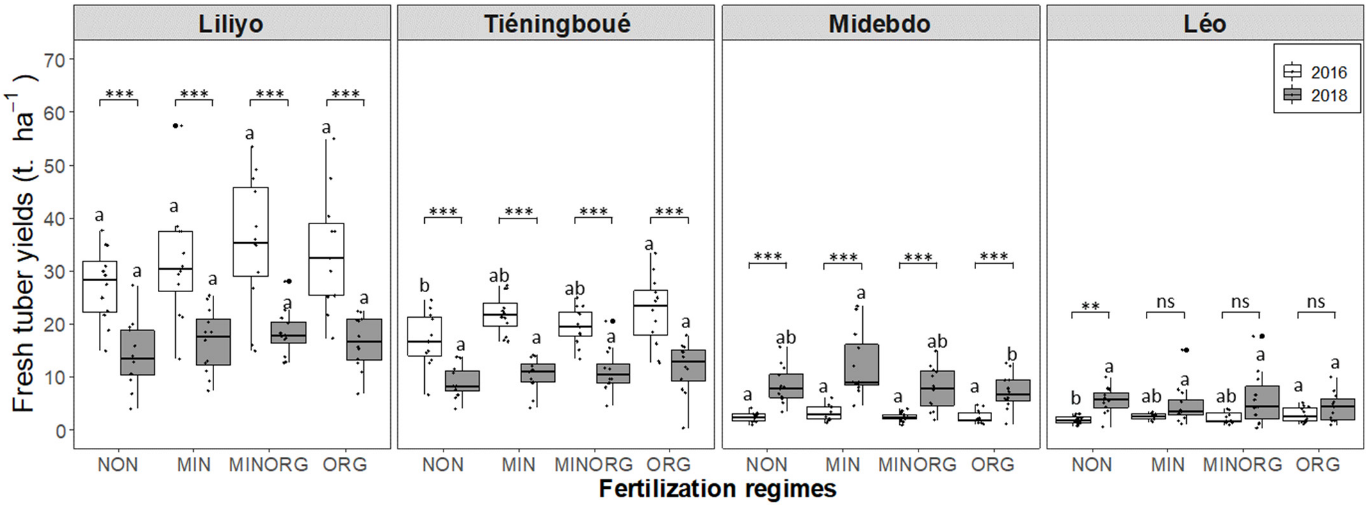

Figure 3. Effect of fertilization regimes and years on water yam fresh tuber yields in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016 and 2018. In 2016, the varieties cultivated were C18 for Liliyo, woroba for Tiéningboué, and florido for Midebdo and Léo. In 2018, yam variety C18 was cultivated in the four sites after either a cereal, a legume, or a yam for each fertilization regime. For each site and each year, different letters denote significant differences between fertilization regimes calculated by the Tukey test at p-level ≤ 0.05 (n = 12 replicates per fertilization). Asterisks indicate the results of the t-test assessing the significance of the difference between the years for each site and fertilization regimes: ns, not significant, ** $p < 0.01$, *** $p < 0.001$. The fertilization regimes are: NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG combined organic and mineral fertilization), and ORG (sole organic fertilization as manure).

Compared to 2016, yam fresh tuber yields significantly decreased by about 50% in 2018 in Liliyo and Tiéningboué, while they significantly increased by about 180 to 275% in Midebdo, irrespective of rotation and fertilization regimes (Figure 3). In Léo, fresh tuber yields increased by35 to 185% in 2018 compared to 2016, but the increase was significant only in the non-fertilized plots (Figure 3).

3.3. Relationships between Rainfall, Soil Properties, and Water Yam Growth and Yield in 2016 and 2018, as Impacted by Fertilization and Rotation

Correlation analyses performed on the data of the four sites and two years showed a positive non-linear relationship between the amount of rainfall recorded during the growing period of yam and fresh tuber yields, irrespective of rotations and fertilization regimes (Figure 4a). The distribution of rainfall during the yam growing season also affected yam fresh tuber yields. Yam fresh tuber yields were positively correlated to the amounts of precipitation falling between tuber initiation (112 DAP) and maximum canopy development (140 DAP) (Figure 4b).

A positive relationship was found between water yam fresh tuber yields and soil carbon stocks, considering data from the four sites and two years (Figure 5). The rainfall use efficiency (*RUE*) of water yam in 2016 and 2018 is presented in Table S13. The *RUE* of the four sites and two years were significantly positively correlated to soil carbon stocks (Figure S5).

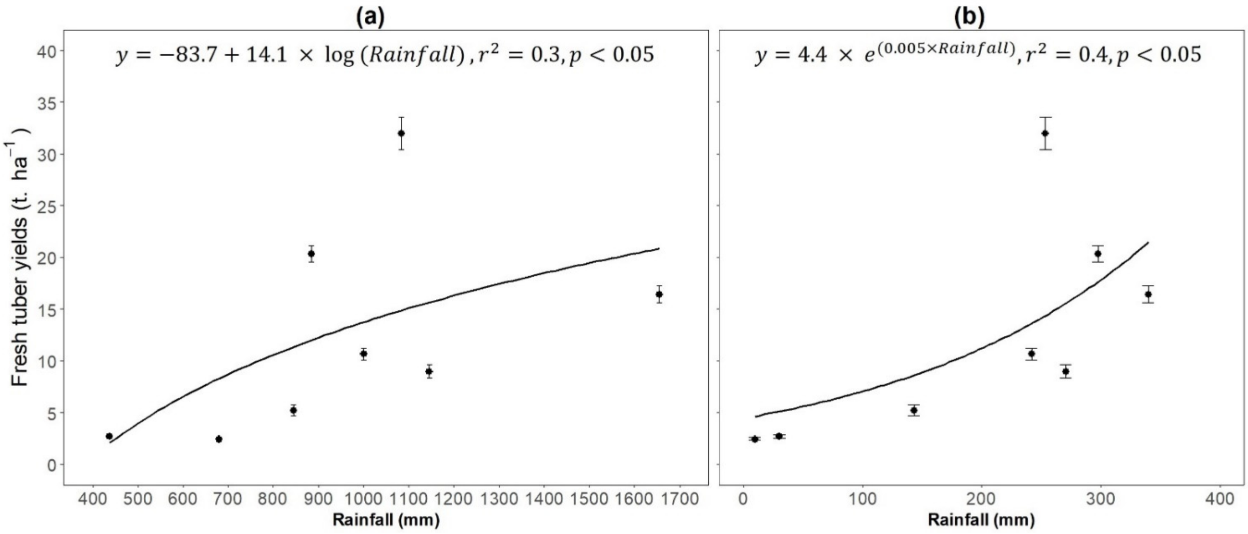

Figure 4. Relationships between the amounts of rainfall and water yam fresh tuber yields measured in 2016 and 2018 in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso): (**a**) total amounts of rainfall recorded during the growing period of yam; (**b**) total amounts of rainfall recorded from tuber initiation at 112 DAP to maximum canopy development (MCD) at 140 DAP. In 2018, yam variety C18 was cultivated in the four sites after either a cereal, a legume, or a yam for each fertilization regime. The regression equations, the coefficients of determination, and the p-values are shown on the graphs. For the fresh tuber yields, each point represents a mean of 48 replicates. The fertilization regimes are: NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG combined organic and mineral fertilization), and ORG (sole organic fertilization as manure).

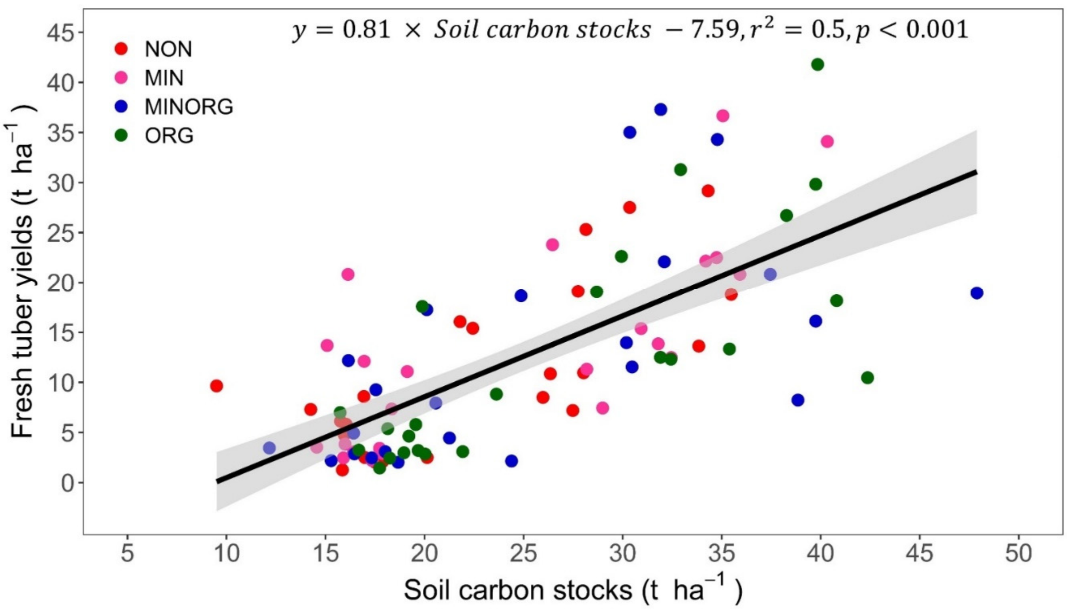

Figure 5. Relationship between soil carbon stocks and fresh tuber yields of water yam measured in 2016 and 2018 in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), under various fertilization regimes. In 2018, yam variety C18 was cultivated in the four sites after either a cereal, a legume, or a yam for each fertilization regime. The linear regression, the coefficient of determination, and the p-values are shown on the graph. For the fresh tuber yields and soil carbon stocks, each point represents a mean of 4 replicates. The grey band indicates the 95% confidence interval. The fertilization regimes are: NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG combined organic and mineral fertilization), and ORG (sole organic fertilization as manure).

The PCA and HCPC performed on the results of 2016 and 2018 showed significant discriminations between sites (Figures 6 and 7).

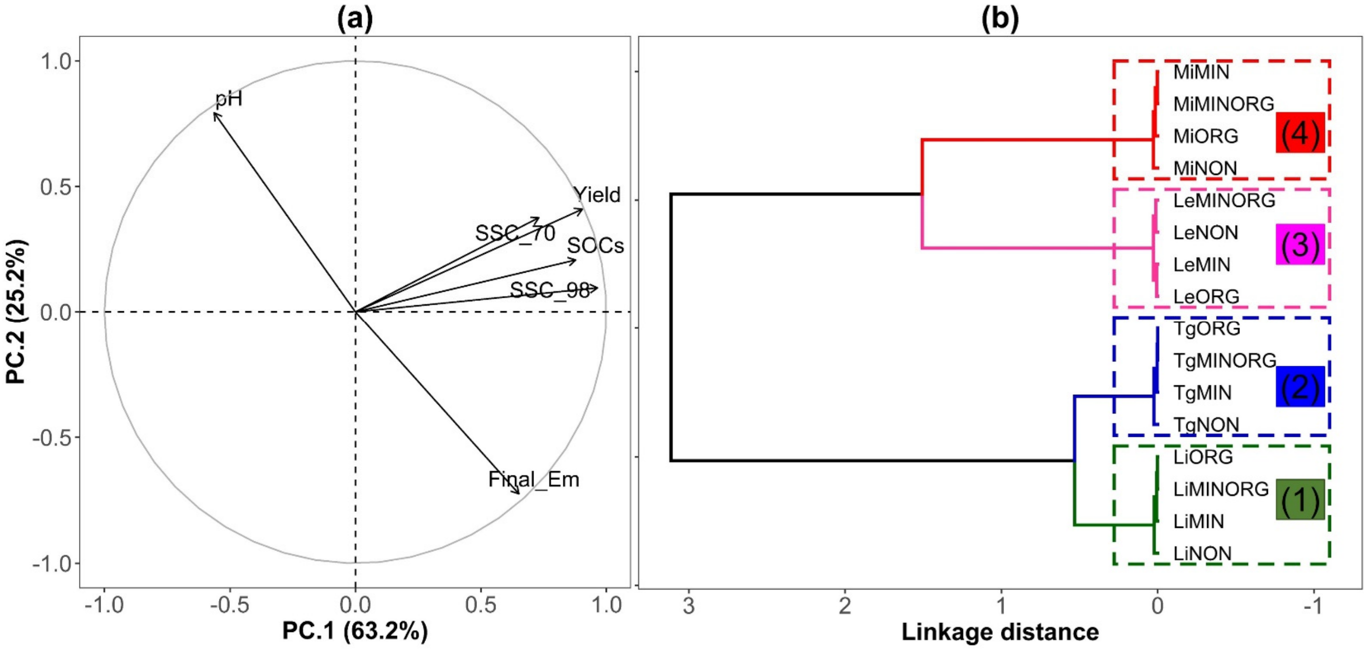

Figure 6. Normalized principal component analysis (PCA) and hierarchical clustering of principal components (HCPC) on soil carbon stocks and pH, measured in May 2016, and water yam growth and yield in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), under various fertilization regimes in 2016: (**a**) correlation circle, (**b**) dendrogram of hierarchical clustering based on the Ward's criterion. The linkage distance of the branches indicates the dissimilarity between clusters. The fertilization regimes are: NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG combined organic and mineral fertilization), and ORG (sole organic fertilization as manure). SOCs = Soil carbon stocks; pH = pH (H_2O); Final_EM = final sprout emergence rate; SSC_70 = Soil surface coverage by water yam above-ground organs at 70 days after planting; Yield = Yam fresh tubers yields in t ha^{-1}; Li = Liliyo; Tg = Tiéningboué; Mi = Midebdo; Le = Léo.

In 2016, the principal components (PC) 1 and 2 explained 63% and 25% of the total between-data variability, respectively (Figure 6a). This variation was driven along PC1 by SOCs (r = 0.9), SSC at 70 DAP (r = 0.7), SSC at 98 DAP (r = 0.9), and fresh tuber yields (r = 0.9), and along PC2 by pH (r = 0.7) and final sprout emergence (r = −0.7) (Figure 7a). The HCPC performed on the two PCs showed four clusters corresponding to the four sites (Figure 6b) with more similarities between the sites of Côte d'Ivoire on one side and those of Burkina Faso on the other side. In three of the four sites, the treatment NON built a cluster on its own, separated from the fertilized treatments. The variables significantly associated with each cluster are presented in Table S14.

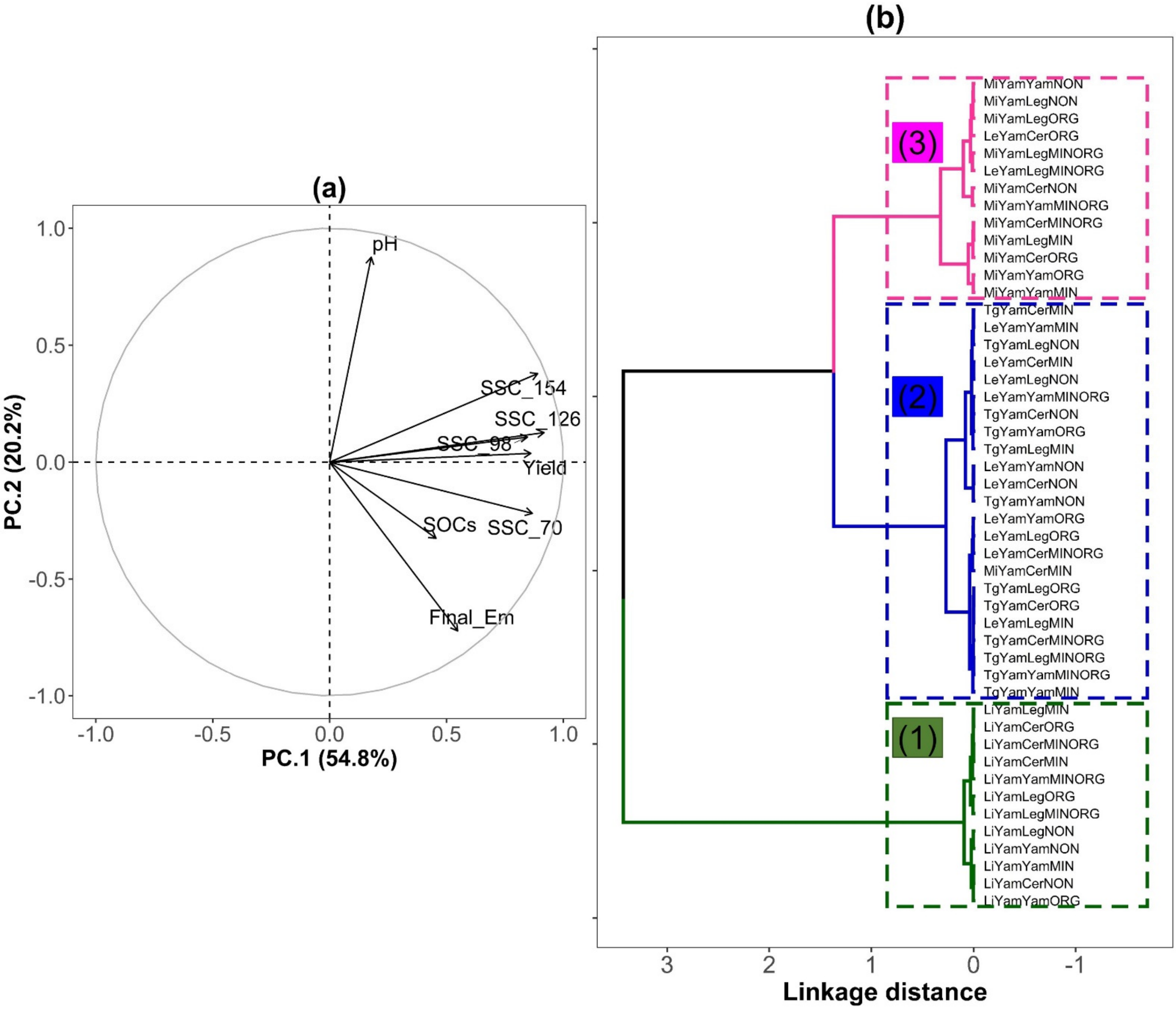

Figure 7. Normalized principal component analysis (PCA) and hierarchical clustering of principal components (HCPC) on soil carbon stocks and pH measured in December 2017, and water yam growth and yield in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), under various fertilization regimes in 2018: (**a**) correlation circle, (**b**) dendrogram of hierarchical clustering based on the Ward's criterion. The yam variety C18 was cultivated in the four sites after either a cereal (YamCer), a legume (YamLeg), or a white yam (YamYam) for each fertilization regime. The linkage distance of the branches indicates the dissimilarity between clusters. The fertilization regimes are: NON (no fertilization), MIN (sole mineral fertilization as NPK), MINORG combined organic and mineral fertilization), and ORG (sole organic fertilization as manure). SOCs = Soil carbon stocks; pH = pH (H_2O); Final_EM = final sprout emergence rate; SC_70, SC_98, SC_126, and 154 = Soil surface coverage by water yam above-ground organs at 70, 98, 126, and 154 days after planting; Yield = Yam fresh tubers yields in t ha^{-1}; Li = Liliyo; Tg = Tiéningboué; Mi = Midebdo; Le = Léo.

In 2018, 75% of the between-data total variability was explained by the PC1 (55%) and PC2 (20%) (Figure 7). The PC1 was related to SOCs (r = 0.5), SSC at 70 DAP (r = 0.7), 98 DAP (r = 0.8), 126 DAP (r = 0.8), 154 DAP (r = 0.8), and fresh tubers yield (r = 0.9), while PC2 was related to pH (r = 0.9) and final sprout emergence (r = −0.8). Yam fresh yields were positively correlated to SOCs (Figure 5) and SSC measured at 70, 98, 126, and 154 DAP (Figure S6). The HCPC performed on the two PCs showed three clusters (Figure 7b). The

cluster 1, which corresponds to all ISFM of Liliyo, was isolated from the other sites, which showed more similarities. The cluster 2 brings together all ISFM of Tiéningboué with ten of the twelve ISFM options of Léo and one ISFM option of Midebdo (Figure 7b). The remaining ISFM options of Midebdo (11) and Léo (2) belong to the cluster 3. In 2018, a weak fertilization effect was seen in the Liliyo cluster, with all the NON treatments grouped in the same cluster, while a non-fertilization effect could be seen in the other sites. No rotation effect was observed in 2018. The variables significantly associated with each cluster are presented in Table S15.

4. Discussion

4.1. Yam Sprout Emergence Rate

Yam emergence rate, measured at 49 DAP (end of phase I according to Craufurd et al. [37]), was not affected by site in 2016, while it was significantly lower in Midebdo and Léo compared to Liliyo and Tiéningboué in 2018 (Table 3 and Table S5). Since all the C18 mother tubers were sourced from the same farmer in 2018, and then distributed among the sites and treated similarly prior to planting, the lowest emergence rate observed in Midebdo and Léo remains unexplained. Apart from that, the independence of emergence rate from the site agrees with Diby et al. [5], who did not observe any difference on water yam emergence between a "fertile" forest site and a "non-fertile" savanna site receiving the same amount of rainfall in central Côte d'Ivoire. This result was expected, as during phase I, the new plant uses energy and nutrients from the setts [37]. The emergence rates observed in this study were higher compared to those of about 60–70% that are generally observed in farmer fields [1]. Our highest emergence rate is probably related to the fact that the setts used in this study were from non-dormant and visually healthy tubers and that the setts had been treated against nematodes, fungi, and insect attacks prior to planting.

4.2. Variability of Yam Growth and Fresh Tuber Yields

Except for data on sprout emergence, all data reported on yam growth and yields were extremely variable (Tables S9 and S12), although precaution had been taken to use the head parts of apparently healthy mother tubers and to protect setts from attacks by pests. This high variability strongly limits our ability to detect statistically significant differences between treatments. The high variability of tuber yields between plants has been highlighted by Cornet et al. [45] as a common trait in yam. These authors related this to the tuber composition, which is known to vary from the head to the most distal part. Hopefully, the reproduction of yam by vine cuttings [46] will lead to a reduced inter-plant variability in the future, but this plant multiplication process still needs to be implemented. The variability of soil properties probably also affected yield variability. Indeed, yam setts are planted at a density of 1 plant per square meter; which means that large fields need to be installed to conduct studies such as the one described here, which increases the risks of observing variations in soil properties, e.g., in deeper horizons.

4.3. Impact of Site-Related Variables

We considered two site-related variables in this work, rainfall (amount and distribution) and soil carbon stocks in the 0–30-cm layer. Both variables had strong impacts in both years on all data describing yam growth and yield, despite the fact that different cultivars of water yam were used in 2016.

In 2016, the rainfall recorded during the yam growing period in Liliyo (1084 mm) and Tiéningboué (885 mm) were higher compared to Midebdo (437 mm) and Léo (679 mm), where rainfall stopped at the beginning of phase III (around 126 DAP) (Figure 1). In 2018, the rainfall recorded during the yam growing period was 1655 mm in Liliyo, 1000 mm in Tiéningboué, 1145 mm Midebdo, and 845 mm in Léo (Figure 1). Lebot [1] states that yam requires an annual rainfall of about 1500 mm, evenly distributed throughout the growing season. The results presented in Figure 4b show that the requirement of yam in terms of rainfall is critical during phase III (from tuber initiation to maximum canopy

development). Despite sufficient rainfall in phases I, II, and IV, any water stress occurring in phase III can lead to early senescence, as observed in Midebdo and Léo in 2016 (Figure 2), to low mean tuber weight (Figure S4), and finally to low tuber yield (Figure 3). Our results agree with the findings of Craufurd et al. [37] and Diby et al. [47], who also noted that any rainfall limitation experienced between tuber initiation and maximum canopy development significantly decreases yam yields.

The second most determinant factor in water yam growth and yield was the soil carbon stocks. Indeed, soil surface coverage and tuber fresh yields in 2016 and 2018 were positively correlated to soil carbon stocks in the four sites (Figures 5, 6a and 7a). Soil organic matter is known as a major source of plant-available nutrients, especially in tropical soils [48], and to improve soil water-holding capacity, soil structure, and biological activity [49]. Since sufficient and well-distributed rainfalls were observed in Midebdo and Léo in 2018 until maximum canopy development (Figure 1), the poor yam growth in these two sites may be explained by the low soil carbon, nitrogen, and exchangeable base contents (Table S3). Similarly, Kassi et al. [50] observed a positive relationship between the yield of water yam cultivated in a forest–savanna interface and soil carbon stocks in Central Côte d'Ivoire. In the same zone, Diby et al. [5] showed that water yam tuber yields were significantly higher in a forest soil (12.1 g C kg^{-1}), compared to a savannah soil (6.5 g C kg^{-1}) having received the same amount and distribution of rainfall. With its high soil carbon contents, the soil of Liliyo could have stored more water and released more N and K during the water yam growing cycle, compared to the studied soils of Burkina Faso, resulting, finally, in higher yields. The rainfall use efficiency of water yam of the two years and in the four sites was also significantly correlated to the soil carbon stocks (Figure S5).

4.4. Impact of Integrated Soil Fertility Management Options (ISFM)

4.4.1. Impact of Fertilization on Yam Growth and Yield

At site level, soil surface coverage was influenced by fertilization treatments (Figure 2). This agrees with Hgaza et al. [51], who observed a positive impact of fertilization on the leaf area index of both water and white yam. This effect is most probably linked to the impact of N on leaf growth. The relation between soil surface coverage and final tuber yields observed in this work (Figure S6) agrees with Hgaza et al. [51], Diby et al. [5], and Frossard et al. [52], who observed a positive relation between leaf area index and final tuber yield.

The impact of fertilization on final tuber yield was weak in 2016 and 2018 (Figure 3 and Table S11). The lack of statistical differences between treatments is probably due in part to the high variability observed in the results discussed above. Another factor that could explain the lack of yield response to fertilizer input could be the limited amount of nutrients recovered by the plant from the added fertilizer. Hgaza et al. [22,51] and Senanayake et al. [53] have demonstrated, using ^{15}N-labelled fertilizer, that most of the N taken up by yam was derived from the soil and not from the added fertilizer. The absence of yield response to fertilizer inputs might have been also related to the lack of rainfall. Hgaza et al. [22] and Senanayake et al. [53] showed, indeed, clear yield responses of water yam to different nutrient inputs in irrigated plots. In 2018, the anthracnose attacks in Liliyo and Tiéningboué were probably responsible for the smaller tubers [54] observed at these sites compared to 2016 and, therefore, for the lowest tuber yields [1,54]. The lower tuber yields observed in these two sites in 2018 compared to 2016 might also have been caused by the lower nutrient inputs.

4.4.2. Impact of Rotation on Yam Growth and Yield

The effect of rotation could only be studied in 2018. The three types of rotations tested in this work, yam–cereal, yam–legume, and yam–yam had no impact on soil surface cover, on yam yield component (number of tubers, mean tuber weight), nor on final tuber yield of the cultivar C18 (Tables S9 and S12). The lack of yam response to rotation might be linked to the high result variability discussed above. The introduction of groundnut in the rotation

had no impact on yam yield, despite the addition of 15 to 59 kg N ha^{-1} by biological fixation in 2017 (Table S16) and 26 to 82 kg N ha^{-1} with the plant residues (Table S2) before yam plantation. Maliki et al. [55] observed, on the contrary, increases in yam tuber yields following one year of herbaceous (*Aeschynomene* and *Mucuna*). They explained that by the return to soil with the legumes of high amounts of nutrients and particularly of N (between 99 and 186 kg N ha^{-1}). Finally, no negative impact of a water yam–white yam rotation was observed, suggesting that during this short rotation, yam-specific pests and diseases had not strongly accumulated. The NON-fertilized yam yields in the yam–yam rotation decreased from 2016 to 2018 in Liliyo and Tiéningboué, and increased in Midebdo and Leo, suggesting that anthracnose and rainfall had probably a stronger influence on yam yield in 2018 than nutrient depletion caused by repeated yam cultivation from 2016 to 2018.

4.5. Concluding Remarks

This work confirmed the importance of rainfall (amount and distribution) and carbon stocks as drivers of yam yield. This is, however, the first publication showing this along a southwest–northeast gradient crossing the yam belt of West Africa. The impacts of fertilization and rotation in three year-long trials were more difficult to identify, as they were over-hidden by variations in rainfall, anthracnose, and the overall results' variability. Such trials should be conducted over longer periods to better observe the impact of new practices. They should be conducted with yam cultivars resistant to anthracnose and, if acceptable by farmers, with herbaceous legumes. New treatments involving intercropping of yam, e.g., with cereals and legumes, could also be included to maximize nutrient use at field level. Finally, the weak reaction of tuber yield to fertilizer additions observed in this study should not be a justification to give up fertilization in yam systems, as the nutrient taken up by this crop should be given back to avoid nutrient depletion in the long term. However, nutrient additions will need to be made in a manner to avoid as much as possible nutrient losses from the field, as quantified recently in Senanayake et al. [53] for nitrogen.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12040792/s1, Figure S1: Map showing the four sites (source: Google Earth, 2022, buildings data layer (SIAO. NOAA. US. Navy. NGA. GEBCO, Image Landsat/Copernicus); available online: http://www.google.com/earth/index.html (accessed on 12 March 2021)). Figure S2: Layout of experiment installed in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), from 2016 to 2018. Table S1: Amount of C, N, P, and K added by mineral and organic fertilizers in 2017 on white guinea yam (*D. rotundata*) in the four sites, maize (*Zea mays*) in Liliyo, Midebdo, and Léo, and rice (*Oryza sativa*) in Tiéningboué. Table S2: Amount of C, N, P, and K added by groundnut (*Arachis hypogea*) straw incorporated in 2017 at Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso). Table S3: Soil total carbon and pH (average ± standard error) of the upper layer (0–30 cm) according to the rotations in December 2017. Table S4: Soil carbon stocks (t ha^{-1}) of the upper layer (0–30 cm) according to the rotations and fertilization regimes in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), measured in May 2016 and December 2017. Figure S3: Relationship between soil surface coverage by water yam above-ground organs measured using the wooden frame (Burstall and Harris, 1983 modified by Diby et al., [5]) and Canopeo (Patrignani and Ochsner, 2015) in Tiéningboué in 2018, from 70 to 168 DAP (n = 4). Table S5. Summary of the linear mixed-effects model fitted by REML to assess the effect of site on sprout emergence rate (%) of water yam setts at 49 DAP in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016 and 2018. Water yam was cultivated in the presence of different fertilization regimes in 2016 and 2018. In 2018, for each fertilization regime, water yam was cultivated after either a cereal, a legume, or a yam. Table S6. Summary of the linear mixed-effects model fitted by REML to assess the effect of site on soil surface coverage (%) by water yam above-ground organs in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016, at 70, 84, and 98 days after planting (DAP). Water yam was cultivated in the presence of different fertilization regimes in 2016. Table S7. Summary of the linear mixed-effects model fitted by REML to assess the effect of site on soil surface coverage (%) by water yam above-ground organs in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2018, at 70, 84, 98, and 126 days after planting (DAP). Water yam was cultivated in

the presence of different fertilization regimes after either a cereal, a legume, or a yam within each fertilization regime. Table S8. Summary of the linear mixed-effects model fitted by REML to assess the effect of site on soil surface coverage (%) by water yam organs in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2018, at 140, 154, and 168 days after planting (DAP). Water yam was cultivated in the presence of different fertilization regimes after either a cereal, a legume, or a yam for each fertilization regime. Table S9: Soil surface coverage by water yam above-ground organs according to the rotations and fertilization regimes in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), measured in 2016 and 2018. The values in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), measured in 2016 and 2018. Figure S4: Effect of years and fertilization regimes on water yam mean tuber weights and tuber number in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016 and 2018. Table S10: Summary of the linear mixed-effects model fitted by REML to assess the effect of site on water yam fresh tuber yields (t ha^{-1}) in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016 and 2018. Water yam was cultivated in the presence of different fertilization regimes in 2016 and 2018. In 2018, for each fertilization regime, water yam was cultivated after either a cereal, a legume, or a yam. Table S11: Summary of the linear mixed-effects model fitted by REML to assess the effect of fertilization regime on water yam fresh tuber yields (t ha^{-1}) in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016, cultivated in the presence of different fertilization regimes. Table S12: Fresh tuber yield (t ha^{-1}) of water yam according to the rotations and fertilization regimes in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), measured in 2016 and 2018. Table S13: Rainfall use efficiency (kg ha^{-1} mm^{-1}) according to fertilization regimes in Liliyo and Tiéningboué (Côte d'Ivoire), Midebdo and Léo (Burkina Faso), in 2016 and 2018. Figure S5: Relationship between rainfall use efficiency (*RUE*) by water yam cultivated under various fertilization regimes (NON, MIN, MINORG, and ORG) and soil carbon stocks in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016 and 2018. Table S14: Summary of variables significantly associated to each cluster identified by the hierarchical clustering of principal components, performed on data of water yam cultivated under various fertilization regimes (NON, MIN, MINORG, and ORG) in Liliyo, Tiéningboué, Midebdo, and Léo in 2016. Figure S6: Relationships between yam fresh tuber yields and soil surface coverage by water yam above-ground organs measured in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2016 and 2018, at 70, 84, and 98 DAP (n = 4). The yam variety C18 was cultivated in the four sites after either a cereal, a legume, or a yam for each fertilization regime (NON, MIN, MINORG, and ORG). Table S15: Summary of variables significantly associated to each cluster identified by the hierarchical clustering of principal components performed on data of water yam cultivated in Liliyo, Tiéningboué, Midebdo, and Léo after either a cereal, a legume, or a yam, under various fertilization regimes (NON, MIN, MINORG, and ORG), in 2018. Table S16: Amount of N (kg ha^{-1}) fixed by groundnut in Liliyo and Tiéningboué (Côte d'Ivoire), and Midebdo and Léo (Burkina Faso), in 2017.

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