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Estimating Yield Components, Limiting Factors, and Yield Gaps of Enset in Ethiopia Using Easily Measurable Above-Ground Plant Traits

Zerihun Yemataw [1], Alemar Said [1], Tesfaye Dejene [1], Walter Ocimati [2], David Amwonya [3] and Guy Blomme [4,*]

[1] Southern Agricultural Research Institute (SARI), Hawassa P.O. Box 06, Ethiopia; zerihunyemataw2@gmail.com (Z.Y.); alemarsao@gmail.com (A.S.); dtesfaye75@yahoo.com (T.D.)
[2] Bioversity International, Kampala Office, Kampala P.O. Box 24384, Uganda; w.ocimati@cgiar.org
[3] International Institute for Tropical Agriculture, Kampala P.O. Box 7878, Uganda; david.amwonya@gmail.com
[4] Bioversity International, Addis Ababa Office, c/o ILRI, Addis Ababa P.O. Box 5689, Ethiopia
* Correspondence: G.Blomme@cgiar.org

Abstract: The quantification of yield for different enset products has mainly been based on farmers' estimates, which are often inaccurate. Several allometric models have been developed to overcome this challenge. Building on past work, the current study developed allometric models for enset fiber, kocho, and bula yield estimation. Enset yield limiting factors and associated yield gaps were also determined. In this study, above-ground growth and yield (kocho, bula, and fiber) traits of five-year-old plants of two widely grown enset landraces, 'Unjame' and 'Siskela', were assessed in farmers' fields at three contrasting altitude sites. Except for bula, a minor yield component, correlation, and PCA analysis showed strong association between the above-ground and yield traits. Allometric equations based on the above-ground traits significantly (R^2 = 25 to 68%) explained the variation in the yield traits. This study, for the first time, generated allometric models that can reliably estimate enset fiber yield. Leaf length, petiole length, and plant height are especially good for estimating fiber and kocho yields. The performance of models for bula were poor possibly due to the very low bula yields per plant. Soil chemical characteristics differently influenced enset yield attributes. For example, improving K supply can potentially enhance fiber yield. Higher yield gaps were observed for bula, with P accounting for the highest yield gaps across yield traits. Through careful targeting, the different yield attributes can thus be enhanced. This and previous studies clearly show that non-destructive enset plant assessments can provide solid information for quick and easy yield assessments for various traits during e.g., agronomic, germplasm evaluation, soil fertility enhancement, and intercropping trials.

Keywords: allometric equations; bula; fiber; kocho; yield gaps

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1. Introduction

Enset (also called false banana; *Ensete ventricosum*) is an important food crop in Ethiopia [1–3]. The crop provides food for about 20% of the Ethiopian population, over 20 million people, mainly in the south and south-west of the country [2]. Over the course of a year, around sixty mature plants can provide enough food for a family of five to six people, when consumed with other dietary components such as cabbage, meat, and dairy products [4].

The crop is not cultivated for bunches and fruits but for the starch that is extracted from the underground corm/rhizome and pseudostem [1–3]. The underground corm or rhizome is a mass of parenchymatous tissues from which the leaf sheaths emerge. The individual leaf sheaths, lying one over the other in a concentric fashion, make up the pseudostem. New leaves emerge from the apical meristem and grow through the center of the pseudostem. At maturity, the flower stalk or real stem emerges from the apical meristem and grows upwards through the center of the pseudostem to produce the inflorescence. The corm, leaf sheaths, and the real stem (in flowering plants only) of mature enset plants are processed, using traditional tools, into a pulp which is fermented in a fermentation pit for at least one month to form the primary product called 'kocho' [2,3]. Byproducts of this process are fiber (from the leaf sheaths) and 'bula', which is a premium starch separated from the liquid pressed out of the fresh pulp. The fermented pulp (i.e., kocho) is used to make a traditional dense flatbread, while bula fetches premium prices in markets as it does not contain any fiber and can be processed into various desserts [1].

Enset production is affected by numerous biophysical factors such as soil fertility, pests (e.g., the enset root mealybug, weevils, nematodes, mole-rats, and porcupines) and diseases (e.g., Xanthomonas wilt of enset). Understanding the extent of losses due to these factors could help in directing efforts towards the management of the key limiting constraints. The quantification of enset production and yield losses has been difficult, with yield estimates mainly reliant on farmer estimates through recall studies and these estimates are hence often incorrect. On-farm yield estimation is complicated by the fact that enset plants on farmers' fields are not always harvested at the same development stage. Moreover, it is common to find multiple landraces with different growth and yield attributes on farm. To overcome this challenge in different crop species (e.g., Reddy et al. [5] for soybean (*Glycine max*); Nyombi et al. [6] and Wairegi et al. [7] for banana (*Musa* spp.); Tittonell et al. [8] for maize (*Zea mays*)), allometric relationships between easily measurable plant growth traits, which could be used for a non-destructive yield assessment, and yield attributes have been developed. For the banana crop, a close relative to enset, Nyombi et al. [6] developed allometric models that use easily measurable above-ground plant growth traits, specifically pseudostem girth to predict banana above-ground biomass and bunch weight/yield. Nyombi et al. [6] reported the pseudostem girth at flowering to be a good predictor of banana yields with $R^2 = 0.70$ (cv. 'Mbwazirume') and $R^2 = 0.57$ (cv. 'Kisansa') obtained between actual and predicted bunch weights.

Several allometric equations have also been developed for predicting enset yield components. Shank and Ertiro [9] using enset pseudostem circumference (Pc) and pseudostem height (Ph) as predictors developed a linear regression equation (i.e., kocho yield = $-32.1 + 0.26 \times \text{Pc} + 0.13 \times \text{Ph}$) that explained 82% of the observed sample variations in kocho yield. However, Shank and Ertiro [9] observed an apparent non-linearity in the real kocho yield for the very small and the very big plants since the model predicted no yield for the very small plants that yielded 2–5 kg/plant and less yield for big enset plants with >100 kg kocho yield/plant. Increasing the sample size in these two categories was suggested for accurate kocho weight prediction. Shank and Ertiro [9] did not develop models to estimate bula or fiber yields.

In another study, Negash et al. [10] developed allometric models for estimating above- and below-ground biomass and organic matter contents of enset grown in indigenous agroforestry systems (1900 to 2400 m.a.s.l.) in south-eastern Ethiopia. Negash et al. [10] measured various traits on harvested plants: pseudostem diameter at various plant heights between 10 cm and 200 cm; pseudostem height (Ph, measured from ground level to the petiole of the last emerging leaf); total plant height (H, measured from the ground to the tip of the longest leaf); and crown height (calculated by subtracting Ph from H). Pseudostem diameter at 10 cm (d10) and total plant height (H) formed the best model ($Y = 0.0007\ \text{d10}^{2.571}\ \text{H}^{0.101}$; $R^2 = 0.91$) for predicting total plant biomass (Y). Model performance decreased as follows: pseudostem > corm > foliage biomass. Negash et al. [10] did not include processed products such as kocho, bula, and fiber in their study.

Building on modeling efforts by Shank and Ertiro [9], Haile [11] measured a large number of above-ground and yield traits on three harvestable plants each for 328 enset landraces (covering a wide range of kocho and fiber yields) collected from the six major enset growing areas of Southern Ethiopia and growing at the Areka Agricultural Research station. The above-ground traits measured at harvesting included plant height (from ground level to the tip of the longest leaf), pseudostem height (from ground level to the start of the leaf petiole), pseudostem circumference at mid-stem height, number of fully expanded green/functional leaves, leaf length (from the end point of the petiole to the tip edge of the leaf), and leaf widest width. Haile [11] also assessed several yield traits including fermented un-squeezed kocho yield (kg), fermented squeezed kocho yield (the fermented un-squeezed kocho is squeezed by applying force until it loses most of its moisture content), and fiber weight (kg) obtained after leaf sheath decortication. Haile [11] similarly reported plant height and pseudostem circumference as the best non-destructive predictors of kocho yield and obtained significant regression equations describing the relationship of fermented un-squeezed (R^2 = 0.78) and squeezed (R^2 = 0.69) kocho yield with enset plant height and pseudostem circumference. Haile [11] did not however obtain significant regression equations (R^2 = 0.01) to estimate fiber yield even when fiber data were log transformed. The author postulated this to be due to the great variability in fiber content across the 328 enset landraces. The author also postulated that data from a large number of plants of a single enset landrace could improve the possibility of estimating enset fiber content from aboveground plant traits using a linear regression model. Haile [11] did not develop models for bula.

In another study, Mellisse et al. [12] collected above-ground growth and yield data of harvestable enset from 20 enset plants of different landraces and ages. The authors observed pseudostem diameter at 50-cm height, pseudostem height, and their combination to be good predictors of the yield variables (i.e., kocho and bula), while diameter at 50-cm height, pseudostem height, edible pseudostem height, total plant height, and their combination were good predictor variables for enset foliage weight. The best performing models explained 84–89% of the variation in kocho, 78–85% in bula, and 60–72% in foliage dry biomass. The model performance of the linear allometric equations derived in Mellisse et al. [12] is comparable and sometimes better than the non-linear models developed for biomass components of enset reported by Negash et al. [10]. The good performance of the linear models in Mellisse et al. [12] could be related to the sampling of all harvestable age ranges (3–7 years) of enset plants, unlike the focus on only 3- and 5-year enset plants by Negash et al. [10]. Similar to Negash et al. [10], Mellisse et al. [12] also reported that pseudostem diameter measurements were better predictor variables for kocho than height, indicating that kocho yield is more influenced by diameter growth than by the height growth. The study by Mellisse et al. [12] also suggests that bula yield is influenced by both pseudostem diameter and height. Mellisse et al. [12] did not develop models to predict enset fiber yield.

Allometric equations using easily measurable above-ground plant growth variables as predictors for kocho and bula yield such as in the above cases are time-saving tools and provide valuable information for identifying productivity challenges and solutions for improving smallholders' food production and cash income. Previous enset studies mainly focused on predicting kocho and bula yield. This study (i) developed allometric models for estimating fiber in addition to kocho and bula yields of enset using growth and enset yield data collected from two widely grown enset landraces at three contrasting altitude sites and (ii) determined the yield limiting factors and gaps due to abiotic/soil factors. This study builds on the existing enset models for estimating kocho and bula yield and develops for the first time successful models to estimate fiber yield.

2. Materials and Methods

2.1. Enset Growth and Yield Traits across Altitudes

Five-year-old enset plants from two widely grown enset landraces, 'Unjame' and 'Siskela', were used in this study. The enset plants were planted at a spacing of 0.5 × 1 m in the first year, and thereafter, thinned to 1 × 2 m and 2 × 2 m in the third and fifth years, respectively. The enset plants were intercropped with cereals and vegetables in the early growth stages while they were in a sole monocrop state at the time of assessment. Plant assessments were carried out in the Kambata-Tambark zone, in southern Ethiopia, at three contrasting altitude sites, namely 'Mino' at 1800 m a.s.l., 'Angacha' at 2400 m a.s.l., and 'Serera' at 2900 m a.s.l. The average annual rainfall at Mino, the lowest elevation site, is 1138 mm, while average annual minimum and maximum temperatures are, respectively, 13.0 and 24.0 °C. At Angacha the average annual rainfall is 1475 mm, while the average annual minimum and maximum temperatures are, respectively, 12.5 and 23.0 °C. The average annual rainfall at Serera, the highest elevation site, is 1728 mm, while average annual minimum and maximum temperatures are, respectively, 10.6 and 22.5 °C.

Soil sample analysis was carried out at the Areka and Hawasa Agricultural Research Center's soil laboratories. Soil pH was read from a 1:2.5 soil:water extract. Soil organic matter content was determined colorimetrically at 600 nm following digestion with potassium dichromate and sulphuric acid (Walkley–Black). Nitrogen was quantified using the Kjeldahl distillation and digestion method, followed by titration. Available phosphorus was determined through the Olsen method using a spectrophotometer at 880 nm, while the CEC (meq/100 gm) and K were determined using the 1N neutral ammonium acetate extraction method. Soil data are presented in Supplementary Table S1.

Bulk soil samples (15–30 cm depth) were collected from within enset plots at the three altitude sites. Enset plants were assessed in plots at 10 to 30 m from the farmhouse in fields that regularly received cow manure and/or household refuse. The five-year-old mature plants were assessed in a destructive manner in order to, in addition to aboveground growth traits, also collect data on yield traits.

The 5-year-old plants were in the flowering stage. Enset plants, in farmers' fields, are only harvested close to flowering stage, when maximum corm and pseudostem biomass has been built-up/achieved. In this study, enset plants reached the flowering stage around 5 years of age for the two assessed landraces. Ten plants were assessed per landrace and altitude. Hence, a total of 60 enset plants were assessed.

The aboveground growth traits included plant height (m) (i.e., from soil level to tip of longest unfolded leaf), pseudostem height (m) (i.e., from soil level to start of petioles of youngest leaves), pseudostem circumference at soil level (m), pseudostem circumference at mid-height of the pseudostem (m), pseudostem circumference at start of petioles of youngest leaves (m), number of functional/green leaves, leaf lamina length (m) (from upper petiole end to leaf tip) and leaf lamina widest width (m), and leaf petiole length (m) of the first outer green leaf. Correlation analysis was performed between above-ground plant growth traits.

Yield traits included number of leaf sheaths, fresh weight of all leaf sheaths before processing (kg), fresh weight of pulp from all processed leaf sheaths (kg), corm fresh weight before processing/grating (kg), corm circumference (m) measured at the middle section of the corm, corm length (m) measured from corm meristem to the bottom of the corm, fresh corm pulp weight after processing/grating (kg), un-squeezed fermented kocho (kg), squeezed fermented kocho (kg), kocho dry weight for 200 g of un-squeezed fermented kocho, enset fiber length (m), fiber dry weight (g) of all leaf sheaths, and fermented bula weight (g).

Fresh and dry weight of kocho and bula and fiber weight were assessed separately for each individual five-year-old enset plant using common processing procedures used by farmers. Leaf sheaths were scraped using a sharp-edged bamboo tool in order to obtain the parenchymatous pulp. The corm tissue was pulverized using a wooden tool with a flat sharp edge. The scraped pseudostem pulp and pulverized corm tissues of each plant were mixed and stored in a fermentation pit for 18–21 days to obtain kocho, the final product after fermentation.

Fibers obtained when processing the middle and inner leaf sheaths were also collected and sun-dried for one week. In addition, the bula starch was also placed in the pit to allow fermentation. After fermentation in the pit, the kocho (called un-squeezed kocho in the paper) and bula were collected and weighed on-site. To determine the kocho dry weight content, a 200 g sample of fresh fermented kocho was sun-dried for 5–6 days and then oven-dried at 65 °C for 24 h. The fresh fermented kocho was subsequently squeezed to remove all water. Fiber, a byproduct of leaf sheath processing was also collected and sun-dried for one week. All processing steps were carried out under the supervision of a scientist to minimize post-harvest losses and assure uniformity across farms and sites.

The means and respective standard deviations of above-ground plant growth and yield parameters were compared between altitude bands and/or landraces using analysis of variance (ANOVA). The growth and yield parameters acted as the dependent variables while altitude and the landraces acted as the independent variables. The R-statistical software (version 2.11.1, [13]) was used for ANOVA.

2.2. Allometric Models for Fiber, Kocho, and Bula Yield Estimation

Data obtained from the five-year-old enset plants were used for the development of the allomeric equations. Regression modeling was applied to assess if enset yield traits can be estimated from simple growth traits assessed in a non-destructive manner. The Spearman correlation coefficient (in Genstat v.12 [14]) was used to examine the relationships between enset yield parameters (i.e., fiber, kocho, and bula yields) as dependent variables with other above-ground enset growth variables to identify highly correlated variables that can explain the dependent variables for inclusion into regression/allometric equations. To further sort the variables to be used in the model, Principal Component Analysis (PCA) was carried out to determine the most important variables explaining enset yield. The biplot and the Kaiser–Meyer–Olkin (KMO) method of eigen values above one was used to select the principal components that explained most of the variation in enset yield and growth parameters. Allometric models using linear equations were independently developed with fiber, kocho, and bula yields as the dependent variables and enset growth variables selected through PCA as the independent variables.

A backward regression analysis was used to automatically determine the most important independent variables and variable combinations that significantly explained the different dependent variables. R statistical software [13] was used for generating the regression equations. The best general models (covering both landraces and three altitude ranges) were selected based on the variation in the dependent variable it explains, i.e., using the adjusted R^2 value. Using the best general models, regression models tailored to specific landraces irrespective of altitude bands were then derived. The performance of the landrace specific models were assessed using the amount of variation explained (adjusted R^2), model significance, and model bias. The final models were also recommended on the basis of the ease with which the independent variables could be measured.

2.3. Allometric Model Validation

To validate the allometric models, the data were split into two datasets, the training dataset taking 80% and the test dataset covering 20% of the entire dataset. This was attained using the k-fold cross-validation method [15,16]. The k-fold cross-validation method randomly splits the dataset into k-subsets (or k-fold) (for example, five subsets), then reserves one subset and trains the model on all other subsets. This is then followed by testing the model on the reserved single subset, with recording of the prediction error. The process is then repeated until each of the k subsets has served as the test dataset. This is followed by computing the average of the k recorded errors. This is called the cross-validation (CV) error or bias which serves as the performance metric for the model. The k-fold cross-validation (CV) is a robust method for estimating the accuracy of a model [17]. The most important advantage of the k-fold CV is that it often gives more accurate estimates of the test error rate than other available methods such as the "Leave one out cross validation" (LOOCV) [18]. For this study, the value of k was set at three considering the moderate sample size. The choice of the best model was based on the Root Mean Squared Error (RMSE). The RMSE measures the average prediction error made by the model in predicting the outcome for an observation, that is, the average difference between the observed known outcome values and the values predicted by the model. The lower the RMSE, the better the model [19].

2.4. Yield Limiting Factors and Yield Gaps

Boundary line analysis following the von Liebig's law of the minimum [20] was conducted to ascertain the most limiting soil factors. The boundary line allometric models were fitted as described by Wairegi et al. [7] and Bhattarai et al. [21]. This was performed for four yield parameters, i.e., the un-squeezed and squeezed fresh fermented kocho weight, the fiber weight, and the bula weight for the two enset landraces combined. Enset landraces were combined due to the limited data points for the soil parameters. Lack of correlation significance did not hinder the study from pursuing the existence of boundary lines indicating cause–effect relationships between the different soil parameters and enset yield. The boundary line analysis followed the procedures below.

i. The outliers were identified and dropped with the help of scatter and boxplots.
ii. The relationship between the enset yield parameters and the biophysical constraints were then identified through a Pearson correlation analysis. The major soil chemical factor effects on each of the 4 yield parameters were identified based on the correlation values which ranged from >–0.1 and <0.1.
iii. For each yield parameter, the maximum yield predicted by the boundary line due to each biophysical factor (Y_{bf}) was then determined.
iv. Boundary lines graphs between enset yield parameters due to each biophysical factor and the corresponding factor were then fitted assuming a nonlinear relationship.
v. The yield gap proportions were then computed as the difference between the attainable yield (Y_{att}) and Y_{bf} (7), Y_{att} being the highest bunch weight observed on farmers' fields.

The statistical analyses and data visualization were carried out using R-statistical software [13] and the ggplot2 package [22].

3. Results and Discussion

3.1. Effect of Altitude on Yield Components

Except for leaf petiole length that sharply decreased with increasing altitude, other plant growth traits increased with increasing altitude (Figure 1, Supplementary Table S2). Altitude had profound effects on fiber weight and kocho yield traits but not on bula yield (Figure 1), irrespective of the enset landrace. For both landraces, fiber and kocho yield generally increased with increasing altitude, whereas bula yield was not significantly different ($p < 0.05$) across the three altitudes (Figure 1, Supplementary Table S3). The increase in enset growth and yield with increasing altitude can be attributed to the favorable cooler temperatures at the higher altitude sites. Enset has been reported to grow best between 2000 and 2750 m characterized by an average temperature between 10 and 21 °C [23].

Pearson correlation coefficients for the easily measurable above-ground enset plant traits of the 5-year-old plants of both enset landraces across three altitude ranges are presented in Table 1. Irrespective of the landraces and altitude, plant height was highly correlated with pseudostem height, pseudostem circumference at ground level, leaf length, and leaf widest width. Pseudostem height was also positively and significantly correlated with pseudostem circumference at ground level, leaf length, and leaf widest width. Pseudostem circumference at middle height was both positively and negatively significantly correlated. Positive correlations were observed between on one hand pseudostem circumference at the petiole level and on the other hand leaf number, leaf length, and leaf widest width. Similarly, various negative correlations were observed between leaf petiole length and other plant traits (Table 1). Significant and high associations between enset above-ground growth traits such as pseuodstem height and plant height have also been reported by Haile [11].

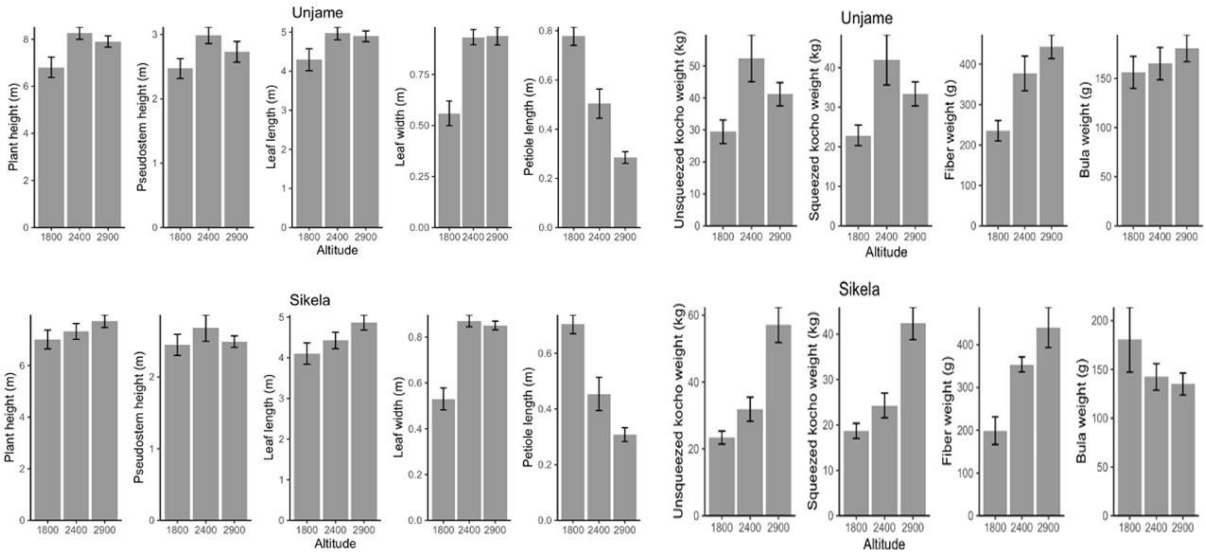

Figure 1. Above-ground plant growth and yield traits for the five-year-old enset landraces, 'Unjame' and 'Siskela'.

Table 1. Correlation coefficients and their significance levels for easily measurable above-ground traits of five-year-old enset plants from two enset landraces assessed across three altitude bands.

	PH #	PSH	PC0	PCMid	PCPet	LN	Lleng	Lwid
PSH	0.74 ***							
PC0	0.41 ***	0.44 ***						
PCMid	0.17	0.11	0.49 ***					
PCPet	0.15	0.13	0.38 ***	0.73 ***				
LN	−0.18	−0.02	0.21	0.43 ***	0.32 **			
Lleng	0.80 ***	0.61 ***	0.37 ***	0.24 *	0.16	−0.14		
Lwid	0.55 ***	0.39 ***	0.26 **	0.52 ***	0.48 ***	0.03	0.48 ***	
PetLeng	−0.21	0.01	0.16	−0.31**	−0.52 ***	0.09	−0.17	−0.61 ***

#: PH: plant height, PSH: pseudostem height, PC0: pseudostem circumference at soil level, PCMid: pseudostem circumference at mid-height of the pseudostem, PCPet: pseudostem circumference at start of petioles of youngest leaves, LN: Leaf number, Lleng: leaf length, Lwid: leaf widest width, PetLeng: petiole length. '***', '**' and '*' respectively denote significantly different at $p < 0.001$, $p < 0.01$ and $p < 0.05$.

Significant and positive correlations were also observed between most enset yield traits of the mature five-year-old plants (Table 2). No significant correlations were observed between bula weight and other yield traits whereas the unprocessed corm fresh weight was only significantly correlated to corm height and processed corm fresh weight. (Table 2).

Table 2. Correlation coefficients and their significance levels between various yield traits of two enset landraces assessed at five years and across three altitudes.

	N° of LS	Un-Processed LS Weight	Processed LS Weight	Un-Processed Corm Fresh Weight	Corm Circum-ference	Corm Height	Processed Corm Fresh Weight	UFK	SFK	Fiber Length	Fiber Weight
Un-processed LS weight	0.56 ***										
Processed LS weight	0.71 ***	0.76 ***									
Un-processed corm fresh weight	−0.05	0.16	0.14								
Corm circumference	0.26 **	0.40 ***	0.44 ***	0.07							
Corm height	0.23 **	0.46 ***	0.36 ***	0.39 ***	0.49 ***						
Processed corm fresh weight	0.34 ***	0.63 ***	0.57 ***	0.46 ***	0.66 ***	0.75 ***					
UFK	0.48 ***	0.76 ***	0.77 ***	0.18	0.40 ***	0.40 **	0.59 ***				
SFK	0.45 ***	0.78 ***	0.75 ***	0.21	0.45 ***	0.47 ***	0.63 ***	0.97 ***			
Fiber length	0.44 ***	0.56 ***	0.60 ***	0.17	0.33 **	0.23 **	0.49 ***	0.63 ***	0.61 ***		
Fiber weight	0.49 ***	0.43 ***	0.61 ***	−0.08	0.34 ***	0.19	0.34 ***	0.49 ***	0.48 ***	0.59 ***	
Bula weight	−0.10	−0.08	0.02	−0.07	0.03	0.07	−0.03	−0.11	−0.07	−0.24	−0.03

*** $p < 0.001$, ** $p < 0.01$; LS: leaf sheath, UFK: un-squeezed fermented kocho; SFK: squeezed fermented kocho.

Un-squeezed and squeezed fermented kocho and fiber weight were strongly correlated with plant height, pseudostem height, leaf length, and leaf widest width (Table 3). In addition, fiber weight was also highly and positively correlated with petiole length, while petiole length was negatively correlated to the kocho traits. Similar observations have also been reported by Haile [11]. In contrast, bula weight was not significantly correlated to any of the easily measurable above-ground traits (Table 3).

Table 3. Correlation coefficients and their significance level between the main yield parameters and easily measurable above-ground enset traits for the 5-year-old plants.

	PH #	PC0	PSH	PCMid	PCPet	LN	Lleng	Lwid	PetLeng
UFK	0.40 ***	0.07	0.27 *	0.09	0.11	−0.12	0.38 **	0.46 ***	−0.37 **
SFK	0.40 ***	0.10	0.29 **	0.10	0.10	−0.12	0.35 ***	0.44 ***	−0.36 **
Fiber weight	0.38 ***	−0.01	0.27 *	0.19	0.25 *	−0.24 *	0.39 **	0.44 ***	0.50 ***
Bula weight	0.03	0.06	0.01	−0.18	−0.21	−0.17	0.08	0.07	0.11

#: PH: plant height, PSH: pseudostem height, PC0: pseudostem circumference at soil level, PCMid: pseudostem circumference at mid-height of the pseudostem, PCPet: pseudostem circumference at start of petioles of youngest leaves, LN: leaf number, Lleng: leaf length, Lwid: leaf widest width, PetLeng: petiole length, UFK: un-squeezed fermented kocho; SFK: squeezed fermented kocho. '***', '**' and '*' respectively denote significantly different at $p < 0.001$, $p < 0.01$ and $p < 0.05$.

3.2. Allometric Equations to Estimate the Yield

3.2.1. Variable Selection

For 'Siskela' and 'Unjame' combined, 'Siskela' alone, and 'Unjame' alone, respectively, three, two, and four principal components were adequate for explaining the variance in the data. The first four principal components for the combined enset landraces or landraces individually accounted for approximately 81–82%, of the total variation in the dataset.

PCA results suggested that for the combined landraces, plant height, pseudostem height, leaf length, leaf widest width, un-squeezed kocho weight, squeezed kocho weight, and fiber weight were grouped together but contrasted with the number of leaves, petiole length, and bula weight (Table 4). PC1 was explained by plant height, leaf length, leaf widest width, plant pseudostem height, kocho yield, and fiber yield. Leaf widest width and leaf length are a good measure of the photosynthetic capacity of the plant, while plant height and pseudostem height represent the plant's translocation and storage capacity. All these above-ground traits positively influence the kocho and fiber yield components and can be used for predicting the kocho and fiber yield. Petiole length was consistently contrasted to other growth and yield variables, except bula weight.

Table 4. PCA values for principal components 1 to 4, for Unjame and Siskela combined, and for the individual landraces. Data from the 5-year-old plants were used.

Variable	Unjame and Siskela Combined				Siskela				Unjame			
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
PH #	−0.4	0.3	−0.1	0.0	−0.4	0.3	−0.2	0.0	−0.4	0.2	−0.1	0.0
PSH	−0.3	0.4	0.0	−0.1	−0.3	0.4	−0.3	−0.1	−0.3	0.3	0.1	−0.3
PC0	−0.2	0.5	0.2	0.1	−0.2	0.4	0.2	−0.1	−0.1	0.6	0.2	0.1
LN	0.1	0.2	0.7	0.1	0.0	0.3	0.7	−0.3	0.2	0.2	0.5	0.3
Lleng	−0.4	0.3	−0.2	0.0	−0.4	0.2	−0.1	0.1	−0.3	0.3	−0.3	0.0
Lwid	−0.4	0.0	0.2	0.5	−0.4	−0.1	−0.2	−0.3	−0.3	0.0	0.1	0.5
PetLeng	0.2	0.4	0.0	−0.6	0.2	0.4	0.1	0.2	0.3	0.3	0.1	−0.6
UFK	−0.4	−0.3	0.2	−0.4	−0.4	−0.3	0.4	0.3	−0.4	−0.3	0.3	−0.2
SFK	−0.4	−0.3	0.1	−0.5	−0.4	−0.3	0.3	0.3	−0.3	−0.3	0.3	−0.2
Fiber weight	−0.3	−0.3	−0.1	0.1	−0.3	−0.2	−0.1	0.1	−0.3	−0.3	−0.1	−0.1
Bula weight	0.0	0.2	−0.6	0.0	0.1	0.2	0.0	0.8	−0.2	0.0	−0.6	0.1
Eigen value	3.73	1.06	1.26	0.86	3.85	2.20	0.99	0.88	3.90	1.81	1.37	1.07
Variance (%)	38.31	21.58	13.61	8.62	38.53	22.03	11.91	9.81	38.97	18.15	13.69	10.53
Cumulative variance (%)	38.31	59.90	73.51	82.12	38.53	60.56	72.47	82.28	38.97	57.12	70.81	81.34

#: PH: plant height, PSH: pseudostem height, PC0: pseudostem circumference at soil level, PCMid: pseudostem circumference at mid-height of the pseudostem, PCPet: pseudostem circumference at start of petioles of youngest leaves, LN: leaf number, Lleng: leaf length, Lwid: leaf widest width, PetLeng: petiole length, UFK: un-squeezed fermented kocho, SFK: squeezed fermented kocho.

PC2 had higher loadings for pseudostem girth at soil level and pseudostem height. These two parameters depict the storage and translocation function of the pseudostem, thus PC2 could be considered as the ability of the plant to store and translocate nutrients and water between the underground portion of the plant and the leaves. PC3 had higher loadings for number of leaves and bula weight, with the two variables contrasting each other. These trends, especially for PC1, were consistent for the individual enset landraces (Table 4).

3.2.2. Allometric Models (for 4 Yield Traits): Fiber Weight, Un-Squeezed Fermented Kocho, Squeezed Fermented Kocho, and Bula Weight

Allometric equations were determined for the combined landraces and for the individual landraces (Table 5). A large set of significant allometric models were obtained for fiber weight, un-squeezed, and squeezed fermented kocho while very few significant models could be obtained to explain bula yield.

The fiber weight models explained between 35 and 57% (adjusted R^2: 0.35 to 0.57) of the observed variation in total fiber weight. Based on the adjusted R^2, model significance, model bias, and RMSE, leaf length, petiole length, and plant height were the best predictors for fiber yield (Table 5). Whereas petiole length had a negative influence on the fiber weight, fiber weight increased with increasing leaf length and plant height under individual and combined landrace scenarios. Unlike the earlier study by Haile [11] that did not find significant relations between fiber weight and plant growth attributes, this study, which focused on two landraces, confirms that fiber weight can be estimated from easily measurable above-ground growth traits, especially leaf length, petiole length, and plant height. This also confirms the assertion from Haile [11] that using data from a large number of plants of a single enset landrace could increase the possibility of using above-ground plant traits to estimate enset fiber yield.

For the fermented un-squeezed kocho and the fermented squeezed kocho yield, the allometric models explained between 21 and 64% of the observed variation in kocho weight. Leaf length, leaf width at the widest point, pseudostem, and plant height were the best predictors for kocho yield. Leaf length, pseudostem, and plant height predominantly had a positive influence on kocho weight. As for fiber weight, petiole length had a negative effect on kocho weight (Table 5). Pseudostem circumference at the start of petioles of youngest leaves and altitude were the best predictors when both landraces were combined. Landrace 'Unjame' was best predicted by pseudostem height, leaf width at the widest point, petiole length, and plant height while 'Siskela' was best predicted by altitude, leaf length, leaf width at the widest point, and plant height (Table 5). Relative to Mellisse et al. [12], Haile [11], and Negash et al. [10], these models explained a smaller portion of the variance in the yield attributes. The higher model accuracies in Mellisse et al. [12], Haile [11], and Negash et al. [10] could be explained by the age range of assessed and processed plants, which was, respectively, 3–7 and 3–5 years. Plant age has a strong link to plant size. Haile [11] measured several above-ground and yield traits on harvestable plants of 328 enset landraces, hence covering a wide range of kocho and fiber yields. In the present study, only five-year-old plants of two widely grown enset landraces were assessed, providing for a lesser variation in growth and yield attributes, possibly influencing model accuracy.

Table 5. Allometric models for fiber weight, squeezed and un-squeezed kocho weight, and bula weight. Data obtained from 5-year-old plants were used.

Enset Landrace	Intercept (s.e)	Lleng (s.e)	Petleng (s.e)	PC0 (s.e)	LN (s.e)	PCMid (s.e)	PCPet (s.e)	PH (s.e)	PSH (s.e)	Lwid (s.e)	Altitude	Adj R^2	Model Sign.	Model Bias	RMSE (Validation)
Fiber weight															
Unjame and Siskela combined	−39 (158)	40 (18) **	−163 (106)	-	-	-	-	-	-	-	0.1 (0.1) **	0.55	1.48×10^{-9}	0.0001	106.09
	241 (87) **	59 (16) ***	−353 (58) ***	-	-	-	-	-	-	-	-	0.52	1.86×10^{-9}	0.0001	108.84
	337 (317) **	-	−342 (61) ***	-	−8 (7)	-	-	30 (12) **	-	-	-	0.48	5.48×10^{-8}	0.0001	108.33
	271 (100) **	-	−350 (61) ***	-	-	-	-	32 (12) **	-	-	-	0.48	1.67×10^{-8}	0.0008	109.87
	493 (97) ***	-	−390 (63) ***	80 (57)	−12 (7)	-	-	-	-	-	-	0.43	4.70×10^{-7}	0.0001	111.08
	379 (79) ***	-	−383 (61) ***	-	-	-	-	-	57 (26) **	-	-	0.45	6.50×10^{-8}	0.0001	112.04
	241 (90) **	59 (21) **	−353 (58) ***	-	-	-	-	-	1 (32)	-	-	0.51	1.18×10^{-8}	0.0001	109.97
	−21 (156)	52 (19) **	−200 (107) *	-	-	-	-	-	-	−132 (81)	0.1 (0.1) **	0.57	2.18×10^{-6}	0.0002	108.08
Unjame	310 (134) **	46 (25) *	−362 (79) ***	-	-	-	-	-	-	-	-	0.52	3.52×10^{-5}	0.0002	109.80
	529 (134) ***	-	−551 (131) ***	-	−13 (9)	-	-	14 (6) **	-	-	-	0.55	0.0001	0.0003	108.79
	292 (140) **	-	−341 (82) ***	-	-	-	-	29 (15) *	-	-	-	0.53	3.22×10^{-5}	0.0002	106.54
	464 (128) **	-	−402 (78) ***	117 (75)	−15 (9) *	-	-	-	-	-	-	0.53	8.93×10^{-5}	0.0004	117.06
	385 (112) **	-	−377 (79) ***	-	-	-	-	-	55 (35)	-	-	0.51	5.46×10^{-5}	0.0006	110.09
	290 (140) **	35 (31)	−360 (80) ***	-	-	-	-	-	27 (43)	-	-	0.51	0.0001	0.0011	111.14
	−75 (155)	-		-	−16 (7)	-	-	-	58 (39)	-	0.2 (0.04) **	0.45	0.0004	0.0011	96.16
Siskela	195 (123)	69 (24) **	−352 (90) ***	-	-	-	-	-	-	-	-	0.48	0.0001	0.0011	110.86
	291 (173)	-	−360 (100) **	-	−7 (12)	-	-	37 (20) *	-	-	-	0.37	0.0034	0.0014	122.69
	150 (206)	87 (30) **		-	−20 (13)	766 (333) **	-505 (265) **	-	-	-	-	0.52	0.0013	0.0001	108.61
	254 (156)	-	−368 (97) ***	-	-	-	-	35 (20) *	-	-	-	0.39	0.0011	0.0063	116.58
	383 (121) **	-	−392 (101) ***	-	-	-	-	-	55 (45)	-	-	0.35	0.0023	0.0089	114.37
	214 (128)	81 (32) **	−339 (93) **	-	-	-	-	-	-31 (53)	-	-	0.47	0.0005	0.0045	116.27
	−359 (168) **	-	-	-	−28 (15) *	601 (229) **	-	-	-	-	0.1 (0.10) *	0.52	0.0002	0.0011	99.36
Un-squeezed kocho weight															
Unjame and Siskela combined	16 (16)	8 (3) **	−30 (10) **	-	-	-	-	-	-	-	-	0.24	0.0004	0.0200	16.12
	14 (16)	7 (4) *	−31 (11) **	-	-	-	-	-	3 (6)	-	-	0.23	0.0012	0.0011	16.32
	13 (17)	-	−28 (11) **	-	-	-	-	5 (2) **	-	-	-	0.23	0.0005	0.0200	15.96
	8 (13)	-	-	-	-	-	-45 (18) **	-	-	-	0.03 (0.01) ***	0.36	2.01×10^{-5}	0.0076	15.51
	−32 (17) *	-	-	-	-	-	-	4 (2)	-	4 (16)	0.02 (0.01) **	0.27	0.0002	0.0052	15.50
Unjame	8 (22)	-	−28 (15) *	-	-	-	-	-	18 (7) **	-	-	0.25	0.0116	0.4024	16.50
	17 (26)	−4 (6)	−27 (15) *	-	-	-	-	-	22 (10) **	-	-	0.24	0.0274	0.0041	16.61
	−29 (21)	-	-	-	-	-	-	-	16 (8) **	31 (15) *	-	0.29	0.0063	0.0043	16.50

Table 5. *Cont.*

Enset Landrace	Intercept (s.e)	Lleng (s.e)	Petleng (s.e)	PC0 (s.e)	LN (s.e)	PCMid (s.e)	PCPet (s.e)	PH (s.e)	PSH (s.e)	Lwid (s.e)	Altitude	Adj R^2	Model Sign.	Model Bias	RMSE (Validation)
Siskela	16 (19)	15 (5) **	−32 (13) **	-	-	-	-	-	−12 (8)	-	-	0.38	0.0028	0.0270	14.13
	8 (19)	10 (4) **	−36 (14) **	-	-	-	-	-	-	-	-	0.34	0.0029	0.0045	13.68
	16 (24)	-	−37 (15) **	-	-	-	-	5 (3)	-	-	-	0.23	0.0177	0.0572	14.96
	−68 (17) ***	10 (4) **	-	-	-	-	-	-	-	−33 (19) *	0.04 (0.01) ***	0.63	8.70×10^{-6}	0.0001	11.84
	−29 (17) *	-	-	-	-	-	7 (20)	-	-	-	0.03 (0.01) ***	0.50	6.64×10^{-5}	0.0001	12.93
	−67 (21) **	-	-	-	-	-	-	6 (3) *	-	−40 (21) *	0.04 (0.01) **	0.57	3.58×10^{-5}	0.0002	12.23
Squeezed kocho weight															
Unjame and Siskela combined	9 (14)	-	−22 (8) **	-	-	-	-	4 (2) **	-	-	-	0.23	0.0005	0.0200	12.73
	15 (12)	6 (2) **	−24 (8) **	-	-	-	-	-	-	-	-	0.22	0.0008	0.0310	12.68
	12 (13)	4 (3)	−24 (8) **	-	-	-	-	-	5 (5.1)	-	-	0.21	0.0019	0.0084	12.87
	11 (10)	-	-	-	-	-	−44 (13) **	-	-	-	0.02 (0.1) **	0.40	4.41×10^{-6}	0.0001	11.87
	−26 (14) *	-	-	-	-	-	-	3 (2) *	-	0.5 (13)	0.01 (0.01) **	0.26	0.0003	0.0021	12.16
Unjame	8 (18)	-	−24 (12) *	-	-	-	-	-	14 (6) **	-	-	0.25	0.0120	0.2201	13.94
	19 (22)	-5 (5)	−27 (13) **	-	-	-	-	-	19 (81) **	-	-	0.25	0.0237	0.0046	13.52
	94 (30) **	-	−46 (14) **	-	-	-	−47 (23) *	−12 (6) *	33 (14) **	-	-	0.31	0.0331	0.0011	14.78
Siskela	14 (14)	10 (4) **	−22 (10) **	-	-	-	-	-	-8 (6)	-	-	0.33	0.0063	0.0142	10.15
	9 (13)	7 (3) **	−25 (10) **	-	-	-	-	-	-	-	-	0.31	0.0048	0.0046	9.64
	11 (17)	-	−25 (10) **	-	-	-	-	4 (2) *	-	-	-	0.23	0.0166	0.0815	10.33
	−18 (12)	-	-	-	-	-	−5 (14)	-	-	-	0.02 (0.01) ***	0.48	0.0001	0.0002	9.49
	−59 (15) ***	-	-	-	-	-	-	6 (2) **	-	-31 (14) **	0.03 (0.01) ***	0.64	6.99×10^{-6}	0.0001	8.49
	6 (23)	-	−24 (13) *	-	-	-	1 (19)	9 (4) **	-12 (7)	-	-	0.27	0.018	0.0161	11.25
Bula weight															
Unjame	124 (75)	20 (12)	-	-7 (4)	-	-	-	-	-	-	-	0.17	0.042	0.3010	43.43
	79 (59)	41 (15) **	-	-	-	-	-	-	−39 (21) *	-	-	0.17	0.023	0.1010	43.49
Siskela	328 (117) **	-	-	118 (68) *	-	−351 (134) **	-	-	-	-	-	0.17	0.048	0.3012	62.56

Level of significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.1$.

With respect to bula yield, the few significant models only explained 17% of the observed variation in bula weight. Only leaf length, number of leaves, and pseudostem height explained the variation in bula yield for 'Unjame' while pseudostem circumference at soil and mid-height explained bula yield in 'Siskela'. Just as for fiber and kocho weight, leaf length contributed positively to bula weight. Pseudostem height and pseudostem circumference at mid-height also contrasted with bula yield. The low R^2 values for the bula yield models in this study contrast with the high R^2 values of over 78% for bula yield models developed by Mellisse et al. [12]. This could be attributed to the fact that bula is a byproduct following the processing of corm and leaf sheaths into kocho and bula yield per plant is very low. Small variations in efficiency of extracting bula from the pulp may also have contributed. Similarly, as for kocho above, the reliance on five-year-old plants of two enset landraces could have affected model efficiency in predicting bula yield.

Previous enset modeling studies mainly used plants of highly varying sizes (e.g., through assessing different enset landraces or plants of varying ages). This high variance in plant trait values could have partly contributed to the reported high significance of the models. Although the accuracy of the presented models in the current study is lower compared to studies that worked with enset plants of highly varying sizes, we show for two commonly grown enset landraces that models using easily measurable above-ground data obtained from flowering stage (i.e., the stage that farmers harvest plants, 5 years in this study) enset plants with limited to modest variance in growth trait values can be used to predict yield traits. This study is especially demonstrating this for kocho and, for the first time, for fiber yield.

3.2.3. The Yield Limiting Factors Computed Using the Boundary Line Analysis

Soil chemical variables differently impacted on the enset yield variables assessed in this study as shown by the scatter plots and boundary line plots in Figure 2. Soil organic matter (SOM) and CEC (meq/100 g) had a positive relationship with all four enset yield components, whereas % N, pH, and P had a negative relationship to fiber, kocho, and bula yield (Figure 2). The positive association between enset yield and SOM could be attributed to the soil's ability to hold moisture for longer time durations. For K, a positive association was observed between the squeezed kocho and fiber weight whereas a negative trend was observed between K and bula weight. The improved yield with increasing soil K can be attributed to its positive effects on water use efficiency, photosynthesis, and partitioning of assimilates. In banana, Taulya [24] observed interaction of K and cumulative rainfall to drive dry matter production and yields. Taulya [24] also observed K to improve banana bunch yields under dry conditions whereas yields declined in the absence of K under dry conditions. In banana, soil N and P were observed to have a lesser to no impact on banana yield compared to K [24]. The maximum attainable weights were 657 g, 52 kg, and 459 g for fiber, squeezed kocho, and bula yields, respectively.

The highest average yield gaps (27–55%) were observed for bula weight, with yield gaps of 55%, 51%, 31%, 51%, 49%, and 27%, respectively, due to P, %N, %Om, pH, K, and CEC (Figure 3). Across all the yield parameters, P accounted for the highest yield gaps. The high yield gaps in bula weight could be attributed to inefficiencies during processing given bula is a byproduct of kocho. Yield gaps due to P were, respectively, 20%, 17%, and 15% for enset fiber weight, un-squeezed kocho, and squeezed kocho. In contrast, CEC had the least yield gaps for bula weight (27%) and fiber weight (11%) whereas %N had the least values for the un-squeezed (6%) and squeezed kocho weight (4%) (Figure 3). These results suggest that P was the most limiting nutrient. This could be attributed to fixation of P by SOM and aluminum (Al) in the soil. Shara et al. [25] observed a decline in P with increasing altitude at sites in Ethiopia and attributed this decline to fixation by Al that increased with altitude. In the current study, mean P also generally declined with increasing altitude (c.f. Supplementary Table S1).

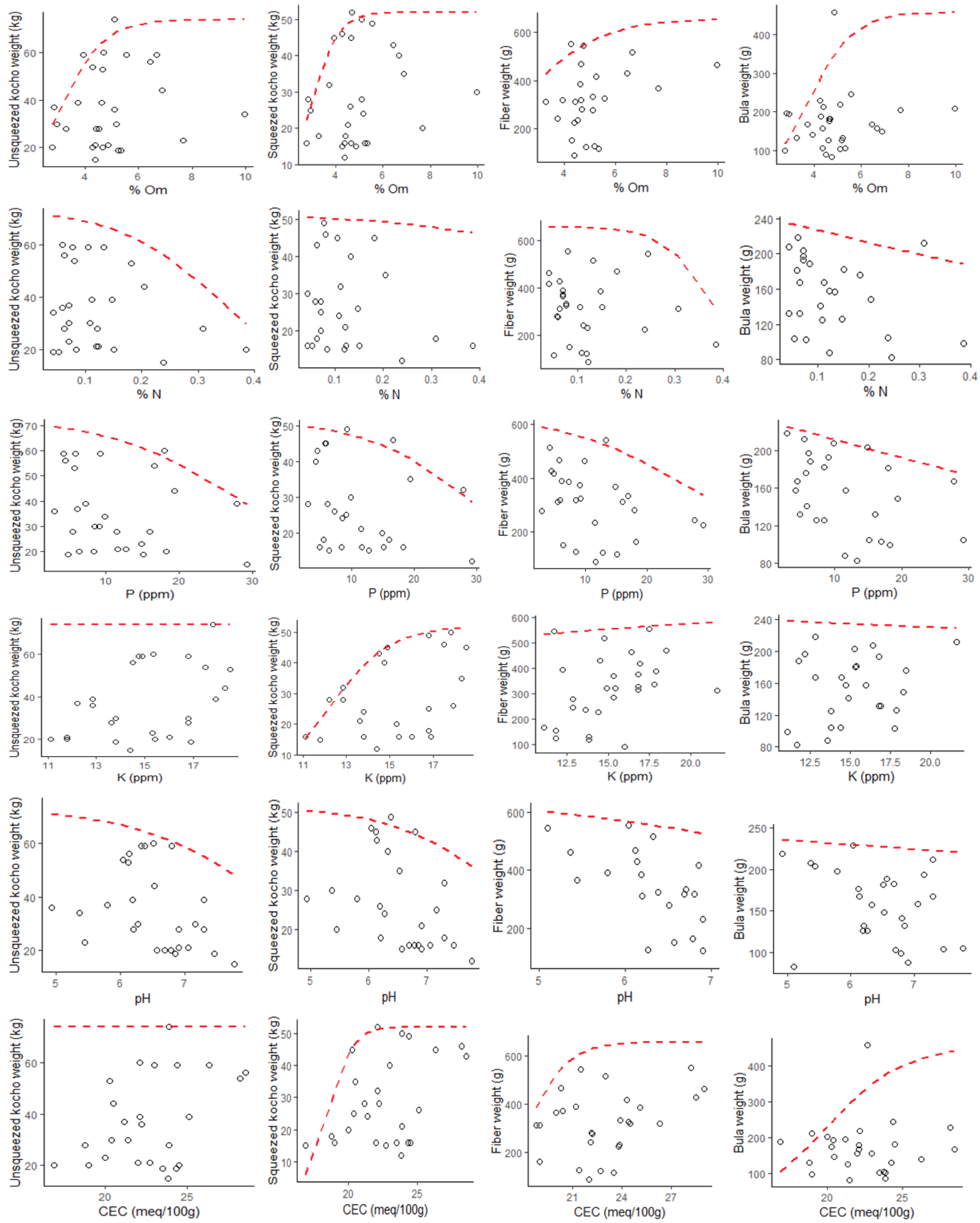

Figure 2. Relationships between enset yield parameters and the soil nutrients. The red lines represent the boundary lines whereas the points represent the observed yield at each farm.

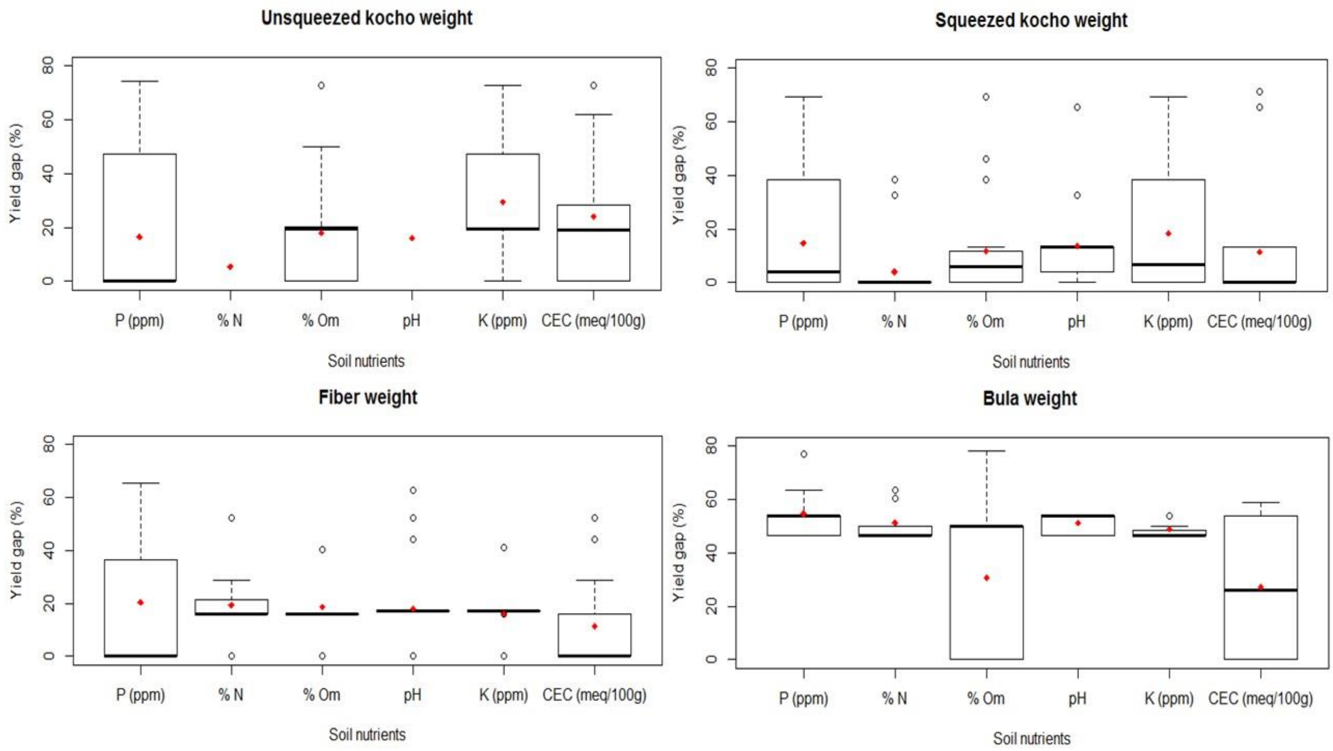

Figure 3. Percentage yield gaps due to selected soil chemical properties and nutrients, expressed as percentage of maximum yield attained for each yield parameter. The solid lines across boxes are medians. The red points represent the mean percentage yield loss by each factor. The boxes represent the interquartile range (25–75th percentile), circles outside the central box represent outliers by between 1.5 and 3 times the interquartile range, while bars represent the smallest and largest observations which are not outliers.

4. Conclusions and Recommendations

Correlation and PCA analysis showed strong links between above-ground traits and enset yield factors, except for bula weight, which is a minor yield component. This trend also transpired in the allometric regressions. This study, for the first time, generates allometric models that can be reliably used for estimating enset fiber yield. This and previous studies clearly show that non-destructive enset plant assessments can provide solid information on various yield traits, thus paving the way for quick and easy yield assessments during, e.g., agronomic, germplasm evaluation, soil fertility enhancement, and intercropping trials. Leaf length, petiole length, and plant height are especially good for estimating fiber and kocho yields. Enset yield had a positive association with soil K, thus improving soil K contents can potentially enhance fiber and other yield variables. Higher yield gaps were observed for bula, with P accounting for the highest yield gaps. The different yield attributes can thus be enhanced through careful targeting of different soil nutrients.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132313255/s1, Table S1: Soil sample analysis results according to altitude. Bulk soil samples were collected from enset plots. Mean values (±standard deviations) are presented, Table S2: Mean values (±standard deviations) of above-ground growth traits assessed on five-year-old enset plants of two landraces growing at three contrasting elevations (i.e., 1800, 2400, and 2900 m.a.s.l.), Table S3: Mean yield (±standard deviations) traits assessed on five-year-old mature plants of two enset landraces growing at three contrasting elevations (i.e., 1800, 2400, and 2900 m.a.s.l.).

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