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Research Article

Modeling Growth and Yield of the Endemic "*Loka Pere*" Banana Based on Soil Macronutrient Availability

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Abstract: Agrobiodiversity is critical to agroecosystem health, and a key source of agrobiodiversity is farmers' varieties. Reintegration of these resources into agroecosystems requires improving their knowledge base, including the creation of crop models. One underutilized farmers' variety is *Loka Pere*, a local banana (*Musa* spp.) found in Adolang and Adolang Dhua villages, Majene Regency, West Sulawesi. The purpose of this study was to create a simple growth model simulating *Loka Pere*'s growth response to soil macronutrient concentrations across three traditional growth environments. Soil samples were collected and analyzed for N_{tot}, C_{org}, C:N, pH, P_{av}, K_{exc}, Na_{exc}, Ca_{exc}, Mg_{exc}, and CEC. Plants were measured for pseudostem circumference at the plant base and 1 meter height, plant height, and hands per bunch at three growth phases. Principal component analysis was used to define a productivity index. Multiple linear regression models and non-linear generalized additive models were fit utilizing soil parameters as input variables and growth parameters individually as response variables. Growth models varied in goodness of fit (R^2 = 0.11 to 0.69). The most important soil variables for *Loka Pere* growth were N_{tot}, Ca_{exc}, and CEC, and the most important soil variables for yield were pH, CEC, and P_{av}. The growth responses of *Loka Pere* to the availability of certain nutrients differed from responses found in studies on other varieties.

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1. Introduction

Crop diversity can contribute to improved farm income (LaFevor, 2022) and resilience (Mofya-Mukuka and Hichaambwa, 2018). Increased intraspecific crop diversity in particular has been shown to generate higher relative yield and yield stability compared to monocultures (Reiss and Drinkwater, 2018). However, in the last 60 years, global agriculture has shifted towards increasing homogeneity, with crops bred to be ecological generalists supplanting localized crops (Pingali, 2019; Khoury et al., 2022). From a global perspective, a relatively homogenous food supply has developed that is species-poor and low in cultivated intraspecific diversity, leading to the risk of reduced nutritional and food security (Khoury et al., 2014).

Yet there are still areas where historic crop diversity is preserved. Many smallholder farmers utilize a diversity of locally adapted crops and varieties in environmental niches for their agronomic characteristics, ecological function, or cultural value (Massawe et al., 2015; Pingali, 2019; Khoury et al., 2022). These crops and crop varieties are often called neglected and underutilized (NU) plants, landraces, or farmers' varieties, and they represent a source for improved agricultural diversification (FAO, 2019, Mustafa et al., 2019).

Many NU farmers' varieties are nutrient dense, stress tolerant, and disease resistant (Ficiciyan et al., 2018; Tadele, 2019; Li et al., 2020). It is thought that the reincorporation and increased utilization of NU farmers' varieties in agricultural systems can help improve nutrition, food security, and food sovereignty, increase climate and market resilience, and alleviate poverty (Mustafa et al., 2019; Padulosi et al., 2019; Li et al., 2020).

Bananas and plantains (*Musa* spp.) are some of the most widely cultivated fruit crops (FAO, 2023) and possess high intraspecific diversity, with over 1500 cultivars (Van den houwe et al., 2020). *Musa* spp. diversity has undergone similar shifts to other major crops, with modern varieties now dominating homogeneous cultivation systems (Chabi et al., 2018). More than 95% of bananas (excluding plantain) grown for export are of the AAA 'Cavendish' subgroup. However, this production only accounts for 50% of all banana production and about 15% of total *Musa* spp. production (CAB International, 2010a; FAO, 2023). Many smallholder farmers continue to cultivate farmers' varieties of *Musa* spp. (Kilwinger et al., 2019).

A center of origin for *Musa* spp. diversity is in Indonesia (Perrier et al., 2011), where 25 crop wild relatives and landraces of *Musa* spp. have been reported (Rahman et al., 2019). However, not all varieties of *Musa* spp. in Indonesia have been classified (Suryani and Owbel, 2019; Hapsari et al., 2022), so this diversity is likely higher. Sulawesi is a major area of banana and plantain production within Indonesia. Here, in the villages Adolang and Adolang Dhua of Pamboang District, Magene Regency, West Sulawesi, is found the endemic farmers' variety *Musa* x *paradisiaca* Linn. cv "*Loka Pere"*, or *Loka Pere.* In the local language "*Loka*" means banana and "*Pere*" means crooked. *Loka Pere* has a unique phenology where the bunches face upwards and the fruits are bent with a pointy tip. (Sirappa et al., 2023).

Loka Pere has been managed locally for generations, but in 2016 was under threat of extinction (BPTP, 2016). However, it has high cultural value and a variety of beneficial characteristics such as disease resistance, long shelf life, and tolerance for dry conditions (BPTP, 2016; Nurhafsah et al., 2022a). A nutritional analysis of *Loka Pere* has revealed its potential as a functional food. (Nurhafsah et al., 2022b). Local conservation projects were initiated for *Loka Pere* in 2017, and in 2018 it was registered at the Center for Plant Variety Protection as a local genetic resource (PPVT, 2018). In 2022 it was registered at the West Sulawesi Institute for Implementation of Agricultural Instrument Standards and the Ministry of Law and Human Rights as communal intellectual property (Dir. Kerjasama dan Pemberdayaan KI, 2022).

Because of the above characteristics, increased utilization of *Loka Pere* may have a positive impact on livelihood (Padulosi et al., 2018 and 2019). One of the challenges to achieving the reintegration of NU crops is limited knowledge systems (Mustafa et al., 2019; Borelli et al., 2020). Sustainable conservation and utilization of a farmers' variety requires the development of its knowledge base, including agro-botanic assessments (FAO, 2019; Brown et al., 2020). Crop growth models can be helpful tools in shrinking knowledge gaps related to agronomic and performance information (Karunaratne et al., 2015a and 2015b; Chimonyo et al., 2022).

However, most major crop models are designed for particular modern cultivars (Wimalasiri et al., 2021), and NU crop models are sparse (Chimonyo et al., 2022). Farmers' varieties are a result of selection by local communities and often have undergone adaptation to ecological niches within an agricultural landscape (Hufford et al., 2019; Cortinovis et al., 2020). A consequence of the genetic diversity within landraces is that different varieties of a crop potentially have different responses to environmental variables (Ahumuza et al., 2015; Kissel et al., 2015; Blomme et al., 2020). For example, Depingy et al. (2016) modeled the growth, development, and yield of 7 plantain varieties, showing that agronomic data and model parameter data differed between varieties. Another feature of many crop models that may hinder their effective application to varieties is that they assume homogeneity of soil variables across a region (Lopez-Jimenez et al., 2021) and rely on databases instead of observed data (Wimalasiri et al., 2020).

So, although process based growth models exist for *Musa* spp. (Tixier et al., 2004 and 2008; Damour et al., 2012), they were developed for *Musa* sp. AAA cv Cavendish 'Grande Naine' under close to ideal growth conditions and have been criticized for being complex and costly (Jayasinghe et al., 2022). Mathematical models represent a different approach to addressing these knowledge gaps. One common approach to mathematical modeling for *Musa* spp. is multiple linear regression (MLR), which has shown a high degree of accuracy and agronomic relevance (Jayasinghe et al., 2022). The most common input variables for *Musa* spp. models are bioclimatic (Blomme et al., 2020), however, soil variables can produce effective models (Taulya, 2013; Olivares et al., 2022). Biotic interactions also influence *Musa* spp. growth (Ortas et al., 2017; Maues et al., 2022), but are outside of the scope of this study.

The purpose of the present research is to develop the knowledge base of *Musa* x *paradisiaca* Linn. cv '*Loka Pere'* in order to support its conservation and utilization by the local community. Specifically, regression models were created simulating the plant's growth response to soil macronutrient concentrations across three traditional growth environments.

2. Material and Methods

2.1. Study area

The study was conducted in the villages of Adolang and Adolang Dhua (Figure 1). These villages are located at the geographical position 2° 40' 26" S, 118° 54' 26" E with an elevation of 79-113 m above sea level (Sirappa et al., 2023). Study area maps were created using QGIS (QGIS, 2023). The climate of the region is dry (Ritung et al., 2016). Soil types in Majene Regency include aquic eutrudepts, lithic eutrudepts, typic eutrudepts, and vertic and typic Endoaquepts (Ritung et al., 2016; Nurhafsah et al., 2022a).

Data collection spanned three land use types: (1) *Loka Pere* cultivation plots (Production plot), (2) plots where *Loka Pere* is a secondary crop (Integrated plot), and (3) areas with *Loka Pere* growing on marginal land (Marginal plot). In both villages, three of each site type were selected via purposive snowball sampling and documented via georeferencing (Table 1).

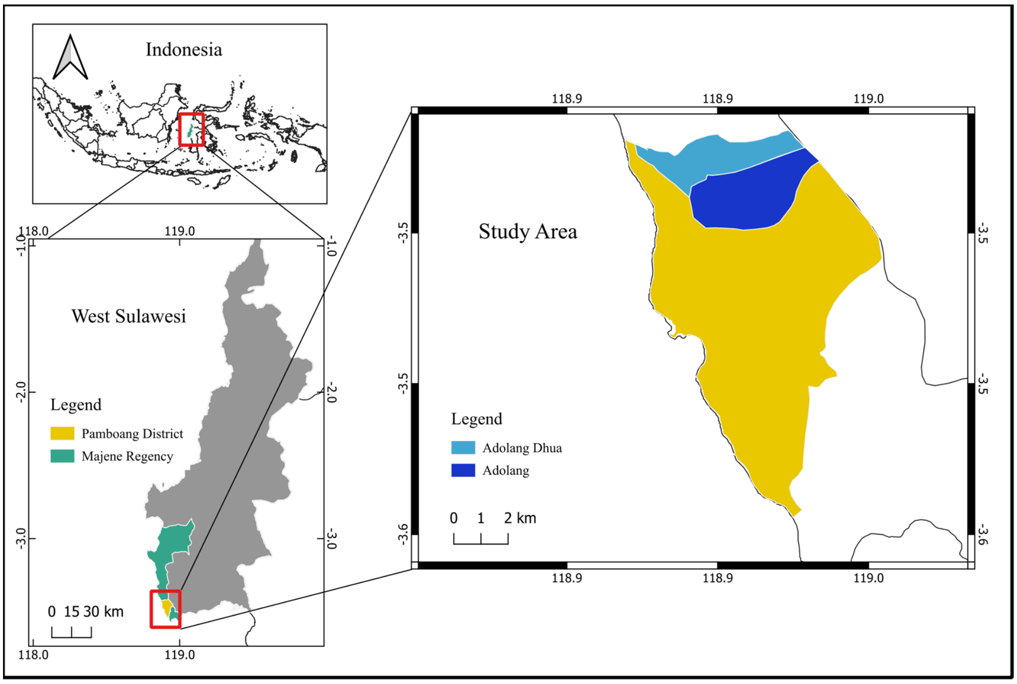

Figure 1. Study area map.

Table 1. Sample site locations

Site	Coordinates	Village	Site Type
1	-3.428196, 118.887569	Adolang Dhua	Productive
2	-3.428251, 118.887902	Adolang Dhua	Productive
3	-3.428017, 118.887671	Adolang Dhua	Productive
4	-3.425444, 118.885887	Adolang Dhua	Integrated
5	-3.42545, 118.885644	Adolang Dhua	Integrated
6	-3.4259, 118.885747	Adolang Dhua	Integrated
7	-3.431059, 118.890879	Adolang Dhua	Marginal
8	-3.43074, 118.89077	Adolang Dhua	Marginal
9	-3.4307495, 118.8908343	Adolang Dhua	Marginal
10	-3.44543, 118.894594	Adolang	Productive
11	-3.445748, 118.894556	Adolang	Productive
12	-3.446009, 118.894333	Adolang	Productive
13	-3.444901, 118.89338	Adolang	Marginal
14	-3.444898, 118.893461	Adolang	Marginal
15	-3.444947, 118.893314	Adolang	Marginal
16	-3.444245, 118.896309	Adolang	Integrated
17	-3.444264, 118.89632	Adolang	Integrated
18	-3.444282, 118.89633	Adolang	Integrated

2.2. Data collection

In each plot, nine soil sample points were selected using a simple random sampling design. Soil samples were collected using a soil core probe to rooting depth (40 cm). Samples from each site were composited and analyzed for total nitrogen (N_{tot}), soil organic carbon (C_{org}), carbon-nitrogen ratio (C:N), pH by H_2O (pH), available phosphorus (P_{av}), exchangeable potassium (K_{exc}), exchangeable sodium (Na_{exc}), exchangeable calcium (Ca_{exc}), exchangeable magnesium (Mg_{exc}), and cation exchange capacity (CEC) at the Brawijaya University Faculty of Agriculture Soil Labs.

Plants were measured at three growth stages, namely: (1) vegetative independent, (2) vegetative reproductive, and (3) bunch emergence. Growth measurements included: pseudostem circumference at base (BC), pseudostem circumference at 1 meter height (CBH), pseudostem height (HT), and hands per bunch (HPB). At each site, three *Loka Pere* plants from each growth stage were selected via stratified random sampling and measured for growth parameters.

2.3. Data analysis

Data analysis and modeling were done using R in RStudio (Posit Team, 2023). A Shapiro-Wilk test was used to evaluate data normality for each variable. Data uniformity was evaluated using single sample Kolmogorov-Smirnov tests.

The differences within soil and growth variables between each site type were analyzed using a one-way analysis of variance (ANOVA). ANOVA results were checked via normality of residuals, Shapiro tests, eta squared, Levene tests, and post-hoc pairwise t-tests. Kruskal-Wallis rank sum tests were utilized to evaluate variables that violated the parameters of ANOVA.

Principal component analysis (PCA) was used to combine plant growth variables and define a "productivity index" (PI) (Olivares et al., 2020). The eigenvalues for each canonical function were recorded, along with percent variance and standard deviation.

2.4. Regression modelling

Regression modeling was used to model *Loka Pere* growth based on soil nutrient availability (Figure 2). Multiple linear regression (MLR) models were fit utilizing soil parameters as input variables and growth parameters as individual response variables. When MLR models were insufficient, non-linear generalized additive models (GAM) were utilized. Degrees of freedom for GAM models were limited to 3 or 4.

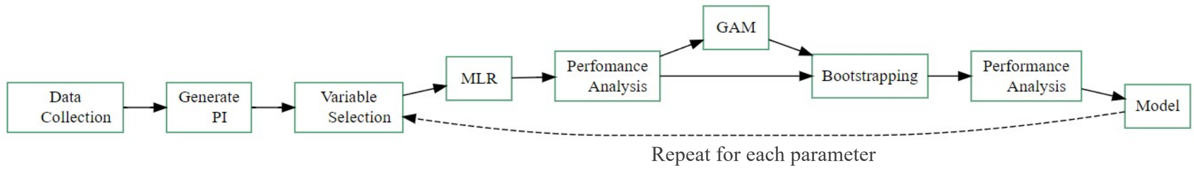

Figure 2. Regression modeling process.

Input variables for each model were optimized by checking for multiple collinearities and using stepwise reduction. Performance was evaluated by calculating AIC, RMSE, R^2, NSE, and MAE. The best performing models were stabilized via bootstrapping and reevaluated for performance metrics. Bootstrapping the models allowed the limitations of the relatively small sample size to be minimized.

3. Results

3.1. Soil nutrient evaluation

The results of the soil analysis are listed in Table 2. Data for soil variables were normally distributed except for K_{exc} (W = 0.61, p-value = 0.00). The data for each soil variable was not uniform compared to a random normal distribution. For C_{org}, C:N, pH, P_{av}, K_{exc}, Ca_{exc}, Mg_{exc}, and CEC values between site types were not significantly different.

ANOVA revealed that there was a difference in N_{tot} between some land use types (F = 4.33, p = 0.03) (Figure 3). Production plots had the highest average N_{tot}, significantly different than Integrated and Marginal plots. There was not a statistically significant difference in N_{tot} between Marginal and Integrated plots. Eta-squared indicated a weak to moderate effect of site type on N_{tot}.

K_{exc} showed statistically significant differences between site types using a Kruskal-Wallis test (chi-squared = 8.89, p = 0.01) (Figure 3). Production plots had the highest average K_{exc}, significantly different than Integrated and Marginal plots. There was not a statistically significant difference in K_{exc} between Integrated and Marginal plots. Eta-squared indicated a weak effect of site type on K_{exc}.

Table 2. Soil analysis results

Parameter[1]	Unit	Production	Integrated	Marginal	p-value[2]	eta-squared
pH		6.533 ± 0.41	6.150 ± 0.35	6.150 ± 0.46	0.66	0.04
N_{tot}	%	0.112 ± 0.01	0.073 ± 0.01	0.075 ± 0.01	0.03*	0.37
C_{org}	%	1.482 ± 0.15	1.100 ± 0.10	1.157 ± 0.14	0.13	0.24
C:N		13.44 ± 1.01	16.09 ± 1.72	15.47 ± 1.24	0.38	0.12
P_{av}	ppm	33.88 ± 8.03	45.37 ± 6.22	30.05 ± 6.22	0.13	0.15
K_{exc}	me $100g^{-1}$	2.572 ± 0.88	0.983 ± 0.09	1.153 ± 0.20	0.01*	0.27
Ca_{exc}	me $100g^{-1}$	17.50 ± 2.04	13.93 ± 2.33	18.66 ± 3.19	0.31	0.11
Mg_{exc}	me $100g^{-1}$	0.390 ± 0.11	0.543 ± 0.12	0.587 ± 0.11	0.45	0.10
CEC	me $100g^{-1}$	40.27 ± 1.68	35.45 ± 3.56	43.17 ± 3.41	0.22	0.18

[1] Analysis method: Electronomy for pH; Kjeldahl for N; Walkley & Black for C; HCl 0.1N for P; NH_4OAC 1N pH 7 for K, Ca, Mg, and CEC.
[2] Variance of pH, P, K, and Ca were analyzed with Kruskal-Wallis tests, and other soil characteristics were analyzed using ANOVA.
* statistically significant at p < 0.05.

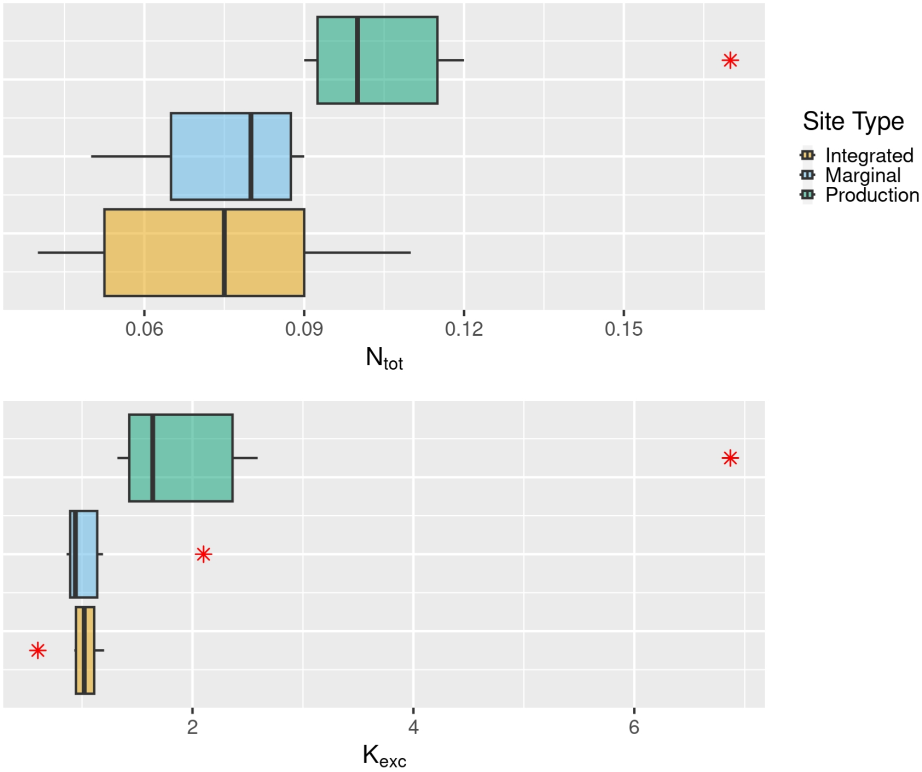

Figure 3. Boxplots showing observed values of N_{tot} (%) and K_{exc} (me $100g^{-1}$) by site type (* indicates outliers).

3.2. Measuring plant growth

The results of the plant growth measurements are recorded in Table 3. Data for plant growth variables had normal distributions but were not uniformly distributed when compared to random normal distributions. ANOVA and Kruskal Wallis tests revealed significant differences between land use types for all growth variables (Figure 4). For all these differences, eta-squared indicates weak to moderate effects of site type on growth variables.

Production plots had the highest average BC1, significantly higher than Integrated or Marginal plots. The difference between Integrated and Marginal plots was not statistically significant for BC1. Marginal plots had the lowest BC2, significantly different from Production or Integrated plots. There was not a statistically significant difference in BC2 between Production and Integrated plots. Production plots had higher average BC3 than Integrated plots, but the differences between Marginal plots and Production plots or Integrated plots were not statistically significant.

CBH2 was similar for Production plots and Integrated plots and was significantly lower in Marginal plots. Production plots had a higher average CBH3 than Integrated plots, but differences between Marginal plots and both Production and Integrated plots were not statistically significant.

HT1 average was highest in Production plots, significantly higher than both Integrated and Marginal plots. The difference between HT1 in Integrated and Marginal plots was not statistically significant. Marginal plots had the lowest average HT2, and the difference between Integrated and Production plots was not statistically significant. Production plots had the highest average HT3, significantly higher than both Integrated and Marginal plots. The difference in HT3 between Integrated and Marginal plots was not statistically significant.

Average HBP was highest in Integrated plots, significantly higher than Marginal plots but not significantly higher than Production plots.

Table 3. Plant growth measurement results

Growth variable	Unit	Production	Integrated	Marginal	p-value[1]	eta-squared
BC1	cm	30.72 ± 1.18	22.78 ± 0.81	25.89 ± 1.91	0.001**	0.26
BC2	cm	62.39 ± 1.65	61.17 ± 3.69	46.83 ± 1.87	< 0.001***	0.31
BC3	cm	74.44 ± 1.82	67.06 ± 2.22	68.83 ± 2.18	0.04*	0.12
CBH2	cm	37.17 ± 1.19	39.17 ± 2.80	30.61 ± 1.15	0.01*	0.18
CBH3	cm	50.11 ± 1.43	44.00 ± 1.58	45.83 ± 1.79	0.03*	0.13
HT1	cm	97.67 ± 4.16	72.39 ± 2.86	76.61 ± 5.25	< 0.001***	0.29
HT2	cm	223.7 ± 10.6	201.4 ± 16.07	164.1 ± 8.21	0.003**	0.20
HT3	cm	337.7 ± 17.5	264.3 ± 9.27	275.9 ± 11.59	< 0.001***	0.26
HPB	hands	4.39 ± 0.24	4.89 ± 0.23	4.06 ± 0.19	0.03*	0.12

[1] Variance of BC1, BC2, CBH2, and HT2 were analyzed with Kruskal-Wallis tests, and other growth variables were analyzed using ANOVA.
* statistically significant at $p < 0.05$.
** statistically significant at $p < 0.01$.
*** statistically significant at $p < 0.001$.

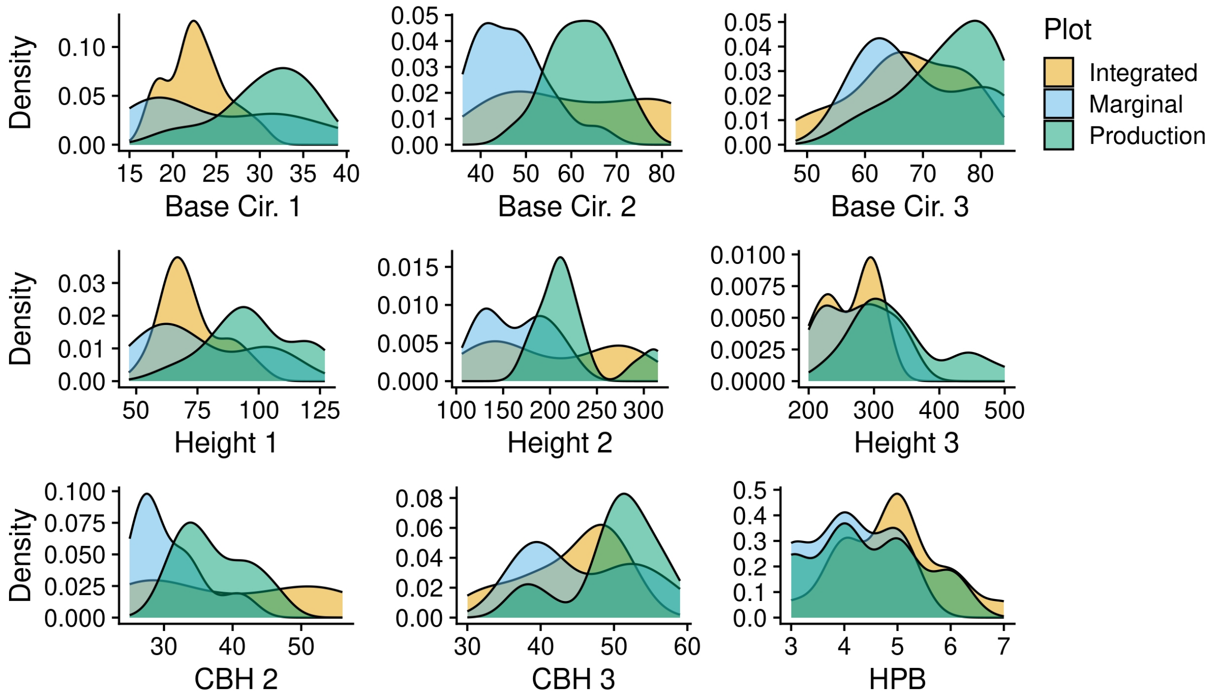

Figure 4. Density plots of measured growth parameters by site type.

3.3. Productivity index

The first principal component (PC) accounted for 68.78% of total variance and the second PC accounted for 26.89% (Table 4). HT3 (62.26%) and CBH2 (30.64%) had the largest contributions to PC1, and the next largest contribution was from HT1 (4.31%). The values of the first PC were used as the PI.

When data was plotted along the first 2 PCs, site types showed differentiation along PC1 (Figure 5), with Integrated plot data points grouped separately from Production or Marginal plots. Data for villages did not form distinct groups.

Table 4. PCA of *Loka Pere* growth variables

Principal Component	Standard Deviation	Proportion of Variance (%)	Cumulative Variance (%)	Eigenvalue
PC1	74.13	68.78	68.78	5495.40
PC2	46.36	26.89	95.67	2148.86
PC3	14.78	2.73	98.41	218.44
PC4	7.92	0.79	99.19	62.77
PC5	6.49	0.53	99.72	42.17
PC6	3.34	0.14	99.86	11.15
PC7	2.58	0.08	99.94	6.64
PC8	2.16	0.06	100	4.66

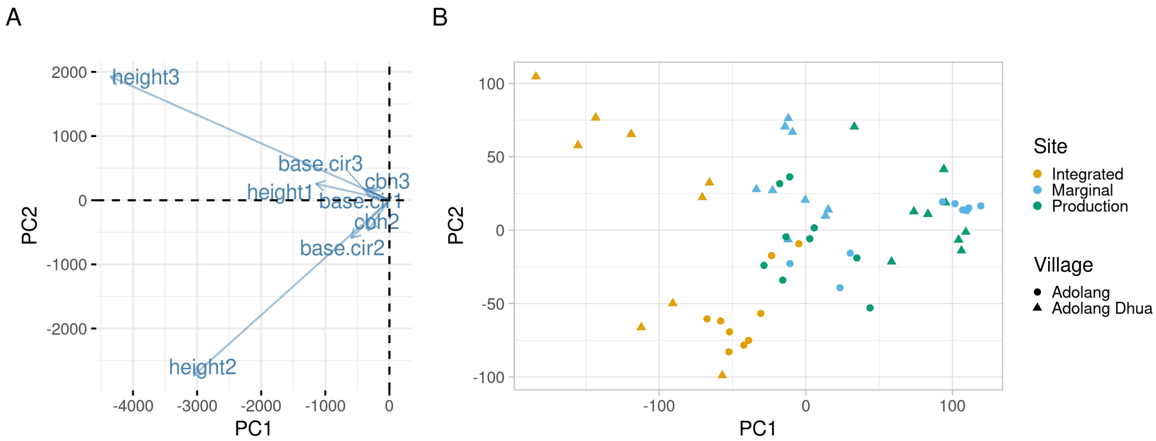

Figure 5. (A) vectors showing the contribution of each parameter and (B) the distribution of data points along PCs 1 and 2, separated by site type and village.

3.4. Regression modelling

Regression models of *Loka Pere* growth variables in response to soil properties varied in fit, with R^2 values ranging from 0.11 (HPB based on PI) to 0.69 (HT3) (Table 5). Growth variables with models that were statistically significant for all coefficients included BC1, BC2, CBH2, CBH3, HT1, and PI.

The best model for BC1 used MLR, and BC1 showed positive relationships with N_{tot} and Ca_{exc}. GAM was the best performing method for BC2, and BC2 displayed a positive linear relationship to N_{tot} and an asymmetrical convex smooth curve in response to CEC. The best model of BC3 was a GAM model, where BC3 showed a positive linear relationship to N_{tot}, a negative linear relationship to P_{av} and Mg_{exc}, and asymmetric convex curves in response to C_{org} (not statistically significant) and CEC (not statistically significant) (Figure 6).

The best model for CBH2 was a GAM with asymmetrical convex smooth curves in response to CEC and pH. CBH3 was modeled using MLR and showed a positive relationship to N_{tot} and a negative relationships to C_{org}, P_{av}, and Mg_{exc} (Figure 7).

HT1 showed a nearly linear, positive relationship with N_{tot} and Ca_{exc} in the selected GAM model. HT2 was modeled using MLR and showed a positive relationship to C_{org} and pH and a negative relationship to K_{exc}, CEC, and C:N. HT3 was modeled using MLR and showed positive relationships to N_{tot} and Ca_{exc} and negative relationships to P_{av} (not statistically significant) and CEC (Figure 8).

HPB, when modeled based on soil variables using MLR, showed a positive relationship to P_{av} (not statistically significant), CEC (not statistically significant), and pH and a negative relationship to C_{org}, Ca_{exc}, and Mg_{exc}. When modeled using GAM based on PI, HPB had an asymmetric concave smooth response (not statistically significant). The selected model for PI utilized MLR and showed a positive relationship with C_{org}, P_{av}, and Mg_{exc}, and a negative relationship with N_{tot} (Figure 9).

Table 5. *Loka Pere* growth models

Output	Method	Input	Coefficients	p-value	R^2	RMSE	MAE
BC1	MLR	N_{tot}+Ca_{exc}	Int[a] = 6.44·	0.082	0.43	4.98	4.17
			N_{tot} = 111.60***	<0.001			
			Ca_{exc} = 0.61***	<0.001			
BC2	GAM	N_{tot}+CEC (knots = 3)	Int = 56.78***	<0.001	0.46	9.11	7.25
			N_{tot} = 1.00***	<0.001			
			CEC = 1.89***	<0.001			
BC3	GAM	N_{tot}+C_{org}+P_{av}+Mg_{exc}+CEC (knots = 4)	Int = 72.75***	<0.001	0.38	7.19	5.96
			N_{tot} = 27.04*	0.046			
			C_{org} = -10.95	0.304			
			P_{av} = -11.43 ·	0.067			
			Mg_{exc} = -8.61 ·	0.067			
			CEC = -10.65	0.101			
CBH2	GAM	CEC+pH (knots = 3)	Int = 35.69***	<0.001	0.56	5.48	4.61
			CEC = 1.95***	<0.001			
			pH = 1.87***	<0.001			
CBH3	MLR	N_{tot}+C_{org}+P_{av}+Mg_{exc}	Int = 52.32***	<0.001	0.35	5.71	4.92
			N_{tot} = 230.93***	<0.001			
			C_{org} = -12.67***	<0.001			
			P_{av} = -0.17**	0.002			
			Mg_{exc} = -6.92*	0.025			
HT1	GAM	N_{tot}+Ca_{exc} (knots = 3)	Int = 82.17***	<0.001	0.55	13.41	10.82
			N_{tot} = 1.52***	<0.001			
			Ca_{exc} = 1.52***	<0.001			
HT2	MLR	C_{org}+K_{exc}+CEC+pH+C:N	Int = 47.10	0.432	0.51	38.31	31.25
			C_{org} = 129.34*	0.018			
			K_{exc} = -23.18 ·	0.098			
			CEC = -3.63***	<0.001			
			pH = 43.48*	0.030			
			C:N = -6.88**	0.008			
HT3	MLR	N_{tot}+P_{av}+Ca_{exc}+cec	Int = 167.13***	<0.001	0.69	35.47	28.67
			N_{tot} = 1631.03***	<0.001			
			P_{av} = -0.61	0.116			
			Ca_{exc} = 7.64***	<0.001			
			CEC = -3.11**	0.008			
HPB	MLR	C_{org}+P_{av}+Ca_{exc}+Mg_{exc} +CEC+pH	Int = 3.62 ·	0.057	0.33	0.80	0.66
			C_{org} = -1.37**	0.005			
			P_{av} = 0.01	0.128			
			Ca_{exc} = -0.15 ·	0.052			
			Mg_{exc} = -1.28*	0.018			
			CEC = 0.05	0.108			
			pH = 0.54 ·	0.096			
PI	MLR	N_{tot}+C_{org}+P_{av}+Mg_{exc}	Int = 47.22 ·	0.098	0.56	48.53	40.91
			N_{tot} = -2643.40***	<0.001			
			C_{org} = 82.53**	0.007			
			P_{av} = 1.06*	0.026			
			Mg_{exc} = 74.16**	0.003			
HPB	GAM	PI (knots = 4)	Int = 4.33***	<0.001	0.11	0.92	0.77
			PI = 0.96	0.118			

[a] Int = y intercept.
. statistically significant at $p < 0.1$.
* statistically significant at $p < 0.05$.
** statistically significant at $p < 0.01$.
*** statistically significant at $p < 0.001$.

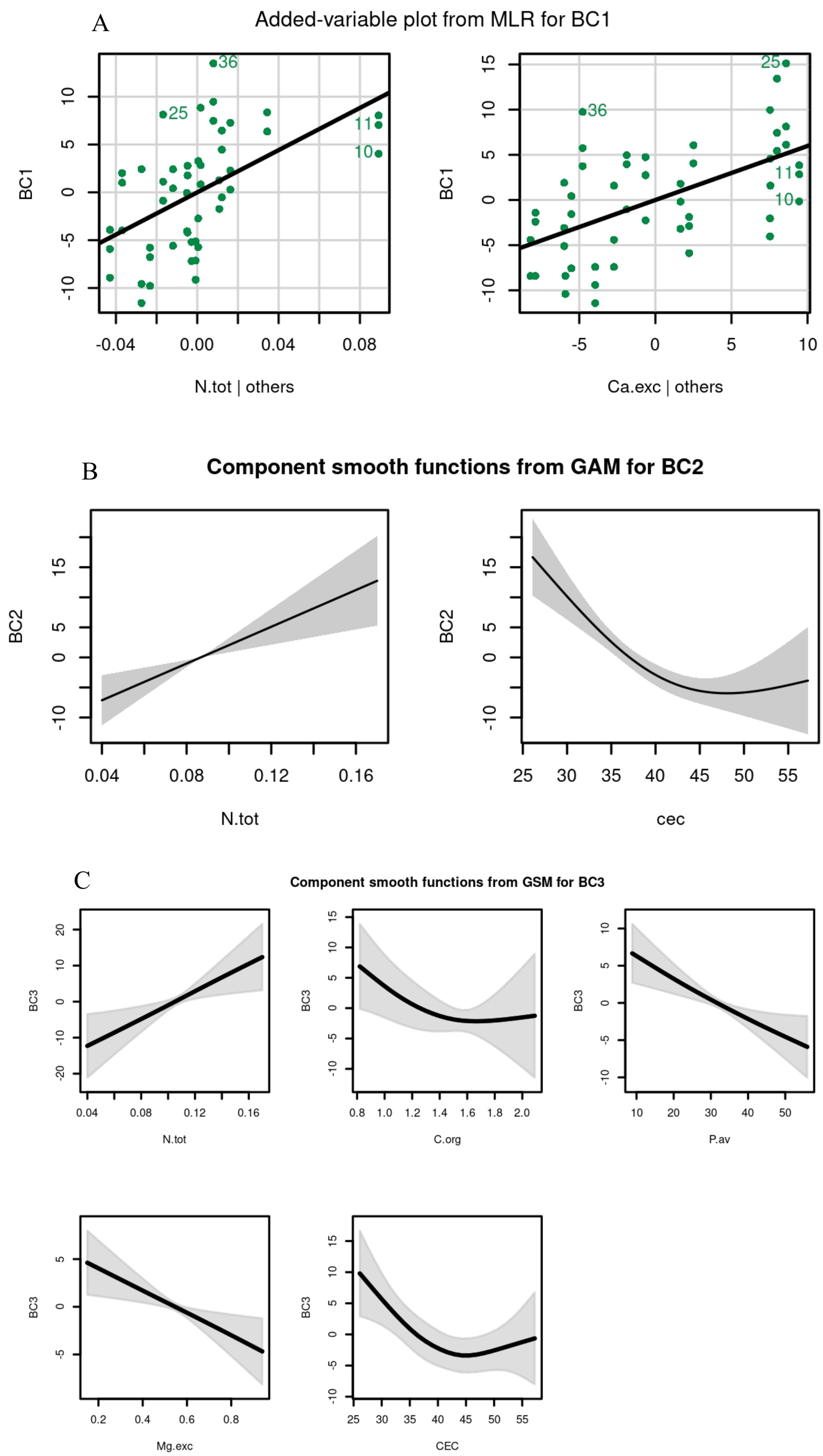

Figure 6. Model response curves for (A) BC1, (B) BC2, and (C) BC3.

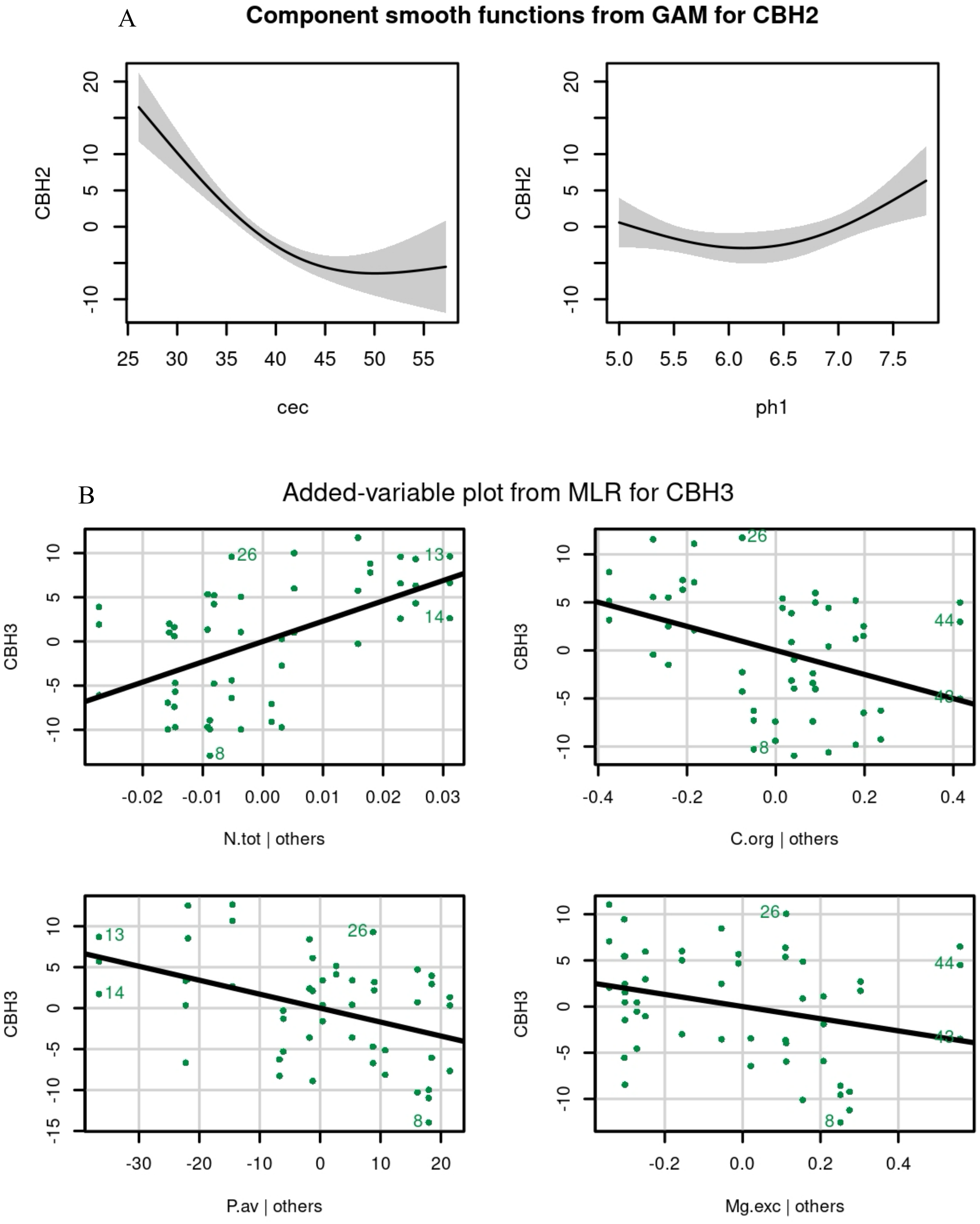

Figure 7. Model response curves for (A) CBH2 and (B) CBH3.

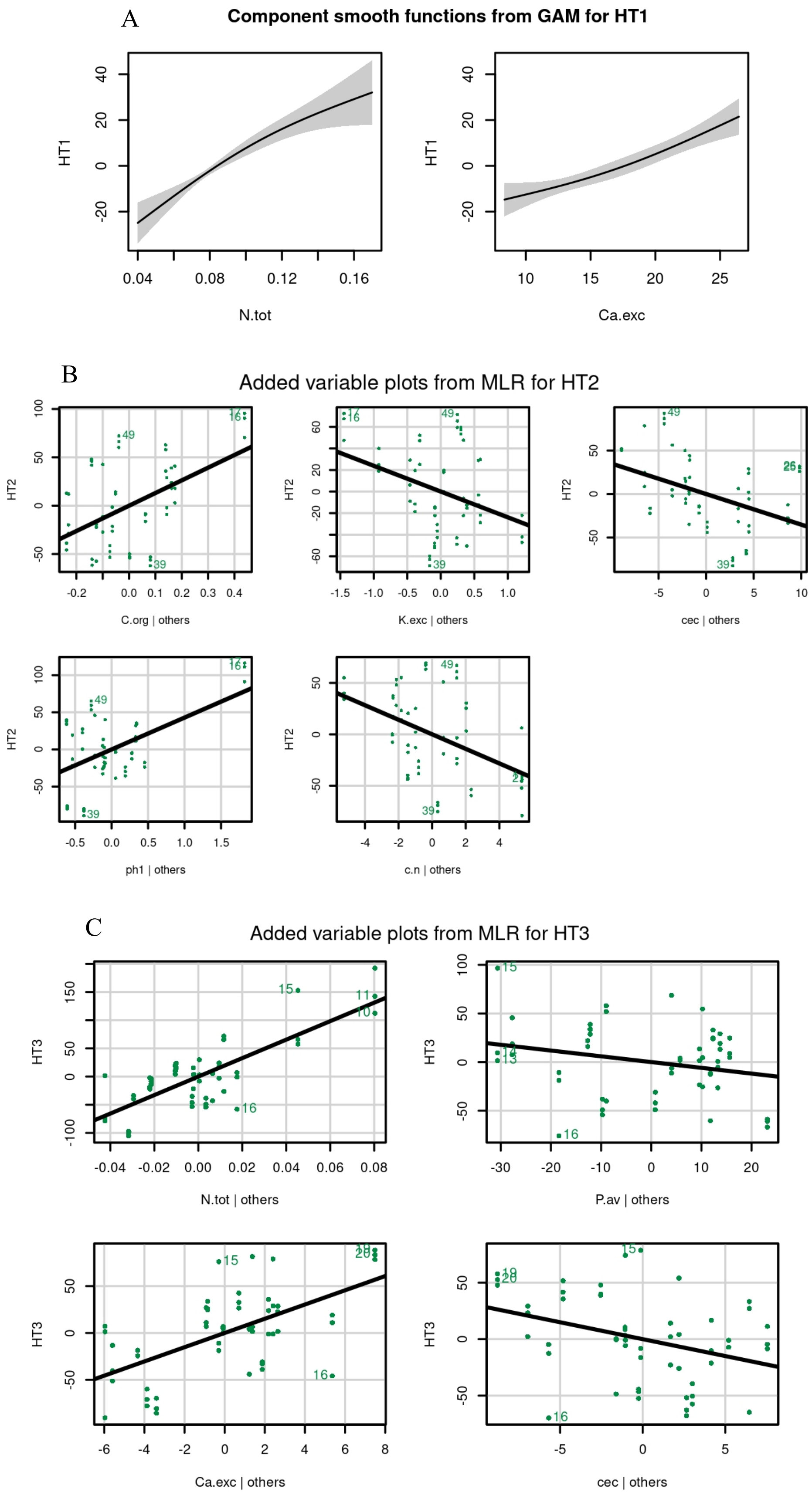

Figure 8. Model response curves for (A) HT1, (B) HT2, and (C) HT3.

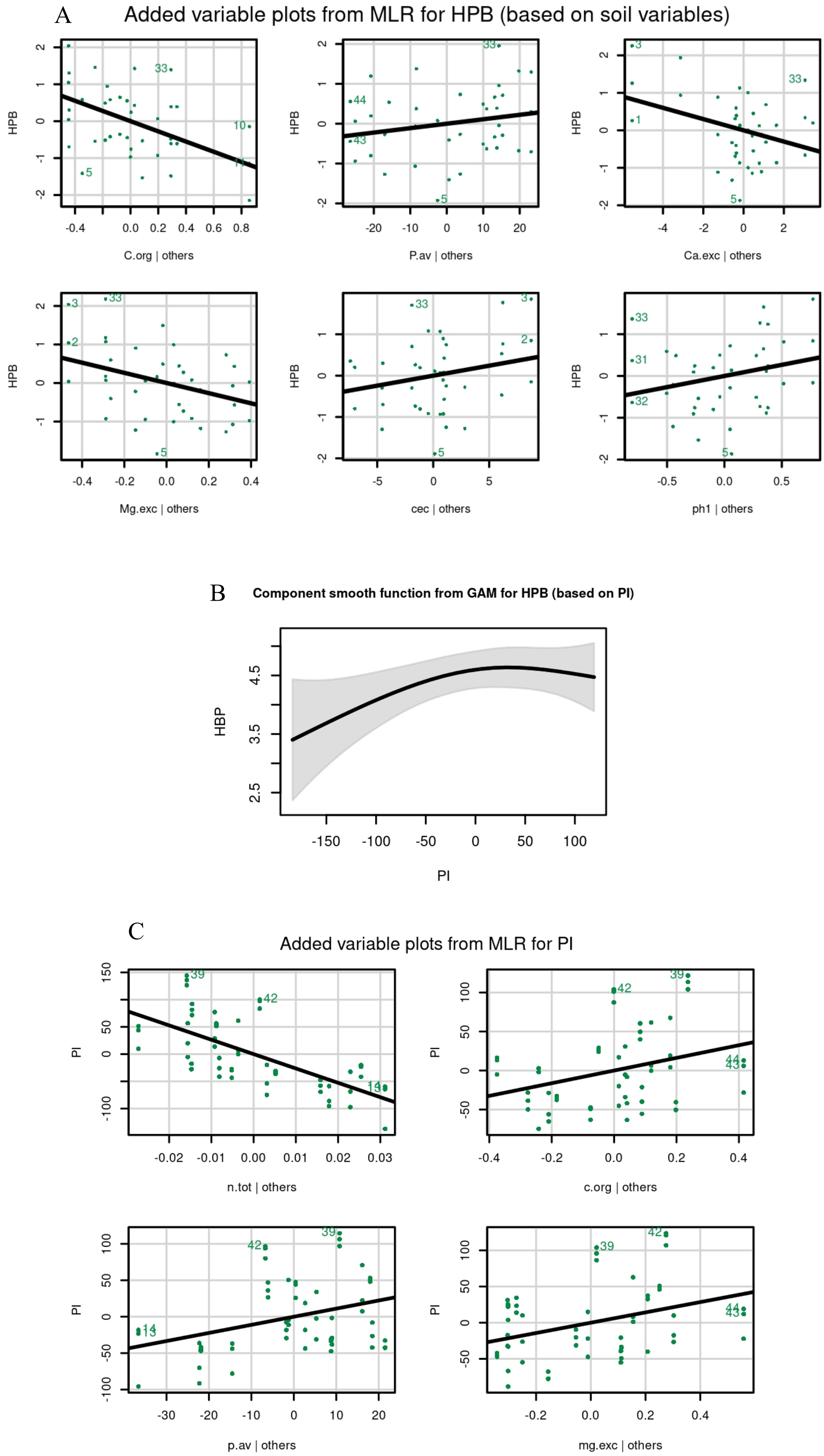

Figure 9. Model response curves of (A) HPB based on soil variables, (B) HPB based on PI and (C) PI.

4. Discussion

The only soil variables with statistically significant differences between site types were N_{tot} and K_{exc}, indicating that site type had a weak effect on soil nutrient properties in *Loka Pere* cultivation areas.

Production plots tended to have the highest average growth variables, followed by Integrated plots, indicating that site type impacts *Loke Pere's* growth. This is likely due to differences in several factors, such as management, microclimate, and soil quality. However, there were exceptions to this trend. Integrated plots had the highest average HPB, although this was not significantly different from Production plots. Marginal plots were not significantly different from Production plots for BC3 and CBH3. NU plants can be well suited to marginal environments (Mustafa et al., 2019; Li et al., 2020), and sometimes even show better quality in these environments than under controlled conditions (Guijarro-Real et al., 2019). However, growth and yield are generally expected to improve under better management conditions.

The PI for *Loka Pere* was influenced by HT3 (62.26%) and CBH2 (30.64%). A PI developed for the 'Gran Nain' banana was explained by CBH and HPB (Olivares et al., 2020). Integrated plot data formed a significant grouping apart from Production and Marginal plots concerning PI, indicating that productivity is distinct in Integrated plots compared to Production or Marginal plots. However, PI was not strongly linked to yield ($R^2 = 0.11$). Soil variables explained HPB better than PI ($R^2 = 0.33$) and showed better significance.

pH showed a parabolic relationship to CBH2 ($p = 0.001$), and positive relationships with HT2 ($p = 0.030$) and HPB ($p = 0.096$). Nyombi (2020) reports that the ideal pH range for banana production is 5.5 to 8.0, roughly the same as the study area. Yield variables of other banana varieties have shown a correlation to soil pH (Hu et al., 2021). This suggests the impact of soil pH on *Loka Pere* yield is similar to other varieties.

N_{tot} showed a positive relationship to BC1 ($p = 0.001$), BC2 ($p = 0.001$), BC3 ($p = 0.046$), CBH3 ($p = 0.001$), HT1 ($p = 0.001$), and HT3 ($p = 0.001$), and a negative relationship to PI ($p = 0.001$). N_{tot} had an outsized influence on PI, likely due to its strong influence on HT3 which is the main contributor to PI. Nitrogen is considered a key element for *Musa* spp., showing a strong link to total dry matter production (CAB International, 2010b). Some banana cultivars, including landraces and hybrids, have shown increased height, pseudostem diameter, and yield with increased availability of N (Aba et al., 2015; Nomura et al., 2016; Meya et al., 2023). Similar to these other varieties, N_{tot} seems to be crucial for *Loka Pere's* growth.

C_{org} showed a positive relationship to HT2 ($p = 0.018$) and PI ($p = 0.007$) and a negative relationship to BC3 ($p = 0.304$), CBH3 ($p = 0.001$) and HPB ($p = 0.005$). It showed a strong influence on HT2 and HPB. Studies of other varieties have also shown a connection between plant height and soil organic matter (Hu et al., 2021). C:N was only included in the model for HT2, where it had a negative relationship ($p = 0.008$). For the 'Williams' banana Perez and Torres-Bazurto (2020) concluded that increased C:N tended to improve production. These findings suggest that the influences of C_{org} and C:N in *Loka Pere* may differ from other *Musa* spp. varieties.

P_{av} had positive relationships with HPB ($p = 0.128$) and PI ($p = 0.026$), and negative relationships with BC3 ($p = 0.067$), CBH3 ($p = 0.002$), and HT3 (0.116). P is generally considered important for *Musa* spp. fruit formation (Nyombi, 2020), and P_{av} have shown a correlation to yield variables in other varieties as well (Leonel et al., 2020; Sun et al., 2020; Hu et al., 2021).

Only the model for HT2 included K_{exc} as an input variable, showing a negative relationship ($p = 0.098$). K is generally one of the most essential nutrients for *Musa* spp. across growth stages (Nomura et al., 2016; Hu et al., 2021). In one study, the banana varieties 'PITA 24' and 'Agbagda' showed increased height and pseudostem girth as K supply increased (Aba et al., 2015). The hill banana 'Sirumalai' had increased height, pseudostem girth, and HBP with increased K application (Sathappan et al., 2019). This suggests that the influence of K_{exc} on *Loka Pere* may differ from other varieties.

Ca_{exc} showed a positive relationship to BC1 ($p = 0.001$), HT1 ($p = 0.001$), and HT3 (0.001) and a negative relationship to HPB (0.052). Ca imbalance can impact the quality of fruit, causing peels to split (Nyombi, 2020) which was reported for *Loka Pere* (Nurhafsah et al., 2022b).

Mg_{exc} had a positive relationship to PI ($p = 0.003$), coinciding with the findings of Olivares et al. (2020) who also related PI and Mg for the 'Gran Nain' banana. Mg_{exc} also showed a negative relationship with BC3 ($p = 0.067$), CBH3 ($p = 0.025$), and HPB ($p = 0.018$). This contrasts the findings of He et al. (2022) who found that Mg application in *Musa* sp. AAA cv 'Baxijaio' improved plant growth. Mg supply has also shown a positive impact on the growth and yield of 'Williams B6' banana (Zhang et al., 2020). This suggests the specific influence of Mg on *Loka Pere* growth may differ from other varieties.

CEC had a positive relationship to BC2 ($p = 0.001$) and HPB ($p = 0.108$), a negative relationship to BC3 ($p = 0.101$), HT2 ($p = 0.001$) and HT3 ($p = 0.008$), and a parabolic relationship with CBH2 ($p = 0.001$). Cation balances are viewed as an important component of soil fertility for *Musa* spp., and the plants can be very sensitive to imbalances (CAB International, 2010c). The optimal balances may be variable across varieties.

One possible reason for differences in the physiological responses of *Loka Pere* to nutrient availability in this study compared to findings for other varieties may be genotype differences. Genotype has been shown to lead to variability in the nutrient budgets for different parts of *Musa* spp. plants (Hu et al., 2021), nutrient use efficiencies (Aba et al., 2015), tolerance ranges to soil properties (Santana Junior et al., 2020), and response to nutrient deficiency (He et al., 2021). For example, particular genetic pathways influence the uptake and utilization of K by *Musa* spp. plants. Xiong et al. (2021) report that expression of the gene MaCBL2 plays a role in *Musa* spp. potassium shortage resistance. Genetic diversity between *Loka Pere* and other *Musa* spp. varieties may lead to differences in soil K tolerance ranges and in the impact of K on plant development.

Conclusion

This study set out to create a simple growth model of *Loka Pere* based on soil macronutrient concentrations across three traditional growth environments. The most important soil variables for *Loka Pere* growth were N_{tot}, Ca_{exc}, and CEC. The most important soil variables for yield (HPB) were pH, CEC, and P_{av}. The growth responses of *Loka Pere* to the availability of certain nutrients differed from responses found in studies on other varieties.

These findings shed light on the agronomic performance of *Loka Pere* and the physiological differences between *Loka Pere* and other *Musa* spp. varieties. The models can help farmers and other stakeholders identify suitable areas for *Loka Pere* cultivation, make management decisions, and pursue higher yields. The existence of NU variety specific models means *Loka Pere* producers and future researchers will not have to rely on crop models calibrated to modern cultivars.

This study had a few limitations. The growth of *Loka Pere* was modeled in traditional cultivation environments that were rain-fed and had minimal nutrient input. These models simulate the growth of *Loka Pere* across the nutrient gradients found naturally within the study area, not under optimal conditions. These models focused on a handful of soil chemical properties, but other factors are known to impact *Musa* spp. development, including climate, topography, and biotic interactions.

Continued investigation of the impact of land use and management on *Loka Pere* growth and of *Loka Pere* nutrient dynamics and growth responses is recommended to better understand the agronomic characteristics of the plant. The modeling of *Loka Pere* will improve via the inclusion of other model variables and parameters.

Ethical Statement

Ethical approval is not required for this study because neither the subject or methods of the study constituted review by an ethics committee.

Conflict of Interest

The Authors declare that there are no conflicts of interest.

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This study was self-funded by the authors.

Author Contributions

Cahyo Prayogo: conceptualization, methodology, supervision, validation, writing – review and editing. Jacob Fettig: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft preparation, writing – review and editing. Marthen P. Sirappa: investigation, project administration, supervision, writing – review and editing. Syahrul Kurniawan: supervision, validation.

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References

Aba, S. C., & Baiyeri, K. P. (2015). Nitrogen and potassium fertilizer influenced nutrient use efficiency and biomass yield of two plantain (*Musa* spp. AAB) genotypes. *Afr J Agric Res, 10*(6), 458-471. doi:10.5897/AJAR2014.9198

Ahumuza, B., Basamba, T. A., Van Asten, P., & Tushemereirwe, W. K. (2015). Physiological nutrient use efficiency of banana hybrids across agro ecological regions in Uganda. *Afr J Plant Sci*, *9*(2), 97-105. doi:10.3389/fsufs.2020.545926

Blomme, G., Ntamwira, J., Kearsley, E., Bahati, L., Amini, D., Safari, N., & Ocimati, W. (2020). Sensitivity and tolerance of different annual crops to different levels of banana shade and dry season weather. *Front Sustain Food Syst*, *4*, 545926. doi: 10.3389/fsufs.2020.545926

Borelli, T., Hunter, D., Padulosi, S., Amaya, N., Meldrum, G., de Oliveira Beltrame, D. M., Samarasinghe, G., Wasike, V. W., Guner, B., Tan, A., Dembele, Y. K., Lochetti, G., Sidibe, A., & Tartanac, F. (2020). Local solutions for sustainable food systems: The contribution of orphan crops and wild edible species. *Agronomy*, *10*, 231. doi:10.3390/agronomy10020231

BPTP, (2016). *Menggali potensi pisang 'Loka' pere Kabupaten Majene*. http://sulbar.litbang.pertanian.go.id/ind/index.php/info-teknologi/316-menggali-potensi-pisang-loka-pere-kabupaten-majene. Access date: 05.25.2020.

Brown, D., Van den Bergh, I., de Bruin, S., Machida, L., & van Etten, J. (2020). Data synthesis for crop variety evaluation. A review. *Agron Sustain Dev*, *40*, 25. doi:10.1007/s13593-020-00630-7

CAB International. (2010a). Distribution and importance. In J.C. Robinson & V. Galan Sauco (Eds.), *CABI Bananas and Plantains 2nd Edition* (pp. 1-20). CAB International.

CAB International. (2010b). Nutritional requirements. In J.C. Robinson & V. Galan Sauco (Eds.), *CABI Bananas and Plantains 2nd Edition* (pp. 161-178). CAB International.

CAB International. (2010c). Site selection, soil requirements and soil preparation. In J.C. Robinson & V. Galan Sauco (Eds.), *CABI Bananas and Plantains 2nd Edition* (pp. 115-123). CAB International.

Chabi, M. C., Dassou, A. G., Dossou-Aminon, I., Ogouchoro, D., Aman, B. O., & Dansi, A. (2018). Banana and plantain production systems in Benin: Ethnobotanical investigation, varietal diversity, pests, and implications for better production. *J Ethnobiol Ethnomed*, *14*, 78. doi:10.1186/s13002-018-0280-1

Chimonyo, V. G. P., Chibarabada, T. P., Choruma, D. J., Kunz, R., Walker, S., Massawe, F., Modi, A. T., & Mabhaudhi, T. (2022). Modelling neglected and underutilized crops: a systematic review of progress, challenges, and opportunities. *Sustainability*, 14, 13931. doi:10.3390/su142113931

Cortinovis, G., Di Vittori, V., Bellucci, E., Bitocchi, E., & Papa, R. (2020). Adaptation to novel environments during crop diversification. *Curr Opin Plant Biol*, *13*, 1-15. doi:10.1016/j.pbi.2019.12.011

Damour, G., Ozier-Lafontaine, H., & Dorel, M. (2012). Simulation of the growth of banana (*Musa* spp.) cultivated on cover-crop with simplified indicators of soil water and nitrogen availability and integrataed plant traits. *F Crops Res*, *130*, 99-108. doi:10.1016/j.fcr.2012.02.013

Depingy, S., Lescot, T., Achard, R., Diouf, O., Cote, F. X., Fonbah, C., Sadom, L., & Tixier, P. (2016). Model-based benchmarking of the production potential of plantains (*Musa* spp., AAB): Application to five real plantain and four plantain-like hybrid varieties in Cameroon. *J Ag Sci*, *155*(6), 1-14. doi:10.1017/S0021859616000964

Dir. Kerjasama dan Pemberdayaan KI. (2022). *Surat pencatatan inventarisasi kekayaan intelektual komunal sumberdaya genetik pisang Loka Pere.* Kementerian Hukum dan HAM RI.

FAO, (2019). *Voluntary guidelines for the conservation and sustainable use of farmers' varieties/landraces*. Rome: FAO Commission on Genetic Resources for Food and Agriculture Assessments.

FAO, (2023). *Banana market review 2022*. Rome: FAO.

Ficiciyan, A., Loos, J., Sievers-Glotzbach, S., & Tscharntke, T. (2018). More than yield: Ecosystem services of traditional verses modern crop varieties revisitied. *Sustainability*, *10*, 2834. doi: 10.3390/su10082834

Guijarro-Real, C., Adalid-Martinez, A. M., Aguirre, K., Prohens, J., Rodriquez-Buzzuezo, A., & Fita, A. (2019). Growing conditions affect the phytochemical composition of edimal wall rocket (*Diplotaxis erucoides*). *Agronomy*, *9*, 858. doi:10.3390/agronomy9120858

Hapsari, L., Damaiyant, J., Yulistyarini, T., Auliya, I., Gusmiati, L. H., & Zaro, R. M. (2022). Characterization, potential and conservation of *Pisang Kates* (*Musa* cv. ABB), a unique local banana cultivar from Pasuruan, East Java, Indonesia. *Biodiversitas*, *23*(7), 3521-3532. doi:10.13057/biodiv/d230727

He, H., Khan, S., Deng, Y., Hu, H., Yin, L., & Huang, J. (2022). Supplemental foliar-applied magnesium reverted photosynthetic inhibition and improved biomass partitioning in magnesium-deficient banana. *Horticulturae*, *8*, 1050. doi: 10.3390/horticulturae8111050

Hu, W., Yang, B., He, Z., & Li, G. (2021). Magnesium may be a key nutrient mechanism related to Fusarium wilt resistance: a new banana cultivar (Zhongjiao No. 9). *PeerJ*, *9*, e11141. doi:10.7717/peerj.11141

Hufford, M. B., Teran, J. C. B. M., & Gepts, P. (2019). Crop biodiversity: an unfinished magnum opus of nature. *Ann Rev Plant Biol*, *70*, 727-51. doi: 10.1146/annurev-arplant-042817-040240

Jayasinghe, S. L., Ranawana, C. J. K., Liyanage, I. C., & Kaliyadasa, P. E. (2022). Growth and yield estimation of banana through mathematical modelling: a systematic review. *J Ag Sci*, *160*, 152-167. doi:/10.1017/S0021859622000259

Karunaratne, A. S., Walker, S., & Azam-Ali, S. N. (2015a) Assessing the productivity and resource-use efficiency of underutilized crops: Towards an integrative system. *J Ag Wat*, *147*, 129-134. doi:10.1016/j.agwat.2014.08.002

Karunaratne, A. S., Azam-Ali, S. N., Walker, S., & Ruane, A. (2015b). Modelling the productivity of underutilized crops for climate resiliance. *Acta Hortic*, *1101*, 113-118. doi: 10.17660/ActaHortic.2015.1101.17

Khoury, C., Bjorkman, A. D., Dempenwolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L. H., & Struik, P. C. (2014). Increasing homogeneity in global food supplies and implications for food security. *PNAS*, *111*(11), 4001-4006. doi: 10.1073/pnas.1313490111/-/DCSupplemental

Khoury, C. K., Brush, S., Costich, D. E., Curry, H. A., de Haan, S., Engels, J. M. M., Guarino, L., Hoban, S., Mercer, K. L., Miller, A. J., Nabhan, G. P., Perales, H. R., Richards, C., Riggins, C., & Thormann, I. (2022). Crop genetic erosion: Understanding and responding to loss of crop diversity. *New Phytologist*, *223*, 84-118. doi: 10.1111/nph.17733

Kilwinger, F. B. M., Rietveld, A. M., Groot, J. C. J., & Almekinders, C. J. M. (2019). Culturally embedded practices of managing banana diversity and planting material in central Uganda. *J Crop Improvement*, *33*(4), 456-477. doi:10.1080/15427528.2019.1610822

Kissel, E., van Asten, P., Swennen, R., Lorenzen, J., & Carpentier, S. C. (2015). Transpiration efficiency verses growth: Exploring the banana biodiversity for drought tolerance. *Sci Hortic-Amsterdam*, *185*, 175-182. doi:10.1016/j.scienta.2015.01.035

LaFevor, M. C. (2022). Crop species production diversity enhances revenue stability in low-income farm regions of Mexico. *Agriculture*, *12*, 1835. doi:10.3390/agriculture12111835

Leonel, M., Bolfarini, A. C. B., da Silva, M. J. R., Souza, J. M. A., & Leonel, S. (2020). Banana fruits with high content of resistant starch: Effect of genotypes and phosphorus fertilization. *I J Bio Mac*, *150*, 1020-1026. doi:10.1016/j.ijbiomac.2019.10.217

Li, X., Yadav, R., & Siddique, K. H. M. (2020). Neglected and underutilized crop species: The key to improving dietary diversity and fighting hunger and malnutrition in Asia and the Pacific. *Front Nutr*, *7*, 593711. doi:10.3389/fnut.2020.593711

Lopez-Jimenez, J., Quijano, N., & Vande Wouwer, A. (2021). An agent-based crop model framework for heterogeneous soils. *Agronomy*, *11*, 85. doi:10.3390/agronomy11010085

Massawe, F. J., Mayes, S., Cheng, A. Chai, H. H., Cleasby, P., Symonds, R., Ho, W. K., Siise, A., Wong, Q. N., Kendiabie, P., Yanusa, Y., Jamalluddin, N., Singh, A., Azman, R., & Azam-Ali, S. N. (2015). The potential for underutilized crops to improve food secuirity in the face of climate change. *Procedia Environ Sci*, 29, 140-141. doi:10.1016/j.proenv.2015.07.228

Maues, T. M. S., Costa, R. R., dos Santos, M. A. S., & da Silva, G. B. (2022). Agroeconomic performance of banana tree under nutritional management with *Trichoderma asperellum*, in a family production system. *AIMS Agr Food, 7*(2), 297-311. doi:10.3934/agrfood.2022019

Meya, A. I., Swennen, R., Ndakidemi, P. A., Mtei, K. M., & Merckx, R. (2023). Better nitrogen fertilizer management improved Mchare banana productivity and profitability in Northern Highlands, Tanzania. *Agronomy*, *13*, 1418. doi:10.3390/agronomy13051418

Mofya-Mukuka, R., & Hichaambwa, M. (2018). Livelihood effects of crop diversification: a panel data analysis of rural farm households in Zambia. *Food Security*, *10*, 1449-1462. doi: 10.1007/s12571-018-0872-6

Mustafa, M. A., Mayes, S., & Massawe, F. (2019). Crop diversification through a wider use of underutilized crops: a strategy to ensure food and nutrition security in the face of climate change. In A. Sarkar *et al* (Eds.), *Sustainable Solutions for Food Security: Combating Climate Change by Adaptation* (pp 125-147). Springer Nature Switzerland. doi:10.1007/978-3-319-77878-5_7

Nomura, E. S., Cuquel, F. L., Junior, E. R. D., Fuzitani, E. J., Borges, A. L., & Saes, L. (2016). Nitrogen and potassium fertilization on 'Caipira' and 'BRS Princesa' bananas in the Riberia Valley. *R Bras Eng Agric Ambiental*, *20*(8), 702-708. doi: 10.1590/1807-1929/agriambi.v20n8p702-708

Nurhafsah, Sirappa, M. P., & Fitriawaty. (2022a). *Loka pere: Kandungan nutrisi dan potensi pengembangan*. Makassar: CB Inzani.

Nurhafsah, Fitriawaty, Rahmi, H., Andriani, I., & Aras, M. (2022b). Loka Pere: Potensi lokal di tanah Pamboang. In, *Pertanian buletin teknologi & inovasi pertanian vol 1* (pp 23-28). Kementrian Pertanian Pusat Perpustakaan dan Penyebaran Teknologi.

Nyombi, K. (2020). Diagnosis and management of nutrient constraints in bananas (*Musa* spp.). In A. K. Srivastava & Chengxiao Hu (Eds.), *Fruit crops: Diagnosis and managmenet of nutrient constraints*. Elselvier Inc. doi:10.1016/B978-0-12-818732-6.00044-7

Olivares, B. O., Araya-Alman, M., Acevedo-Opazo, C., Rey, J. C., Canete-Salinas, P., Kurina, F. G., Balzarini, M., Lobo, D., Navas-Cortez, J. A., Landa, B. B., & Gomez, J. A. (2020). Relationship between soil properties and banana productivity in the two main cultivation areas in Venezuela. *J Soil Sci Plant Nutr, 20*, 2512-2524. doi:10.1007/s42729-020-00317-8

Olivares, B. O., Calero, J., Rey, J. C., Lobo, D., Landa B. B., & Gomez, J. A. (2022) Correlation of banana productivity levels and soil morphological properties using regularized optimal scaling regression. *Catena*, *208*, 105718. doi:10.1016/j.catena.2021.105718

Ortas, I., Rafique, M., Akpinar, C., & Kacar, Y. A. (2017). Growth media and mycorrhizal species effect on acclimatization and nutrient uptake of banana plantlets. *Sci Hortic-Amsterdam*, *217*, 55-60. doi: 10.1016/j.scienta.2017.01.025

Padulosi, S., Cawthorn, D., Meldrum, G., Flore, R., Halloran, A., & Mattei, F. (2018). Leveraging neglected and underutilized plant, fungi, and animal species for more nutrition sensitive and sustainable food systems. *Encycl Food Security & Sustain*, *3*, 361-371. doi:10.1016/B978-0-08-100596-5.21552-7

Padulosi, S., Roy, P., & Rosado-May, F. J. (2019). *Supporting nutrition sensitive agriculture through neglected and underutilized species – operational framework*. Rome: Biodiversity International and IFAD.

Perez, W. A., & Torres-Bazurto, J. (2020). Carbon-nitrogen ratio in soils with fertilizer applications and nutrient absorption in banana (*Musa* spp.) cv. Williams. *Agron Colomb, 38*(2), 253-260. doi:10.15446/agron.colomb.v38n2.78075

Perrier, X., De Langhe, E., Donohue, M., Lentfer, C., Vrydaghs, L., Bakry, F., Carreel, F., Hippolyte, I., Horry, J., Jenny, C., Lebot, V., Risterucci, A., Tomekpe, K., Deutrelepont, H., Ball, T., Manwaring, J., de Maret, P., & Denham, T. (2011). Multidisciplinary perspectives on banana (*Musa* spp.) domestication. *PNAS*, *108*(28), 11311-111318. doi:10.1073/pnas.1102001108/-/DCSupplemental

Posit Team, (2023). RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, MA. http://www.posit.com/

Pingali, P. (2019). The green revolution and crop biodiversity. In Dasgupta, P., Raven P., & McIvor, A. (Eds.), *Biological Extinction: New Perspectives* (pp 175-192). Cambridge University Press. doi: 10.1017/9781108668675.009

PPVT, (2018). *Tanda daftar varietas tanaman: tanaman lokal nomor 502/PVL/2018*. Bogor: Kementrian Pertanian Pusat Perlindungan Varietas Tanaman dan Perizinan Pertanian.

QGIS, (2023). QGIS Geographic Information System. QGIS Association.

Rahman, W., Brehm, J. M., & Maxted, N. (2019). Setting conservation priorities for the wild relatives of food crops in Indonesia. *Genet Resour Crop Evol*, *66*, 809-824. doi:10.1007/s10722-019-00761-1

Reiss, E., & Drinkwater, L. (2018). Cultivar mixtures: a meta-analysis of the effect of intraspecific diversity on crop yield. *Ecol Appl*, *28*(1), 62-77. doi:10.1002/eap.1629

Ritung, S., Andriyanto, C., Lukman, F., Purnanto, R., Sudrajat, D. (2016). *Atlas peta tanah semi detail skala 1:50,000 – Kabupaten Majene, Provinsi Sulawesi Barat.* Mamuju: Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian.

Santana Junior, E. B., Coelho, E. F., Goncalves, K. S., & Cruz, J. L. (2020). Physiological and vegetative behavior of banana cultivars under irrigation water salinity. *R Bras Eng Agric Ambiental, 24*(2), 82-88. doi: 10.1590/1807-1929/agriambi.v24n2p82-88

Sathappan, C. T., Sivanesh, K., & Dhanasekaran, D. (2019). Studies on the influence of potassium on growth, yield and quality of hill banana var. Sirumalai. *Plant Arch, 19*(2), 1603-1605.

Sirappa, M. P., Hiola, M. S., Kusrini, N., Heryanto, H., Indrayana, K., Anam, K. & Nas, M. (2023). *55 SDG lokal terdaftar Sulawesi Barat*. BPSIP Sulawesi Barat, Badan Standardisasi Instrumen Pertanian, Kementerian Pertanian (Unpublished).

Suryani, R., & Owbel. (2019). Pentingnya eksplorasi dan karakterisasi tanaman pisang sehingga sumber daya genetic tetap terjaga. *Agro Bali*, *2*(2), 64-76.

Sun, J., Li, W., Li, C., Chang, W., Zhang, S., Zeng, Y., Zeng, C., & Peng, M. (2020). Effect of different rates of nitrogen fertilization on crop yield, soil properties and leaf physiological attributes in banana under subtropical regions of China. *Front Plant Sci*, *11*, 613760. doi:10.3389/fpls.2020.613760

Tadele, Z. (2019). Orphan crops: Their importance and the urgency of improvement. *Planta*, *250*, 677-694. doi:10.1007/s00425-019-03210-6

Taulya, G. (2013). East African highland bananas (*Musa* spp. AAA-EA) 'worry' more about potassium deficiency than drought stress. *F Crops Res*, *151*, 45-55. doi:10.1016/j.fcr.2013.07.010

Tixier, P., Malezieux, E., & Dorel, M. (2004). SIMBA-POP: a cohort population model for long-term simulation of banana crop harvest. *Ecol Model*, *180*, 407-417. doi: 10.1016/j.ecolmodel.2004.04.028

Tixier, P., Malezieux, E., Dorel, M., & Wery, J. (2008). SIMBA, a model for designing sustainable banana-based cropping systems. *Agric Sys*, *97*(3), 139-150. doi:10.1016/j.agsy.2008.02.003

Van den houwe, I., Chase, R., Sardos, J., Ruas, M., Kempenaers, E., Guignonn, V., Massart, S., Carpentier, S., Panis, B., Rouard, M., & Roux, N. (2020). Safeguarding and using global banana diversity: a holistic approach. *CABI A&B,* 1, 15. doi:10.1186/s43170-020-00015-6

Wimalasiri, E. M., Jahanshiri, E., Chimonyo, V., Azam-Ali, S. N., & Gregory, P. J. (2021). Crop model ideotyping for agricultural diversification. *MethodsX*, *8*, 101420. doi:10.1016/j.mex.2021.101420

Xiong, Y., Li, R., Lin, X., Zhou, Y., Tang, F., Yao, Y., Liu, J., Wang, L., Yin, X., Guo, J., Zhao, Y., & He, Y. (2021). Genome-wide analysis and expression tendency of banana (*Musa acuminata* L.)

calcineurin b-like (MaCBL) genes under potassium stress. *Horticulturae*, *7*, 70. doi:10.3390/horticulturae7040070

Zhang, J., Li, B., Zhang, J., Christie, P., & Li, X. (2020). Organic fertilizer application and Mg fertilizer promote banana yield and quality in an Udic Ferrasol. *PLoS ONE, 15*(3), e0230593. doi:10.1371/journal.pone.0230593