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Research Article

Biophysical Constraints to Robusta Coffee Productivity in Low, Moderate, and High Rainfall Areas

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Globally, coffee (*Coffea* spp.) is a major commodity in terms of production and trade. Although Uganda is seventh among the major producing countries, yields remain low at 500 kg/ha. Understanding the biophysical constraining factors is vital to inform efforts toward closing the yield gap. A diagnostic study was conducted in 150 coffee fields to determine the most yield-limiting factors under varying rainfall thresholds, categorized as low ≤ 1100 mm/year, moderate ≥ 1100 to 1200 mm/year, and high ≥ 1200 mm/year. Robusta yield, soil parameters, pest and disease proportions, and tree and banana intercrop densities were measured under the thresholds. Parametric methods and the boundary line approach were used to analyze limiting factors and yield gaps. The results indicated that yields were significantly ($p < 0.001$) higher in moderate ($960 \pm 234\,\mathrm{kg\,ha^{-1}}$) than low ($803 \pm 188\,\mathrm{kg\,ha^{-1}}$) and high ($713 \pm 193\,\mathrm{kg\,ha^{-1}}$) rainfall thresholds. The proportion of pests and diseases doubled in high than low rainfall thresholds. Soil parameters and tree or banana intercrop were the main yield-limiting factors. Magnesium limited yield in 47%, 26%, and 14% of coffee fields, causing 23%, 20%, and 21% yield gaps in high, moderate, and low thresholds, respectively. The maximum yield was $1492\,\mathrm{kg\,ha^{-1}}$; the explainable yield gap was 32%. A larger yield gap of 42%, 36%, and 32% was observed in high, moderate, and low rainfall thresholds. Therefore, long-term integrated soil fertility and tree or banana intercrop management are suggested for high thresholds, focusing on pests and diseases in moderate and low rainfall thresholds. Additionally, frequent field monitoring is needed to determine the prevalence of pests and diseases at different times of the year and season. Hence, matching thresholds of rainfall variability to the Robusta coffee yield is critical for closing the yield gap and achieving Uganda's anticipated 20 million 60-kg bags $\mathrm{year^{-1}}$.

Keywords: boundary line analysis; coffee yield gap; pests and diseases; rainfall thresholds; Robusta coffee; soil parameters

1. Introduction

Globally, coffee (*Coffea* spp.) is only second to oil among traded products [1]. Uganda is ranked seventh among the 50 major coffee-producing countries, the third Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) producer with a share of about 9% of world trade. It is Africa's leading Robusta coffee exporter, with over 6 million 60-kg bags [2]. About 80% of the Robusta coffee produced in Uganda comes from the central, a native habitat, where it is a major cash crop. Although it accounts for over 80% of Uganda's coffee production and exports, the on-farm yields of 300–870 $\mathrm{kg\,ha^{-1}}$ are very low, compared to 2000 $\mathrm{kg\,ha^{-1}}$ from on-station and 3500 $\mathrm{kg\,ha^{-1}}$ under intensive coffee production systems of Vietnam and Brazil [3]. The prevalent coffee production gaps have social and economic implications for producers and Uganda's economy. Nevertheless, there are inadequate local data on the major biophysical constraints on productivity and the yield gap. To achieve the 20 million 60-kg bags $\mathrm{year^{-1}}$, anticipated by the government of Uganda, it is indispensable to narrow the yield gap by increasing Robusta coffee yield $\mathrm{ha^{-1}}$ from the current average of 500 $\mathrm{kg\,ha^{-1}}$ to at least 2000 $\mathrm{kg\,ha^{-1}}$.

The low Robusta yield may result from several limiting biophysical factors that affect its productivity, for example, (i) poor agricultural practices [4, 5], (ii) low soil fertility [6], and extremes of soil pH (below 5 and above 6), which can affect cation levels and their availability, (iii) low coffee density and old coffee trees [4], and (iv) high prevalence of pests and diseases. The main coffee pests are coffee berry borer (CBB) (*Hypothenemus hampei* Ferrari) and black coffee twig borer (BCTB) (*Xylosandrus compactus* Eichhoff) [4, 7, 8]. The main diseases are coffee wilt (*Fusarium xylarioides* Steyeart), coffee leaf rust (CLR) (*Hemileia vastatrix* Barkeley & Broome) and coffee red blister (*Cercospora coffeicola*) [9]. In addition to rainfall variability, Magrach and Ghazoul [8] and inadequate rainfall are associated with low Robusta yield and vice versa [4]. Erratic rainfall can increase the already wide yield gap among smallholder coffee farmers, but there are limited local data on the major limiting biophysical constraints and the associated yield gaps at the plot level under rainfall variability.

Furthermore, in Uganda, more than 80% of the coffee fields are planted with trees and or bananas [5, 10, 11]. Although trees provide beneficial shade for coffee, however, when interplanted at a closer range, they compete with coffee plants for light and soil nutrients [12]. Trees can also create a favorable microclimate for certain coffee pests and diseases [13] and act as alternative hosts if not properly managed [14]. For instance, a high ratio of bananas to coffee and a high tree density is observed to reduce yield [4]. However, a higher tree diameter at breast height (DBH) is associated with low BCTB infestation [15]. Therefore, data on tree and/or banana intercrop, its effect on coffee yield, and yield gaps under variable rainfall are needed.

In central Uganda, the analysis of the Robusta yield gap is inadequately applied in areas with varying rainfall. This study defines the coffee yield gap as the difference between two levels of yield based on biophysical factors[16]: the actual or observed farmer's yield and the maximum attainable yield [4, 17–19]. The yield gap analysis was based at coffee plot level. Previous researchers have used the boundary line method (BOLIDES) to determine limiting factors under local conditions, even when data from field trials were not available [20–22]. The BOLIDES method was first suggested by the author in [23]. Since then, the boundary line method has been widely applied to annual crops. Nevertheless, Wang et al. [4] carried out a yield gap on coffee at the regional level, but less than 10 coffee plots were involved in Greater Luweero. Farmers' yield recall data were used, which may not fully represent the greater Luweero. Additionally, the FAO data and national statistics from the Uganda Bureau of Statistics (UBoS) are not from direct plot-level measurements. Furthermore, most coffee research focuses on pests and diseases that may have some shortcomings. Therefore, this study uses the Robusta yield gap analysis at the local level, which can improve understanding of the biophysical factors that affect its productivity in site-specific plots and the varying local rainfall conditions in central Uganda. Therefore, it was essential to perform direct field measurements to understand the biophysical factors limiting Robusta coffee productivity, quantify the associated yield gaps, and explore effective research measures to narrow the yield gap amid rainfall variability.

The study used information collected from the detailed farm diagnostic study to obtain the actual and maximum farmer yield and determined the contribution of biophysical factors to the Robusta yield gap. Studying and understanding the actual yield of Robusta coffee with local rainfall is a source of evidence as to why some management solutions may have failed. The study aims were to (i) determine the main site-specific yield-limiting biophysical constraints and (ii) quantify the Robusta yield gaps associated with identified limiting biophysical constraints under different rainfall thresholds of low (< 1100 mm/year), moderate (> 1100 to 1200 mm/year), and high (> 1200 mm/year) in central Uganda. The study hypothesized that the Robusta yield gap observed at plot level is an aggregate effect of the amount of rainfall received in a threshold, the agricultural production practices, the pests and diseases that occur, and the physical–chemical state of the soil. The study results will improve the yield on site-specific plots due to its greater potential to close the yield gap associated with selected biophysical factors and may increase coffee productivity to attain the 20 million 60-kg bags $\mathrm{year^{-1}}$.

2. Materials and Methods

2.1. Description of the Study Area

2.1.1. Study Site and Climate. The study was carried out in the Agro-Ecological Zone of the Lake Victoria Crescent (LVAEZ), central Uganda. Three districts and five study sites classified into three rainfall thresholds were involved in this study. The districts were Luweero, Nakaseke, and Nakasongola, while the five study sites were Luwero, Katikamu, Zirobwe, Nakaseke, and Kakoge subcounties. The area is located between 31°E, 32°E and 0.5°N, 1.3°N, at an altitude of

1008 to 1200 m above sea level (masl). The study area experiences a tropical savanna climate and spatially variable rainfall ranging from 700 to 1500 mm year^{-1} with a bimodal distribution [24]. However, the study area was classified into three rainfall thresholds representing a rainfall gradient Fick and Hijmans [25]: low (< 1100 mm/year), moderate (> 1100 to 1200 mm/year), and high (> 1200 mm/year) (Figure 1).

The first and longest rains usually arrive from March to May, and the dry season is from June to August. The second and short rains are received from September to November and another dry season from December to February. The area is predicted to experience high variability in annual rainfall, associated with climate change [26]. In central Uganda, the main harvest season for Robusta is from May to August. However, there is one distinct main coffee harvesting season for Greater Luweero, beginning November to January, and a fry crop harvest from June to July. The average daily temperature is 25°C; a minimum of 18°C and a maximum of 30°C. Soils in the study area are generally classified as ferralsols, with red sandy loam textures in Luweero and Nakaseke and Sandy loam in Nakasongola districts [27]. These soils are inherently low in fertility and productivity [28].

2.2. Data Collection. Diagnostic studies were carried out in 150 coffee fields (~0.5–2.7 ha). The studies suited the boundary line analysis method used to determine the limiting biophysical factors and the Robusta yield gaps. Within each rainfall threshold, a randomly selected sample of approximately 50 smallholder ordinary mature coffee plots with comparable management practices was used. The sample size was based on the Cochran equation [29] at 0.05 marginal error. Although farmers own more than one coffee plot [4], data were collected from one main coffee plot by direct farm measurements. The plot sizes were determined using a Global Positioning System (GPS).

2.2.1. Determination of Robusta Coffee Yield on the Farm. Robusta yield was measured from 150 coffee plots. Ten representative coffee trees of relatively similar age per plot were selected. The yield sampling was carried out just before the start of the harvest season. Data collected include (i) the number of stems (N_S) divided into productive (N_P) and unproductive (N_U); (ii) the number of primary branches (N_B), also divided into productive ($\mathrm{B_P}$) and unproductive (B_U); (iii) the number of clusters (bundle of coffee berries) on a primary branch (N_C); and (iv) the number of coffee berries per cluster (bundle) (C_{BC}). Stems and branches were considered productive if they had clusters/bundles with coffee berries. Subsequently, the yield was estimated using allomeric yield functions [30]; the fresh weight of 100 randomly selected red coffee berries (RCBs) was determined and extrapolated to the yield (kg) plant^{-1} [31]. The Robusta yield per hectare was assessed by multiplying the yield (kg plant^{-1}) by coffee density hectare^{-1}. The coffee density was determined using distance from a randomly selected coffee bush to at least four to five adjacent coffee bushes in a given plot and extrapolated to coffee plants per hectare. Nonproductive coffee bushes (N_U) were physically counted, and their proportion was determined and deducted from the estimated yield for each coffee field (Y_E),

$$Y_E = \left[N_S * \left(N_P + N_U\right) * N_B * \left(B_P + B_U\right) * N_C * C_{BC}\right] - N_U. \tag{1}$$

2.2.2. Pests and Disease Prevalence. Using the same coffee plants mentioned above, the proportional incidence of the major pests and diseases of Robusta was assessed. Dry branches with signs of BCTB bore were counted and expressed as a proportion of the total number of dry branches per coffee plot [32]. The berries infested with CBB were counted and expressed as a proportion of the entire coffee tree [33]. Similarly, the infestation level of coffee mealy bags (*Coccus* spp.) and scales (*Saissetia coffea*, Walker) was assessed; the presence of tending ants and the sooty material on the coffee tree bushes were recorded as present or absent. The proportion of CLR and the infestation of RCB disease on the berries was determined using three primary branches per coffee bush and 10 bushes per coffee field. The results were extrapolated to the total number per coffee field [33].

2.2.3. Tree and/or Banana Intercrop. The number of coffee bushes, shade trees, and banana mats was counted in each coffee field and reported on a per-hectare basis [4]. In addition, the ratio of coffee bushes to banana mats was calculated. The average spacing of coffee was determined by taking measurements of the distance from a randomly selected coffee bush to the nearest four to five coffee bushes. Shade cover was recorded using a Model A spherical crown densiometer with a convex mirror (The James C. Doster, from Forestry Suppliers, USA), which estimates the amount of light that penetrates the canopy of agroforestry. The average percentage of canopy closures was collected from six points and calculated per coffee field [15]. The common shade trees included *Albizia chinensis, Maesopsis eminii*, *A. coriaria*, *Ficus natalensis*, *F. ov*ata, *Artocarpus heterophyllus*, *Persea Americana*, and bananas [34]. The size of the shade tree was estimated by measuring the diameter of each tree (cm) at breast height [5, 15]. Two experienced research technicians from the National Coffee Research Institute (NaCORI) determined the age of the coffee based on the researcher's experience, the farmer's knowledge, and the stump size.

2.2.4. Soil Sampling and Analysis. The soil samples were collected from the 150 coffee fields, at a depth of 0–30 cm, using a hand auger, to determine soil fertility status. Within each assessed coffee field, samples were selected from five random points located in a radius of 1 m from the coffee bushes. The five samples were thoroughly mixed, and a one-kilogram subsample per coffee field was taken, air-dried, ground, and sieved through a 2-mm particle-sized sieve, ready for chemical analysis at the National Agricultural Research Laboratories (NARL) Kawanda, Uganda. Soil pH in 1:2.5 (soil:water), soil organic matter (SOM) content

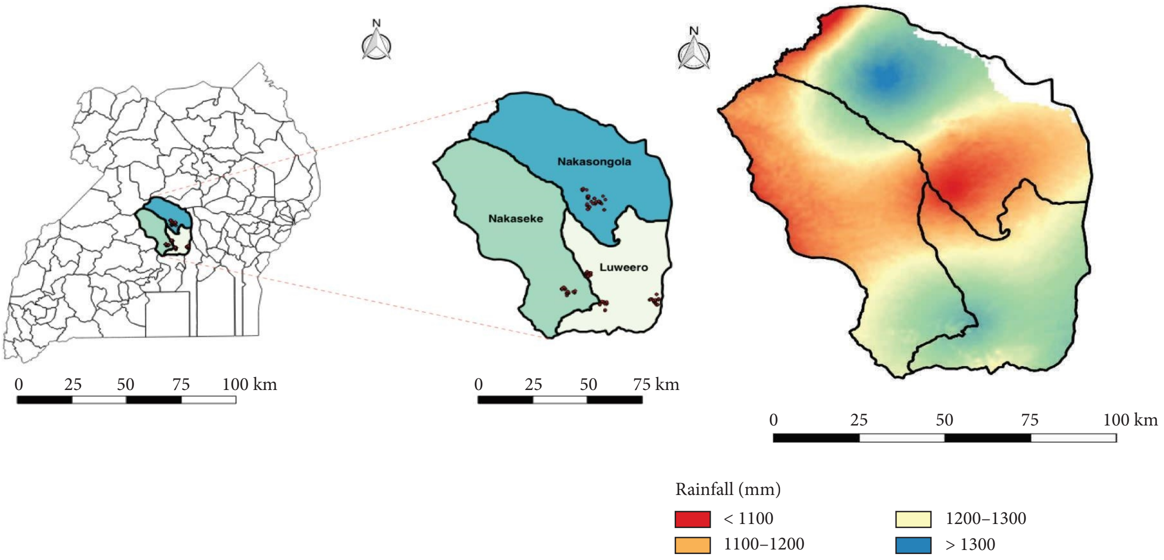

FIGURE 1: Greater Luweero and rainfall variability maps (WorldClim since 1970).

(Walkley-Black), total soil nitrogen (N) (Kjeldahl method), available soil phosphorus (P) (Mehlich 3), and soil extractable potassium (K), magnesium (Mg), and calcium (Ca) (ammonium acetate extraction) were evaluated following standardized laboratory protocol according to Ref. [35].

2.3. Analysis of Statistical Data. Data were entered in the Microsoft Access program and cleaned for easy management and analysis. The cleaned, organized data were subjected to normality tests and parametric methods for analysis using Stata 14 and R Version 4.2.1. Descriptive statistics, Pearson correlation, analysis of variance (ANOVA), and boundary line analysis methods were carried out. One-way ANOVA was used to determine the differences in the Robusta yield, tree and/or banana intercrop, soil parameters, cation ratios, pests, and disease proportions among the rainfall thresholds. p values less than 0.05 were considered statistically significant. A post hoc comparison of threshold means was performed to determine significant differences using Sidak at $p = 0.05$ [36]. Pearson's correlation was carried out to identify the main biophysical factors associated with coffee production. The boundary line analysis was used to determine the most limiting biophysical factors and associated yield gaps.

A statistical box plot method was used to identify outliers in each biophysical factor and Robusta yield under a rainfall threshold. The relationships between constraining factors and Robusta yield were explored, and biophysical factors were correlated with yield using Spearman's correlation tests for parametric continuous data. The effect of biophysical factors on yield was modeled based on Liebig's law of minimum limiting factors ($Y_{\min}$). The law assumes that coffee production is limited by only the biophysical factor that resulted in a minimum yield of the maximum actual yield [21] (equation (2)). The factor with the highest frequency of minimum Robusta yield was considered the major limiting for a given coffee field in the study area [17, 19, 21],

$$y = \min f_1(x_1),\ f_2(x_2),\ldots,f_n(x_n),\ y_{-}\max_{ij}. \tag{2}$$

Using nonlinear logistic models, individual boundary lines defined the relationship between biophysical factors and Robusta yield at the highest possible coefficients of determination (R^2) [4]. A yield scatter was plotted against each potential limiting factor. The boundary line points for positively correlated biophysical factors were calculated, and S curves were used to draw the fitted boundary lines. Negative relationships with yield were fitted using inverse S curves. Clear boundary lines were obtained by plotting a line of best fit through the points at the outer boundary of the scatter plot [37] (equation (3)). Therefore, the upper boundary points represented the maximum Robusta yield for a given level of the biophysical factor under a rainfall threshold,

$$Y_1 = \frac{Y_{\max}}{1 + (K * \exp(-(R * x)))}, \tag{3}$$

where Y_1 is the maximum attainable yield predicted for a given independent variable (x) for a rainfall threshold, $Y_{\max}$ is the the maximum observed yield that can be achieved on a rainfall threshold, X is the independent biophysical variable, and K and R are constants.

The yield gap was assessed to interpret coffee-related biophysical data quantified at a rainfall threshold level. The coffee yield gap is the difference between the highest possible yield for the entire threshold dataset and the average yield for a given limiting biophysical factor. The observed yield gap (Y_g) was made up of explainable and unexplainable portions. The explainable yield gap (Y_g) was the difference between the maximum ($Y_{\max}$) and the average minimum yield ($Y_{\min}$) at a specified threshold [37, 38]. Otherwise, the unexplainable yield gap was the average difference between the minimum yield ($Y_{\min}$) and the actual average yield (Y_a) obtained in the threshold [17, 19].

Due to the need for appropriate data, the cost of carrying out extensive data collection, the data collection method, and the BOLIDES method used to analyze the yield gaps, this study considered a limited number of factors. Although numerous factors are measured for the analysis of yield gaps, soil fertility and management issues are frequently considered and explain the yield gap better in Africa, where larger yield gaps are observed in smallholder farms [22, 37]. Therefore, it was suggested that soil fertility should be considered in any evaluation of yield gaps specifically at the local level [22]. Similarly, several authors have used soil fertility to explain yield gaps [17, 19, 39]. Therefore, the factors considered in the study included soil fertility parameters, diseases, pests, and tree and/or banana intercrop. These factors formed the basis for the most yield-limiting biophysical factors, the yield gaps, and how the gaps could best be closed at the plot level.

Studies indicate that the factors used in yield gap analysis differ between ecological conditions, farming systems, locations, and crops [18, 37, 39]. In addition, yield gaps can be studied on different scales with different benchmark yields, depending on the location and crop [38]. The spatial scale selected to benchmark the yield gap in the study focused on Robusta coffee at the plot level, with a single period of data. Maximum local measurements of the actual coffee production for one year from the farmer's coffee fields were used. The farm yields were associated with the actual average yield to capture the effects of biophysical factors under the rainfall thresholds [39]. Therefore, the yield gap (Y_g) was calculated as the difference between the maximum Robusta yield ($Y_{\max}$) and the actual average yield (Y_a) measured for individual farmer coffee plots [4, 17, 38]. The actual yield benchmark was appropriate to define the yield gap in such a case, where agronomic management practices, diseases, pests, weeds control, and nutrient supply are low and there are inadequate long-term data records [39].

3. Results

3.1. The Robusta Coffee Yield. Average Robusta yields were significantly ($p = 0.001$) higher in coffee fields under the moderate rainfall threshold of 960 ± 234 kg ha^{-1} compared to fields in the high threshold of 713 ± 193 kg ha^{-1} and a low rainfall threshold of 803 ± 188 kg ha^{-1} (Figure 2). The general Robusta yield ranged from 316 to 1492 kg ha^{-1} with an overall mean of 835 ± 232 kg ha^{-1}.

3.2. Yield-Constrained Biophysical Factors

3.2.1. Pests and Diseases. The main insect pest constraint for coffee was BCTB and CBB, which occurred at 12% and 1.79%, respectively, in the coffee sampled fields. The percentage of BCTB-infested twigs was significantly ($p < 0.001$) higher at the high rainfall threshold (mean = 22%; range: 0%–84%) than in the moderate (mean = 10%, range: 0%–32%) and low (mean = 2.4%; range: 0%–16%) rainfall thresholds. Similarly, the percentage of CBB-infested berries was significantly ($p < 0.001$) higher at the high rainfall threshold (mean = 3.4%, range: 0%–19%) than at the moderate rainfall thresholds (mean = 0.7%, range: 0%–2.7%) and low (mean = 1.4%, range: 0%–5.2%). Pests, specifically BCTB, increased with increasing rainfall thresholds (Figure 3). However, coffee mealybugs and scales were detected in only 1% of the fields sampled.

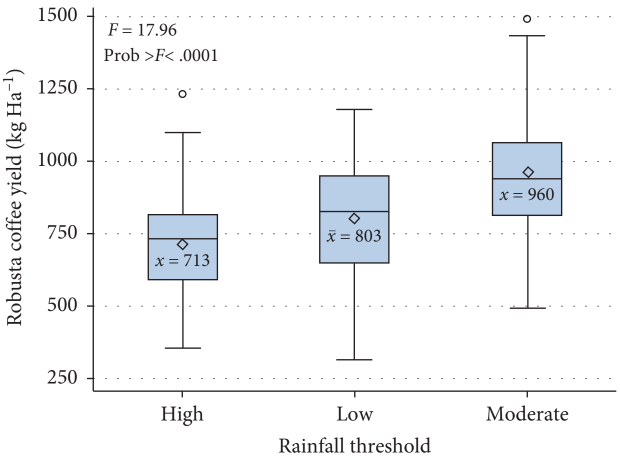

Figure 2: The mean coffee yield at the rainfall thresholds. The boxes represent the interquartile range (the lower and upper), the solid lines in the boxes are the median, and the diamond dots (◊) are the means. The lower bars indicate the lowest observation, and the upper bars indicate the largest observation and the upper quartile range (95% values). Thresholds are low ≤ 1100 mm year^{-1}, moderate ≥ 1100 to 1200 mm year^{-1}, and high ≥ 1200 mm year^{-1}.

CLR and RCB were the major diseases that occurred in 7.4% and 10% of the coffee sampled fields, respectively. The percentage of leaves infested with CLR was significantly ($p < 0.001$) higher at the high rainfall threshold (mean = 11.1%, range: 0%–25.5%) than at the low rainfall threshold (mean = 0.38, range: 0%–3.2%). Similarly, the percentage of berries infested with RCB disease was significantly ($p < 0.001$) higher at the high rainfall threshold (mean = 14.3%, range: 0%–53.1%) than at the low rainfall threshold (mean = 1.8%, range: 0%–12.9%). Similar to pests, the percentage of leaves and berries infested with disease increased with increasing rainfall (Figure 4).

Furthermore, the low rainfall threshold was associated with a significantly ($p < 0.001$) higher shade tree density ha^{-1} of 140 ± 97 than the high threshold of 72 ± 29 trees ha^{-1} and moderate threshold of 83 ± 46 trees ha^{-1} (Figure 5). However, intercropping coffee with bananas was common in areas with high rainfall. The ratio of coffee to banana was significantly ($p < 0.001$) higher in moderate (mean = 10.1, range: 0–40.9) than in high (mean = 2.3, range: 0–5.1) and low (mean = 5.4, range: 0–16) rainfall thresholds (Figure 5). The average tree size and percentage canopy closure were not significantly ($p > 0.05$) different among the rainfall thresholds.

3.2.2. Soil Fertility Parameters. The average soil pH of 6.07 ± 0.43 in the study area was within the required range of 5.5 to 6.3 for optimal Robusta coffee production. The soil fertility status of the surveyed coffee fields ranged from low to normal. The organic matter content of soil (SOM), nitrogen (N), calcium (Ca), and magnesium (Mg) in the coffee

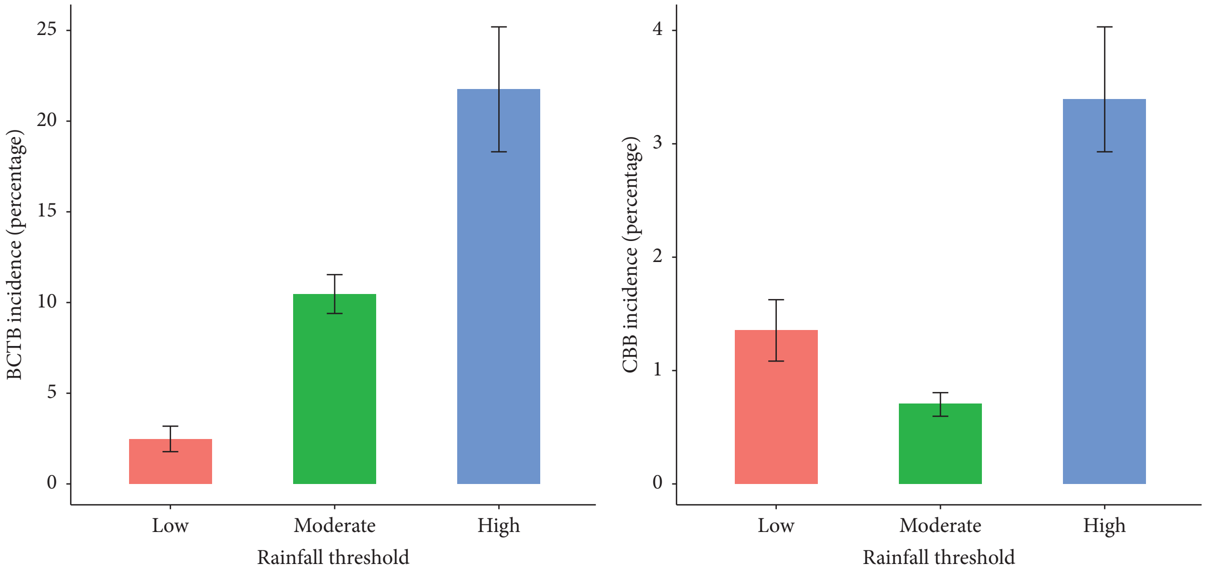

Figure 3: Proportion of Robusta coffee pests in the rainfall thresholds. The error bars represent the standard errors of the proportions of the pests (%) in the coffee plots per threshold. Thresholds are low ≤ 1100 mm year^{-1}, moderate ≥ 1100 to 1200 mm year^{-1}, and high ≥ 1200 mm year^{-1}.

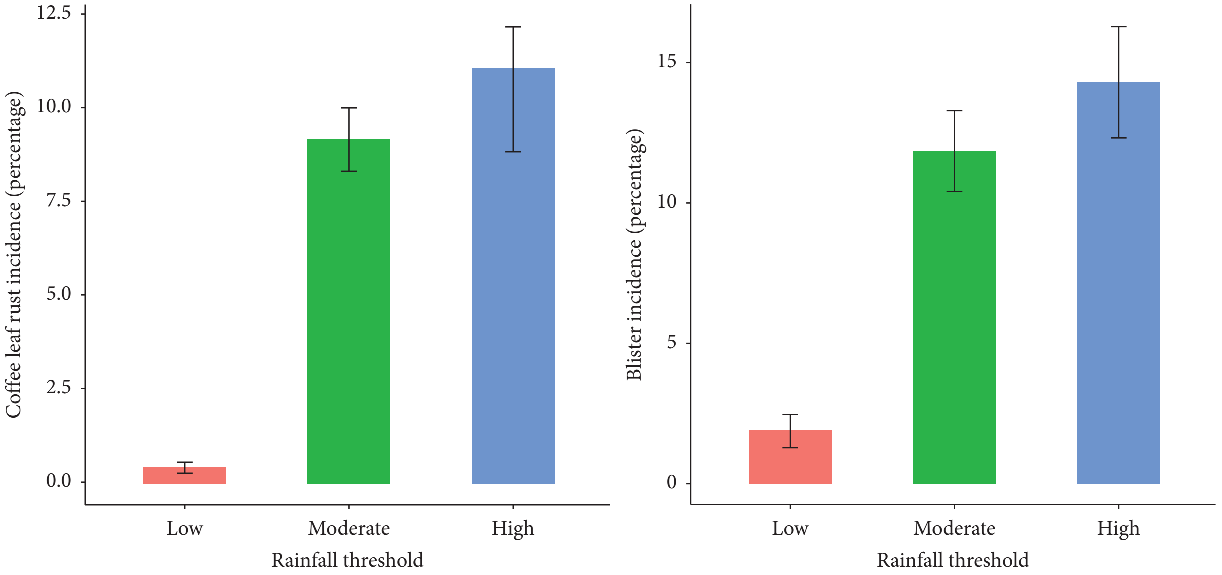

Figure 4: Proportion of Robusta coffee diseases in rainfall thresholds. The error bars represent the standard errors of the proportion of the disease (%) in the coffee fields per threshold. Thresholds are low ≤ 1100 mm year^{-1}, moderate ≥ 1100 to 1200 mm year^{-1}, and high ≥ 1200 mm year^{-1}.

fields sampled was equal to or above the critical nutritional level (CNL) required for coffee production, except for phosphorus (P) and potassium (K) that were below the CNL. Coffee fields in the high rainfall threshold had significantly ($p = 0.001$) more SOM, N, and P than fields at the low and moderate rainfall thresholds. Nitrogen and P were below the CNL at low and moderate rainfall thresholds. Magnesium was significantly ($p < 0.05$) different between rainfall thresholds. Generally, macronutrients increased with increasing rainfall; soil pH decreased with decreasing rainfall (Table 1).

Cation ratios in the study fields included 2.8 for Ca/Mg, 2.41 for Ca/(Mg + K), and 0.70 for Ca/(Ca + Mg + K). There was a significantly ($p < 0.05$) higher cation ratios in the low rainfall threshold than the moderate and high rainfall thresholds (Table 1). However, the calcium-to-potassium ratio (28.66) was significantly ($p < 0.05$) higher in the high than low rainfall threshold. Furthermore, the K/Ca, K/Mg, K/(Ca + Mg) and K/(K + Ca + Mg) ratios were 0.056, 0.15, 0.04, and 0.038, respectively. The ratios were significantly ($p < 0.05$) higher under the low threshold than high rainfall threshold. The Mg/Ca, Mg/K, Mg/(Ca + K), and Mg/

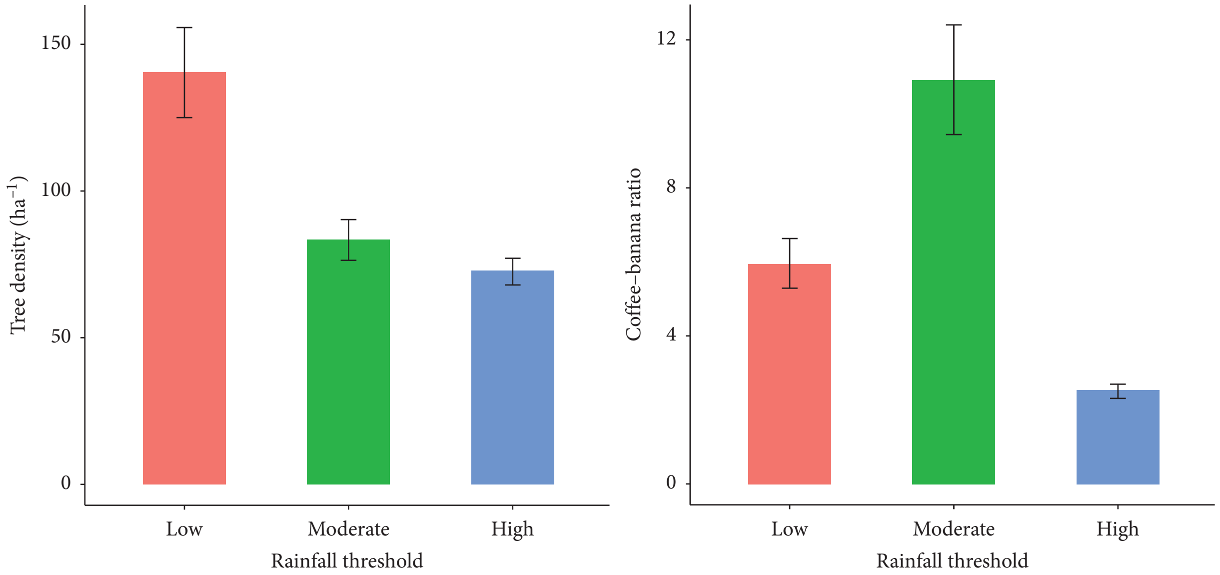

Figure 5: Tree density and the ratio of coffee to bananas in the rainfall thresholds. The error bars represent the standard errors of the tree density and coffee–banana ratio in coffee fields. Thresholds are low ≤ 1100 mm year^{-1}, moderate ≥ 1100 to 1200 mm year^{-1}, and high ≥ 1200 mm year^{-1}.

Table 1: Variation in soil parameters and major cation ratios across rainfall thresholds.

Soil parameter	High		Moderate		Low		Pooled		CNL	p value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
Soil pH	6.18^{a}	0.34	6.14^{a}	0.32	5.87^{b}	0.57	**6.07**	**0.43**	5.5	0.0012
Organic matter	5.86^{a}	1.53	4.61^{b}	1.49	3.95^{b}	0.92	**4.79**	**1.55**	3	0.0011
Total nitrogen (%)	0.25^{a}	0.07	0.19^{b}	0.05	0.18^{b}	0.03	**0.21**	**0.06**	0.2	0.0011
Phosphorous (ppm)	15.61^{a}	12.3	9.44^{b}	6.59	7.92^{b}	4.68	**11.13**	**9.18**	15	0.0012
Calcium $_{(+)}$(cmol/kg)	15.06^{a}	3.59	13.80^{a}	2.61	10.48^{b}	3.94	**13.2**	**3.84**	0.3	0.0011
Magnesium $_{(+)}$(cmol/kg)	7.42^{a}	2.1	6.15^{b}	1.59	4.15^{c}	1.82	**5.95**	**2.24**	2	0.0011
Potassium $_{(+)}$(cmol/kg)	0.62^{a}	0.28	0.58^{a}	0.22	0.55^{a}	0.23	**0.58**	**0.24**	2	0.37
Ca/Mg	2.08^{a}	0.3	2.34^{a}	0.53	2.80^{b}	0.94	**2.4**	**0.69**		0.0011
Ca/K	28.66^{a}	12.7	27.49^{a}	11.9	20.98^{b}	9.14	**25.89**	**11.8**		0.0036
Ca/(Mg + K)	1.92^{a}	0.28	2.11^{a}	0.4	2.41^{b}	0.69	**2.14**	**0.52**		0.0011
Ca/(Ca + Mg + K)	0.65^{a}	0.03	0.67^{ab}	0.04	0.70^{b}	0.07	**0.67**	**0.05**		0.0013
Mg/Ca	0.49^{a}	0.07	0.45^{ab}	0.08	0.40^{b}	0.16	**0.45**	**0.11**		0.0017
Mg/K	13.92^{a}	6.44	12.62^{a}	6.94	8.02^{b}	3.95	**11.64**	**6.46**		0.0011
Mg/(Ca + K)	0.47^{a}	0.06	0.43^{ab}	0.82	0.38^{b}	0.14	**0.43**	**0.11**		0.001
Mg/(Mg + Ca + K)	0.32^{a}	0.03	0.30^{a}	0.4	0.27^{b}	0.07	**0.29**	**0.05**		0.0011
K/Ca	0.040^{a}	0.02	0.04^{ab}	0.02	0.06^{b}	0.02	**0.05**	**0.02**		0.0013
K/Mg	0.09^{a}	0.03	0.10^{a}	0.05	0.15^{b}	0.07	**0.11**	**0.05**		0.0011
K/(Ca + Mg)	0.03^{a}	0.01	0.03^{a}	0.01	0.04^{b}	0.01	**0.03**	**0.01**		0.0011
K/(K + Ca + Mg)	0.03^{a}	0.01	0.03^{a}	0.01	0.04^{b}	0.01	**0.03**	**0.01**		0.0011

Note: Means followed by the same letters in the rows indicate that there are no significant ($p > 0.05$) differences, while different letters in the row indicate the significant ($p < 0.05$) differences according to LSD (0.05). Thresholds are low = <1100 mm year^{-1}, moderate = >1100 to 1200 mm year^{-1}, and high = >1200 mm year^{-1}.

(Mg + Ca + K) ratios were 0.49, 13.92, 0.47, and 0.32, respectively. The ratios were significantly ($p < 0.05$) higher in the high rainfall threshold. Generally, the cation ratios were significantly ($p < 0.05$) different between the high and moderate; and the high and low rainfall thresholds (Table 1).

3.3. Limiting Factors to Coffee Yield and Yield Gap. The biophysical factors used in the boundary line analysis for the estimation of Robusta yield variability included soil fertility parameters, pests, diseases, and tree and/or banana intercrop. The reference yield used was the maximum and average actual Robusta yield of the farmer's coffee plots under a given rainfall threshold. The relationship between biophysical factors and Robusta yield indicated clear boundary regression lines in the scatter plots fitted with the best-fit lines. The observed maximum yield ($Y_{\max}$) was 1177 ± 188 kg ha^{-1}, 1232 ± 193 kg ha^{-1}, and 1432 ± 234 kg ha^{-1} for low, high, and moderate rainfall thresholds, respectively.

Single-factor yield response curves were created per biophysical factor identified under each rainfall threshold. The Robusta yield increased with an increase in the number of coffee trees ($R^2 = 0.89$) and tree size ($R^2 = 0.72$) under a high rainfall threshold. Furthermore, an increase in the yield was observed with increased phosphorus ($R^2 = 0.74$) availability, the coffee-to-the-banana ratio ($R^2 = 0.43$), and tree size ($R^2 = 0.36$) under moderate rainfall threshold. Under the low rainfall threshold, the yield increased with coffee age ($R^2 = 0.94$), coffee tree number ($R^2 = 0.92$), and canopy closure ($R^2 = 0.73$) (Figure 6).

However, coffee–banana ratio ($R^2 = 0.88$), magnesium ($R^2 = 0.76$), and soil pH ($R^2 = 0.68$) highly estimated the yield gap at the high rainfall threshold. The CBB ($R^2 = 0.92$), BCTB ($R^2 = 0.90$), tree density ($R^2 = 0.89$), and magnesium concentration ($R^2 = 0.84$) had the highest R^2 in estimating the yield gap in the moderate rainfall threshold. Under the low rainfall threshold, magnesium ($R^2 = 0.89$), tree density ($R^2 = 0.79$), and BCTB ($R^2 = 0.67$) had the highest R^2 in estimating the yield gap (Figure 7).

The variation in limiting factors between rainfall thresholds indicated soil parameters and tree and/or banana intercrop among the major biophysical factors that limit yield in coffee fields. Specifically, the main biophysical factors were magnesium (47%), soil pH (40%), and the ratio of coffee to banana (13%), which limited the Robusta yield in coffee plots under high rainfall thresholds. Under the moderate rainfall threshold, CBB (28%), magnesium (26%), tree density (24%), and BCTB (22%) were the major limiting factors in coffee plots. Moreover, the most yield-limiting factors in coffee plots under low rainfall thresholds were BCTB (51%), magnesium (14%), banana mats (7%), and tree density (3%) (Figure 8).

Actual average yield gaps were 42% (517.4 kg ha^{-1}) for the high threshold, 36% (532 kg ha^{-1}) for moderate threshold, and 32% (374 kg ha^{-1}) for low rainfall thresholds (Figure 9). Although the yield gap (amount in kilograms) was slightly higher at the moderate rainfall threshold (532 kg ha^{-1}), a higher percentage yield gap (42%) was observed at the high than low and moderate rainfall thresholds. Magnesium, soil pH, and coffee banana ratio caused 23%, 11%, and 10.7% of the yield gap, respectively, in a high rainfall threshold. Yield-limiting factors such as CBB, magnesium, tree density, and BCTB caused 17%, 20%, 20%, and 10%, of the yield gap, respectively. In contrast, BCTB, magnesium, tree density, and banana mats caused a yield gap of 13%, 21%, 17%, and 20% in the low rainfall threshold. Generally, the actual yields were below the boundary functions for all rainfall thresholds. Furthermore, the actual yield points for the fields were below the diagonal line (Figure 9).

The overall explainable yield gap was higher (32%) than that observed in the individual rainfall thresholds at 25% (312 kg ha^{-1}) for the high threshold, 22% (328 kg ha^{-1}) for the moderate threshold, and 22% (247 kg ha^{-1}) for low rainfall thresholds (Figure 9). However, the overall unexplainable Robusta yield gaps observed from the study were 18% (183 kg ha^{-1}) and 23% (212 kg ha^{-1}) for high threshold, 18% (210 kg ha^{-1}) for moderate threshold, and 13% (121 kg ha^{-1}) for low rainfall thresholds.

4. Discussion

4.1. Constraint Factors on Coffee Yield. Soil parameters were the main biophysical factors that limited coffee production at rainfall thresholds. The low soil fertility can be attributed to the inherently low soil nutrient status due to the high weathering of the parent material and subsequent leaching of nutrients [28]. Besides, the soil texture in the area is sandy loam with low soil nutrients [28]. Also, the lack of and or low use of fertilizers may explain the low observed Robusta yield [4, 5]. For example, the national fertilizer use in Uganda is below 2.0 kg ha^{-1} [40]. Yet, the recommended average nitrogen rate is 120 kg ha^{-1} per year. Other producing countries like Brazil, Vietnam and the world level have high fertilizer inputs, which range from 120 to 186 kg ha^{-1}, 305 to 430 kg ha^{-1}, and 108–to 141 kg ha^{-1}, respectively. Furthermore, young soils and irrigation have played a major role in achieving high yields at a lower cost in Vietnam compared to poor soils (Ferralsols) in Uganda [28]. The high extraction, leaching, and depletion of nutrients associated with sandy loam soil texture and perennial crops such as coffee, where recycling is minimal, are major causes of low coffee yield in central Uganda.

The high soil pH (above 6) observed (Table 1) could account for the imbalanced soil nutrient concentration, particularly at the high rainfall threshold. In Africa, nutrient imbalances limit crop productivity more than water availability [22]. Therefore, low rainfall may not be the only factor that led to low yield. For example, the low Robusta yields observed (Figure 2) between high threshold and low rainfall threshold could be associated with factors such as high magnesium, low and high soil pH (Table 1), BCTB pest, coffee banana ratio, and tree density. Lower levels of the major macronutrients, especially nitrogen, phosphorus, and potassium, organic matter, and low soil pH (Table 1) at low rainfall thresholds are additional causes of the reduced Robusta yield [20, 36, 40]. Furthermore, less moisture at the low rainfall threshold may have affected carbon decomposition in the topsoil, nutrient uptake, and availability, which eventually reduced yield; high rainfall may have led to competition between potassium and calcium leading to low yield in high rainfall threshold [41]. Integrated soil fertility management (ISFM) and nutrient retention capacity enhancement strategies for these ferritic soils with a sandy loamy texture are important considerations for effective management, for example, reduce magnesium levels, and increase potassium and organic matter input.

Furthermore, the low yield could be due to a high proportion of pests and disease-affected twigs, berries, and leaves [4, 7, 8] under a high rainfall threshold (Figures 3 and 4). This can be attributed to a large amount of rainfall, resulting in warm and humid conditions which favor the

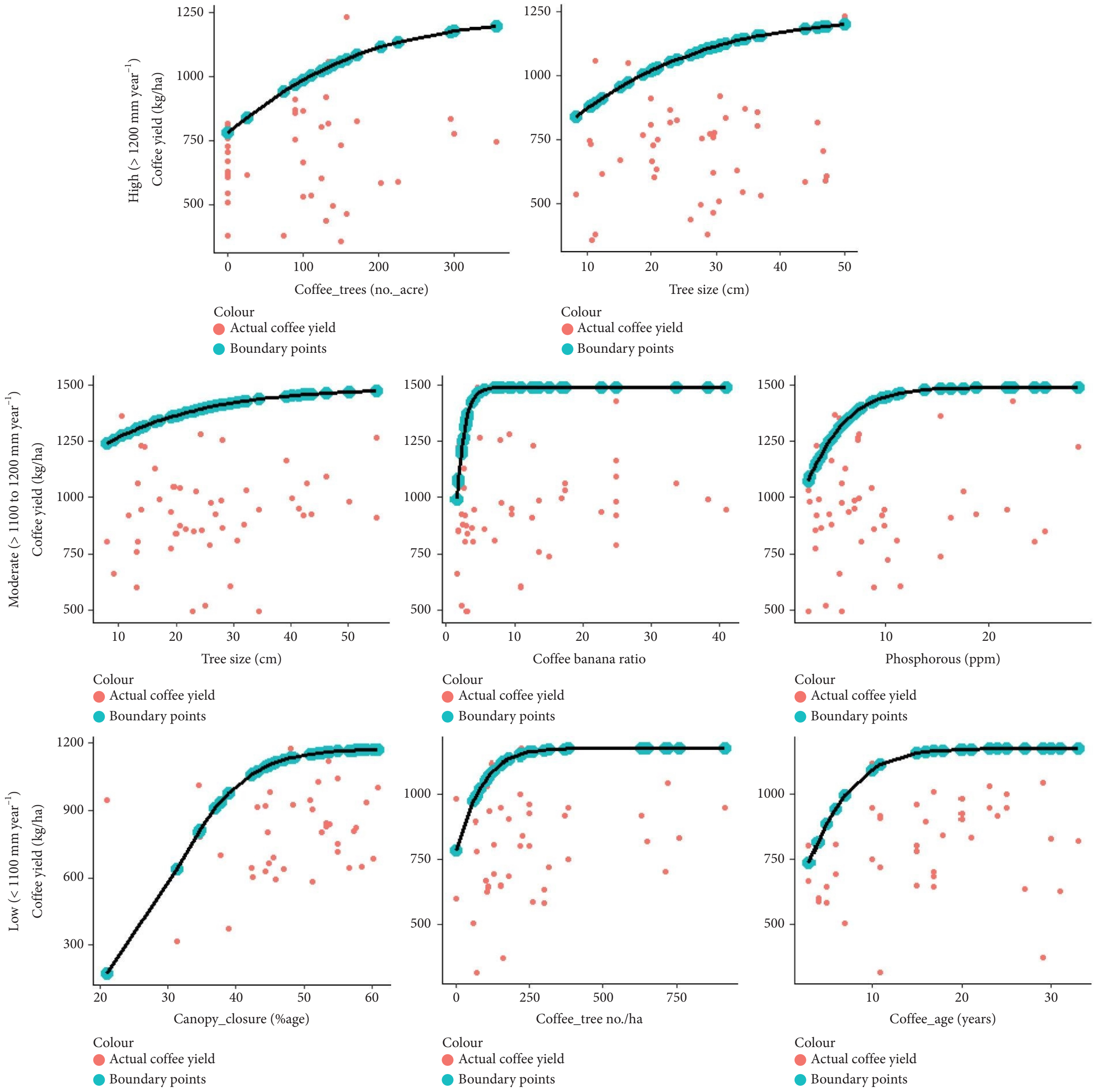

Figure 6: The positive relationship between the Robusta yield and the identified biophysical factors under a given rainfall threshold estimated by BOLIDES. Thresholds are low = <1100 mm year^{-1}, moderate = >1100 to 1200 mm year^{-1}, and high = >1200 mm year^{-1}.

growth of pests and fungal diseases and their interaction [42]. Previous studies show that the main pests and diseases observed (e.g., coffee leaf rust and BCTB) prefer high humidity, vital for their development [32, 42]. Furthermore, high humidity favors the ambrosia fungus associated with BCTB [43]. This may explain why the identification of biotic factors was particularly significant in high rainfall and low prevalence at low rainfall thresholds. Surprisingly, pests and diseases were not among the most yield-limiting factors in the high rainfall threshold; the opposite was true with the low and moderate rainfall thresholds. However, the results may call for integrated pest management, especially the use of pesticides to close the yield gap.

4.2. Robusta Yield Gap. The results indicated a large variation in the Robusta yield (316 kg ha^{-1} to 1492 kg ha^{-1}) with a 32% overall explainable yield gap. The average coffee yield (Figure 2) is comparable to the yields reported for central Uganda by Wang et al. [4] but were approximately 38% higher than the national estimates and FAO statistics. However, the attainable yield was lower than the 1737 kg ha^{-1} observed by [4]. The low Robusta yields can be attributed to biophysical factors such as low soil nutrients, pests and diseases, and tree and or banana intercrop other than low rainfall. The data support the hypothesis that the yield gap at the plot level was an aggregate effect of the amount of rainfall received, the agricultural production

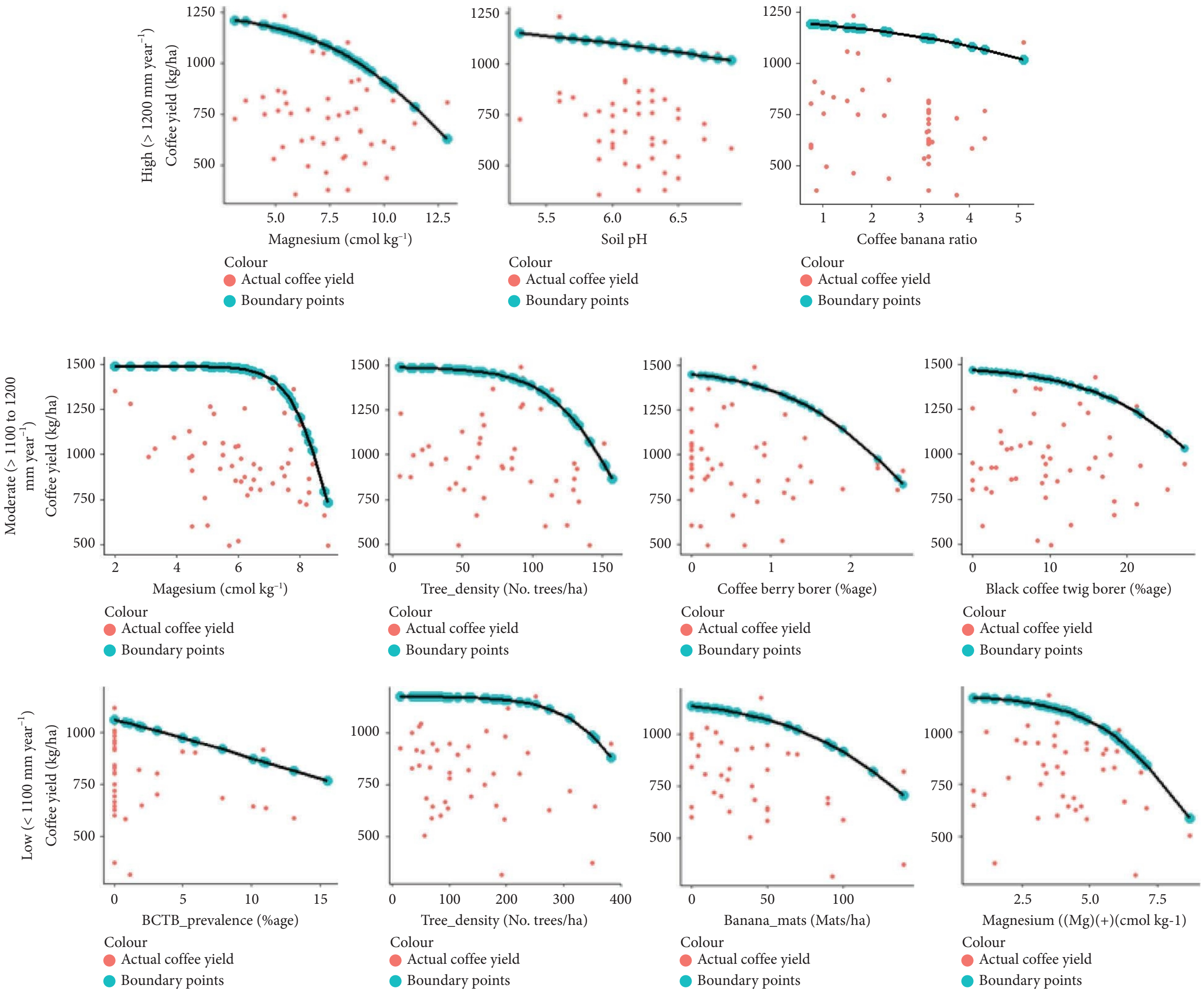

Figure 7: The negative relationship between Robusta yield and the identified biophysical factors estimated by BOLIDES. Thresholds are low = <1100 mm year^{-1}, moderate = >1100 to 1200 mm year^{-1}, and high = >1200 mm year^{-1}.

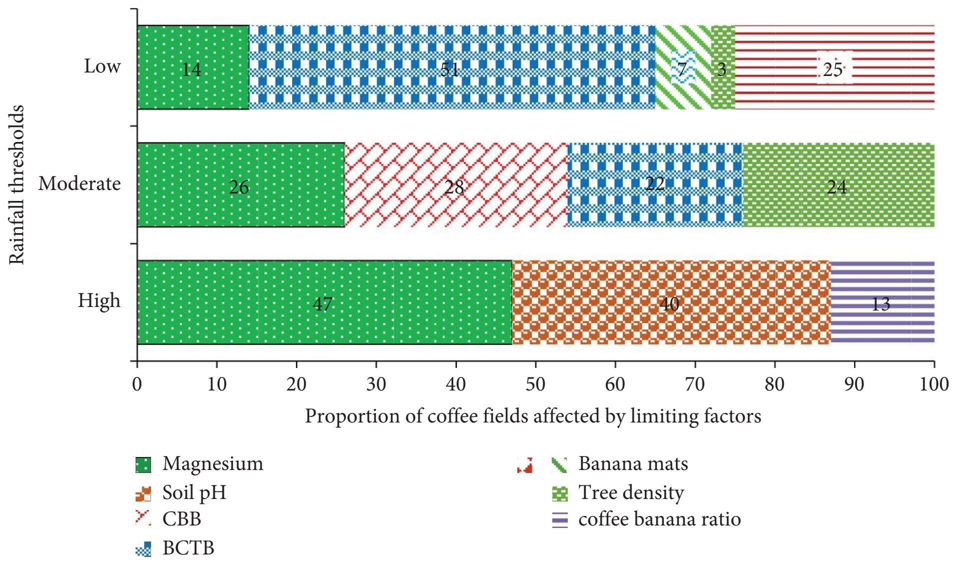

Figure 8: The proportion of coffee fields affected by the main yield-limiting factors under each rainfall threshold. Thresholds are low ≤ 1100 mm year^{-1}, moderate ≥ 1100 to 1200 mm year^{-1}, and high ≥ 1200 mm year^{-1}.

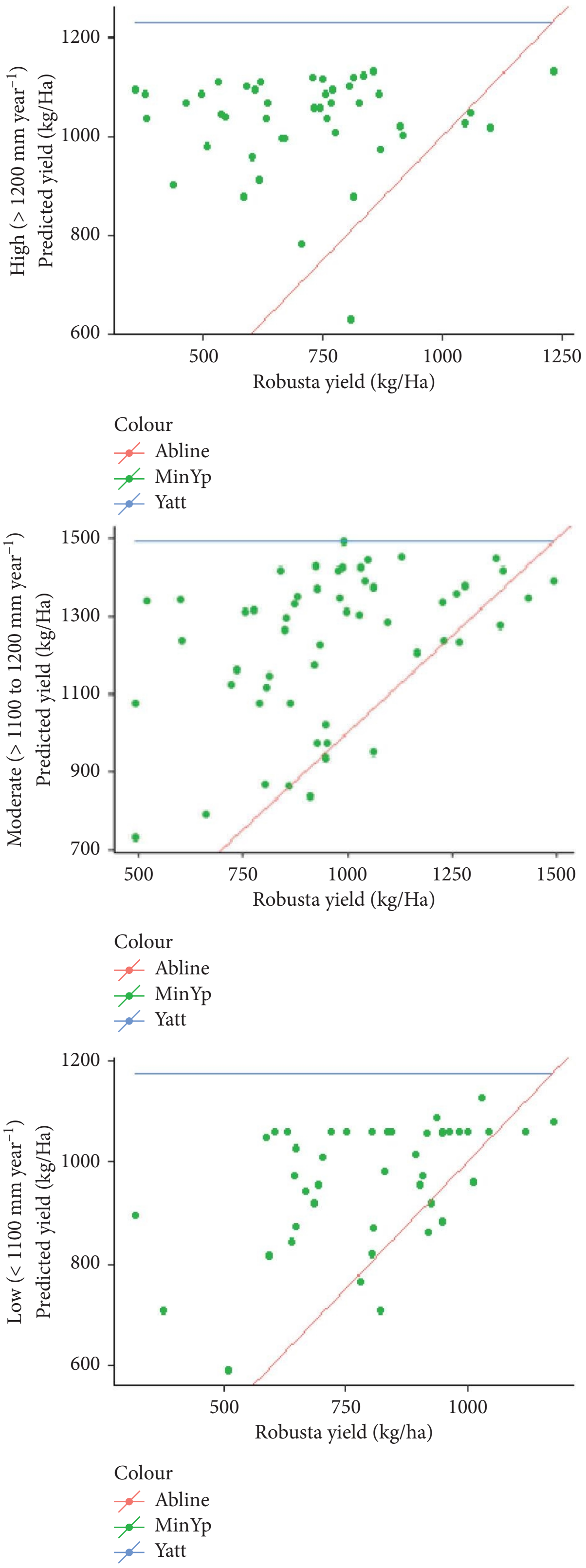

FIGURE 9: Actual observed and predicted Robusta yield (kg ha^{-1}) from the boundary line analysis for high, moderate, and low rainfall thresholds. The predicted yield was the minimum prediction based on the biophysical factors considered. The continuous line $Y = 1232$ kg ha^{-1}, $Y = 1492.2$ kg ha^{-1}, and $Y = 1177$ kg ha^{-1} represents the maximum observed Robusta yield below the threshold for, low, moderate, and high rainfall. The diagonal line shows the relationship 1 : 1 ($Y = X$). Thresholds are low = <1100 mm year^{-1}, moderate = >1100 to 1200 mm year^{-1}, and high = >1200 mm year^{-1}.

practices, the pests and diseases that occur, and the physical–chemical state of the soil. Although the explainable yield gap was small (less than 50%), the observed R^2 was high. Nevertheless, the boundary line method may have overestimated the actual Robusta yield, as indicated by the majority of data points way above the diagonal lines (Figure 9). This could be due to the constraining biophysical factors considered in the study, the BOLIDES method used, and the actual yield other than the potential yield [21]. However, the higher Robusta yield than national and FAO statistics could be due to direct measurements from farmer fields rather than estimates from field surveys, where farmers tend to underreport the yield for fear of being taxed. However, these yields are still lower than station yields in Uganda, experimental yields, and yields in major producing countries [3]. Still, the results indicate a high potential to improve yield in coffee fields across rainfall thresholds if site-specific biophysical factors and their long-term interactions could be considered, with multiple years of data.

Although the proportion of diseases and pest infestation was greater at the high rainfall threshold, the results from the boundary line analysis indicate that these did not significantly influence the Robusta yield compared to other biophysical factors, especially soil parameters. Similar observations were made by van Asten et al. [11] who indicated that soil fertility was a greater constraint on banana production than pests. Therefore, the yield gaps attributed to pests and diseases in the high rainfall threshold were not quantified, as they did not emerge among the major limiting factors. Although BCTB was the major limiting in the study carried out by Wang et al. [4], this study indicated soil parameters as the most limiting in coffee fields with high rainfall compared to moderate and low rainfall thresholds. This may be due to other interactive factors and the tree banana intercrops involved. However, it is essential to monitor coffee fields more than once to determine the prevalence of pests in different months and seasons due to their variability and relationship with weather conditions.

Banana interculture with coffee was associated with a reduction in yield under high rainfall thresholds (Figure 2). A low ratio of coffee to bananas in high rainfall may indicate increased competition between bananas and coffee. There may be increased competition for space, light, water, and soil nutrients, especially potassium [4]. This may have contributed to the inadequacy of potassium in the sampled fields, especially at the high and low rainfall threshold (Table 1). Although trees provide shade for optimal coffee production, the high tree density at the low rainfall threshold may have led to competition between coffee and shade trees for nutrients and moisture [4, 10, 43]. This may have affected coffee productivity under such low rainfall conditions. Alternatively, the low DBH associated with several small trees under high rainfall threshold indicates that the trees were not adequate to provide shading benefits to coffee but instead created favorable microclimatic conditions for BCTB, CLR, and coffee blister [15]. The variation in shading, banana competition, and high tree density in the study area may have contributed to the low Robusta yields observed [4, 15]. Although the results indicate that stress to coffee yield was not minimized during the diagnostic study, it provided site-specific information on the main biophysical limitations to yield in studied coffee plots; yield gap analysis provided the foundation for identifying the major biophysical factors that limit Robusta yields in central Uganda. The boundary lines represented the actual yield gaps in the fields of farmers. Subsequently, the estimated coffee yield gap for central Uganda is attributed to these suboptimal biophysical production conditions. Hence, the need to optimize tree and/or bananas and tree density in coffee fields as an immediate option to sustainably improve Robusta yields on farms amid rainfall variability and future climate change.

5. Conclusions

The study results indicate an overall coffee yield gap of 32% in central Uganda. The yield gap is attributed to several biophysical factors with the most yield-limiting being soil parameters and tree or banana intercrop. For example, magnesium limited yield in 47%, 26%, and 14% of fields in high, moderate, and low rainfall thresholds, respectively. In addition, soil pH limited yields in 40% of fields in high rainfall threshold. The BCTB limited yields in 51% and 22% of fields in low and moderate rainfall thresholds, respectively. Besides, CBB affected 28% field in moderate, while the tree density affected 24% of fields in moderate and only 3% of fields in low rainfall thresholds. The coffee–banana ratio and banana mats affected only 13% and 7% of fields for high and low thresholds, respectively. Besides, a higher yield gap was observed in high (42%) than moderate (36%) and low (32%) rainfall thresholds. The soil fertility parameter, magnesium, caused yield gaps of 23%, 20%, and 21% in high, moderate, and low rainfall thresholds, respectively. Restricting the factors to the average actual yield decreased the yield gap in the farmer fields, especially those with low levels of actual yield. Although the coffee yield gap is above 20% of the maximum yield, there is an opportunity to increase the yield and close the gap. This is mainly through lowering the soil pH and magnesium in the high rainfall threshold, focusing on pest and disease monitoring under moderate and low rainfall thresholds. Besides, frequent field monitoring is needed to determine the prevalence of coffee pests and diseases at different times of the year and season. Identifying specific management aspects of biophysical factors may also require on-farm field experimentation. In addition, the benefit of tree shade in coffee production may require planting fast-growing shade tree species or planting trees before establishing coffee fields. However, coffee farmers must prioritize long-term integrated management practices to guide resource allocation and narrow the yield gap. The emphasis should be on sustainably increasing Robusta yields in specific rainfall thresholds through medium- and long-term soil fertility, and tree or banana intercrop management other than the main current focus on pests and diseases. Nevertheless, pests, especially BCTB, remain a major threat to Robusta yield in central Uganda, as not addressing it can further affect productivity. Addressing these limitations and additional factors with a focus on multiple constraints in the different rainfall thresholds is critical to achieving the 2000 kg ha^{-1} and 20 million 60-kg bags year^{-1}.

Data Availability Statement

The data used to support the findings of this study are included within the paper.

Disclosure

This work is part of the Ph.D. thesis.

Conflicts of Interest

The author declares no conflicts of interest.

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