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Research Article

Performance of Cassava under Lime, Fertilizer, and Legume Intercropping on Exhausted Land in Northern Zambia

Peter Kaluba ,[1,2] Sydney Mwamba ,[2,3,4] Dany Pascal Moualeu-Ngangue ,[2] Martin Chiona,[5] Kalaluka Munyinda,[4] Etti Winter,[6] Hartmut Stützel,[2] and Benson H. Chishala[1]

[1]*Department of Soil Sciences, School of Agricultural Sciences, University of Zambia, P.O Box 32379, Lusaka, Zambia*
[2]*Institute of Vegetable Production Systems, Leibniz Universität Hannover, Herrenhäuserstr 2 30419, Hannover, Germany*
[3]*Seed Control and Certification Institute, Ministry of Agriculture, Chilanga, Zambia*
[4]*Zambia Agriculture Research Institute, Mansa Research Station, P.O. Box 710129, Mansa, Zambia*
[5]*Department of Plant Sciences, School of Agricultural Sciences, University of Zambia, P.O Box 32379, Lusaka, Zambia*
[6]*Institute for Environmental Economics and World Trade, KönigswortherPlatz 1 30167, Leibniz University of Hannover, Hannover, Germany*

Correspondence should be addressed to Peter Kaluba; kaluba04@gmail.com

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Cassava yields of 6 t ha^{-1} are lower than the potential yield of 20–25 t ha^{-1} obtained in Northern Zambia. It is grown in legume intercropping with little or no fertilizer, causing nutrient depletion with consequent land abandonment. Therefore, the study objective was to investigate the performance of cassava under lime, fertilizer, and grain legume intercropping on exhausted land in Northern Zambia. A split-split plot design experiment was conducted over two seasons, comprising two lime rates (0 and 300 kg ha^{-1}), two fertilizer rates (0 and 100N : 23P:80 K kg ha^{-1}), and three grain legumes (common beans, cowpea, and soybean) intercropped in cassava and sole cassava arranged in RCBD with three replications. Periodic measurements of leaf area index (LAI), light interception, weather data, and yield components were recorded. A linear mixed model with year as a random factor was performed to assess the treatment effect of lime, fertilizer, and legume species intercropping on cassava growth characteristics, radiation-use efficiency (RUE), and selected yield components. Lime, fertilizer rates, and legume species intercropping were assigned as main, sub-, and sub-sub-treatments, respectively. Fertilization and fertilization + lime treatments in sole cassava and cassava-common bean intercropping significantly increased the RUE and light extinction coefficient (k) compared to nonfertilized and only lime treatments. Lime x fertilizer x cropping system interaction was significant on chlorophyll index and plant height, RUE, tuber yield, HI, and total dry matter (TDM) yield. Cropping system x year interactions were significant on season LAI. On average, every kg of cassava yield loss in intercropping was compensated by 0.46 kg soybean, 0.20 kg common beans, and 0.26 kg of cowpea. NPK fertilizer + lime, NPK fertilizer, and grain legume intercropping may be adopted to increase cassava tuber yields and legume grain yield response on nutrient-depleted soils in high rainfall areas of Zambia.

1. Introduction

Sub-Saharan Africa (SSA) is the largest producer of cassava (*Manihot esculenta* Crantz) in the world, with more than half produced under intercropping systems [1]. Cassava intercropping with short-duration legumes crop is more productive than the sole-cropping of individual species [2]. Intercropping plants with different aerial and subterranean architectures increases the resource use efficiency for light, water, and nutrients [3]. Cassava intercropping with grain legumes has several advantages over sole-cropped cassava. It helps to reduce soil nutrient exhaustion [4] and maintenance of soil fertility [5], to improve yield stability [6], and to reduce the adverse effects of diseases, weeds, and pests [2, 7].

The low protein content of cassava validates the need for cassava grain legume mixes in order to satisfy dietary requirements [7].

Cassava is intercropped with legumes or cereals under shifting cultivation systems by resource-poor farmers in the tropics. The continuous cultivation of cassava with little or no inorganic fertilizer has led to nutrient mining and increased soil acidity [4, 9]. Therefore, smallholder farmers open a new piece of land after nine years. Recently, there is a rising population that has increased demand for food and fuel [11]. Furthermore, there is an increasing demand for cassava as a raw material by local agro- and industrial markets [10]. However, cassava intensification in response to commercialization under these low input systems may lead to loss and degradation of agriculture with consequent and food insecurity [4] due to reduced fallow durations [11, 12]. At the farm level, the restoration of soil fertility such as liming in tandem with legume intercropping is imperative to ameliorate soil acidity and increase the availability of inorganic fertilizers and other nutrients [13].

Cassava leaves grow slowly and take 3 months after planting to completely cover the ground, which makes the plant prone to early competition if planted with late maturing legumes [14]. Most grain legumes such as common beans (*Phaseolus vulgaris* L) and cowpea (*Vigna unguiculata* L. Walp) develop very rapidly and often complete their growth cycle in 90 days or less [15]. The legume species requires to mature before severe competition develops between the two species, thus minimizing effects on cassava growth and yield [16]. Willey [17] suggests that in cassava legume intercropping, competition should be minimized, and complementary effects be maximized. Despite such agronomic manipulation, intercropping may have detrimental effects on the performance of component crops. For example, Kawano and Thung [18] reported insignificant cassava yield reduction of 9–13% due to common beans or soybean intercropping at a plant density of 25 plants m^{-2}. Makinde et al. [19] observed 10–23% increase in the cassava yield due to soybean residue incorporation, but only after two years of cassava-soybean intercropping. Although the contributions from biological nitrogen fixation (BNF) by the legumes cannot be expected to meet the N needs of the cassava crop, it is still beneficial to the cassava crop.

Cassava productivity can be expressed as a function of radiation interception, radiation-use efficiency, and harvest index [20]. Several authors have reported higher total intercepted photosynthetic active radiation (TIPAR) and ascribed it to the higher leaf area index (LAI) at no water and nitrogen stress conditions [21]. Radiation-use efficiency (RUE) is defined as the amount of biomass accumulated per unit radiation intercepted. It is used as a key measure of the photosynthetic performance of field crops growing in different environments [22–24]. Mwamba et al. [25] have reported a significant higher fraction of intercepted photosynthetic active radiation (f), when nitrogen (N), phosphorus (P), and potassium (K) were applied at the rate of 100 : 23 : 80 kg ha^{-1} in cassava than at 0 kg ha^{-1} of at almost all stages of its measurement. Muchow [26] has reported lower RUE values of 0.72 and 0.60 g MJ^{-1} PAR and attributed them to the low specific leaf nitrogen. Pellet and EL-Sharkawy [27] have reported a significant increase in RUE, across cassava varieties by 41% in response to fertilization enhanced by increased LAI. Similarly, Ezui et al. [28] have reported high values of RUE in treatments with K fertilizer application at 50 and 100 kg K ha^{-1} of 1.26 and 1.29 g DM MJ^{-1} PAR, respectively, and 0.92 without K application. The RUE of fertilized crops is generally higher than that of unfertilized treatments [25, 27, 28].

The evaluation of the performance of cassava in common bean, soybeans, and cowpea intercropping systems under liming and NPK fertilizer on degraded land has rarely been assessed. This led us to the hypothesis that intercropping common bean, soybeans, and cowpea in cassava on abandoned degraded land with fertilizer and liming would still produce reasonable cassava yields. The radiation-use efficiency of cassava under degraded land could help model these systems and provide food security in the future. Therefore, the objective of this study was to investigate the performance of cassava under lime, fertilizer, and grain legume intercropping on exhausted land in Northern Zambia. The specific objectives of this study were to assess the effects of lime, NPK fertilizer, and intercropping grain legumes (common bean, cowpea, and soybeans) on cassava: (1) growth and development, (2) radiation-use efficiency (RUE), and (3) yield trade-off.

2. Materials and Methods

2.1. Description of the Study Area. The study was conducted at the Zambia Agricultural Research Institute (ZARI), Mansa, Luapula Province. The study site is located at a longitude of 28.9508 °E and latitude of 11.2414 °S at 1249 m above sea level. The area is located in agroecological region III, which receives above 1000 mm of rainfall annually, and the rainfall pattern is unimodal (Figure 1). According to the Köppen climate classification, Zambia is dominated by a humid subtropical climate [29]. The study was conducted for 2 years during the 2017–2018 and 2018–2019 growing seasons (Figure 1).

2.2. Establishment of Trial. The experiment was conducted at a site that had been abandoned for nine years following continuous cultivation of cassava. Prior to the establishment of the trial, 10 soil samples were collected randomly over the experimental area using a soil auger at 0–30 cm and thoroughly mixed to make a composite soil sample. The soil samples were dried and sieved through a 2-mm sieve before being analyzed for selected soil chemical and physical properties. Soil reaction (pH), soil texture, exchangeable acidity, soil carbon, total nitrogen, exchangeable cations, and phosphorus were determined (Table 1). All the analyses were carried out in triplicate. The particle size distribution was determined by following the hydrometer method [30], the soil organic carbon content was determined using the Walkley–Black procedure [31], the soil pH was measured in 1 : 2.5 soil-water suspension using a pH meter, the total nitrogen content by the Kjeldahl method with sulfuric acid

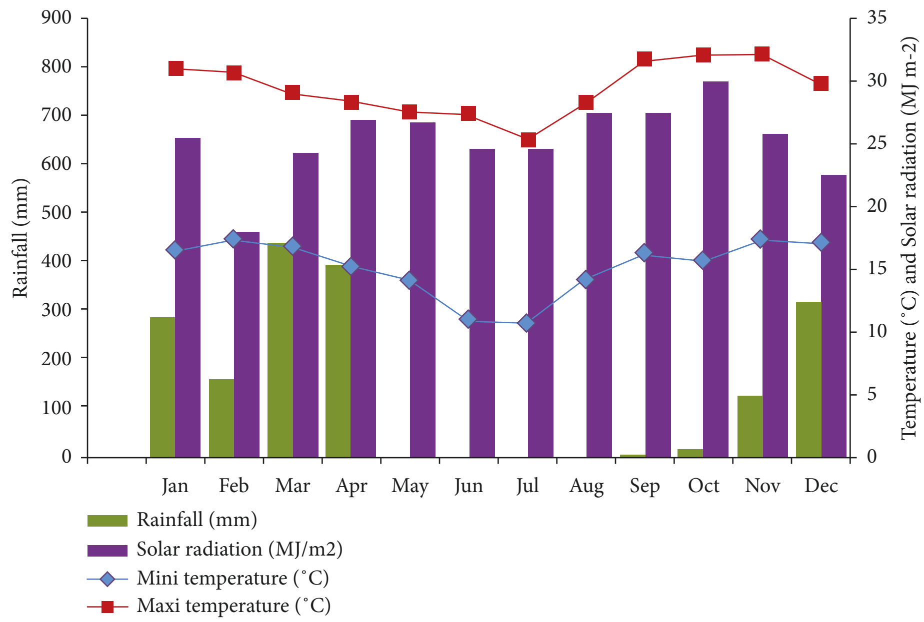


Figure 1: Mean monthly maximum and minimum temperature with total monthly rainfall for 2017–2018 and 2018–2019 seasons. The bar graphs show the total monthly rainfall and solar radiation, and the line graphs show the mean maximum and minimum temperatures.

Table 1: Selected physicochemical properties of topsoil (0–30 cm depth) of the experimental sites.

Soil parameter	Soil analysis	Cassava suitability production levels
pH (H_2O)	4.47	4.5–7.0
Total nitrogen (%)	0.015	0.20–0.50
OC (%)	0.39	2.0–4.0
C/N	26	
P (mg kg^{-1})	11	10–14
Exchangeable acidity (cmol kg^{-1})	0.54	
Exchangeable bases (cmol kg^{-1})		
K	0.07	0.15–2.5
Ca	0.865	1.0–5.0
Mg	0.165	0.4–1.0
Na	0.004	
Micronutrients (mgkg^{-1})		
Zn	0.64	0.5–1.0
Cu	5.18	0.1–0.3
Mn	51	5–10
Fe	71	1–10
Particle size (%)		
Sand	75	
Clay	4.8	
Silt	20.2	
Textural class	Sandy loam	

Cassava suitability production levels. Source: CIAT [36].

and selenium as a catalyst [32], available phosphorus was extracted using the Bray 1 method and colorimetrically measured using the molybdenum blue method [33], and exchangeable bases were extracted using ammonium acetate (NH_4OAc) buffered at pH 7. Magnesium and calcium in the extract were determined after strontium chloride addition using the atomic absorption spectrophotometer (AAS), while the other cations (Na and K) were determined using a flame photometer [34]. Exchangeable acidity was extracted using 1M KCl and quantified by titration [35].

The soil texture at the experimental area is sandy loam. The soil reaction was slightly acidic and in the critical optimum range of 4.5–7.0 for cassava production. The soil organic carbon and total nitrogen were very low and below the critical levels suitable for cassava production. The P levels were above the critical level of 11 mg kg^{-1}. The exchangeable K level was below the optimum range of 0.15–2.5 cmol kg^{-1} required for cassava production. The soils are classified as Ferric Acrisol in the FAO legend. These are characterized by highly weathered soils with low base cations and experience strong phosphorus fixation due to higher acidity. Daily rainfall was measured on each site using manual rain gauges. Daily solar radiation, daily minimum and maximum temperatures, air humidity, and wind speed data were obtained from the nearest weather station to the experiment site.

2.3. Description of Experimental Design and Treatments. The field experiments were conducted for two consecutive growing seasons of 2017–2018 and 2018–2019, and all crops were planted in early December. The experimental design was a split-split plot design in a completely randomized block (CRBD). The experiment was laid out as a 2 by 2 by 4 design comprising of two levels of lime—0 and 300 kg ha^{-1}, two levels of compound fertilizer—0 and 100 kg N ha^{-1}, and three types of grain legumes—common beans, cowpea, and soybean intercropped in cassava and sole cassava. These were replicated three times giving a total of 48 plots. Fertilizer rates of 0 and 100N : 23P:80 K kg N ha^{-1} were applied per plot prior to planting in early December of each year. The individual nutrient requirement from straight fertilizers of urea 46% (N) giving 217 kg of urea per ha was calculated to meet 100 kg ha^{-1} of N, triple superphosphate 46% (P_2O_5) giving 150 kg per ha to achieve the above phosphorous application rate 23 kg ha^{-1} and 50% muriate of Potash (K_2O) amounting to 160 kg ha^{-1} to meet 80 kg ha^{-1} of potassium. The lime application was done using the recommended rate in Agroecological Region III of Zambia following a lime requirement of 1.5 × Al (cmol kg^{-1}). The plot size was 4 m by 7 m with cassava planted at a spacing of 1 m by 1 m. The cassava variety Mweru, which matures in 12 months after planting, was used in the study due to its dominance among smallholder farmers. The varieties of common beans, cowpea, and soybean intercropped in cassava were Lukupa, Lutembwe, and Magoye, respectively, and exhibit an indeterminate growth habit. The common beans and cowpea had the earliest maturing period of 80 days compared to soybeans at 120 days. Three grain legume seeds were sown by interplanting on the ridge at a spacing of 0.10 m between the 1-m cassava intrarow spacing according to the farmers' practice. At two weeks after sowing, the plants were thinned targeting 100,000 plants/ha. At six weeks after sowing, the crop was sprayed with Karate (Lambda-cyhalothrin) 2.5 E C to control aphids. Weed control was achieved by traditional methods with the hand hoe through re-ridging and banking, to achieve a weed-free seedbed.

2.4. Data Collection. Data on grain legumes phenology included 50% flowering and physiological maturity, which was defined as the day when 90% of the pods were dry. For the grain weight assessment, 10 of the mature and ripened bean pods from each randomly selected individual plant within two middle rows were harvested for assessment. These samples were oven-dried at 60 to 65°C until constant dry mass. The number of pods $plant^{-1}$, seeds pod^{-1}, pod length, and 100 seed weight per plant was recorded. To obtain grain yield and pods, plants harvested from an area of 2 m × 5 m were dried in the sunlight before threshing and drying. Only data on grain weight at harvest are presented in this article.

Cassava growth characteristics were measured on 5 tagged plants located in the middle of the plot. In a 3 m × 3 m portion in the middle of the whole plots, six sequential harvests were taken at 85, 173, 240, 272, and 344 days after planting, and final harvests were at 410 days after planting (DAP). At each harvest, 10 plants were sampled and plant parts were separated into storage roots and shoots (leaves + stems), before determining the fresh weights using the digital balance. For the roots and stems, subsamples of 300 g, and 200 g of leaves, were sampled for dry weight determination. The materials were oven-dried to constant weight under 80°C for 48 hours. Dry matter was determined as a ratio of dry to fresh weight of the samples, while the harvest index (HI) was calculated as the ratio of storage root dry weight to total plant dry weight at harvest. For the legumes, the HI was computed as the ratio of grain yield to total dry biomass.

In each plot, the leaf area index and fraction of intercepted photosynthetically active radiation (f) were measured starting at 3 months after planting, thereafter a 2-month interval up to 6 measurements. The LAI and PAR were measured using the canopy analyzer (LI-2200, LICOR Inc., Lincoln, NE, USA) and line quantum sensor and LI COR 190R (LICOR Inc., Lincoln, NE, USA). For each plot, the daily fractional intercepted photosynthetically active radiation (f) was calculated on the basis of the ratio daily incident solar radiation (I_0) and solar radiation transmitted (I). All sets of measurements were taken under clear-sky conditions during a period of constant irradiance. Meteorological data including precipitation, air temperature and other relevant parameters were recorded daily at the study site. The radiation extinction coefficient (k) being the effectiveness with which canopy intercept radiation was calculated as the slope of the relationship between the daily fractional intercepted solar radiation and leaf area index (LAI) according to Veltkamp [37]:

$$\mathrm{Ln}\left(\frac{I}{Io}\right) = -k\mathrm{LAI}, \tag{1}$$

where I is light received under the canopy (three positions per plot), I_O is incoming light above the crop canopy, k is extinction coefficient.

The radiation-use efficiency (RUE) was estimated as the regression between the accumulated total above-ground biomass and cumulative intercepted photosynthetically active radiation [27]. RUE represents the effectiveness with which the common bean converts the intercepted radiation into dry matter. The photosynthetically active radiation (PAR) was assumed to be 45% solar radiation in this study.

2.5. Statistical Analysis. A linear mixed model with year as a random factor was performed to assess the treatment effect of lime and fertilizer rates and legume species intercropping (common bean, cowpea, and soybean) on plant growth characteristics, RUE, and selected yield components. Lime and fertilizer rates and legume species intercropping were assigned as main, sub-, and sub-sub-treatments, respectively. Where treatments differed statistically, the least significant differences (LSD) were used to separate the means at $p \leq 0.05$. For parameters where the "year x treatment" interaction was not significant, data were combined over years, and means were presented. Mean values were separated according to the LSD test at $P = 0.05$. Correlation analysis was performed using Pearson's simple correlation coefficients to test the strength relationship of variables and their strength of association. Statistical analyses were conducted in R-3.5.2 [38].

3. Results and Discussion

3.1. Impacts on Leaf Area Index and Fraction of Intercepted Photosynthetic Active Radiation (F). The effects of lime, fertilizer, and sole cassava and cassava-soybean, common bean, and cowpea intercropping (cropping system) on cassava leaf area index are presented in Figure 2(a). The mean LAI ranged from 1.51 to 2.37 with a mean of 1.96 in the first season. In the second season, the LAI ranged from 1.51 to 2.48 with a mean of 2.05. The fastest increase in LAI was recorded in the common bean and sole cassava compared to cassava-cowpea and cassava-soybean intercropping in both seasons. The canopy growth pattern reached a higher value after a few months of growth coinciding with the rain season. The development of cassava LAI was slow during the crop establishment phase up to the third month. The two sharp decreases at 170 and 272 days after planting corresponded to the cold and hot seasons of the year. This pattern is consistent with several authors who have reported that during drought and cold stress, there is a reduction in LAI, f, and dry matter partitioning to stems and leaves since the photoassimilates are mostly channeled to the growth of storage roots and only increase with the onset the rainfall [4, 28]. Generally, the final regrowth was high in fertilized treatments than in unfertilized treatments. These patterns are consistent with findings reported by several authors who have observed enhanced LAI for high soil fertility [25, 27, 28]. The reduced LAI during the cold and dry season corresponds to a mechanism, which allows the crop to consume limited amount of available water slowly during the dry season, resulting in greater dry matter gain during stress periods and larger water use efficiency [36]. Cassava leaves may also drop or fold to decrease the interception of sunlight, in turn decreasing leaf temperature and water loss [37, 39, 40].

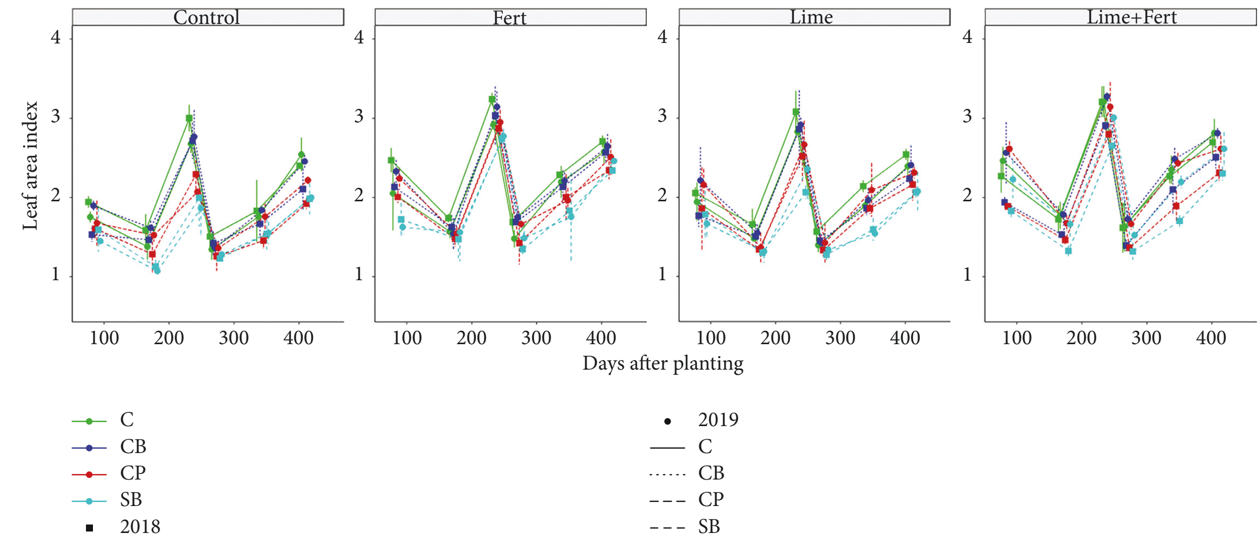
The significantly lower LAI of cassava in soybean intercropping is consistent with findings reported by Tsay et al. [16] in a cassava-soybean intercropping experiment. Contrary to our findings, Cenpukdee and Fukai [41] have reported the cassava LAI planted at 6.7 plants m^{-2} not to be affected in soybean intercropping. The unfertilized cassava regardless of the intercropped species developed a smaller LAI compared to the fertilized in both years, thus intercepted lower PAR (Figure 2(b)). The higher LAI in the mixed N : P: K fertilized treatments is attributed to significant increases in leaf expansion via cell division and enlargement [25, 42, 43]. There was a significant ($p < 0.05$) cropping system by year interaction on the LAI (Figure 2(a)). Soybean intercropping reduced the pooled cassava LAI by 21 and 16% in 2017–2018 and 2018–2019 season, respectively. The pooled cassava LAI reduction in cassava-cowpea intercropping was 16 and 6% in 2017–2018 and 2018–2019 season, respectively. The pooled cassava LAI reduction in cassava-common bean intercropping was 9.4 and 4.5% in 2017–2018 and 2018–2019, respectively. The positive effect of the cropping system by year interaction on the LAI indicates the need for routinely applying liming fertilizer and legume intercropping in cassava smallholder farming systems.

There was a significant ($p < 0.05$) cropping system by year interaction on f (Figure 2(b)). The f ranged from 38 to 84% across all the treatments for two seasons. Similar to the LAI, the cassava intercepted the lowest f at 170 and 272 DAP, which are the cold and hot seasons of the year. The highest intercepted f was achieved at 240 and 410 DAP for 2017/18 and 208/19 seasons, respectively, which coincide with the spring season and the peak of the rain season. The cassava in the cassava-soybean intercropping reduced the pooled f by 16 and 11% in the 2017–2018 and 2018–2019 season, respectively. The reduction in pooled f of cassava in cowpea intercropping was 13 and 6% in the 2017–2018 and 2018–2019 season, respectively. The reduction in pooled f of cassava in common bean intercropping was 6 and 1.8% in the 2017–2018 and 2018–2019, respectively. Fertilizer resulted in a 5 and 16% significant ($p < 0.001$) increase in f in the 2017–2018 and 2018–2019 season, respectively.

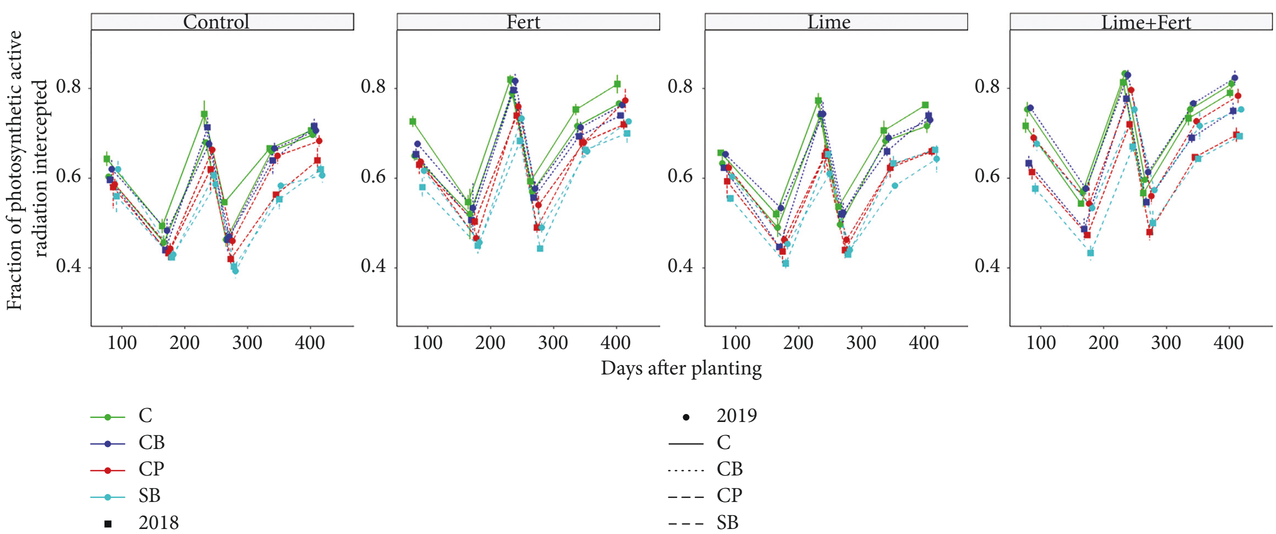
The low LAI and f in cassava-soybean and cowpea intercropping compared to the sole cassava and cassava-bean intercropping in this study results from crowding and competition for light. The soybean and cowpea grew vigorously and intercepted more f than the cassava and that the LAI and f only increased after the two legumes were harvested at 170 DAP. The f of cassava in common bean intercropping was not significantly different from sole cassava. This indicates that common beans did not strongly compete for light with cassava. The low f of cassava in legume species intercropping agrees with the results of Cenpukdee and Fukai [41] who have reported lower intercepted f in cassava in soybean intercropping at 6.7 plants m^{-2}, which only rose after harvesting soybean at 101 DAP and became similar to sole cassava.

3.2. Effects of Fertilizer and Year on the Canopy Extinction Coefficient (K) of Cassava under Legume Species Intercropping. There was a significant ($p \leq 0.05$) fertilizer by year interaction on k (Figure 3). Fertilizer application significantly increased the k value by 6.49% relative to the unfertilized treatments in 2018–2019 seasons. Fertilizer application was not significant on the k values in the 2017–2018 seasons relative to the unfertilized treatments. The canopy extinction coefficient ranged from 0.47 to 0.55 over the two growing seasons (Figure 3).

The k values obtained in this study are lower compared to the lower bound of 0.50–0.78 of cassava reported by Pellet and EL-Sharkawy [27]. Similarly, the k values in the study are lower than those estimated by Ezui et al. [28], which



(a)



(b)

Figure 2: Effects of intercropping soybean (SB), beans (CB), and cowpea (CP) on the cassava leaf area index (LAI) and fraction of intercepted PAR under various fertilizer and lime rate in 2017–2018 and 2018–2019 seasons.

ranged from 0.66 to 0.77 of cassava under different treatments with an overall value of 0.66. The author attributed the variation in k and RUE to variety. In the current study, the k values were higher for fertilized treatments than those for unfertilized treatments. This is attributed to enhanced better leaf positioning, due to differences in leaf curving and leaf angles among treatments. This result indicates that severe stress conditions such as no fertilizer application can modify the leaf angle and orientation, thus resulting in a lower k. These findings are consistent with those reported by the other authors who have reported low k values and attributed them to the modification of leaf angle and orientation in response to water deficits [42]. Similarly, Pellet and EL-Sharkawy [27] and Mwamba et al. [25] have reported fertilizer to significantly increase the k values of cassava varieties in Colombia and Zambia. Our results showed no significant differences in k between the unfertilized and fertilized treatments in the 2017–2018 season, which indicates a similar distribution of radiation within the canopies of the different treatments since the soils were of low soil fertility (Table 1), a result consistent with Bassu et al. [21].

3.3. Effects on the Radiation-Use Efficiency (RUE). The lime by fertilizer x cropping system x year interaction was highly significant ($p \leq 0.001$) on RUE (Figure 4). The positive response of RUE to lime by fertilizer x cropping system x year is due to the liming effect, which neutralizes the soil acidity, hence increasing the available nutrients for crop growth. The legumes in cassava intercropping further fixed the nitrogen and improved the organic carbon, which improves the soil fertility which is poor at the study site (Table 1). The strongest responses of RUE to lime x fertilizer x cropping system were in the second year, indicating the need for such

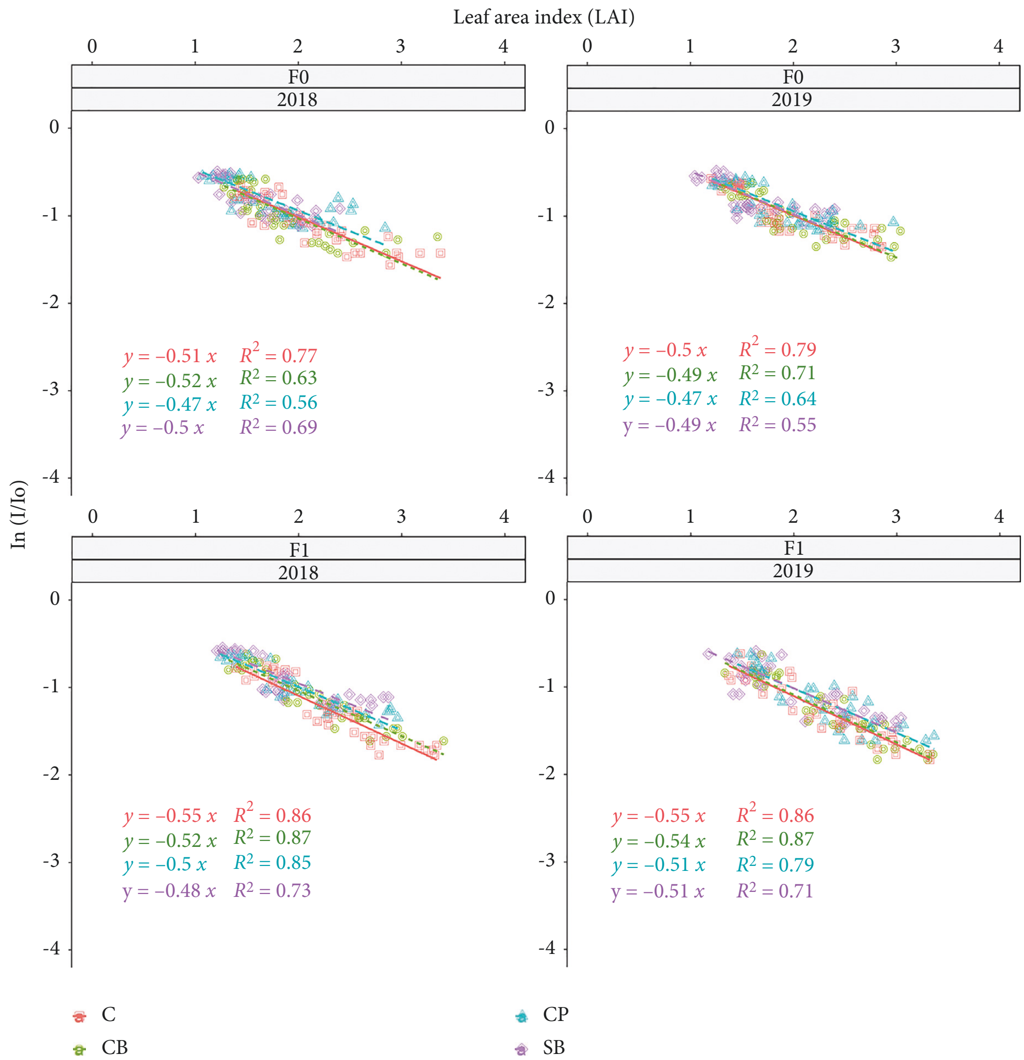


Figure 3: Effects of fertilizer and year on the cassava canopy extinction coefficient (k) under soybean (SB), common beans (CB), and cowpea (CP) intercropping.

practices to be incorporated in land management for sustainable land management for cassava production without resorting to deforestation.

The pooled RUE of 0.60–1.80 g DM MJ^{-1} PAR obtained in our study is lower than the lower bound of 1.34–1.40 g DM MJ^{-1} but higher on the upper bound reported by Veltkamp [34] during the first 6 months after planting (MAP) for four different cassava cultivars. However, Veltkamp [37] further reported a decrease in RUE at more than 6 MAP. The RUE values in our study were the lowest in unfertilized treatments compared to the lower bound of Pellet and El-Sharkawy [27] of between 1.15 and 2.30 g DM MJ^{-1} but within the range of the upper bound. The higher RUE values reported by Pellet and El-Sharkawy [26] could be ascribed to the higher rainfall regime of 1800 mm per year than to 1200 mm in the study area. The RUE values for individual treatments were variable and within the range of 0.55–2.30 g DM MJ^{-1} found by Ezui et al. [28] in West Africa. The higher RUE values on the upper bound found by Ezui et al. [28] compared to this study is attributed to the bimodal rainfall distribution with annual rainfall of 574–736 mm. The RUE values obtained in this study are comparable with those of Tsay et al. [16] who found 0.88 and 1.01 g MJ^{-1} PAR for cassava/soybean intercropping and sole cassava, respectively.

The significant increase in RUE is ascribed to the fertilizer, which enhances LAI growth, thus intercepting more f, which results in higher biomass per unit of radiation absorbed than in the unfertilized treatments. These findings are consistent with Pellet and El-Sharkawy [27] and Mwamba et al. [25] who observed different cassava genotypes to show a significant increase in RUE in response to fertilizer application and ascribed it to increased LAI. Similarly, Ezui et al. [28] observed the smallest values of RUE in treatments without fertilizer with an RUE of 0.92 g DM MJ^{-1} PAR without K application, and 1.26 and 1.29 g DM MJ^{-1} PAR with the application of 50 and 100 kg K ha^{-1}, respectively. Ezui et al. [28] explained the poor RUEs with a low K concentration in cassava due to highly deficient soil K, which consequently lowers the cytosol K^+ concentration.

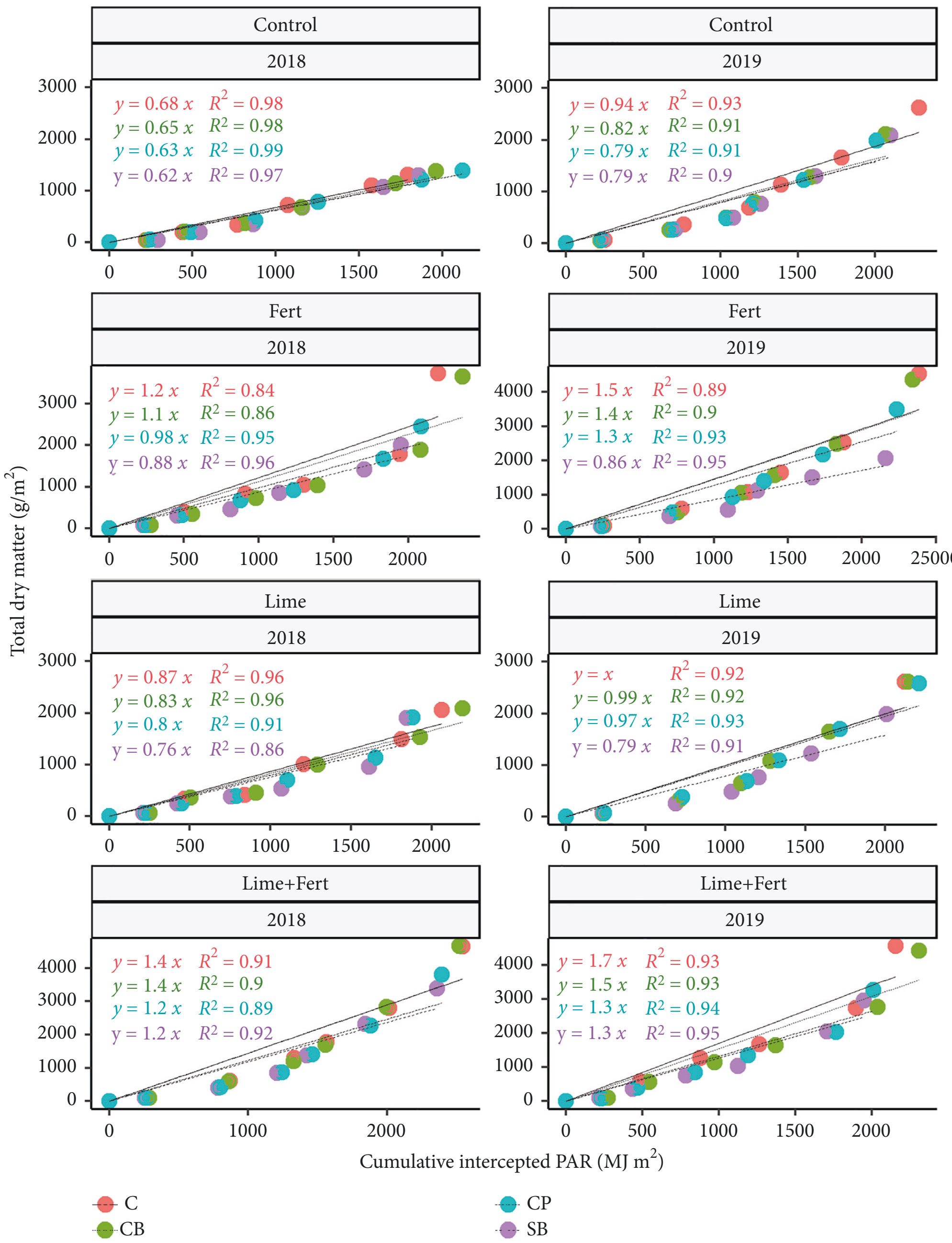


Figure 4: Interaction effects of fertilizer, lime, legume species intercropping, and year on the radiation-use efficiency.

Also, Uhart and Andrade [44] reported decreased RUE values due to nutrient deficiency. The RUE values of unfertilized treatments obtained in this study were very low suggesting that cassava is more stressed due to the poor soil fertility status explaining why farmers opt to abandon land.

The RUE values obtained within individual fertilized and individual unfertilized treatments were comparable within each group regardless of the lime and intercropping species. This indicates that the effects of lime take time and liming should be incorporated in cassava systems. The legume species intercropping effects on the comparable RUE are attributed to the fact that nitrogen fixation cannot substitute inorganic fertilizer and that soil organic matters build up from the legumes, which takes a long time. The beneficial effects of the legume nitrogen fixation and soil organic matter build up in cassava systems may require that legume species intercropping is done periodically. The exchangeable soil K in this study was 0.07 cmol (+) kg^{-1}, which was below the critical limit of 0.15–0.25 cmol (+) kg^{-1} suitable for cassava production. This could indicate that fertilizing NPK fertilizer on K-deficient soil may increase the RUE in the short run. Pooled over the seasons, the RUE was more strongly and significantly correlated (0.85^{***}) to fertilizer than TIPAR (0.53^{*}). This result agrees with those of Ezui et al. [28] who have reported that K fertilizers mainly affect the efficiency of converting light into photosynthates than the amount of light intercepted.

3.4. Effects on the Total Dry Matter Production (TBM) and Total Intercepted PAR (TIPAR). The pooled effects of lime, fertilizer, and legume intercropping on cassava total dry biomass (gm^{-2}) are presented in Figure 5. Generally, the fertilized and lime plus fertilized treatments had a higher TBM than unfertilized and limed only treatments regardless of the legume species intercropping. There was a highly significant ($p \leq 0.001$) interaction effect of lime by fertilizer by cropping system on total dry biomass (Figure 5). This is attributed to the combined effects of liming, which neutralized the soil acidity, resulting in more nutrients available for plant growth, and further, the legume intercropping fixed the nitrogen, which is limited in the study site soil (Table 1) and organic carbon.

The low dry matter production in cassava-soybean and cassava-cowpea intercropping was compared to the sole cassava and cassava-common bean intercropping. This is mainly attributed to vigorous growth of cowpea and soybean, which outgrew cassava, thus intercepting less PAR [41, 45]. The common beans had slightly affected the cassava TBM compared to soybean due to their shortest growing period of about 80 days. Since soybean took 120 days to harvest, this coincides with the sensitive period for cassava growing into a full canopy. Thus, the soybean severely competed for PAR more than the cassava resulting in low TBM (Figure 5). This result agrees with those reported by Willey [17] who reported a longer duration to maturing of grain legumes to cause more severe competition for light and is also consistent with Tsay et al. [16, 46, 47] who have reported soybean growth dominating cassava in intercropping and cassava only recovers after the soybean is harvested [16, 46–49].

Cassava TDM and tuber yield under intercropping were much less than those under sole-cropping at any harvest [38] (Figure 5). Tsay et al. [16, 46] reported a cassava N yield reduction due to soybean intercropping and attributed it to N competition as the major factor, which reduced the growth of intercropped cassava before soybean was harvested. However, several authors have reported the wider maturity gap between the grain legumes of about 90 days and 360 days for cassava combined by its slow initial growth to enhance their compatibility in intercropping systems [46, 47].

The TIPAR was highly significant ($p \leq 0.001$) and positively correlated ($r = 0.87$) with the cassava TDM yield. The linear relationship between TIPAR and TDM depicted that 59% variation in the TDM yield of cassava yield was explained by TIPAR. Pooled over the seasons, tuber yield was significantly related to RUE ($r2 = 0.85$, $p \leq 0.001$) and TIPAR ($r2 = 0.83$, $p \leq 0.001$). This indicates that 85 and 83% of the variability in the tuber yield can be explained by RUE and TIPAR, respectively. In the current study, the strong significant correlation between TDM and RUE and TIPAR visibly indicates that RUE and TIPAR are key factors for TDM and tuber yield formation as reported by Adeboye et al. [24]. Therefore, maximizing TIPAR and RUE via breeding large canopy cassava varieties, appropriate fertilizer, liming, and legume intercropping is vital for increased and stable cassava productivity on degraded land.

3.5. Effect on Yield, Yield Components, and Source Traits of Cassava across the Growing Seasons. Significant differences for lime x fertilizer x legume species intercropping x year were observed for chlorophyll index ($p \leq 0.05$) and plant height (0.005) (Table 2). There was a significant interaction effect of legume species x year on seasonal LAI ($p \leq 0.05$) and number of branches ($p \leq 0.01$). There was a significant interaction effect of fertilizer x legume species intercropping on number of tubers and tuber diameter. Lime x fertilizer x legume species intercropping had a significant effect on tuber yield ($p \leq 0.001$), total dry matter (TBM), and HI ($p \leq 0.001$) (Table 2, Figures 5 and 6). This is attributed to the combined effects of liming, which neutralized the soil acidity and made more nutrients available and stimulated the uptake of other nutrients by the crops. Furthermore, the legume intercropping fixed the nitrogen and provided organic carbon, which is limited in the study site soils (Table 1). The response of cassava tuber yield in fertilized and fertilizer + lime treatment (Figure 6 and Table 2 and 3) is lower than that of the findings by Howeler [4] who reported a significant yield increase of up to 162 to 172% in the first year to fertilizer application on exhausted soils.

Similar to this study, Carsky and Toukourou [13] also observed fertilizers' application in cassava to increase the uptake of nutrients, such as N, P, and K. Agbaje and Akinlosotu [50] reported that only sufficient K levels are required to stimulate cassava response to other nutrients such as N. In this study, the lime application neutralized the soil acidity and made more nutrients available for plant growth. Cassava tuber yield has been reported to respond positively to K when cassava is grown continuously in the same field [51]. The application of NPK fertilizer in this study ensured that the nitrogen increased the storage root DM, biomass DM, and intercepted PAR, while the K increased the RUE, storage roots, and biomass as reported by Ezui et al. [28].

The poor response in cassava yield to fertilizer and lime application could be attributed to the poor soil fertility levels (Figure 6 and Table 2). Similarly, Pypers et al. [2] have reported the nonsignificant increase in cassava yield to fertilizer application on soils with low fertility with consequent inefficient use of the fertilizer nutrients applied. Sanchez [52] suggests the use lime is applied to ameliorate soil acidity to have a short residual effect. The liming effects on degraded soils are significant starting from the second year of experiments [52]. Liming made available nutrients such as phosphorus for plant growth. Phosphorus is an important plant nutrient for plant growth and plays a role in plant metabolism, structure, and reproduction and a key element in energy transport in plants [53]This implies that P is a limiting

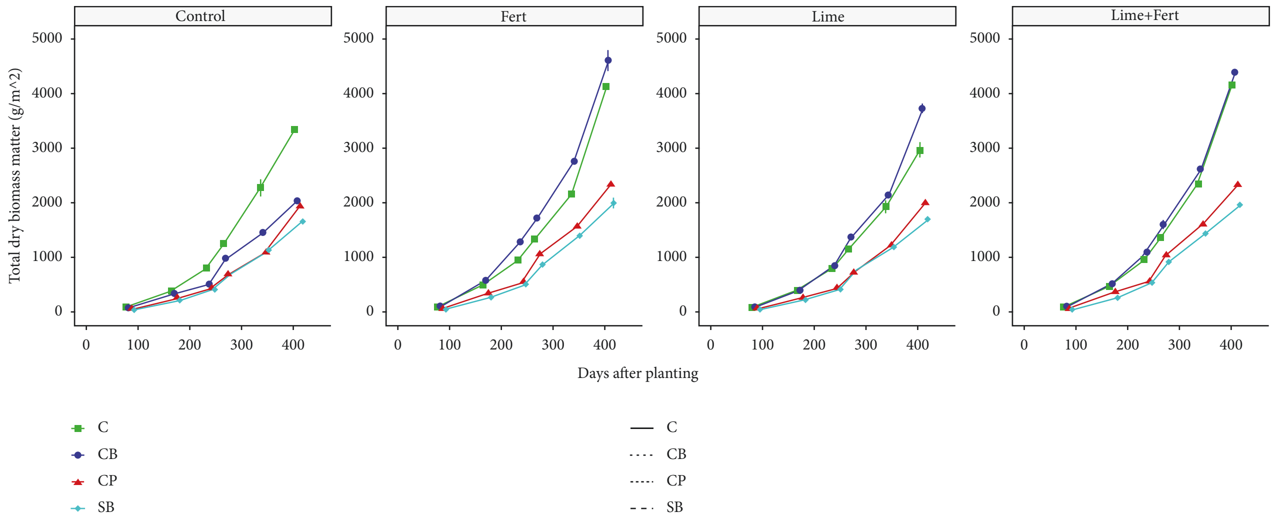


Figure 5: Effects of fertilizer on cassava total dry biomass (gm^{-2}) in monocropping (C), soybean (SB), common beans (CB), and cowpea (CP) intercropping pooled over two seasons (Fert-fertilized and Control-unfertilized + unlimed treatments).

Table 2: Analysis of the variance for lime, fertilization, cropping systems, and year effects, and their on interaction effects on yield, and physiological and morphological plant traits.

Source of variation	Seasonal LAI	Chlorophyll Index	Number of branches	Plant height (cm)	Number of Tubers	Tuber diameter (mm)	Tuber yield (t ha^{-1})	TDM (g/m^{-2})	HI
Lime	20.68***	484.10***	4613.60***	49.74***	17.17***	0.03 ns	7.80*	1.99 ns	31.44***
Fert	4613.60***	6687.86***	20.68***	3514.78***	342.06***	131.16***	2873.52***	1885.43***	717.71***
Cropping system	133.71***	150.19***	133.71***	19.56***	7.96***	17.47***	196.95***	42.14***	788.44***
Year	24.49***	262.26***	24.49***	1.97 ns	7.45*	0.03 ns	12.78***	3.47 ns	97.99***
Lime* Fert	18.70***	274.57***	18.70***	45.28***	2.95 ns	0.74 ns	0.37 ns	0.07 ns	4.61*
Lime* Cropping system	1.06 ns	10.38***	2.93*	15.74***	2.22 ns	0.46 ns	15.85***	11.33***	36.36***
Fert* Cropping system	2.93*	6.29***	1.06 ns	4.32*	**12.84** ***	**3.31** *	85.78***	114.93***	335.30***
Lime* Year	0.04 ns	2.52 ns	0.80 ns	0.01 ns	3.69 ns	0.55 ns	3.31 ns	0.77 ns	17.83***
Fert* Year	0.80 ns	2.71 ns	0.04 ns	25.16***	1.24 ns	0.07 ns	10.66*	0.16 ns	178.50***
Cropping system* Year	**2.79** *	3.15*	**2.79** *	1.47 ns	0.77 ns	0.08 ns	3.07*	9.75***	49.52***
Lime* Fert* Cropping system	1.09 ns	5.22*	1.09 ns	21.23***	0.53 ns	0.13 ns	10.50***	6.39***	9.45***
Lime* Fert* Year	0.08 ns	6.00*	0.08 ns	1.47 ns	0.50 ns	1.22 ns	0.12 ns	0.06 ns	8.86***
Lime* Cropping system* Year	2.05 ns	6.54***	0.50 ns	0.66 ns	0.45 ns	0.11 ns	2.51 ns	3.67*	2.33 ns
Fert* Cropping system* Year	0.5 ns	4.81*	2.05 ns	1.81 ns	0.99 ns	0.18 ns	**3.78** *	**5.28** *	**5.08** *
Lime* Fert* Cropping system* Year	1.32 ns	**4.06** *	1.32 ns	**4.66** *	0.31 ns	0.14 ns	2.00 ns	2.31 ns	40.41 ns

Sig. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 "" 1, ns: not significant. The bold shows the significant interaction effects on a trait or parameter.

factor for cassava productivity and production in highly weathered soils (Table 1). Therefore, rather than waiting for the land to degrade, the use of fertilizer and lime in tandem with legume intercropping could increase fertilizer use efficiently and increase both grain and cassava yield.

In this study, the highest cassava storage root yields were under common beans intercropping relative to other legume intercrops (cowpea and soybean) (Figure 6 and Table 3). The lower tuber yield and HI of cassava in cowpea and soybean intercropping is due to the severe competition, which slows the grow rate of cassava. This result agrees with those of Thung and Cock [14] who found common beans population not to affect cassava tuber yield. This result is similar to that of Eke-Okoro et al. [54] who observed the lowest cassava storage root yields

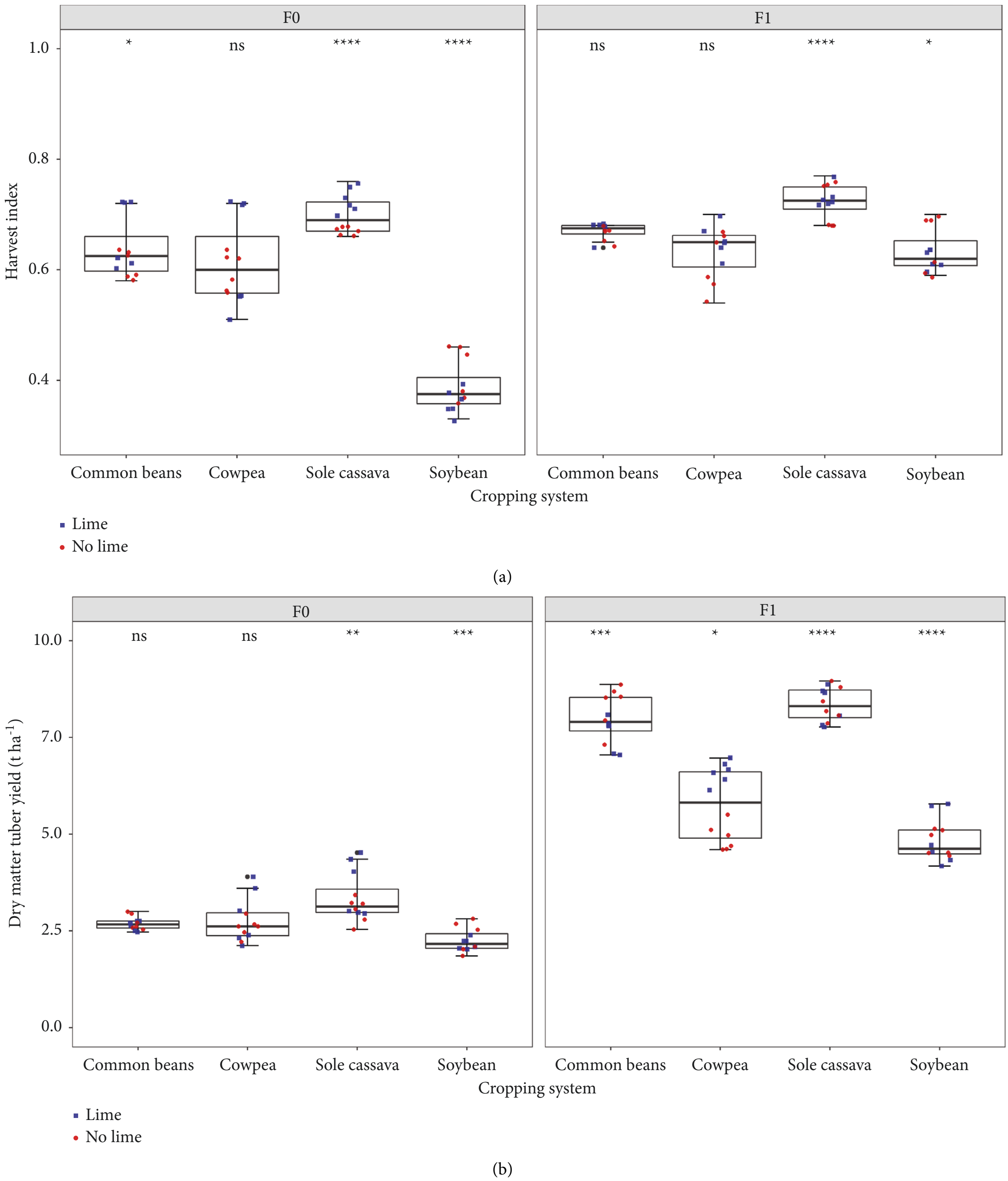


FIGURE 6: Interaction effects of lime, fertilizer, and cropping system on cassava tuber yield and harvest index pooled over two seasons (F1, fertilized, and F0, unfertilized, treatments).

when intercropped with soybean, cowpea, and bambara relative to groundnut. The plant height was the highest for the cassava in soybean, followed by cassava in cowpea, and common beans intercropping and sole cassava were the lowest (Table 3). This is evident that the cassava under intercropping responded by partitioning more assimilates to enhance height rather than to the root tubers in order to compete for light. The intercropping of legumes may build up organic matter and fix N, which can enhance K uptake and therefore contribute to increase RUE on N- and K-deficient soils. The liming reduces soil acidity making more nutrients available and ensures a quick increase in the tuber yield without nutrient depletion with the application of NPK fertilizers.

Table 3: Liming, fertilizer, cropping system, and year effects on cassava yield components across two growing seasons.

Treatments	Seasonal LAI	Chlorophyll Index	Number of branches	Plant height (cm)	Number of Tubers	Tuber diameter (mm)	Tuber yield (t ha^{-1})	TDM (t ha^{-1})	HI	RUE (g MJ^{-1} PAR)
Lime (300 kg/ha^{-1})										
0	1.90 ns	33.50 b	3.04a	131.0a	9.06a	60.17a	4.64a	7.35 b	0.62 b	0.95 b
300	1.82 ns	38.16a	2.81a	125.2 b	8.21 b	59.95a	4.84 b	7.54a	0.63a	1.12a
LSD (0.05)	0.037	0.992	0.2429	1.623	0.412	2.357	0.1481	0.242	0.006	0.026
Fertilizer (10 : 20 : 10 N : P : K kg/ha^{-1})										
0	1.23 b	27.17 b	2.74 b	104.0 b	6.73 b	53.3 b	2.754 b	4.82 b	0.58 b	0.83 b
200	2.50a	44.49a	3.10a	152.2a	10.54a	66.81a	6.725a	10.06a	0.66a	1.24a
LSD (0.05)	0.037	1.986	0.2429	1.623	0.412	2.357	0.1481	0.242	0.006	0.026
Cropping system										
Common beans	2.01a	36.99ab	2.91 b	127.1c	8.71a	62.09 b	5.325 b	8.08ab	0.65a	1.04 b
Cowpea	1.83ab	34.46bc	2.75bc	129.5 b	8.67 b	55.64c	4.248c	6.78c	0.62 b	1.02 b
Sole cassava	2.04a	38.85a	3.38a	123.6 d	9.29a	66.07a	5.845a	8.15a	0.71a	1.17a
Soybeans	1.57 b	33.02c	2.67bc	132.1a	7.88c	56.42c	3.541 d	6.75c	0.51c	0.90c
LSD (0.05)	0.053	0.599	0.3435	2.296	0.583	3.334	0.2094	0.342	0.009	0.037
2018	1.81a	34.11 b	2.5 b	128.7a	8.92a	59.96a	4.607 b	7.33a	0.61a	0.94 b
2019	1.91a	37.55a	3.35a	127.5a	8.35 b	60.15a	4.872a	7.55a	0.64a	1.12a
LSD(0.05)	0.037	0.992	0.2429	1.623	0.412	2.357	0.1481	0.242	0.006	0.026

Means with the same letter are not significantly different.

3.6. Effects of Legume Intercropping on Cassava Tuber Yield. Tuber yield of cassava trade-off in common bean, soybean, and cowpea intercroppings for the 2017–2018 (a) and 2018–2019 (b) seasons is presented in Figure 7. There was a reduction in cassava tuber yield intercropped with the three legume species. On average, every kg of cassava yield loss was compensated by 0.49 kg soybean, 0.19 kg common beans, and 0.23 kg of cowpea in the 2017–2018 season (Figure 7(a)). In the 2018–2019 seasons, every kg of cassava yield loss was compensated by 0.42 kg soybean, 0.21 kg common beans, and 0.28 kg of cowpea (Figure 7(b)). The large reduction in cassava tuber yield was compensated by the highest grain yields of soybean.

The obtained reductions in cassava yield as affected by legume intercropping's in this study are much lower than those reported by several other studies. This is attributed to the low legume density population and poor soil fertility status in the study area. For example, reductions of 40–50% in soybean [16], 20–40% common beans [7], 30% by cowpea in South America [55], 9–13% due to bean or soybean [17], and 22–36% and 44–48% due to soybean, maize, and cowpea [6]. Similarly, Pypers et al. [2] have reported a significant tuber yield loss of 6–8 t ha^{-1} when soybean was grown as the first legume intercrop in a 1 m × 1 m or 2 m × 0.5 m arrangement relative to beans or groundnut. Similarly to this study, Pypers et al. [2] have also reported poor tuber yields of 2–5 t ha^{-1} in common beans and groundnuts intercropping than in the current study. Contrary to this study, Makinde et al. [19] observed a 10–23% increase in cassava yield in after incorporation soybean residues in after 2 years of cassava-soybean intercropping. Contrary to this study, Cenpukdee and Fukai [41]found a higher mean tuber yield of 10.21 t ha^{-1} when intercropped with soybean than sole-crop yield at 9.46 t ha^{-1}, although the difference was not significant.

The higher soybean yield in this study (Figure 8(a)) is consistent with those reported by Tsay et al. [16] who reported soybean cultivars to dominate intercropped cassava, without affecting their dry matter growth and seed via competition. Contrary to this study, Cenpukdee and Fukai [41] found soybean yield was affected more severely by tall cassava with high TDM production during the early stages, thus reducing intercepted f by soybean. Severe shading was likely to account for its adverse effects on cowpea yield. Podding and seed formation of cowpea were severely affected because of shading [16]. The low yield of common beans could be attributed to the competition for nitrogen and severe shading from cassava.

3.7. Effects on Grain Yield and HI of Common Beans, Cowpea, and Soybeans. There was a significant lime x fertilizer x year interaction effect on the grain yield ($p \leq 0.001$) and HI ($p \leq 0.01$) of the three legume species (Figure 8(a) and 8(b)). Grain yield and HI were significantly increased in the fertilized and lime + fertilizer treatments than in the control.

Lime-only treatments (Figure 8(a) and 8(b)): in all treatments, soybean had the highest grain yield and HI followed by cowpea and common beans (Figure 8(a) and 8(b)). In both seasons, there was a relative increase in grain yield due to fertilizer application of 51–76, 44–52, and 67% for soybean, common beans, and cowpea, respectively. Common bean and cowpea yields were severely affected by light competition in cassava intercropping than soybean yield [17] and poor soil fertility status (Table 1). The low seed yield and HI of common beans agree with the findings of Tsay et al. [16] who reported soybean to produce low seed yield and attributed it largely to low the harvest indices.

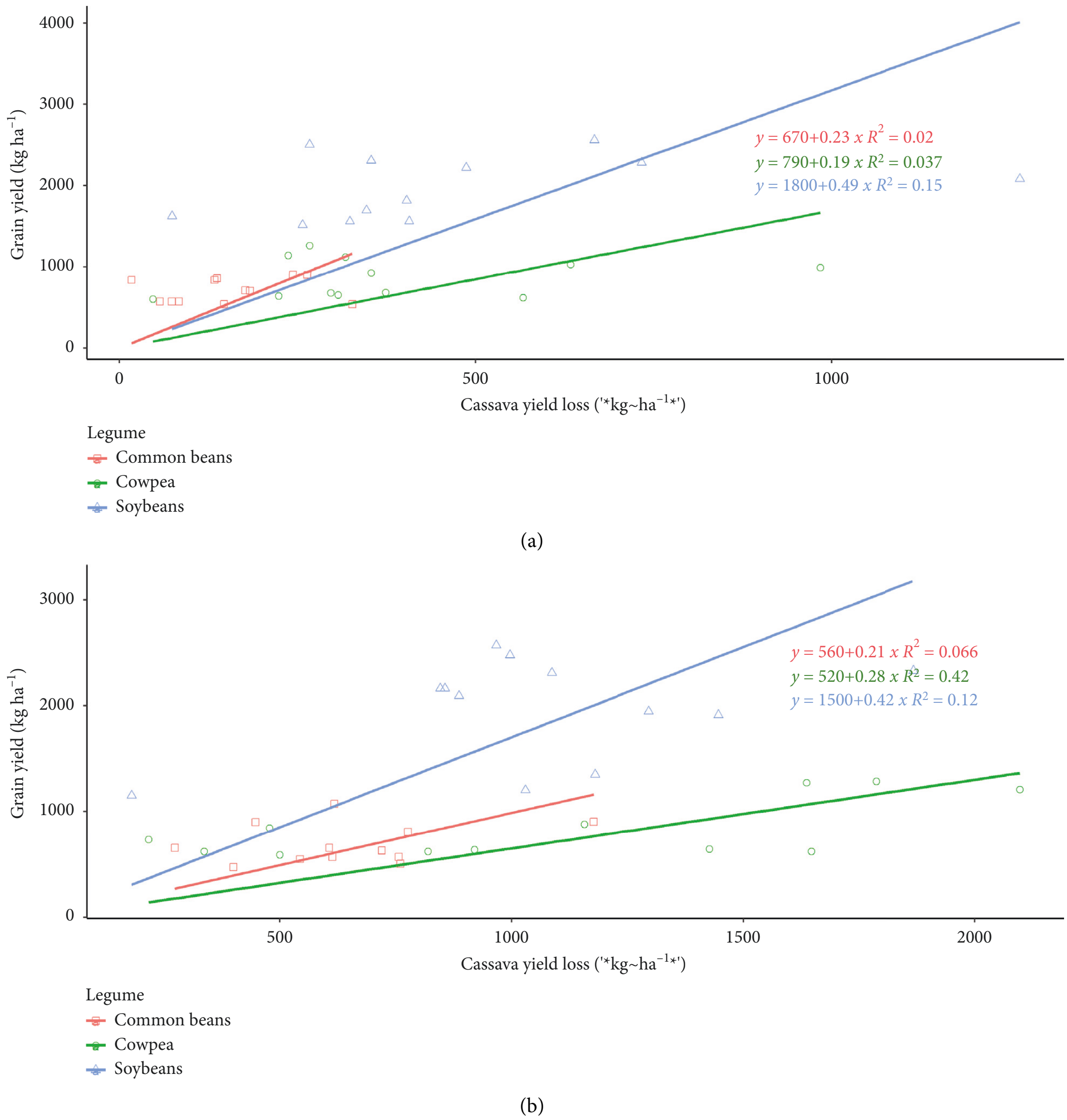
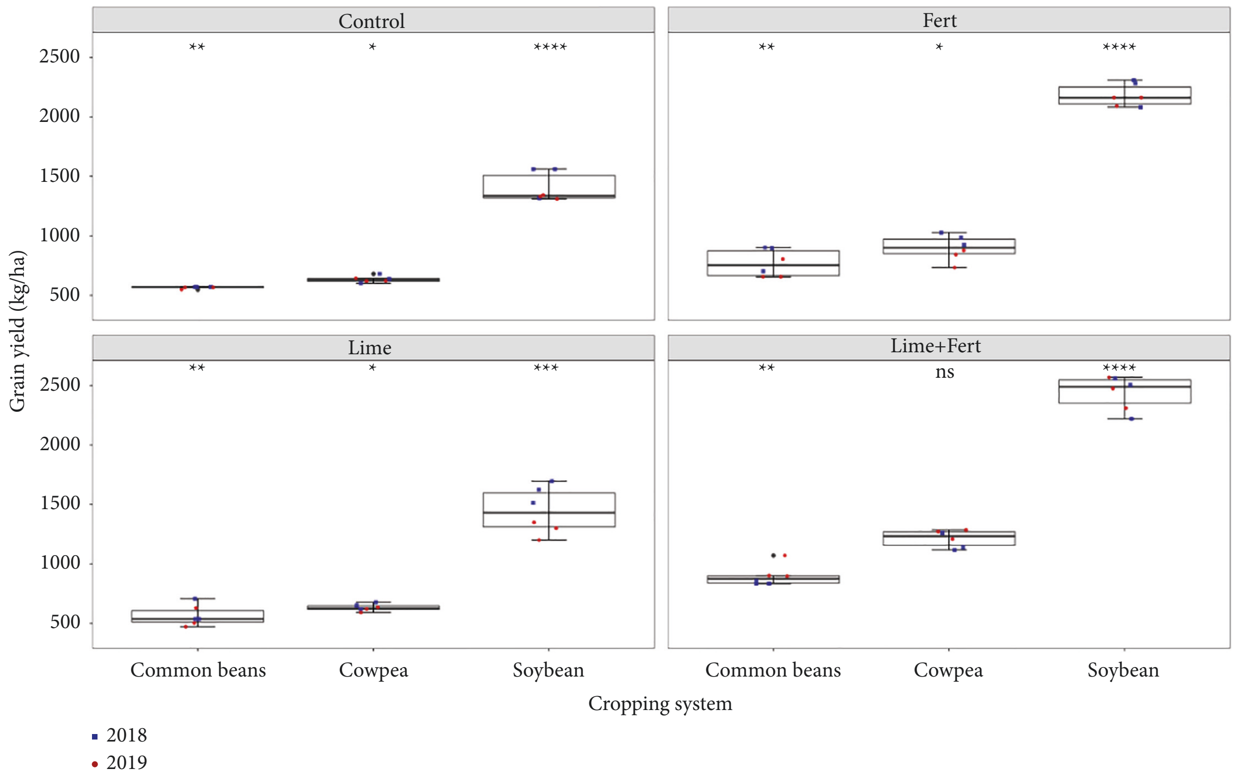
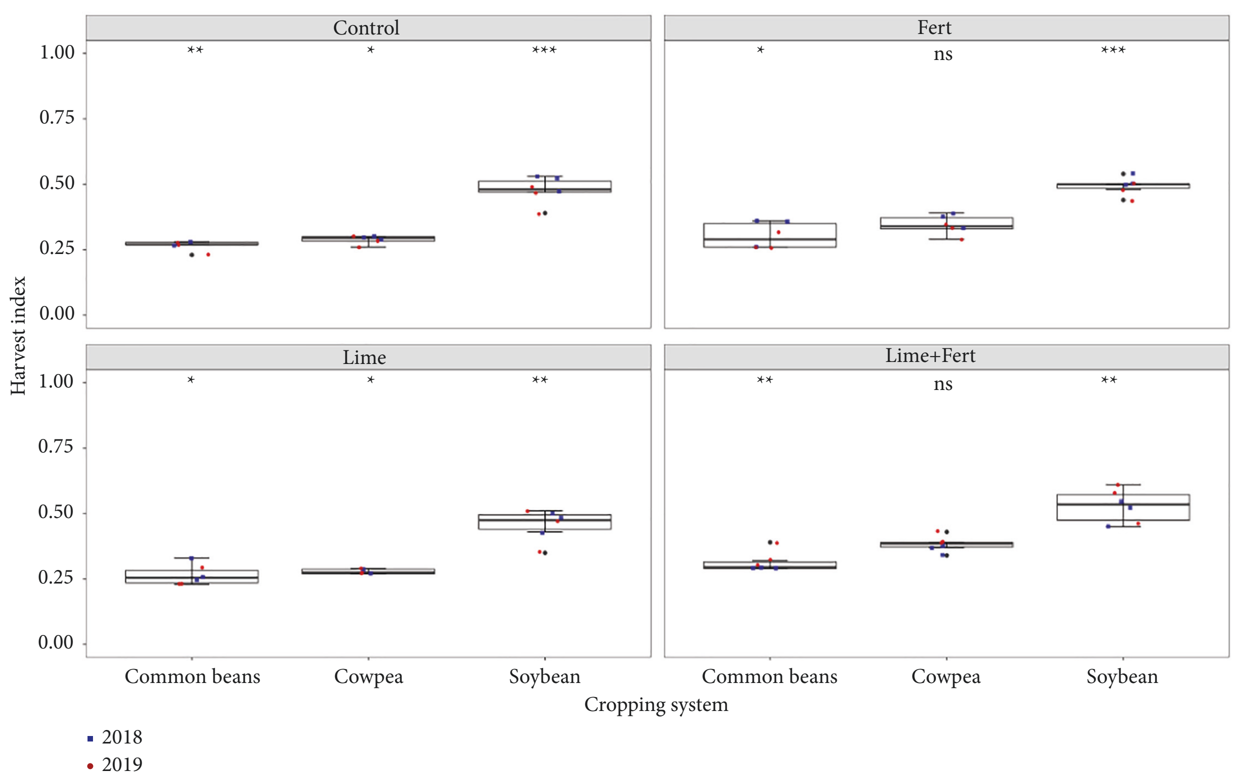


FIGURE 7: Tuber yield of cassava trade-off in common bean, soybean, and cowpea intercroppings for the 2017–2018 (a) and 2018–2019 (b) seasons, respectively.

Legume intercropping with short maturing period (common beans, cowpea, and soybean) can enhance the effects of lime and fertilizer on exhausted soils and allow smallholder farmers obtain reasonable cassava and legume yields. In this study, soybean and cowpea intercropping produced the highest grain yield than common beans. This is due the competitive effects of the two legumes and thus produced the lowest tuber yield (Figures 6 and 7). Similar to this study, Leihner [8] reported common beans and cowpea to be more suitable legume intercrops than soybean because of their shorter maturity period. Soybean reduced the cassava LAI, TIPAR, RUE, and tuber yield in this study. These findings agree with those reported by Makinde et al. [19] that intercropping late maturing soybean varieties have severe negative effects on cassava growth and production. However, Ennin and Dapaah [56] suggested delaying soybean planting or reducing the soybean crop density to reduce cassava yield penalties. Tsay et al. [16] have shown that cassava intercropped with early maturing soybean varieties recovers quickly, producing storage root yields similar to sole cassava. Total nitrogen was very low (0.015%) and below the critical levels suitable for cassava production. Thus, cassava could benefit from the nitrogen fixed by the soybean, common beans, and cowpea as well as from the organic matter via residues after harvest [5]. Assessment of RUE is vital in informing cassava growth models in simulating potential yields under rapid declining soil fertility characterizing shifting cultivation by smallholder farmers and provides sustainable management of abandoned fields, ultimately increasing food security without deforestation.



(a)



(b)

Figure 8: (a-b) Interaction effects of lime, fertilizer, and year on the grain yield and Harvest index of the three legume species.

4. Conclusion

The use of fertilizer and fertilizer + lime increased the leaf area index, which consequently captured more photosynthetic active radiation (PAR) and resulted in higher radiation-use efficiency (RUE) and tuber yield. The intercropping of legumes resulted in insignificant loss in cassava tuber yield for common beans compared to cowpea and soybeans. Intercropping these legumes in cassava over time may increase the organic matter content and also may help in fixing nitrogen while providing a cheaper source of protein, which ensures food security. Farmers should consider the fertilizer and lime rates used in this study in cassava grain legume intercropping to ensure sustainable use of land and food security. Tuber yield and total dry matter were strongly significantly correlated to RUE and total intercepted photosynthetic active radiation (TIPAR), indicating that RUE and TIPAR are key factors for total dry matter (TDM) and tuber yield formation. Therefore, maximizing TIPAR and RUE via breeding large canopy cassava varieties, appropriate fertilizer, liming, and short maturing grain legume intercropping is vital for smallholder farmers to increase and stabilize cassava productivity rather than abandoning degraded land [48, 49, 54]

Data Availability

All data supporting the conclusions of this article are included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

PK carried out the experiment and wrote the manuscript. SM helped with the field interview, cassava, and soil sampling, and HS and BCH initiated and suggested the experiments and are responsible for this study. SM helped to complete the plant and soil sampling in the field. SM performed the laboratory measurements. MC helped in government protocol and linkage between the farmers in the study area. KM helped in study location and read and approved the final manuscript. PK, SM, and DPM carried out the statistical analysis and reviewed the manuscript. AS created the figures and reviewed the manuscript. HS and BHC reviewed and finalized the manuscript. EI acquired the funding for the research and read the manuscript. All authors read and approved the final manuscript.

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