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Optimizing Soil Fertility Management Strategies to Enhance Banana Production in Volcanic Soils of the Northern Highlands, Tanzania

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Received: 13 December 2019; Accepted: 31 January 2020; Published: 18 February 2020

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Abstract: Banana is an important crop in high altitude areas of Tanzania, grown widely both as a food staple and as the main source of income. However, its production is constrained by low soil fertility, a result of gradual nutrient mining by the crop. Currently, soil fertility management in banana-based farming systems in the country relies mainly on applications of animal manure. However, the amount of manure produced in most farms is not enough to replenish soil fertility due to the small number of animals kept by smallholder resource-poor farmers who are the major producers in the country. Field experiments were conducted at three sites with varying soil types and contrasting weather conditions along the altitudinal gradients on the slopes of the volcanic mountains of Kilimanjaro and Meru, northern Tanzania to (1) investigate the effect of mineral nitrogen (mineral N) fertilizer applications on the growth and yield of Mchare banana (*Musa* spp., AA, a traditional East African highland cooking banana sub-group), at the four levels of 0, 77, 153, and 230 kg N ha^{-1} $year^{-1}$ as a starter strategy to improve the current soil fertility management strategies, and (2) evaluate the effect of the combined use of inorganic and organic N sources on growth and banana fruit production as an alternative strategy to manage soil fertility and minimize animal manure requirements. The treatment factors were trial sites (Tarakea, Lyamungo, and Tengeru) as the main factor and N fertilization strategies (as urea alone, sole cattle manure, and in combination with urea, sole common bean (*Phaseolus vulgaris* L.) haulms as well as in combination with urea) as a sub factor. Bean haulms and cattle manure were applied each year for two years. Fertilization at 153 kg N ha^{-1} $year^{-1}$ derived solely from urea significantly ($p < 0.001$) resulted in high yield increment of up to 42% relative to the control. However, the increase was highest (52%) with the same N dose derived from cattle manure in combination with urea at 50% substitution. Sole bean haulms resulted in a smaller yield increment, the same as the lowest N dose from the sole urea fertilization treatment. The study concludes that soil fertility management in smallholder banana-based farming systems should not solely rely on animal manure and mineral fertilizers.

Keywords: East African highland banana; fertilizer efficiency; integrated soil fertility management; Mchare banana; *Musa* spp.; Tanzania

1. Introduction

Banana is a major food staple and an important cash crop in highland areas of Tanzania [1,2], normally grown in association with the common bean [2] in homestead gardens with little or no fertilizer input [1,2] due to limited access to financial credit [2,3]. Bean grains play a significant role in household nutrition as a source of protein whereas residues (haulms) are animal fodder for indoor dairy cattle that serve as an important source of organic fertilizer for banana-homestead gardens [2,3]. However, the smallholder dairy cattle industry is constrained by the inadequate availability of fodders due to high population pressure on the land caused by high population densities of up to 345 residents per km^2 with each household living on a farmstead of less than 0.5 ha [3]. Consequently, pasture plots have been converted to crop land to produce food to feed the ever increasing population [2,3]. As such, dairy cattle feed largely on crop residues (pseudostems, banana leaves, and haulms) produced in the farmstead [3] and it is common practice for livestock keepers to supplement these materials by buying from non-livestock keepers in the neighborhood. In this way, banana-homestead gardens owned by livestock keepers benefit from nutrient input brought in by the obtained manure at the expense of soil fertility in banana-homestead gardens owned by non-livestock keepers. In light of this, importation of additional fodders from low altitude areas should be considered, but transport costs of up to US $57 per trip of a 2.5 ton truck are too high for a resource-poor farmer. Banana ranks fourth after maize, cassava, and sweet potato in terms of the quantities produced [4] and is estimated to feed up to 30% of the total human population in the country [2]. Approximately 30% of the total produce is consumed at the homestead while the remaining 70% is sold in the local market [5], hence contributing significantly in food security and income stability. Nearly 80% of the cultivated bananas belong to the traditional East African highland cooking banana (EAHB), 10% are brewing bananas, 8% are dessert bananas, and 2% are plantains [2,6], indicating that they are of considerable cultural importance for the community.

The current banana fruit yields under the farmer's conditions are low (7 t ha^{-1}) [4], only 10% of the potential yield in East Africa [7] primarily caused by low soil fertility due to continuous production without proper nutrient replenishment [2,3,8,9]. Previously, Baijukya et al. [3], Raeymaekers and Stevens [9], Mizota et al. [10], Kaihura et al. [11], Ndakidemi and Semoka [12], Pabst et al. [13], and Maro et al. [14] reported that soil N deficiency was amongst the main constraints to crop production in most areas of the country, inclusive of the study area. This nutrient is required by banana plants in large amounts, only second to K, and is a constituent of many plant cell components including amino and nucleic acids [15]. Therefore, in order to increase banana fruit yields, the current soil N levels need to be improved.

Crop nutrient requirements in banana-based farming systems are currently addressed via cattle manure only. However, in most farms, the quantity of manure produced by stall-fed dairy cows is not enough to maintain the soil fertility of the farms [2,3,8,9]. For instance, the average size of a banana homegarden in the study area is 0.8 ha [9]. If 20 kg of cattle manure (N = 0.48% [3]) mat^{-1} year^{-1} which is currently used by resource endowed farmers to fertilize the crop has to be applied as the sole source of N, then 25 t year^{-1} of manure is needed. The average number of dairy cows kept per household is 3 [9], with the average production of 650 kg manure animal^{-1} year^{-1} [16], so the potential production is 2 t year^{-1}, which is only 8% of the total requirement. Supplementation with poultry, goat, and swine manure produced at the homestead or additional cattle manure from nomadic pastoralists in the lowlands should be considered. However, poultry, goat, and swine manure is produced in negligible quantities [9], while the transport costs of cattle manure of up to $52 USD per trip of a one ton pickup are too high. This explains the need to supplement organic with inorganic fertilizers, which are relatively cheap. For instance, the retail price of a 50 kg bag of urea, which is commonly available in most villages, ranges between $19 and $21 USD and can be found in the market throughout the year. The combined use of organic and inorganic fertilizer resources in turn will reduce the total reliance on animal manure while maintaining good soil fertility and high yield levels. Earlier studies by Chivenge et al. [17] and Ripoche et al. [18] indicated that combined applications of organic and inorganic fertilizers consistently resulted in the highest yields, relative to manure or mineral fertilizers alone. Nevertheless, banana growers in Tanzania do not use this strategy due to lack of knowledge on its appropriate use.

This paper aimed to improve our knowledge on the appropriate use of N fertilizer in terms of application rate and strategy as an alternative approach to manage soil N under highland conditions. Therefore, this study was conducted to (i) estimate the optimum N fertilizer application rate as a starter strategy to improve traditional soil fertility management practices in banana-based farming systems; (ii) understand the additive effect of integrating mineral and organic N resources on growth, plant nutrition, and banana fruit yield; and (iii) assess the contribution of common bean haulms to improve banana production.

2. Materials and Methods

2.1. Site Description, Experimental Field Establishment, and Soil Characterization

Field experiments were performed in 2016 to 2017 in three farms established at three sites with varying soil types and contrasting weather conditions located along the altitudinal gradients on the volcanic slopes of Mount Kilimanjaro and Mount Meru in the northern highlands, Tanzania. These included (i) Tarakea, at the farm of Tarakea secondary school (latitude 03°02′17.0′′ S, longitude 037°35′24.9′′ E; 1608 m.a.s.l.) in the Rombo district, Kilimanjaro region; (ii) Lyamungo, at the farm of Tanzania Coffee Research Institute (latitude 03°13′49.6′′ S, longitude 037°14′55.9′′ E; 1346 m.a.s.l.) in the Hai district, Kilimanjaro region; and (iii) Tengeru, at the farm of Nelson Mandela African Institution of Science and Technology (latitude 03°02′17.0′′ S, longitude 037°35′24.9′′ E; 1106 m.a.s.l.) in the Arumeru district, Arusha region. The first field was established in the high altitude agro-ecological zone, the second field in the mid altitude zone, and the third was established in the interflow zone between mid and low altitude agro-ecological zones. Precipitation was recorded at each trial site for the entire experimental period to evaluate its effect on banana fruit production.

A representative soil profile pit was dug with dimensions of 2 m depth, 2.5 m length, and 1 m width at each experimental site for soil characterization. Top soil samples (30 cm surface soil layer) were collected using an Edelman auger for fertility analysis. Soil pH was measured in water using a soil to water ratio of 1:2.5 [19]. Total C was determined according to the Walkley and Black wet oxidation method [20]. Soil total N was determined by the Kjeldahl wet digestion-distillation method [21] to obtain an overview of soil quality in the trial sites related to soil organic matter. Soil available P was extracted following the Bray-1 procedure [21]. Cation exchange capacity was determined by the ammonium saturation method [22]. Soil exchangeable (Ca, Mg, and K) was determined by atomic absorption spectrophotometry in a 1 M ammonium acetate extract buffered at pH 7 [22]. Then, particle size distribution was measured by the hydrometer method [23] and textural classes of the soils were determined according to the guidelines for soil description [24]. Soil classification was done using soil classification guidelines provided in the USDA Soil Taxonomy [25] and in the World Reference Base for Soil Resources (WRB) FAO [26]. Soil types varied from an Endo-Eutric Calcic Vitric Andosol (Aric, Clayic, Sideralic) in Tarakea to a Luvic, Rhodic Nitisol in Lyamungo, and a Phaeozem (Clayic, Humic, Geoabruptic) in Tengeru. The initial top soil properties ranged between 5.4 and 6.5 (pH), 1.0 and 2.2 g kg^{-1} (total N), 16 and 22.2 g kg^{-1} (total C), 6.3 and 7.9 mg kg^{-1} (P), 0.8 and 3.5 $cmol_c$ kg^{-1} (K), 1.6 and 4.8 $cmol_c$ kg^{-1} (Mg), 8.9 and 23.6 $cmol_c$ kg^{-1} (Ca), and 18.2 and 44.1 $cmol_c$ kg^{-1} (CEC) (Table 1). In general, soil C and N in Tarakea and Tengeru was low [27].

Table 1. Salient features of the experimental sites.

Characteristics	Tarakea	Lyamungo	Tengeru
Elevation (m.a.s.l.)	1608	1346	1106
Geographical location	03°02′17.0″ S; 037°35′24.9″ E	03°13′49.6″ S, 037°14′55.9″ E	03°02′17.0″ S, 037°35′24.9″ E
Top soil (30 cm surface layer) characteristics			
Clay (%)	46.0 ± 0.0	31.3 ± 0.7	40.0 ± 1.2
Silt (%)	26.0 ± 1.2	30.0 ± 1.2	29.3 ± 3.7
Sand (%)	28.0 ± 1.2	38.7 ± 0.7	30.7 ± 2.9
Textural class	Clay	Clay loam	Clay
pH H_2O 1:2.5	5.9 ± 0.1	5.4 ± 0.0	6.5 ± 0.2
Total C (g kg^{-1})	18.7 ± 2.4	22.2 ± 3.0	17.1 ± 2.5
Total N (g kg^{-1})	1.2 ± 0.2	2.2 ± 0.1	1.4 ± 0.0
Available P (mg kg^{-1})	6.9 ± 0.1	6.3 ± 0.0	7.9 ± 0.8
Exchangeable K ($cmol_c$ kg^{-1})	0.9 ± 0.2	0.8 ± 0.1	3.4 ± 0.2
Exchangeable Mg ($cmol_c$ kg^{-1})	3.5 ± 0.1	1.6 ± 0.1	4.9 ± 0.4
Exchangeable Ca ($cmol_c$ kg^{-1})	11.0 ± 0.8	7.9 ± 0.5	24.0 ± 0.4
CEC	22.8 ± 2.1	16.4 ± 0.8	44.1 ± 0.9
Soil profile characteristics (a) horizon depth (cm)			
Horizon 1	20	20	18
Horizon 2	50	45	62
Horizon 3	30	70	55
Horizon 4	40	70	30
Relative soil depth	140	205	165
(b) Soil color (when dry)			
Horizon 1	Dark brown 10 YR 3/3	Dark brown 10 YR 3/4	Brownish black 7,5 YR 3/2
Horizon 2	Brownish black 10 YR 2/2	Very dark brown 7,5 YR 2/3	Black 10 YR 2/1
Horizon 3	Brownish black 5 YR 2/2	Brownish black 7,5 YR 2/2	Brownish black 7,5 YR 2/2
Horizon 4	Dark reddish brown 5 YR 3/4	Dark brown 7,5 YR 3/4	Dull yellow orange 11 YR 6/4
Classification (WRB-FAO)	Endo-Eutric Calcic Vitric Andosol (Aric, Clayic, Sideralic)	Luvic, Rhodic Nitisol	Phaeozem (Clayic, Humic, Geoabruptic)

2.2. Experimental Design and Fertilization Treatments

The experiment involved a randomized complete block design and was replicated three times. Banana planting holes were dug 0.9 m long by 0.9 m wide by 0.7 m deep. Each experimental plot was 15 m long by 10 m wide and contained five rows spaced 3 m by 2 m, and a plot area measured 150 m^2. Banana seedlings (Mchare AA, the traditional East African highland cooking banana (EAHB)) [6] were obtained from the Crop Bio-Science laboratory based in Arusha, Tanzania, as in vitro plants. Banana seedlings were planted at the onset of a long rainy season. Common bean (*Phaseolus vulgaris* L. var. "Lyamungo 90", bush type) was planted as an intercrop in the respective treatment plots between banana mats in four rows spaced 0.2 m by 0.5 m in both the short and long rainy season in each year. Legume seeds were obtained from the Selian Agricultural Research Institute (SARI) based in Arusha, Tanzania.

The experiment consisted of eight fertilization treatments (Table 2). All fertilization treatments were applied in each year in all locations. Treatments 3, 5, and 6 were designed to equalize the total N contents derived from different amounts of urea and cattle manure. This was calculated on the basis of equal N amounts (153 kg N ha^{-1} $year^{-1}$ equivalent to 92 g N mat^{-1} $year^{-1}$ determined according to organic N traditionally applied by resource-endowed farmers). Fertilization treatments included (N rates expressed in kg ha^{-1} $year^{-1}$): T1 = 0 N (control); T2 = 77 kg N (derived from urea, 50% below the N dose applied by resource-endowed farmers); T3 = 153 kg N (derived from urea, corresponding the traditional N rate derived from cattle manure); T4 = 230 kg N (derived from urea, 50% above the traditional N rate); T5 = 50% urea (containing 77 kg mineral N) + 50% cattle manure (containing 77 kg organic N); T6 = 100% cattle manure (containing 153 kg organic N, the current N rate applied by resource-endowed farmers); T7 = 50% urea (containing 77 kg mineral N) + bean haulms (containing 52 kg organic N); and T8 = 100% bean haulms (containing 52 kg organic N). In the first four treatments, we intended to estimate the optimum N fertilizer application rate as a starter strategy to improve the traditional soil fertility management practices in banana-based farming systems. On the other hand, T6 (100% cattle manure), which represents the traditional farmers practice, was used as the reference. Cattle manure was locally sourced from one farm and was found to contain 0.2% N, 0.3% P, and 1.2% K. Each banana mat in T5 received 23 kg (equivalent to 38 t ha^{-1}) of cattle manure + 100 g (equivalent to 77 kg ha^{-1}) of urea $year^{-1}$. As for 100% cattle manure treatment (T6), each mat was amended with 46 kg (equivalent to 76 t ha^{-1}) manure $year^{-1}$. In addition, every banana mat in T8 received 1 kg (equivalent to 1.6 t ha^{-1}) of dry common bean haulms $year^{-1}$, while in T7, every banana mat received this amount in combination with the lowest dose of urea (Table 2). Bean haulms contained 3.1% N, 0.3% P, and 2.4% K. Mineral fertilizers used in this study were triple super phosphate (TSP, 46% P_2O_5), urea (46% N), and muriate of potash (MOP, 60% K_2O) as a source of K. Cattle manure and TSP were applied once in every year. On the other hand, urea and MOP were applied in three splits (Table 3) in each year.

Table 2. Fertilization treatments, nutrient sources and application rates.

Fertilization Treatments	Cattle Manure & Haulms Rate (kg ha^{-1} Year^{-1})		Nutrients Supplied by Manure & Haulms (kg ha^{-1} Year^{-1})			Nutrients Supplied by Mineral Fertilizer (kg ha^{-1} Year^{-1})		
	Manure	Haulms	N	P	K	N	P_2O_5	K_2O
T1: No N (control)	0.0	0.0	0.0	0.0	0.0	0.0	119	471
T2: 77 kg N [urea (50% below optimum rate)]	0.0	0.0	0.0	0.0	0.0	77	119	471
T3: 153 kg N [urea (optimum rate)]	0.0	0.0	0.0	0.0	0.0	153	119	471
T4: 230 kg N [urea (50% above optimum rate)]	0.0	0.0	0.0	0.0	0.0	230	119	471
T5: 77 kg N (urea) + 77 kg N (cattle manure)	38,318	0.0	77	119	471	77	0.0	0.0
T6: 153 kg N [cattle manure (farmer's practice)]	76,636	0.0	153	238	942	0.0	0.0	0.0
T7: 77 kg N (urea) + 52 kg (bean haulms)	0.0	1600	52	5.0	40	77	119	471
T8: 52 kg N (bean haulms)	0.0	1600	52	5.0	40	0.0	119	471

Table 3. Mineral fertilizers applied mat^{-1} in each split.

Fertilization Treatments	Nutrient Fertilizer (g mat^{-1} Year^{-1})			Fertilizer Source (g mat^{-1} Year^{-1})			1st Split: at Planting (g mat^{-1})			2nd Split 60 DAP (g mat^{-1})			3rd Split 150 DAP (g mat^{-1})		
	N	P_2O_5	K_2O	Urea	TSP	MOP	Urea	TSP	MOP	Urea	TSP	MOP	Urea	TSP	MOP
T1: No N (control)	0.0	55	283	0.0	120	590	0.0	120	118	0.0	0.0	236	0.0	0.0	236
T2: 77 kg N [urea (50% below optimum rate)]	46	55	283	100	120	590	25	120	118	25	0.0	236	50	0.0	236
T3: 153 kg N [urea (optimum rate)]	92	55	283	200	120	590	50	120	118	50	0.0	236	100	0.0	236
T4: 230 kg N [urea (50% above optimum rate)]	138	55	283	300	120	590	75	120	118	75	0.0	236	150	0.0	236
T5: 77 kg N (urea) + 77 kg N (cattle manure)	46	0.0	0.0	100	0.0	0.0	25	0.0	0.0	25	0.0	0.0	50	0.0	0.0
T6: 153 kg N [cattle manure (farmer's practice)]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T7: 77 kg N (urea) + 52 kg (bean haulms)	46	55	283	100	120	590	25	120	118	25	0.0	236	50	0.0	236
T8: 52 kg N (bean haulms)	0.0	55	283	0.0	120	590	0.0	120	118	0.0	0.0	236	0.0	0.0	236

2.3. Growth and Yield Assessment

Growth and yield data were assessed on nine banana plants from central rows. Growth observations were made based on plant size and crop cycle. Plant size expressed in m^3 was computed from measurements on (i) plant height from the soil level to the top of the plant where the petiole of the two youngest leaves come together, and (ii) stem girth at 100 cm above the soil using the formula given in Equation (1) below.

$$Plant\ volume = \pi h r^2 \tag{1}$$

where r and h are the radius and height of the stem, respectively.

Growth measurement was done at flowering. The crop cycle was assessed as the period in number of days from planting to shooting. Yield and yield parameters included (i) crop maturity, (ii) fingers per bunch, (iii) finger length and girth, (iv) finger weight, (v) bunch weight, and (vi) yield ha^{-1} $cycle^{-1}$. To obtain finger weight without peduncle, all hands were cut, weighed, and their weights subtracted from the respective bunch total weight. Average fruit weight was determined from three individual middle fingers of the second hand, as described by Alvarez et al. [28]. Duration to crop maturity was the period in number of days from planting to harvesting. Yield ha^{-1} $cycle^{-1}$ was calculated using the formula given in Equation (2). At harvest, pseudostem and leaf residues were chopped into small pieces and left in the field for the recycling of nutrients.

$$Yield = bunch\ weight\ x\ number\ of\ bunches\ ha^{-1}\ cycle^{-1} \tag{2}$$

2.4. Nutritional Status of Mchare Banana Leaves

Nutritional status of the banana leaves was assessed at nine months after planting (MAP) by analyzing a sub-sample of 10 cm by 20 cm collected from both sides of the midrib at the midpoint of the lamina of the third fully open leaf [29]. A composite sample consisted of leaves collected from nine plants grown in the central rows of each treatment plot. Samples were thoroughly washed with distilled water to remove dust and oven dried at 70 °C until constant weight. Dry samples were ground with an agate ball mill to less than 2 mm, digested by 2 mL, of concentrated nitric acid-analytical grade, and analyzed for P, K, Mg, Ca, B, Cu, Fe, Mn and Zn concentrations using Inductively coupled plasma optical emission spectrometry (ICP-OES). Total N was determined by subjecting Sn capsules to oxidative digestion under a controlled oxygen supply at around 1700 °C. Foliar macronutrient concentrations were evaluated with the norms obtained through compositional nutrient diagnosis (CND) for the EAHB as developed by Delstanche [30], who established 2.35–2.81, 0.13–0.18, 3.23–4.12, 0.32–0.45%, and 0.49–0.80as sufficiency ranges for N, P, K, Mg, and Ca, respectively. In addition, foliar micronutrient concentrations were compared with sufficiency ranges published in Reuter and Robinson [31], who identified 11, 9, 80, 25, and 18 mg kg^{-1} as critical concentrations for B, Cu, Fe, Mn, and Zn, respectively.

2.5. Total Nutrients Content in the Above Ground Biomass at Harvest

During harvesting, pseudostem, leaves, peduncle, and fruits were weighed separately. Thereafter, sub-samples were collected from each part and weighed for their fresh weight. Sample preparation and tissue analysis was done as described in Section 2.2. Tissue nutrient concentrations were then used to calculate the total nutrient contents in the above ground biomass using Equation (3). Nutrient content was calculated by multiplying the nutrient concentration in the tissue with the dry matter yield. This information was then used to calculate the internal and utilization efficiency of N fertilizer applied to the crop using Equations (4) and (5) given below [32].

$$Total\ nutrient\ contents = tissue\ concentration\ \times tissue\ mass,\ for\ above\ ground\ parts \tag{3}$$

$$Internal\ efficiency = ((yield\ (N\ treatment) - yield\ (control)) \div N\ uptake \tag{4}$$

$$Utilization\ efficiency\ = 100((N\ uptake\ (N\ treatment) - N\ uptake\ (control)) \div N\ applied \quad (5)$$

2.6. Statistical Analysis

Rainfall data collected in the experimental sites were analyzed by t-test (group by group) using STATISTICA software to compare variations among the experimental sites. Data on growth, foliar nutritional status, yield, total nutrient contents in the above ground biomass, and the efficiency N fertilizer applied to the crop were subjected to analysis of variance (ANOVA) using STATISTICA software to evaluate the performance of fertilization treatments and their interaction. Means across the study sites and within the site were separated using the Tukey test at the $p = 0.05$ level of significance. The relationship among the investigated parameters was determined by the Pearson's correlation coefficient (r) at $p = 0.05$ level of significance.

3. Results

3.1. Variations in Weather Conditions among the Experimental Sites

Rainfall intensity during the experimental period varied widely (df = 3; t = 4.71; $p = 0.00016$) among the sites (Figure 1). Precipitation in Lyamungo exceeded 1300 mm year^{-1}, which was suitable for optimum growth and fruit production [33]. Rainfall in Tarakea and Tengeru was below the optimum [33]. In general, rainfall distribution in these sites followed a bimodal pattern with a long rainy season from March to July and short rainy season from October to January.

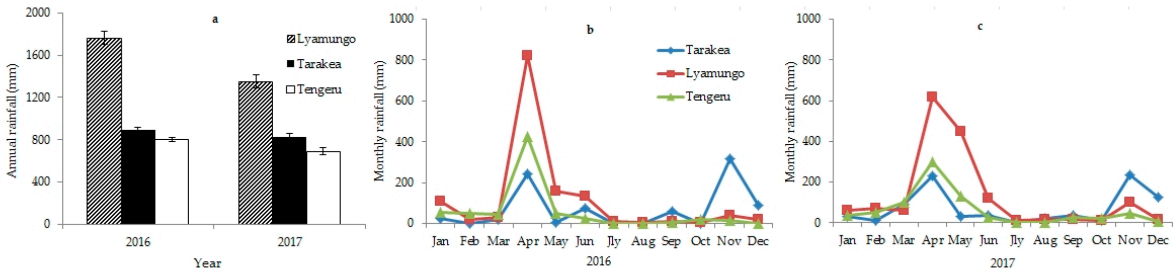

Figure 1. Annual rainfall (**a**) and rainfall distribution pattern (**b**,**c**) in the experimental sites located along the altitudinal gradients on the slopes of Mount Kilimanjaro and Mount Meru in northern Tanzania.

3.2. Effects of Weather Conditions and Fertilization Treatments on Plant Size, Crop Cycle, and Yield

3.2.1. Plant Size

Site characteristics significantly ($p < 0.001$) influenced plant size (Table 4). Banana plants under the higher rainfall conditions of Lyamungo were larger than those in Tarakea and Tengeru. Compared with the control, fertilization treatments significantly ($p < 0.001$) enhanced plant growth (Table 4). Applications of cattle manure alone (T6) or in combination with urea (T5) resulted in the largest plants, followed by urea only (in T3 and T4) or in combination with bean haulms (T7). Sole haulms fertilization treatment (T8) led to small plants as the lowest rate of urea alone (T2).

Table 4. Effects of fertilization treatments on the growth and yield of Mchare banana at the three sites located along the altitudinal gradients in volcanic soils of the northern highlands, Tanzania.

Factors	Plant Size (m^3)	Crop Cycle (Days)	Fingers Bunch^{-1}	Finger Weight (g)	Bunch Weight (kg)	Total Fruit Yield (t ha^{-1} Cycle^{-1})	Increment (%) ^{y}
Sites							
Tarakea (1608 m.a.s.l.)	0.04 ± 0.002b	400.61 ± 11.40b	74.64 ± 2.54c	220.59 ± 7.45b	19.27 ± 1.07b	33.76 ± 1.43b	
Lyamungo (1346 m.a.s.l.)	0.06 ± 0.003a	397.73 ± 6.11b	107.99 ± 2.67a	235.82 ± 7.23a	28.03 ± 1.30a	47.79 ± 2.21a	
Tengeru (1106 m.a.s.l.)	0.04 ± 0.002b	412.77 ± 7.49a	87.66 ± 2.47b	170.74 ± 5.54c	17.06 ± 0.92c	28.88 ± 1.52c	
Fertilization treatments							
T1: No N (control)	0.03 ± 0.002d	462.48 ± 6.79a	71.16 ± 4.27f	165.04 ± 8.48e	13.81 ± 1.00g	23.90 ± 1.57g	-
T2: 77 kg N [urea (50% below optimum rate)]	0.04 ± 0.003c	422.03 ± 8.66c	87.47 ± 5.87d	195.04 ± 11.37d	19.38 ± 1.77e	33.43 ± 2.98e	28.5
T3: 153 kg N [urea (optimum rate)]	0.05 ± 0.002b	383.43 ± 3.81c	94.88 ± 5.26c	230.43 ± 12.23b	24.02 ± 2.09c	40.85 ± 3.60c	41.5
T4: 230 kg N [urea (50% above optimum rate)]	0.05 ± 0.003b	395.00 ± 4.85c	92.72 ± 5.42cd	216.64 ± 10.99c	22.34 ± 1.70d	38.38 ± 2.64d	37.7
T5: 77 kg N (urea) + 77 kg N (cattle manure)	0.06 ± 0.004a	354.94 ± 2.79d	107.54 ± 4.67a	247.74 ± 11.07a	29.30 ± 1.93a	50.65 ± 3.40a	52.8
T6: 153 kg N [cattle manure (farmers practice)]	0.06 ± 0.004a	356.36 ± 4.11d	101.19 ± 5.63b	247.89 ± 12.06a	27.54 ± 2.01b	47.42 ±3.31b	49.6
T7: 77 kg N (urea) + 52 kg N (bean haulms) ^{z}	0.05 ± 0.002b	406.75 ± 8.27b	87.14 ± 5.41d	198.02 ± 9.85d	19.49 ± 1.88e	32.84 ± 2.92e	27.2
T8: 52 kg N (bean haulms)	0.04 ± 0.003c	448.62 ± 11.69a	78.68 ± 5.13e	171.59 ± 10.02e	15.73 ± 1.50f	27.05 ± 2.55f	11.2
2-Way ANOVA (F-Statistics)							
Site	61.51 ***	3.24 *	168.25 ***	133.03 ***	390.22 ***	2137.97 ***	
Fertilization treatments	28.97 ***	39.56 ***	30.68 ***	44.15 ***	127.46 ***	727.49 ***	
Site* fertilization treatments	1.74 ns	1.79 ns	0.45 ns	0.62 ns	2.80 **	18.19 ***	

Values presented are means ± SE; *, **, and *** indicates differences at $p = 0.05$, $p < 0.01$ and $p < 0.001$ respectively; ns = not significant at $p = 0.05$; SE = standard error; ^{z} = maximum bean haulms attained in banana-bean intercropping ha^{-1}; ^{y} = yield increase was calculated by dividing the difference between the yield attained in respective fertilization technique (T2–T8) and control (T1) multiplied by 100. Means with similar letters in the same column are not significantly different at $p = 0.05$.

3.2.2. Crop Cycle

The crop cycle ranged between 356 and 462 days and the gap between the shortest and longest cycle was 106 days (approximately four months). Site characteristics had significant ($p < 0.05$) influence on crop cycle (Table 4). The shortest cycle was recorded under the rain intensive conditions of Lyamungo and the longest in the drier conditions of Tengeru. Furthermore, the results of this study demonstrate that all tested fertilization treatments (except sole bean haulms (T8)) significantly ($p < 0.001$) enhanced growth rate (Table 4). Applications of cattle manure alone (T6) or in combination with urea (T5) resulted in a shorter crop cycle than the sole urea treatments (T2–T4) or in combination with bean haulms (T7). Fertilization via haulms only (T8) resulted in the same long cycle as the control (T1).

3.2.3. Yield

Banana yield ranged between 24 and 51 t ha^{-1} and the gap between the lowest and the highest yield was 27 t ha^{-1} crop^{-1} equivalent to 53%. Site characteristics significantly affected ($p < 0.001$) the yield (Table 4), with the most humid site of Lyamungo having the highest yield (48 t ha^{-1} cycle^{-1}) and the drier area of Tengeru producing 29 t ha^{-1} cycle^{-1}. Fertilization treatments resulted in a significant ($p < 0.001$) increase in banana yield and the highest yield was attained in the cattle manure + urea treatment (T5), slightly producing more than the sole cattle manure treatment (T6). Sole urea treatments (T2–T4) also resulted in considerable yield with T3 producing more than the other two treatments. Bean haulms in combination with urea (T7) gave the same yield as T2. The sole haulms treatment (T8) resulted in the lowest yield compared with the other fertilization treatments. Yield levels attained in all fertilization treatments were significantly larger than those obtained under the farmer's fields.

3.3. Effects of Fertilization Treatments on Nutrition Status of the Third Fully Open Leaf of 9 Month Old Mchare and Total Nutrient Contents in the Above Ground Biomass at Harvest

3.3.1. Foliar Nutritional Status

Nutrient concentrations in banana leaves differed significantly ($p < 0.001$ for Ca, Cu, Fe, and Zn; $p < 0.01$ for B and N; $p < 0.05$ for K) among the experimental sites with those in the most humid zone of Lyamungo containing the largest levels of N, P, Mg, Ca, and Cu (Table 5). Fertilization treatments had a significant influence ($p < 0.001$ for Ca; $p < 0.01$ for B, N, and Mn; $p < 0.05$ for K and Zn) on the nutrition status of the banana leaves. Foliar analyses revealed that banana leaves in all fertilization treatments contained insufficient concentrations of Cu and Zn. Moreover, tissue levels of K in the sole urea (T2–T4), bean haulms (T8), or in combination with urea (T7) were significantly smaller than the proposed optimum level for EAHB as in the control (T1).

3.3.2. Total Nutrient Contents in the Above Ground Biomass at Harvest

Nutrient contents in the above ground biomass differed significantly ($p < 0.01$ for N, K, Mn; $p < 0.001$ for P, Mg, Ca, S, B, Cu, Fe, and Zn) among the experimental sites (Tables 6 and 7). Banana plants in the more humid zone of Lyamungo contained the largest quantities of the studied nutrients (except B and Zn). Additionally, fertilization treatments significantly affected ($p < 0.01$ for N, K, Mn; $p < 0.001$ for P, Mg, Ca, S, B, Cu, Fe, and Zn) the nutrient contents in the above ground plant organs (Tables 6 and 7). Fertilization via cattle manure only (T6) or in combination with urea (T5) resulted in larger nutrient contents than urea alone (T2–T4), sole haulms (T8), or in combination with urea (T7). Plants in the sole bean haulms treatment (T8) contained the smallest nutrient quantities, second only to the control (T1). The results indicate further that total nutrient uptake by the above ground plant organs was in the order of K > N > Ca > Mg > P > S > Mn > Fe > Zn > B > Cu, which is almost similar to those recorded in Cavendish bananas (AAA) [34]. Nevertheless, the total nutrient distribution pattern in the above ground plant organs was realistic for N, P, Mg, S, and Cu compared with the other nutrients (data not presented).

Table 5. Effects of fertilization treatments on nutrient concentrations in the third fully open leaf of nine month old Mchare plants at three sites located along the altitudinal gradients in volcanic soils of the northern highlands, Tanzania.

Factors	**N**	**P**	**K** (%)	**Mg**	**Ca**	**B**	**Cu** (mg kg^{-1})	**Fe**	**Zn**
Sites									
Tarakea (1608 m.a.s.l.)	3.4 ± 0.05b	0.22 ± 0.00b	3.3 ± 0.14b	0.5 ± 0.02a	1.3 ± 0.04b	11.1 ± 0.12b	6.4 ± 0.12b	148.0 ± 6.90a	12.6 ± 0.32c
Lyamungo (1346 m.a.s.l.)	3.6 ± 0.04a	0.24 ± 0.00a	3.5 ± 0.06a	0.5 ± 0.02a	1.5 ± 0.06a	10.2 ± 0.19c	8.9 ± 0.16a	105.4 ± 6.71b	13.7 ± 0.29b
Tengeru (1106 m.a.s.l.)	3.2 ± 0.08c	0.20 ± 0.00c	3.0 ± 0.06c	0.4 ± 0.01b	0.9 ± 0.02c	24.4 ± 0.98a	5.9 ± 0.22b	126.3 ± 3.44ab	15.2 ± 0.22a
Fertilization treatments									
T1: Zero N (control)	3.1 ± 0.14d	0.22 ± 0.01a	3.5 ± 0.16ab	0.4 ± 0.03a	1.1 ± 0.06c	15.5 ± 2.29b	6.6 ± 0.68a	121.3 ± 9.80a	13.5 ± 0.63ab
T2: 77 kg N [from urea (50% below optimum rate)]	3.5 ± 0.04b	0.22 ± 0.01a	3.0 ± 0.18b	0.5 ± 0.03a	1.3 ± 0.10a	14.4 ± 2.10c	6.9 ± 0.52a	120.4 ± 8.64a	13.6 ± 0.52ab
T3: 153 kg N [from urea (optimum rate)]	3.6 ± 0.02b	0.22 ± 0.01a	3.1 ± 0.14ab	0.5 ± 0.04a	1.4 ± 0.14a	14.6 ± 2.12c	7.4 ± 0.48a	142.0 ± 17.75a	13.8 ± 0.53ab
T4: 230 kg N [from urea (50% above optimum rate)]	3.8 ± 0.04a	0.22 ± 0.01a	3.1 ± 0.18ab	0.5 ± 0.04a	1.3 ± 0.08a	13.1 ± 1.14d	7.1 ± 0.52a	118.5 ± 10.87a	13.8 ± 0.48ab
T5: 77 kg N (from urea) + 77 kg N (from cattle manure)	3.4 ± 0.10c	0.22 ± 0.01a	3.7 ± 0.11a	0.4 ± 0.02a	1.0 ± 0.05c	15.8 ± 2.57b	7.4 ± 0.44a	132.0 ± 15.32a	14.9 ± 0.53a
T6: 153 kg N [from cattle manure (farmers practice)]	3.3 ± 0.04c	0.22 ± 0.00a	3.6 ± 0.13ab	0.4 ± 0.02a	1.0 ± 0.06c	18.2 ± 4.11a	7.0 ± 0.31a	126.4 ± 11.48a	14.9 ± 0.48a
T7: 77 kg N (from urea) + 52 kg N (Common bean haulms) ^{z}	3.5 ± 0.06b	0.22 ± 0.01a	3.1 ± 0.14ab	0.5 ± 0.04a	1.4 ± 0.16a	14.1 ± 1.62c	7.3 ± 0.61a	131.1 ± 8.08a	13.5 ± 0.52ab
T8: 52 kg N (common bean haulms)	2.9 ± 0.08e	0.22 ± 0.01a	3.2 ± 0.15ab	0.4 ± 0.04a	1.2 ± 0.11b	16.0 ± 2.43b	6.6 ± 0.70a	121.0 ± 3.29a	12.7 ± 0.68b
2-Way ANOVA (F-Statistics)									
Site	160.0 **	61.65 ***	8.446 **	7.912 *	361.96 ***	4917.74 **	108.63 ***	11.30 ***	29.97 ***
Fertilization treatment	165.7 **	1.16 ns	3.168 *	2.102 ns	32.82 ***	71.16 **	1.68 ns	0.60 ns	3.69 *
Site* fertilization treatment	31.9 **	2.33 *	0.684 ns	2.033 *	13.22 ***	91.60 **	2.16 *	0.56 ns	1.76 ns

Nitrogen fertilizer sources: urea, cattle manure and common bean haulms. Values presented are means ± SE; *, **, and *** indicates differences at $p = 0.05$, $p < 0.01$. and $p < 0.001$, respectively; SE = standard error; MAP = months after planting; ^{z} = maximum common bean haulms attained under banana-bean intercropping ha^{-1}; ns = not significant. Means with similar letters are not significantly different at $p = 0.05$.

Table 6. Effects of fertilization treatments on total nutrient contents in the above ground biomass of Mchare banana at harvest at three sites located along the altitudinal gradients in volcanic soils of the northern highlands, Tanzania.

Factors	N	P	K (g Plant^{-1})	Mg	Ca	S
Sites						
Tarakea (1608 m.a.s.l.)	130.68 ± 9.03a	14.47 ± 0.50b	571.66 ± 32.36a	35.54 ± 1.78b	77.36 ± 4.78a	7.80 ± 0.32b
Lyamungo (1346 m.a.s.l.)	130.70 ± 7.86a	17.08 ± 0.48a	575.48 ± 27.99a	40.80 ± 1.75a	77.98 ± 4.16a	9.54 ± 0.54a
Tengeru (1106 m.a.s.l.)	110.71 ± 6.79b	13.08 ± 0.32c	509.91 ± 27.80b	32.76 ± 1.46c	72.98 ± 5.60b	7.06 ± 0.20c
Fertilization treatments						
T1: No N (control)	81.34 ± 2.00f	12.38 ± 0.48d	364.26 ± 6.31g	25.89 ± 0.56f	49.76 ± 2.52g	6.22 ± 0.22e
T2: 77 kg N [urea (50% below optimum rate)]	94.34 ± 2.98e	14.46 ± 0.49c	449.84 ± 15.38e	31.60 ± 1.18e	54.63 ± 1.61f	6.98 ± 0.14d
T3: 153 kg N [urea (optimum rate)]	134.31 ± 6.30c	16.06 ± 0.80b	589.30 ± 13.26c	38.86 ± 1.73c	82.95 ± 3.54c	8.04 ± 0.29bc
T4: 230 kg N [urea (50% above optimum rate)]	133.43 ± 7.62c	14.82 ± 0.58c	541.01 ± 2.40d	38.68 ± 1.70c	76.21 ± 1.10d	8.48 ± 0.54b
T5: 77 kg N (urea) + 77 kg N (cattle manure)	182.26 ± 6.00a	17.67 ± 0.90a	809.76 ± 17.38a	49.85 ± 1.44a	112.88 ± 2.12a	10.82 ± 0.88a
T6: 153 kg N [cattle manure (farmers practice)]	176.42 ± 4.78b	17.42 ± 0.72a	703.20 ± 16.82b	43.74 ± 1.16b	108.10 ± 3.66b	10.36 ± 0.76a
T7: 77 kg N (urea) + 52 kg (bean haulms) ^{z}	100.38 ± 3.94d	14.08 ± 0.61c	533.77 ± 24.94d	34.97 ± 2.22d	66.48 ± 2.18e	7.41 ± 0.35c
T8: 52 kg N (bean haulms)	89.72 ± 3.16e	12.09 ± 0.61d	427.62 ± 12.73f	27.36 ± 1.19f	57.90 ± 2.86f	6.72 ± 0.20de
2-Way ANOVA (F-Statistics)						
Site	289.8 **	150.81 ***	444.4 **	172.81 ***	33.36 ***	173.82 ***
Fertilization treatment	1257.4 **	59.81 ***	2677.0 **	257.61 ***	963.74 ***	113.11 ***
Site* fertilization treatment	46.1 **	2.52 *	61.6 **	10.51 ***	43.52 ***	16.81 ***

Values presented are means ± SE; *, **, and *** indicates differences at $p = 0.05$, $p < 0.01$ and $p < 0.001$, respectively; SE = standard error; ^{z} = maximum bean haulms attained in banana-bean intercropping ha^{-1}. Means with similar letters in the same column are not significantly different at $p = 0.05$.

Table 7. Effects of fertilization treatments on total nutrient contents in the above ground biomass of Mchare banana at harvest at three sites located along the altitudinal gradients in volcanic soils of the northern highlands, Tanzania.

Factors	B	Cu	Mn (mg Plant^{-1})	Fe	Zn
Sites					
Tarakea (1608 m.a.s.l.)	118.46 ± 4.59b	53.13 ± 1.88b	1590.54 ± 49.96b	1085.67 ± 39.45b	124.50 ± 5.24c
Lyamungo (1346 m.a.s.l.)	131.98 ± 4.67a	64.37 ± 2.66a	1983.65 ± 118.32a	1261.68 ± 38.75a	178.04 ± 7.76a
Tengeru (1106 m.a.s.l.)	106.32 ± 3.54c	43.21±1.52c	1353.75 ± 44.58c	925.01 ± 32.78c	132.57 ± 5.09b
Fertilization treatments					
T1: No N (control)	89.26 ± 1.68g	38.15 ± 2.17g	1079.96 ± 18.58g	785.04 ± 35.62g	99.77 ± 5.02f
T2: 77 kg N [urea (50% below optimum rate)]	109.32 ± 4.73e	50.22 ± 2.91e	1456.31 ± 72.08e	1002.22 ± 47.98e	125.10 ± 5.58e
T3: 153 kg N [urea (optimum rate)]	126.70 ± 4.58c	58.04 ± 3.44c	1720.00 ± 131.21c	1144.02 ± 54.22c	159.30 ± 9.30b
T4: 230 kg N [urea (50% above optimum rate)]	118.88 ± 3.34d	55.43 ± 4.23d	1881.17 ± 140.81b	1121.66 ± 53.94c	148.14 ± 9.50c
T5: 77 kg N (urea) + 77 kg N (cattle manure)	143.98 ± 3.62b	64.91 ± 4.37b	2053.16 ± 161.84a	1266.26 ± 61.26b	184.28 ± 10.84a
T6: 153 kg N [cattle manure (farmers practice)]	149.71 ± 6.05a	67.60 ± 3.63a	2025.28 ± 148.06a	1379.68 ± 41.36a	185.94 ± 11.32a
T7: 77 kg N (urea) + 52 kg (bean haulms) ^{z}	118.31 ± 3.14d	50.28 ± 2.86e	1629.16 ± 105.79d	1083.12 ± 56.91d	136.42 ± 8.76d
T8: 52 kg N (bean haulms)	95.21 ± 4.66f	43.92 ± 1.64f	1296.12 ± 33.41f	944.27 ± 48.56f	121.32 ± 7.66e
2-Way ANOVA (F-Statistics)					
Site	470.9 ***	999.15 ***	1806.4 **	1655.1 ***	1116.01 ***
Fertilization treatment	485.6 ***	334.91 ***	812.0 **	753.2 ***	467.14 ***
Site* fertilization treatment	14.2 ***	18.40 ***	132.4 **	16.3 ***	13.42 ***

Values presented are means ± SE; ** and *** indicates differences at $p < 0.01$ and $p < 0.001$, respectively; SE = standard error; ^{z} = maximum bean haulms attained in banana-bean intercropping ha^{-1}.

3.4. Effects of Fertilization Treatments on Efficiency of N Fertilizer

Internal and utilization efficiency of the applied N fertilizers varied widely ($p < 0.01$) among the experimental sites (Table 8) with the highest efficiency in the more humid zone of Lyamungo. Significant ($p < 0.01$) differences were also observed among fertilization treatments (Table 8). Fertilization through sole cattle manure (T6) or in combination with urea resulted in the highest values of the aforementioned parameters. Combined application of cattle manure with urea (T5) improved internal efficiency by 15% against the sole cattle manure (T6). Sole urea fertilization treatments (T2–T4) and bean haulms (T7–T8) consistently resulted in the lowest values.

Table 8. Effects of fertilization treatments on the efficiency of N fertilizer applied to the crop.

Factors	Internal Efficiency (kg Fingers kg N Uptake^{-1})	Utilization Efficiency (%)
Sites		
Tarakea (1608 m.a.s.l.)	51.08 ± 5.26b	32 ± 0.04a
Lyamungo (1346 m.a.s.l.)	87.64 ± 4.87a	34 ± 0.04a
Tengeru (1106 m.a.s.l.)	50.39 ± 5.03b	25 ± 0.03b
Fertilization treatments		
T1: No N (control)	-	-
T2: 77 kg N [urea (50% below optimum rate)]	59.04 ± 7.51d	16 ± 0.02c
T3: 153 kg N [urea (optimum rate)]	75.88 ± 9.16b	28 ± 0.03b
T4: 230 kg N [urea (50% above optimum rate)]	67.52 ± 7.29c	18 ± 0.02c
T5: 77 kg N (urea) + 77 kg N (cattle manure)	90.67 ± 5.72a	54 ± 0.02a
T6: 153 kg N [cattle manure (farmers practice)]	76.74 ± 3.69b	52 ± 0.02a
T7: 77 kg N (urea) + 52 kg (bean haulms) ^{z}	51.65 ± 6.26e	29 ± 0.04b
T8: 52 kg N (bean haulms)	19.75 ± 6.26f	14 ± 0.02c
2-Way ANOVA (F-Statistics)		
Site	408.71 ***	50.06 ***
Fertilization treatment	202.84 ***	259.49 ***
Site * fertilization treatment	10.29 ***	20.15 ***

Values presented are means ± SE; ** indicates differences at $p < 0.01$; SE = standard error; ^{z} = maximum bean haulms attained in banana-bean intercropping ha^{-1}.

3.5. Correlation among the Investigated Variables

Precipitation correlated significantly, strongly, and positively with the total nutrient contents in the above ground biomass (Table 9), plant size, fingers per hand and per bunch, finger weight, and yield (Table 10). In addition, there was a significant, strong, and positive correlation between the total N contents in the above ground biomass and other nutrients (except Fe and Mn) (Table 8a). A similar trend was also observed between the yield and nutrient contents in the above ground biomass (Table 8a). Yield correlated significantly, strongly, and positively with plant size, number of hands and fingers per bunch, and finger weight (Table 8b).

Table 9. Pearson's correlation coefficients (r) between the total nutrient contents in the above ground biomass of Mchare banana plant at harvest and (i) annual precipitation, (ii) yield, and (iii) total N contents.

	Total Nutrient Contents in the above Ground Biomass										
	N	**P**	**K**	**Ca**	**Mg**	**S**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
Annual precipitation	0.95 **	0.88 **	0.86 **	0.74 **	0.86 **	0.79 **	0.83 **	0.88 **	0.53 *	0.92 **	0.94 **
Yield	0.95 **	0.87 **	0.88 **	0.80 **	0.88 **	0.77 **	0.85 **	0.91 **	0.54 *	0.96 **	0.93 **
Total N contents in the above ground biomass	1	0.56 **	0.58 **	0.62 **	0.34 **	0.46 **	0.47 **	0.40 **	0.19 ns	0.18 ns	0.30 **

* and ** indicates significance at $p = 0.05$ and 0.01 respectively; ns = not significant at $p = 0.05$.

Table 10. Pearson's correlation coefficients (*r*) between the annual precipitation and plant characteristics of Mchare.

	Plant Size	Crop Cycle	Hands per Bunch	Fingers per Bunch	Finger Weight	Yield
Annual precipitation	0.96 **	0.22 ns	0.81 **	0.86 **	0.75 **	0.99 **
Yield	0.94 **	−0.68 *	0.82 *	0.85 *	0.88 *	1

* and ** indicates significance at $p = 0.05$ and 0.01 respectively; ns = not significant at $p = 0.05$.

4. Discussion

4.1. Effects of Initial Soil Characteristics and Weather Conditions on Crop Performance

The initial soil total C and N in Tarakea and Tengeru was too low to maintain good soil fertility and high banana yields [19]. In addition, our findings demonstrated a wide variation in plant size, yield, foliar nutrition, total nutrient contents in the above ground biomass, and efficiency of N fertilizer among the experimental sites. Large values of the aforementioned variables were obtained in the Nitisol of Lyamungo, followed by the Andosol in Tarakea, and the Phaeozem in Tengeru. The high crop performance in Lyamungo (Table 4) can partly be linked to the higher and better distributed rainfall (Figure 1). While banana requires about 1300 mm of precipitation year^{-1} for optimum growth and yield [29,33], the observed poor crop performance in Tarakea and Tengeru can be attributed to moisture deficit due to less rains in a shorter period (Figure 1). This confirms earlier results of other banana types where drought stress reduced yield by 65% [35–38].

4.2. Effect of Fertilization Treatments on Yields

Our findings revealed that an application of 153 kg mineral N ha^{-1} year^{-1} via urea only (T3) increased yield up to 41 t ha^{-1} cycle^{-1} (Table 4), which is significantly higher than any other mineral N fertilization treatment (T2 and T4). However, this can further be increased, for instance in our study, to 51 t ha^{-1} when the same amount of N comes from a mixture of cattle manure and urea at 50% each (T5). This is in agreement with many previous findings by Chivenge et al. [17], Ripoche et al. [18], Abd el Moniem et al. [39], Otinga et al. [40], Baijukya et al. [41], Wairegi and Van Asten [42], Vanlauwe et al. [43], Vanlauwe et al. [44], and Kihara et al. [45], where the combined use of organic and inorganic fertilizers resulted in the highest yields compared with inorganic or organic fertilizers alone. Therefore, this seems to be the best alternative strategyto manage soil fertility in banana-based farming systems in the study area, as expected. Organic/inorganic interactions not only release plant available nutrients, but also increase the soil OC stock, which improves the retention of the applied mineral fertilizer by the soil, therefore enhancing its utilization efficiency. Inorganic fertilizer also seems to stimulate microbial activities involved in the decomposition of organic materials [46], hence causing a fast release of nutrients relative to sole manure fertilization.

Fertilization with 153 kg N ha^{-1} year^{-1} through cattle manure alone (T6) resulted in a higher yield than with the same amount derived solely from urea (T3). Similarly, Teixeira et al. [47] attained higher banana yields with sewage sludge fertilization than in mineral N fertilizer. Unfortunately, this strategy requires larger quantities of manure, which are not available in most smallholder farms as reported in other parts of the country [3,8]. Consequently, a resource poor farmer applies too small quantities, which do not meet the crop nutrient requirements. Therefore, there is a need to supplement the scarcely available cattle manure with mineral fertilizers to improve the use efficiency of both resources while maintaining good soil quality and high yields in a sustainable manner.

Retaining haulms in the bean-intercrop plots as an organic fertilizer resulted in a substantial yield increment of up to 11% relative to the control. However, this increment was smaller than in any other fertilization treatment due to the limited biomass produced by the system. Similar trends were also published in Baijukya et al. [41] in maize, Banful et al. [48] in plantain, Bekunda et al. [49] in maize, and

Tadesse et al. [50] in maize. This demonstrates that the amount of nutrients supplied by bean haulms at this small rate does not meet the crop nutrient requirements. Therefore, unless unrealistic amounts of legume biomass are generated, legume residues should be supplemented with mineral fertilizer to improve the efficiency of the former and soil quality.

4.3. Effects of Fertilization Treatments on Nutrition of the Third Fully Open Leaf of Nine Month Old Mchare and Total Nutrient Contents in the Above Ground Biomass at Harvest

4.3.1. Foliar Nutrition

Highest foliar nutrient concentrations were attained in the most humid zone of Lyamungo, suggesting that nutrient acquisition in the other two zones was negatively hampered by moisture stress. This supports earlier findings where drought stress reduced the concentration (%) of N by 44–51 and P by 39–48% in barley, corn, and big bluestem [51]. Foliar analyses revealed further that banana plants contained adequate concentrations of N, P, K, Mg, Ca, S, Fe, and Mn, but were deficient in B (in Lyamungo) and Cu and Zn (across the trial sites). In light of this, the formulation of site specific fertilizer programs that include deficient micronutrients should be given special attention. Previous studies in the lowlands by Moreira and Fageria [34], Yadav et al. [52], Krishnamoorthy and Hanif [53], Jegadeeswari et al. [54], and Bindu [55] indicate that the application of B, Cu, and Zn in combination with macronutrients always resulted in significant increases in banana yields.

4.3.2. Nutrient Contents in the Above Ground Biomass

Nutrient uptake by banana plants as reflected in the total nutrient contents in the above ground biomass (Tables 6 and 7) followed similar trends as those in Section 4.3.1. Consistent with the observed decreases in foliar nutrient concentrations in the drier zones of Tengeru and Tarakea, total nutrient contents in the above ground biomass also decreased due to reduced uptake by the plants caused by moisture stress. Under moisture stress condition, a lower nutrient absorption can result from (1) a decrease in water uptake in the top surface soil layer in which nutrient fertilizers are often applied [56], (2) a decrease in microbial decomposition and mineralization of organic matter, thereby decreasing the amount of nutrients available for plant uptake [57,58], and/or (3) a decrease in root function by slowing down the activity of enzymes involved in nutrient assimilation [59]. Earlier, Bista et al. [51] indicated that drought stress decreased the uptake of N and P by 72 and 80% in corn and, 142 and 88% in barley, respectively. Similarly, drought stress was reported to reduce plant N and P by 3.73 and 9.18%, respectively [60], foliar N content in *Coffea canephora* [61], Ca in the above ground biomass of *Quercus ilex* [62], and Mg uptake by *Spartina alterniflora* plants [63]. Fertilization at 153 kg N ha^{-1} year^{-1} from cattle manure alone (T6) or in combination with urea (T5) resulted in larger nutrient contents in the above ground plant organs than the same dose from sole urea (T3), indicating that there were severe losses of the applied mineral N fertilizer, as reported earlier by Mizota et al. [10] and Funakawa et al. [64]. In light of this, we do not encourage the use of sole mineral fertilizers to manage soil fertility as it will lead to environmental pollution. On the other hand, larger nutrient contents in plants fertilized with cattle manure alone (T6) or in combination with urea (T5) can be linked to a (i) better nutrient retention by the soil conditioned by organic soil solids and surfaces from decomposing cattle manure, which in turn, minimizes the leaching losses of the applied mineral fertilizers, and (ii) the slow release of plant nutrients from decomposing manure allows plants to utilize the nutrients for a long time. Our findings are in broad agreement with those of Choudhary and Suri [65], who obtained the highest values for nutrient uptake in wheat and rice under a combined application of organic and inorganic fertilizers.

The findings of this study further demonstrated that one ton of the harvested banana bunches exported 1.7 kg N, 0.2 kg P, 6.3 kg K, 0.3 kg Mg, 0.1 kg Ca, 0.1 kg S, 2 g B, 1 g Cu, 10 g Fe, 2 g Mn, and 2 g Zn. This trend corresponds well with that reported earlier in the triploid lowland bananas [66]. High yielding plants, for instance in T5, exported up to 88 kg N, 12 kg P, 318 kg K, 15 kg Mg, 7 kg Ca, 6 kg S, 100 g B, 50 g Cu, 510 g Fe, 100 g Mn, and 100 g Zn ha^{-1} $cycle^{-1}$ from the farm via harvested bunches. This indicates that nutrient removal from the farm by Mchare, a diploid highland banana via crop harvest can be as high as by triploid bananas like Cavendish [66]. Similarly, pseudostem and banana leaves all together accumulated up to 71 kg N, 13 kg P, 618 kg K, 45 kg Mg, 125 kg Ca, 9 kg S, 120 g B, 90 g Cu, 1 kg Fe, 1 kg Mn, and 120 g Zn ha^{-1} $cycle^{-1}$. This implies that the management decision to remove or leave pseudostem and leaf residues in the field is crucial, as it should play a significant role in the recycling of nutrients to the soil stock following decomposition. While pseudostem and leaves were allowed to recycle in this study, these materials are normally used to feed zero grazed dairy cows due to high demand as fodder. As such, retaining pseudostem and leaf residues in the field limits the accessible amounts of fodder for stall-fed livestock and supplementation with additional fodders from the lower altitude zone or feed concentrate is too expensive. In light of the above, the current soil fertility management strategies in banana-based farming systems need to be optimized to ensure that nutrients exported via crop harvest are replenished as much as possible.

4.4. Effects of Fertilization Treatments on N Efficiency

Site characteristics had a significant influence on the internal and utilization efficiency of the N fertilizer applied to the crop. The highest values of the listed parameters were attained in the most humid zone of Lyamungo (Table 8). The value of N utilization in Lyamungo was comparable with that in the drier zone of Tarakea. This implies that drought affects the yields more than the total N uptake and that there was little translocation of the nutrient from the shoot to fingers. In addition, the values of the aforementioned parameters increased as the N rate increased up until 153 kg ha^{-1} $year^{-1}$, and the increase was more prominent with the combined use of cattle manure and urea at 50% per each as such. We postulate a higher N efficiency in the integrated strategy to the increased nutrient uptake by shoot biomass, in addition to a better translocation to the banana fingers as conditioned by improved soil physical conditions.

4.5. Correlation among the Investigated Variables

Significant, high, and positive correlation coefficients (r) validated that high yield was linked to large precipitation volumes, plant size, more numerous and heavy fingers, total P, Mg, S, B, Cu, Fe, Mn, and Zn contents in the above ground plant biomass (Tables 6 and 7). The observed significant, strong, and positive correlation between N and K, Mg, Ca, and B uptake by the plants indicates synergism. In general, the results of this study reveal that the increased uptake of N by plants also enhanced the uptake of other plant nutrients. This implies that attempts to enhance soil N supply have to take into consideration that all other plant nutrients will also have to be supplied in adequate amounts.

5. Conclusions

Trial sites and fertilization treatments demonstrated a significant influence on plant growth, yield, and efficiency of the N fertilizer applied to the crop. The largest values of the listed parameters were attained in the more humid zone of Lyamungo. Inorganic fertilization led to a significant and positive increase in the growth and yield of the Mchare banana. However, the combination of urea with cattle manure was superior to any other fertilization treatments. It also shows that inorganic/organic interactions enhanced the efficiency of the applied nutrient fertilizer. This infers that a combined use of inorganic and organic fertilizers could be used as an excellent alternative strategy to manage soil fertility in farms with insufficient quantities of animal manure. Given that the price and application costs of inorganic fertilizers are relatively lower than those of organic fertilizers, this is a welcome observation, potentially removing reservations among farmers against mineral fertilizer use. Integrated soil fertility management will, in turn, contribute toward improved soil fertility, increased crop production, and sustainable banana-based farming systems. The yields obtained in this study in Mchare ranged between 24 and 51 t ha^{-1} $crop^{-1}$, which is at the same level as the triploid export Cavendish bananas. This is an entirely new given, as global banana production is focused on triploids as diploids are believed to be very low yielders. This indicates that more diploids need to be investigated and that banana breeding programs need to revisit the concept that the end product of a breeding program should always be a triploid.

Author Contributions: A.I.M. conducted the field experiments, collected the soil samples and plant tissue samples, growth and yield data, analyzed the data and wrote the manuscript; K.M.M. supervised the research and reviewed the first draft of the manuscript; P.A.N., R.S., and R.M. conceived, supervised the research, and revised the final draft manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The authors wish to thank the Government of Belgium through the VLIR-UDC program for institutional support to the Nelson Mandela African Institution of Science and Technology (NM-AIST), Tanzania. The authors thank all donors who supported this work through their contributions to the CGIAR Fund (http://www.cgiar.org/who-we-are/cgiar-fund/fund-donors-2/), and in particular to the CGIAR Research Program Roots, Tubers, and Bananas (RTB-CRP).

Acknowledgments: We acknowledge the efforts made by laboratory staff of KU Leuven, Belgium, Division of soil and water management for carrying out plant tissue and soil analyses.

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

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