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# Cassava-maize intercropping systems in southern Nigeria: Radiation use efficiency, soil moisture dynamics, and yields of component crops

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ABSTRACT

Efficient utilization of incident solar radiation and rainwater conservation in rain-fed smallholder cropping systems require the development and adoption of cropping systems with high resource use efficiency. Due to the popularity of cassava-maize intercropping and the food security and economic importance of both crops in Nigeria, we investigated options to improve interception of photosynthetically active radiation (IPAR), radiation use efficiency (RUE), soil moisture retention, and yields of cassava and maize in cassava-maize intercropping systems in 8 on-farm researcher-managed multi-location trials between 2017 and 2019 in different agro-ecologies of southern Nigeria. Treatments were a combination of (1) maize planting density (low density at 20,000 maize plants ha$^{-1}$ versus high density at 40,000 maize plants ha$^{-1}$, intercropped with 12,500 cassava plants ha$^{-1}$); (2) fertilizer application and management targeting either the maize crop (90 kg N, 20 kg P and 37 kg K ha$^{-1}$) or the cassava crop (75 kg N, 20 kg P and 90 kg K ha$^{-1}$), compared with control without fertilizer application. Cassava and maize development parameters were highest in the maize fertilizer regime, resulting in the highest IPAR at high maize density. The combined intercrop biomass yield was highest at high maize density in the maize fertilizer regime. Without fertilizer application, RUE was highest at low maize density. However, the application of the maize fertilizer regime at high maize density resulted in the highest RUE, soil moisture content, and maize grain yield. Cassava storage root yield was higher in the cassava fertilizer regime than in the maize fertilizer regime. We conclude that improved IPAR, RUE, soil moisture retention, and grain yield on nutrient-limited soils of southern Nigeria, or in similar environments, can be achieved by intercropping 40,000 maize plants ha$^{-1}$ with 12,500 cassava plants ha$^{-1}$ and managing the system with the maize fertilizer regime. However, for higher cassava storage root yield, the system should be managed with the cassava fertilizer regime.

## 1. Introduction

In the future, there will be a growing scarcity of natural production resources for agriculture (Alexandratos and Bruinsma, 2012). Agricultural intensification as currently promoted aggravates competition for resources and can lead to overexploitation and unsustainable use of production resources such as water, soil, and nutrients (Kopittke et al., 2019). Land degradation and water scarcity are among the most visible manifestations of such unsustainable competition (FAO, 2017). It is estimated that overall 52% of agricultural land is already moderately or severely degraded as a result of agricultural crop commodification (ELD Initiative, 2015); a process which has resulted in little or no attention being paid to the traditional production systems of mixed- or intercropping. Intercropping is a traditional cropping system that supports the livelihoods of smallholder households (Fung et al., 2019) and possesses the potential to use natural resources such as nutrients and water more efficiently than sole cropping (Corak et al., 1987; Horton and Hart, 1998). Thus, intercropping offers opportunities of mitigating the

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challenges in current agriculture through species diversification and complementarity that results in increased resource use efficiency (Ogindo, 2003). For many farmers, a lack of adequate attention to intercropping systems has created barriers to improving livelihoods and escaping poverty (FAO, 2017; Rundgren, 2015). Hence, there is a need for locally adapted agronomic management strategies that improve the capture, conservation, and use efficiencies of natural production resources in crop mixtures.

In response to environmental factors, plants develop roots and canopy structures, absorb water and nutrients, intercept incident radiation, convert absorbed energy into photosynthates, and partition assimilates between plant components (Keating and Carberry, 1993). Solar radiation provides the energy for photosynthesis, which ultimately sets the potential for crop productivity (Murchie and Reynolds, 2013; Zhu et al., 2008). Naturally available incident solar radiation in the global tropics presents a great opportunity to improve crop production (Awal, Koshi, and Ikeda, 2006). Regrettably, incident solar radiation cannot be stored for later use by crops; hence strategies to improve its capture and instant utilization should be explored, especially under conditions where other production resources, such as water and nutrients, are also limiting.

Improved utilization of solar radiation, soil moisture, and nutrients, is demonstrated either by more efficient production of biomass or increased proportion of biomass partitioned to the desired sinks (Keating and Carberry, 1993; Kermah et al., 2017; Ogindo, 2003). Net biomass accumulation under optimal growth conditions has been shown to linearly relate to a cumulative light interception for crops, such as eggplant (Rosati et al., 2003), cassava (Ezui et al., 2017), wheat, pea, and mustard (O'Connell et al., 2004). The slope of this relationship, i.e., the amount of dry matter produced per unit of intercepted solar radiation, is termed the crop radiation-use efficiency (RUE) (Ezui et al., 2017, 1993). Furthermore, the relationship between the rate of leaf photosynthesis of crop canopies and solar radiation is approximately linear. This indicates that the rate of gross photosynthesis is largely determined by the radiation interception of the canopy (Green, 1987; Rosati et al., 2003).

Improved productivity per unit of incident radiation can result from the adoption of a cropping system that either increases the interception of solar radiation and or permits higher radiation-use efficiency (Keating and Carberry, 1993; Kermah et al., 2017) and increases transpiration relative to evaporation (Walker and Ogindo, 2003). This can be accomplished by manipulating field crops to minimize the proportion of radiation reaching the ground versus being captured by crops as demonstrated by Kermah et al. (2017) and Olasantan et al. (1994). With the right crop combinations and good management, intercropping can increase the capture and utilization of solar radiation (Awal et al., 2006) and conserve more soil moisture (Walker and Ogindo, 2003). It has been shown that the additional solar energy captured and utilized at favorable growing conditions by the intercrop canopy can lead to improved crop productivity, and thus greater economic yield (Awal et al., 2006; Keating and Carberry, 1993) compared to the sole cropping. Absorption of radiation by crop canopies depends on three factors: chlorophyll content of the foliage, spatial distribution and orientation of canopy constituents, and canopy area (Green, 1987). Solar radiation interception and radiation use efficiency, hence photosynthesis of leaves, was found to increase with N supply and subsequent increase in leaf N concentrations in many crops (Green, 1987; Rosati et al., 2003). Thus adequate nutrient management is required to maximize the efficiency of solar radiation capture and utilization in cassava-maize intercropping systems.

Cassava-maize intercropping is traditional and popular in southern Nigeria where solar radiation and rainfall are abundant. Maize can be harvested early in the season, i.e., 3–4 months after planting, for food and sales, while cassava can be harvested piecemeal starting from 9 to 12 months after planting in most cases, throughout the year (Rahmani, 2016). Reports have shown that the combination of short and long season crops enhanced radiation capture and efficient utilization through improved temporal patterns of canopy development compared to sole cropping: e.g., maize and groundnut (Awal et al., 2006), maize and cowpea or groundnut or soybean (Kermah et al., 2017), sorghum and pigeon pea (Natarajan and Willey, 1980), and pigeon pea and maize (Sivakumar and Virmani, 1980). Crops of long duration, such as cassava, have an initial slow increase in growth and leaf area development per unit of thermal time (Olasantan et al., 1994; Silva et al., 2016) and therefore have an extended period during which radiation is lost (Keating and Carberry, 1993). Intercropping such long duration crops (~ 8–18 months before final harvest) with species attaining maturity within 3–4 months, such as maize, can consequently provide the opportunity for enhanced radiation capture over time (Olasantan et al., 1996) and possibly reduce soil moisture loss via unproductive evaporation. However, such benefits are reduced or completely lost when crops with similar growth and development are intercropped (Keating and Carberry, 1993). Few reports on cassava-maize intercropping have investigated the overall system efficiency in solar radiation capture (Olasantan et al., 1994, 1996). Despite its popularity and the roles of cassava and maize in global food and nutrition security, especially for rural smallholder households, there is a lack of knowledge on the radiation use efficiency in cassava-maize intercropping systems.

Thus this study was designed to investigate the effects of maize planting densities and of N versus K dominant fertilizers on (i) the growth and development of cassava and maize as intercrops, (ii) the capture and utilization of photosynthetically active radiation (PAR), (iii) the soil moisture dynamics in the system, and (iv) the maize grain and cassava storage root yields in cassava/maize intercropping systems. We hypothesized that increasing maize planting density combined with the application of N dominant fertilizer in the system will improve the growth and grain yield of maize, that the application of K dominant fertilizer will improve the growth and storage root yield of cassava, yet that with fertilizer application the proportion of captured incident PAR, and thus the radiation use efficiency of the system will increase.

## 2. Materials and methods

### 2.1. The study area

The experiments were carried out in three agro-ecological zones: The Derived Savanna (DS) in Anambra State, the Rain Forest (RF) in Cross Rivers State, and the Guinea Savanna (GS) in Benue State (Table 1). Rainfall is bimodal with peaks in July and September and lasts for 7–8 months, spanning from April through October/early November. Rains begin in mid-April in Cross River, mid-May in Anambra, and mid-June in Benue. Usually, there is a short dry season or reduced rainfall in August. Typically, the months of November through early April are without rainfall, in very few cases, intermittent rains are experienced within this period.

### 2.2. Experimental design and treatment arrangement

A completely randomized block design with four replicates was implemented in both years, in each site. In 2017, two maize planting densities (LM: low density of 20,000 maize plants ha$^{-1}$ versus HM: high density of 40,000 maize plants ha$^{-1}$) were each intercropped with cassava at a density of 12,500 plants ha$^{-1}$ under a management of three NPK fertilizer rates that favor either the maize crop (FM: 90 kg N, 20 kg P and 37 kg K ha$^{-1}$) or the cassava crop (FC: 75 kg N, 20 kg P and 90 kg K ha$^{-1}$), next to a control without fertilizer application (F0). Thus, in total 6 treatments were installed: (i) cassava and low maize density at 20,000 plants ha$^{-1}$ without fertilizer (C-LM-F0), (ii) cassava and high maize density at 40,000 plants ha$^{-1}$ without fertilizer (C-HM-F0), (iii) cassava and low maize density at 20,000 plants ha$^{-1}$ with fertilizer (90:20:37 kg NPK ha$^{-1}$) targeting the maize crop (C-LM-FM), (iv) cassava and low maize density as in (iii) but with fertilizer (75:20:90 kg NPK ha$^{-1}$) targeting the cassava crop (C-LM-FC), (v) cassava and high maize density at 40,000 plants ha$^{-1}$ with fertilizer (90:20:37 kg NPK ha$^{-1}$) targeting the

**Table 1**
Location and characteristics of experimental sites, duration of crops on fields, and soil textures.

| Year | 2017 | | | | 2018 | | | |
|---|---|---|---|---|---|---|---|---|
| Location/site | Igbariam17 | Omogho17 | Ikom17 | Otukpo17 | Igbariam18 | Omogho18 | Ikom18 | Otukpo18 |
| Longitude | 6.3573°N | 6.0926°N | 5.9635°N | 7.2722°N | 6.3569°N | 6.0929°N | 5.9638°N | 7.2664°N |
| Latitude | 6.9517°E | 7.1550°E | 8.7708°E | 8.1875°E | 6.9514°E | 7.1551°E | 8.7702°E | 8.1756°E |
| Elevation (masl) | 65 | 76 | 107 | 138 | 62 | 78 | 113 | 156 |
| State | Anambra | Anambra | Cross River | Benue | Anambra | Anambra | Cross River | Benue |
| LGA | Awka North | Orumba South | Ikom | Otukpo | Awka North | Orumba South | Ikom | Otukpo |
| Agro-ecology | Derived Savannah | Derived Savannah | Rain Forest | Guinea Savannah | Derived Savannah | Derived Savannah | Rain Forest | Guinea Savannah |
| Previous crop(s) | Cassava-maize intercrop | Cassava-maize intercrop | Cassava-maize intercrop | Cassava-maize intercrop | Yam mini-set sole crop | Cassava-maize intercrop | Cassava-maize-groundnut intercrop | Cassava-maize intercrop |
| Soil texture | Sandy loam | Loamy sand | Sandy loam | NA | Sandy loam | Loamy sand | Sandy loam | Sandy clay loam |
| Year(s) under fallow | 3 | 2 | 2 | 2 | 0 | 1 | 2 | 2 |
| Establishment date | 15th August | 25th May | 8th June | 14th July | 6th June | 30th May | 5th May | 8th August |
| Maize duration | 3 MAP | 3 MAP | 3 MAP | 3 MAP | 3 MAP | 3 MAP | 3 MAP | 3 MAP |
| Cassava duration | 14 MAP | 13 MAP | 15 MAP | N.H | 12 MAP | 12 MAP | 11 MAP | 12 MAP |

LGA: Local government area, masl: meters above sea level; MAP: Months after planting; N.H: not harvested; NA: not available; Soil texture classification according to the Natural Resources Conservation Service (1993).

maize crop (C-HM-FM), (vi) cassava and high maize density as in (v) with fertilizer (75:20:90 kg NPK ha$^{-1}$) targeting the cassava crop (C-HM-FC) (Table 2).

To assess the effects of intercropping on the productivity of cassava and maize, the design was adjusted in 2018 to include in addition to the six treatments of 2017: (vii) a sole crop of low maize density at 20,000 plants ha$^{-1}$ with the maize targeted fertilizer (90:20:37 kg NPK ha$^{-1}$) (LM-S-FM), (viii) a sole crop of high maize density at 40,000 plants ha$^{-1}$ with the maize targeted fertilizer (HM-S-FM), (ix) a sole crop of cassava with the cassava targeted fertilizer (75:20:90 kg NPK ha$^{-1}$) (C-S-FC), and (x) a sole crop of cassava with the maize targeted fertilizer (C-S-FM) (Table 2). The timing of application and the nutrient ratio of 90:20:37 kg NPK ha$^{-1}$ was intended to benefit maize, while the 75:20:90 kg NPK ha$^{-1}$ was intended to benefit cassava.

Plots measured 7.2 m × 7.0 m (50.4 m$^2$) each at all sites, except for Igbariam17 and Igbariam18, where plots measured 7.2 m × 13.0 m (93.6 m$^2$) to allow for intermediate destructive plant observations. Blocks and plots were separated by 2 and 1 m pathways, respectively. Net plots for maize comprised the 4 internal rows of 5 and 5.25 m in length, corresponding to an area of 20 m$^2$ in the LM density treatments and 21 m$^2$ in the HM density treatments, respectively. The net plots for cassava comprised the 5 internal rows of 5 and 5.6 m in length, corresponding to an area of 28 m$^2$.

### 2.3. Site management and crop establishment

In Anambra (Igbariam17 and Igbariam18), and Benue states (Otukpo17 and Otukpo18) the soil was tractor ploughed, harrowed, and ridged at 1 m distance between ridges perpendicular to the field's gentle slopes. In Cross River state (Ikom17 and Ikom18), the field was manually tilled with the handheld hoe and planted on flat soil. At Omogho17 and Omogho18 (Anambra state) the field was ridged with the hand hoe at 1 m distance between ridges. The crest to crest distance between ridges was ensured by straight ropes stretched along the direction of the ridges. The differences in land preparations reflected farmers' choices on specific fields and areas.

In both years, maize variety, EVDT-Y 2000 STR C4 (SAMMAZ 35, yellow grain color) was used in Anambra and Cross River states, whereas variety, 2011-TZE-W DT STR Synthetic (SAMMAZ 48, white grain color) was used in Benue state. The maize varieties were chosen according to farmers' color preferences and market acceptability. All maize varieties were early maturing (~ 3 months) to limit competition between cassava and maize over time. SAMMAZ 48 is classified as a drought-tolerant variety, both varieties are resistant to *Striga hermonthica,* with yield potentials of > 4 Mg ha$^{-1}$ (NACGRAB, 2005). Cassava variety TME 419 was used in all states due to its high storage root and dry matter yields. TME 419 has a yield potential of > 90 Mg ha$^{-1}$ (Adiele et al., 2020). In addition to this, TME 419 is considered suitable for intercropping due to its relatively late branching habit (Eke-okoro and Njoku, 2012). Planting of cassava and seeding of maize was done on the same day (Table 1). Healthy cassava planting stakes of 20–25 cm length, with a minimum of 5 viable nodes, between 11 and 15 months old, were inserted to ¾ of their length into the soil in a slanting position along ridge crests or following a line on flat fields. Cassava was planted at 1 × 0.8 m to give 12,500 plants ha$^{-1}$. Maize was sown with two seeds per position at mid-slope of ridged fields, 25–30 cm away from the cassava stakes and exactly in the middle between cassava rows (50 cm from cassava) on flat fields. Germinated maize was thinned to one plant per position at 2–3 weeks after planting (WAP) in 2017 and at exactly 2 WAP in 2018. Maize spacing was 1 × 0.5 m for LM and 1 × 0.25 m for HM treatments making a total of 20,000 and 40,000 plants ha$^{-1}$, respectively.

### 2.4. Fertilizer application and management

The N dominant fertilizer, targeting the maize crop (FM regime) was applied at planting at a rate of 300 kg ha$^{-1}$ NPK (15:15:15) equivalent to

**Table 2**
Combination of the levels of maize density and NPK application in cassava-maize intercropping systems.

| Treatments in 2017 | C-LM-F0 | C-HM-F0 | C-LM-FM | C-LM-FC | C-HM-FM | C-HM-FC | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatments in 2018 | C-LM-F0 | C-HM-F0 | C-LM-FM | C-LM-FC | C-LM-FM | C-HM-FC | Sole LM FM | Sole HM FM | Sole C FM | Sole C-FC |
| Cassava planting density | 12,500 | 12,500 | 12,500 | 12,500 | 12,500 | 12,500 | Nil | Nil | 12,500 | 12,500 |
| Maize planting density | 20,000 | 40,000 | 20,000 | 20,000 | 40,000 | 40,000 | 20,000 | 40,000 | Nil | Nil |
| NPK ha$^{-1}$ rates in kg | 0:0:0 | 0:0:0 | 90:20:37 | 75:20:90 | 90:20:37 | 75:20:90 | 90:20:37 | 90:20:37 | 90:20:40 | 75:20:90 |

C: cassava (12,500 pants ha-1); LM: low maize density (20,000 plants ha-1); HM: high maize density (40,000 plants ha-1); FC: 75 kg N, 20 kg P, and 90 kg K ha-1; FM: 90 kg N, 20 kg P, and 37 kg K ha-1; F0: 0 kg N, 0 kg P, and 0 kg K ha-1.

45 kg N, 20 kg P, and 37 kg K ha$^{-1}$. Two equal dressings of 22.5 kg N ha$^{-1}$ as urea were applied at 3 and 6 WAP. The NPK fertilizer was applied in holes approximately 5 cm deep and located at the mid-slope between cassava and maize planting positions, or approximately 5 cm next to the maize on flat soil. Following the application, the holes were refilled with soil. Urea application at 3 and 5 WAP was done by making shallow furrows 10 cm away from maize plants along the ridges in the direction of the ridges, and the urea was evenly distributed along the furrow and covered with soil.

The K dominant fertilizer regime, targeting the cassava (FC), all P was applied as triple superphosphate (TSP) at planting (0 WAP: weeks after planting). It was followed by N and K application of 30 kg urea ha$^{-1}$ and 27 kg ha$^{-1}$ muriate of potash (MoP) at 4 WAP. The remaining amount of N and K was applied in 2 equal dressings as urea and MoP at 22.5 and 31.5 kg ha$^{-1}$, separately at 11 and 17 WAP. Maintaining the schedule for the last dose of urea and MoP at 17 WAP was not possible at Igbariam17 and Otukpo17, it could only be applied 5 months later due to lack of rain. The nutrient management and application scheduling decision was to increase plant uptake efficiency and minimize potential losses resulting from extreme weather events in our study environment.

### 2.5. Crop protection

Fall armyworm (*Spodoptera frugiperda*) infestation was controlled on maize plants by spraying a mixture of Ampligo; active ingredient *chlorantraniliprole* (5-bromo-N-[4-chloro-2-methyl-6-(methylcarbamoyl) phe nyl]-2-(3-chloropyridin-2-yl) pyrazole-3-carboxamide) at a dosage of 15 mL per 15-liter knapsack. Spraying targeted the maize funnels to ensure direct contact with the adult moths, eggs, and/or larvae. Ampligo application was repeated in 2017 as required by the reappearance of army-worm attacks. However, in the second year (2018), spraying was scheduled and done at 3 WAP and repeated every fortnight until anthesis. In Anambra state (both years) and in Cross River only in 2018, termites (*Isoptera*) were controlled with a mixture of Termex (active ingredient *imidacloprid*) by soaking planting stakes for 30 min in a solution of 10.5 mL Termex in 5 liters of water before planting.

### 2.6. Soil sampling and analyses

Soil sampling was done in the furrow of the control treatment (without fertilizer) in each block 3 months after planting in 2017 and 2018. It was not possible to sample the soils before planting because most farmers had already prepared their lands and were ready for planting. We could only do it after the soils had settled a bit after the maize harvest. Sampling was done using the trier type soil auger in a "W" pattern to 0 – 20 cm and 20 – 50 cm depths. Ten soil cores were sampled per depth and bulked to form a composite sample representing a block. The collected samples were broken down, mixed, air-dried, and passed through a 2 mm sieve. The samples were analyzed for physico-chemical properties by the analytical services laboratory of the International Institute of Tropical Agriculture, Nigeria. Organic carbon was determined by chromic acid digestion, total N by Kjeldahl digestion and colorimetric determination on a Technicon AAII autoanalyzer, and exchangeable K and available P by Mehlich-3 extraction (Mehlich, 1984), and pH in $H_2O$ on 1:2.5 soil/water ratio (Okalebo et al., 2002). Sand, clay, and silt contents were determined by the hydrometer method.

### 2.7. Soil and rainfall characteristics

In both years, the lowest K contents were recorded at Omogho (Table 4). The soils' textural classes are sandy loam at Igbariam17, Igbariam18, Omogho17, and Omogho18; loamy sand at Ikom17 and Ikom18; and sandy clay loam at Otukpo18. Omogho17 and Omogho18 had the highest sand and the lowest silt and clay contents (Table 4). Soil pH ranged from between 4.4 and 6.2 with Ikom17 and Ikom18 at the lower end and Otukpo18 at the upper end of the pH range. In both years, SOC was highest at Otukpo18 followed by Ikom, and Igbariam, and least at Omogho17 and Omogho18. Total N followed a similar pattern as SOC in both years. Available P was highest at Ikom17 and Ikom18, followed by Otukpo18, and Igbariam18.

Although the rainfall data reflected the typical characteristics of the studied agro-ecologies and states, it is important to mention that the observed difference within sites between years was mainly a result of the longer duration of the cropping season in the first than the second year (Table 1). Rainfall was less at Otukpo17 and Otukpo18; and at Igbariam17 and Igbariam18. The highest cumulative rainfall from planting till harvest was observed at Ikom17 and Ikom18 in both years; 3354 mm in 2017 and 2404 mm in 2018, followed by Igbariam17, Omogho17, and Omogho18 (Fig. 1).

### 2.8. Photosynthetically active radiation interception and volumetric soil moisture measurements

The incident photosynthetically active radiation (PAR) photon fluxes (μmol m$^{-2}$ s$^{-1}$) was recorded daily every half hour in ANA (Igbariam17 and Igbariam18) in the following selected treatments: C-LM-F0, C-HM-F0, C-LM-FM, and C-HM-FM (Table 3). The PAR was recorded using the Apogee QSO-S PAR Photon Flux (PAR sensor | METER Environment) connected to ECHO Em50 Dataloggers. To capture PAR fluxes below the crop canopies, a sensor was placed horizontally on the ground between two cassava stands, in the center of the net plot. A reference sensor to capture the above canopy incident PAR fluxes was fixed horizontally on a flat wooden surface above the crop canopies. PAR measurement lasted 4 months in 2017 and 3 months in 2018. The percentage intercepted photosynthetically active radiation (%IPAR) was calculated for each treatment using the formula:

$$\%IPAR = [1 - I_t / I_0] \times 100$$

where $I_t$ is the PAR measurement below the lowest leaf and $I_0$ is the incident PAR above the crop canopies. IPAR is expressed in MJ PAR m$^{-2}$.

The volumetric soil moisture content (VMC: m$^3$ water per m$^3$ of soil) was recorded every half hour in the same locations and treatments as the PAR with the Apogee EC-5 Soil Moisture sensors (probes) connected to the same ECHO Em50 data loggers (Table 3). A 0.5 m long × 0.5 m wide × 0.7 m deep pit was dug between two cassava plants within the net plots of the selected treatments at 15 days after planting (DAP) in 2017 and 18 DAP in 2018. To minimize damage to the maize roots, the pits were dug on the opposite side of the ridges with no maize stands. Thereafter, moisture probes were inserted into the undisturbed ridged portion.i.e., the wall of the pit. One sensor each was inserted at 20 and 50 cm depths of each pit (Table 3). After the insertions, the pits were

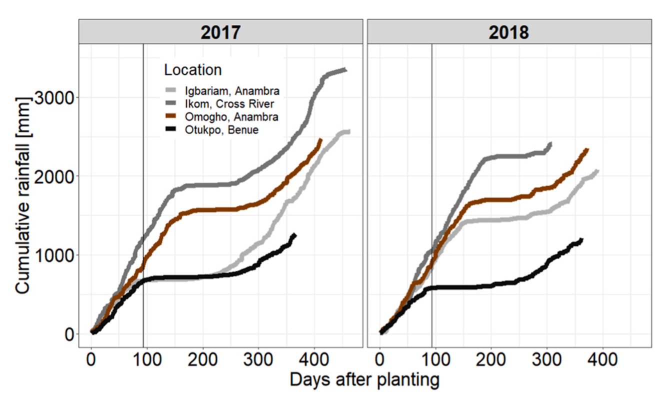


**Fig. 1.** Cumulative rainfall in the trial sites from planting until final harvest for each trial in 2017 and 2018. The horizontal line represents the day of maize harvest at physiological maturity.
Source: CHIRPS (2020).

**Table 3**
Photosynthetically active radiation and soil moisture sensors installations in selected treatments in 2017 (Igbariam17) and 2018 (Igbariam18).

| Sensor | Ref. | C-LM-F0 | C-HM-F0 | C-LM-FM | C-HM-FM | Num. of block | Igbariam17 | Igbariam18 |
|---|---|---|---|---|---|---|---|---|
| **PAR** | 1 | 1 | 1 | 1 | 1 | 3 | ✓ | ✓ |
| **Moisture** | | | | | | | ✓ | ✓ |
| 20 cm | | 1 | 1 | 1 | 1 | 3 | ✓ | ✓ |
| 50 cm | | 1 | 1 | 1 | 1 | 3 | ✓ | ✓ |

Ref.; reference PAR sensor above crop canopy; C: cassava (12,500 pants ha-1); LM: low maize density (20,000 plants ha-1); HM: high maize density (40,000 plants ha-1); FM: 90 kg N, 20 kg P, and 37 kg K ha-1; F0: 0 kg N, 0 kg P, and 0 kg K ha-1; 20 cm: 20 cm soil depth; 50 cm: 50 cm soil depth.

**Table 4**
Variation in soil physicochemical properties at 0 – 50 cm depth at Igbariam, Ikom, Omogho, and Otukpo in 2017 and 2018.

| | **Igabriam17** | | | | **Igbariam18** | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Min | Max | Mean | SEM | Min | Max | Mean | SEM |
| pH (1:2.5 $H_2O$) | 4.80 | 5.80 | 5.15 | 0.03 | 5.50 | 6.40 | 5.81 | 0.06 |
| Organic carbon (g $kg^{-1}$) | 3 | 6.2 | 4.2 | 0.1 | 4.2 | 9.6 | 6.2 | 0.4 |
| Total N (g $kg^{-1}$) | 0.03 | 0.05 | 0.03 | 0.00 | 0.03 | 0.09 | 0.05 | 0.00 |
| P (m $kg^{-1}$) | 0.24 | 3.41 | 1.10 | 0.11 | 0.17 | 4.37 | 1.73 | 0.33 |
| Exch. K (cmol $kg^{-1}$) | 0.06 | 0.61 | 0.18 | 0.02 | 0.11 | 0.33 | 0.18 | 0.01 |
| Sand (%) | 68 | 81 | 75.26 | 0.53 | 57 | 79 | 70.33 | 2.14 |
| Silt (%) | 2 | 5 | 3.53 | 0.12 | 4 | 11 | 6.66 | 0.49 |
| Clay (%) | 15 | 28 | 20.26 | 0.56 | 16 | 40 | 23.86 | 2.28 |
| | **Ikom17** | | | | **Ikom18** | | | |
| | Min | Max | Mean | SEM | Min | Max | Mean | SEM |
| pH (1:2.5 $H_2O$) | 4.20 | 4.80 | 4.45 | 0.03 | 4.90 | 6.00 | 5.50 | 0.16 |
| Organic carbon (g $kg^{-1}$) | 4.7 | 7.8 | 6.0 | 0.2 | 3.2 | 14.0 | 7.1 | 1.3 |
| Total N (g $kg^{-1}$) | 0.03 | 0.06 | 0.04 | 0.00 | 0.04 | 0.17 | 0.07 | 0.01 |
| P (m $kg^{-1}$) | 4.68 | 14.87 | 8.58 | 0.59 | 0.17 | 8.41 | 4.71 | 1.01 |
| Exch. K (cmol $kg^{-1}$) | 0.06 | 0.18 | 0.10 | 0.00 | 0.03 | 0.24 | 0.13 | 0.03 |
| Sand (%) | 60 | 80 | 68 | 1.46 | 69 | 82 | 76.28 | 1.56 |
| Silt (%) | 4 | 10 | 7 | 0.35 | 6 | 10 | 7.71 | 0.52 |
| Clay (%) | 16 | 36 | 25 | 1.40 | 12 | 24 | 16.57 | 1.42 |
| | **Omogho17** | | | | **Omogho18** | | | |
| | Min | Max | Mean | SEM | Min | Max | Mean | SEM |
| pH (1:2.5 $H_2O$) | 5.30 | 6.50 | 5.86 | 0.03 | 5.50 | 6.10 | 5.30 | 0.03 |
| Organic carbon (g $kg^{-1}$) | 2.4 | 5.9 | 3.6 | 0.1 | 2.8 | 6.1 | 3.2 | 0.1 |
| Total N (g $kg^{-1}$) | 0.008 | 0.04 | 0.02 | 0.00 | 0.003 | 0.03 | 0.02 | 0.00 |
| P (m $kg^{-1}$) | 0.24 | 1.82 | 1.00 | 0.04 | 0.28 | 1.71 | 1.00 | 0.03 |
| Exch. K (cmol $kg^{-1}$) | 0.06 | 0.16 | 0.09 | 0.00 | 0.05 | 0.12 | 0.08 | 0.00 |
| Sand (%) | 80 | 88 | 85.12 | 0.21 | 82 | 87 | 84.51 | 0.20 |
| Silt (%) | 1 | 5 | 2.43 | 0.13 | 1 | 5.10 | 2.15 | 0.13 |
| Clay (%) | 9 | 16 | 12.43 | 0.20 | 9 | 14 | 11.83 | 0.21 |
| | **Otukpo18** | | | | | | | |
| | Min | Max | Mean | SEM | | | | |
| pH (1:2.5 $H_2O$) | 5.40 | 6.90 | 6.20 | 0.19 | | | | |
| Organic carbon (g $kg^{-1}$) | 6.4 | 13.5 | 8.1 | 0.8 | | | | |
| Total N (g $kg^{-1}$) | 0.05 | 0.12 | 0.07 | 0.00 | | | | |
| P (m $kg^{-1}$) | 1.26 | 3.22 | 2.09 | 0.22 | | | | |
| Exch. K (cmol $kg^{-1}$) | 0.10 | 0.46 | 0.20 | 0.04 | | | | |
| Sand (%) | 42 | 68 | 53.16 | 3.49 | | | | |
| Silt (%) | 15 | 27 | 23.83 | 1.55 | | | | |
| Clay (%) | 16 | 32 | 22 | 2.48 | | | | |

SEM: standard error of the mean.

properly refilled with soil before connecting all the probes to data loggers. VMC measurements lasted for 6 months in 2017 and 3 months in 2018. The lack of uniformity in the collection of both the PAR and VMC data is a result of the destruction of our equipment by passersby in both seasons.

### 2.9. Crop growth and development measurements

The following measurements were carried out for maize: height, number of leaves, number of leaf collars, and the leaf area. For the cassava, stem length, stem girth, number of leaves, and canopy area were measured. In 2017, repeated measurements for the above listed maize parameters were done at 4, 6, 8, and 12 WAP at Igbariam17. In 2018 at Igbariam18, the measurements were done at 6 and 8 WAP only. This was because of logistics constraints that warranted the prioritization of management operations at other locations, particularly, ensuring that fertilizer was applied as scheduled. In 2018, measurements at Ikom18, Omogho18, and Otukpo18 were targeted at the peak of crop competition. Therefore, the maize height, number of leaves, number of leaf collars, and the leaf area measurements were done once at 8 WAP. For the cassava, the repeated measurements for stem length, stem girth, number of leaves, and canopy area were done at Igbariam17 at 4, 6, 8, 12, and 24 WAP in 2017. In 2018 at Igbariam18, the cassava stem length, stem girth, and number of leaves measurements were done at 6, 8, 12, and 24 WAP whereas the canopy area was measured at 6, 12, 24, and 36 WAP. Targeting the peak of the competition effect on cassava at Ikom18, Omogho18, and Otukpo18 in 2018, the parameters were measured only at 12 WAP. The measurements were carried out on 5 diagonally selected and tagged cassava-maize pairs' close enough for interactions in the intercrop treatments, or on either the cassava or the maize stands in sole crop treatments within the net plot.

Both the cassava stem length and maize height were measured with a measuring tape. The maize height (cm) was determined by measuring from the plant base at the soil level to the highest part of the leaf. The number of green leaves and leaf collars was counted. The leaf area (LA) was determined by measuring the length and width (widest point) on three leaves per plant; at the top, middle, and lower regions of sampled maize plants. The length and width values were multiplied by a constant factor of 0.75 (Montgomery, 1911 cited in Karatassiou et al., 2015), and the average value from the 5 plants was used for analysis. The leaf area index (LAI) was calculated according to Watson (1958) as the ratio of maize leaf area ($m^2$) per unit ground surface area ($m^2$). The cassava stem length (cm) was measured from the plant base at soil level up to the plant's apex; when a branch was present, measurement continued following one selected branch until its apex was reached. The cassava stem girth (mm) was gauged with a vernier caliper between 5 and 10 cm above the point where the main stem emerged from the planting stake. The canopy area was measured with the measuring tape by measuring the distance between the furthest apart leaves along and across the planting direction (ridges) of each sampled cassava plant. On branched cassava plants with no overlapping canopy, the canopy area of each branch was independently measured and summed for each plant (Ezui et al., 2017). Cassava canopy area was calculated as canopy area ($m^2$) per unit area ($m^2$).

Cassava and maize biomass were destructively sampled at Igbariam17 and Igbariam18. Sampling of biomass was done in both years at 4, 8, and 12 WAP. Four maize plants were sampled from an area of $1.0 \times 1.0$ m in the HM density treatments and on 2.0 m $\times$ 1.0 m in the LM density treatments. Three cassava plants were sampled from an area of $2.4 \times 1.0$ m in every cassava treatment. Sampling of maize was done by cutting plants at the base and recording the fresh weight of different parts – shoot and cobs when cobs were present. For cassava, sampling was done by uprooting the sampled plants, discarding the planted stakes, and retrieving the storage roots and shoots. The entire plant was partitioned into roots, stems (lignified stems when present), and green stems and leaves. For each crop, half of each part was sub-sampled per treatment and the fresh biomass was recorded before transportation to the plant handling laboratory of the National Root Crops Research Institute (NRCR) Umudike, Nigeria. The samples were oven-dried at 60 $^{o}$C until constant mass and the dry matter contents and yield (g $m^{-2}$) were determined.

### 2.10. Final harvests and yield assessments

#### 2.10.1. Maize

Maize was harvested at physiological maturity at 13 WAP. Maize plants were counted and cobs were removed from all plants in the net plots. The collected cobs were partitioned into four categories: (1) unfit cobs; these were cobs with no market value, (2) small cobs, (3) medium cobs, and (4) large cobs before the cobs were counted by category. This was specifically done to ensure that cob sampling for grain yield determination was a representation of cob yield in each treatment. Fresh weights per cob category were determined in the field using the Burgwächter digital hanging scale (200 g to 40 kg weight range with up to 10 kg $\pm$ 100 g accuracy). Thereafter, 2 representative cobs were selected from each cob category. Their fresh weights were recorded with a Camry digital kitchen scale (1 g resolution) before placing them in a properly labeled paper bag. The cob samples were oven-dried in the laboratory at 60 $^{o}$C to constant mass. After drying, the samples were shelled to separate the grains from the empty cobs and each component was weighed separately. Subsequently, the grain dry matter (DM) content was calculated before the fresh cob yields conversion to DM yield. Maize grain yields are expressed in Mg $ha^{-1}$.

#### 2.10.2. Cassava

The 2017 planted trials were harvested in 2018 at 13 MAP at Omogho17, 14 MAP at Igbariam17, and 15 MAP at Ikom17. The Otukpo17 trial was pilfered before we could harvest it. Harvesting of the 2018 planted trials in 2019 was done at 12 MAP at Igbariam18, Omogho18, and Otukpo18, and 11 MAP at Ikom17. Cassava plants within the net plot rows were uprooted manually from the soil and marketable storage roots were counted and weighed per plot using the Burgwächter digital hanging scale. These were only storage roots with a diameter $>$ 1.5 cm, without diseases or rot. From each plot, fresh storage root samples of about 400 g were collected. The sampled storage roots were sliced into 1–2 cm discs, taken to the laboratory, and oven-dried at 60 $^{o}$C to constant mass. The sample dry matter content was calculated and the fresh storage root yields converted to DM yield. Cassava storage root yields are expressed in Mg DM $ha^{-1}$.

### 2.11. Statistical analysis

All statistical analyses were done using the linear mixed-effects package ('lme4()') (Bates et al., 2015) in the Rstudio environment (R Core Team, 2020). Cassava storage root and maize grain yields, including non-repeated measurements in 2018 were analyzed across all locations, but separately for each year because our design differed in both years. For our linear mixed model, we used maize density, fertilizer regime, location, and their interactions as fixed factors; the blocks at each location were used as random factors. For the destructive and the non-destructive repeated measurements at Igbariam17 and Igbariam18, we used the repeated measurements approach for each location or year separately. Here, the maize density, fertilizer regime, sampling time (expressed in WAP), and their interactions were the fixed factors and the blocks, the random effect factor. For the IPAR and volumetric moisture content data at 20 and 50 cm soil depths, the average daily mean was computed from the daily half-hour measurements and used for analysis for each year. In this case, the sampling time was expressed in days after planting (DAP) and accordingly used in the model. The significance of differences was evaluated at $P \leq 0.05$ and $P \leq 0.01$. Data visualization was plotted in the Rstudio environment using the "ggplot2()" package command (Gómez-Rubio, 2017).

## 3. Results

### 3.1. Maize growth and development response to maize density and fertilizer regime

The analysis of the 2017 and 2018 maize growth and development data from Igbariam17 and Igbariam18 showed significant ($p < 0.001$) effects of maize density, fertilizer, and sampling times on maize height, visible leaf collars, leaf area index (LAI), and leaf production (only at Igbariam18) (Table 5). Except for leaf production, the parameters were highest at HM density (Fig. 2) regardless of cropping systems (Fig. 3). Similarly, maize growth and development were highest in the maize fertilizer regime treatments followed by the cassava fertilizer regime; worst performance was recorded in the control treatment at both sites. At Igbariam17 (in 2017), maize height, leaf collars, leaf production, and the LAI peaked at 8 WAP (Fig. 2). In 2018 (Igbariam18), maize height, leave collars, and leaf production were highest at 8 WAP, LAI was highest at 6 WAP.

Except for the LAI in 2017 (Igbariam17), no interactive effect of maize density and fertilizer; and maize and sampling times were observed (Table 5). In 2018, there were interactive effects ($p < 0.001$) of maize density and fertilizer; maize and sampling times; and fertilizer and sampling times (Table 5). In 2017, LAI was higher ($p < 0.001$) at high maize density in the maize fertilizer regime followed by in cassava fertilizer regime in sole and intercropping (Figs. 2 and 3). In the maize fertilizer regime at high maize density, LAI, height, and leaf collars were highest at all sampling periods in 2017 (Fig. 2). LAI peaked at 8 WAP and dropped afterward in 2017 (Fig. 2), peak in 2018 was at 6 WAP. In 2017, by 8 WAP in the high maize density treatments, LAI was 2.3 $m^2$ $m^{-2}$ in the maize fertilizer regime and 2.0 $m^2$ $m^{-2}$ in cassava fertilizer regime. In 2018, averaged across sampling times, at high maize density in maize

**Table 5**
Analysis of variance of treatments imposed during the experimental years in cassava-maize intercropping systems in 2017 and 2018.

| **Maize** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Source of variation | Height | | Leaf collars | | Leaf production | | Leaf area index | | Biomass | |
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Maize density | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 1.00 | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** |
| Fertilizer | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** |
| WAP | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** |
| Maize density × Fertilizer | 0.07 | 0.00 * ** | 0.20 | 0.00 * ** | 0.49 | 0.00 * * | 0.00 * ** | 0.00 * ** | 0.12 | 0.00 * ** |
| Maize density × WAP | 0.74 | 0.03 * | 0.27 | 0.00 * ** | 0.62 | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * * | 0.00 * ** |
| Fertilizer × WAP | 0.00 * ** | 0.00 * * | 0.00 * * | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * * | 0.00 * * | 0.00 * ** |
| Maize density × Fertilizer × WAP | 0.60 | 0.01 * | 0.28 | 0.57 | 0.93 | 0.00 * ** | 0.00 * ** | 0.02 * | 0.05• | 0.00 * ** |
| Location | – | 0.00 * ** | – | 0.01 * | – | 0.03 * | – | 0.01 * | – | – |
| Maize density × Location | – | 0.00 * ** | – | 0.00 * ** | – | 0.00 * * | – | 0.00 * ** | – | – |
| Fertilizer × Location | – | 0.00 * ** | – | 0.00 * ** | – | 0.00 * ** | – | 0.18 | – | – |
| Maize density × Fertilizer × Location | – | 0.50 | – | 0.00 * ** | – | 0.00 * ** | – | 0.22 | – | – |
| **Cassava** | | | | | | | | | | |
| | Stem length | | Stem girth | | Leaf production | | Canopy area | | Biomass | |
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Maize density | 0.58 | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.20 | 0.00 * ** | 0.24 | 0.00 * ** | 0.01 * | 0.03 * |
| Fertilizer | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** |
| WAP | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** |
| Maize density × Fertilizer | 0.41 | 0.08 | 0.55 | 0.13 | 0.72 | 0.25 | 0.33 | 0.00 * ** | 0.31 | 0.02 * |
| Maize density × WAP | 0.57 | 0.00 * ** | 0.52 | 0.00 * ** | 0.95 | 0.00 * ** | 0.28 | 0.00 * ** | 0.53 | 0.84 |
| Fertilizer: WAP | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * * | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * * | 0.02 * |
| Maize density × Fertilizer × WAP | 0.54 | 0.53 | 0.75 | 0.01 * | 0.98 | 0.02 * | 0.92 | 0.03 * | 0.73 | 0.88 |
| Location | – | 0.00 * ** | – | 0.00 * ** | – | 0.00 * ** | – | 0.00 * ** | – | – |
| Maize density × Location | – | 0.00 * * | – | 0.00 * * | – | 0.13 | – | 0.00 * ** | – | – |
| Fertilizer × Location | – | 0.00 * ** | – | 0.00 * * | – | 0.00 * ** | – | 0.00 * ** | – | – |
| Maize density × Fertilizer × Location | – | 0.03 * | – | 0.00 * ** | – | 0.00 * * | – | 0.23 | – | – |
| **Other parameters** | | | | | | | | | | |
| | Combined biomass | | Volumetric moisture content<br>2017 2018 | | | | Maize grain | | Storage root | |
| | 2017 | 2018 | 20 cm | 50 cm | 20 cm | 50 cm | 2017 | 2018 | 2017 | 2018 |
| Maize density | 0.00 * * | 0.00 * ** | 0.00 * ** | 0.00 * * | 0.00 * * | 0.00 * ** | 0.00 * ** | 0.04 * | 0.56 | 0.00 * ** |
| Fertilizer | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.18 | 0.00 * ** | 0.02 * | 0.00 * ** | 0.00 * ** |
| WAP | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * ** | – | – | – | – |
| Maize density × Fertilizer | 0.46 | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.53 | 0.00 * * | 0.36 | 0.90 | 0.14 | 0.52 |
| Maize density × WAP | 0.21 | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.43 | 0.00 * ** | – | – | – | – |
| Fertilizer × WAP | 0.01 * | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.00 * * | 0.00 * ** | – | – | – | – |
| Maize density × Fertilizer × WAP | 0.25 | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.01 * | 0.00 * ** | – | – | – | – |
| Location | – | – | – | – | – | – | 0.00 * ** | 0.00 * ** | 0.00 * ** | 0.23 |
| Maize density × Location | – | – | – | – | – | – | 0.40 | 0.80 | 0.84 | 0.10 |
| Fertilizer × Location | – | – | – | – | – | – | 0.70 | 0.95 | 0.00 * * | 0.03 * |
| Maize density × Fertilizer × Location | – | – | – | – | – | – | 0.89 | 0.71 | 0.52 | 0.77 |
| | IPAR | | | | | | | | | |
| | 2017 | 2018 | | | | | | | | |
| Maize density | 0.00 * ** | 0.00 * ** | | | | | | | | |
| Fertilizer | 0.00 * ** | 0.00 * ** | | | | | | | | |
| WAP | 0.00 * ** | 0.00 * ** | | | | | | | | |
| Maize density × Fertilizer | 0.03 * | 0.00 * ** | | | | | | | | |
| Maize density × WAP | 0.08 | 0.00 * ** | | | | | | | | |
| Fertilizer: WAP | 0.00 * ** | 0.00 * * | | | | | | | | |
| Maize density × Fertilizer × WAP | 0.07 | 0.03 * | | | | | | | | |

IPAR: Intercepted photosynthetically active radiation; WAP: weeks after planting.

fertilizer regime, LAI was significantly ($p < 0.001$) higher in intercropping (2.4 $m^2$ $m^{-2}$) than in sole cropping (2.1 $m^2$ $m^{-2}$).

There were maize density and fertilizer effects on the one-time point growth and development measurements on maize at 8 WAP at all locations in 2018 (Table 5). Treatment affected all variables in the same way at all locations. However, the worst response to fertilizer was recorded at Omogho18 (Supplementary Fig. A1:A4). Maize at high density was taller in the maize fertilizer regime than at low density. In most cases, maize height was slightly higher in intercropping than sole cropping (Supplementary Fig. A1). Fertilizer effect at Igbariam18, Ikom18, and Otukpo18 was in the following order: FM > FC > F0; at Omogho18: FM = FC > F0. At high maize density intercropping (C-HM), maize leaf collar was highest (Supplementary Fig. A2). Regardless of maize density, intercropping on average resulted in highest leaf production only at Igbariam18 and Ikom18. With or without fertilizer application, LAI was highest at high maize density at Igbariam18 and Ikom18, and in sole cropping at Omogho18 (Supplementary Fig. A4). No apparent difference in LAI was observed between the sole and intercropped maize at high maize density at Otukpo18 (Supplementary Fig. A4).

### 3.2. Cassava growth and development response to maize density and fertilizer regime

In 2017 (Igbariam17), maize density did not affect the cassava stem length, leaf production, and canopy area from 4 to 24 WAP (Table 5). However, in 2018 (Igbariam18), both the maize density and fertilizer application affected cassava stem length, stem girth, leaf production, and canopy area. Stem diameter was smaller ($p < 0.001$) in the high maize density treatments compared with low density treatments in both years (Figs. 4 and 5). In the maize fertilizer regime, longer stems, larger diameters, more leaves, and larger canopy areas were observed than in the cassava fertilizer regime in both years (Figs. 4 and 5). Within the periods of our measurements (4–24 WAP) at Igbariam17, stem length

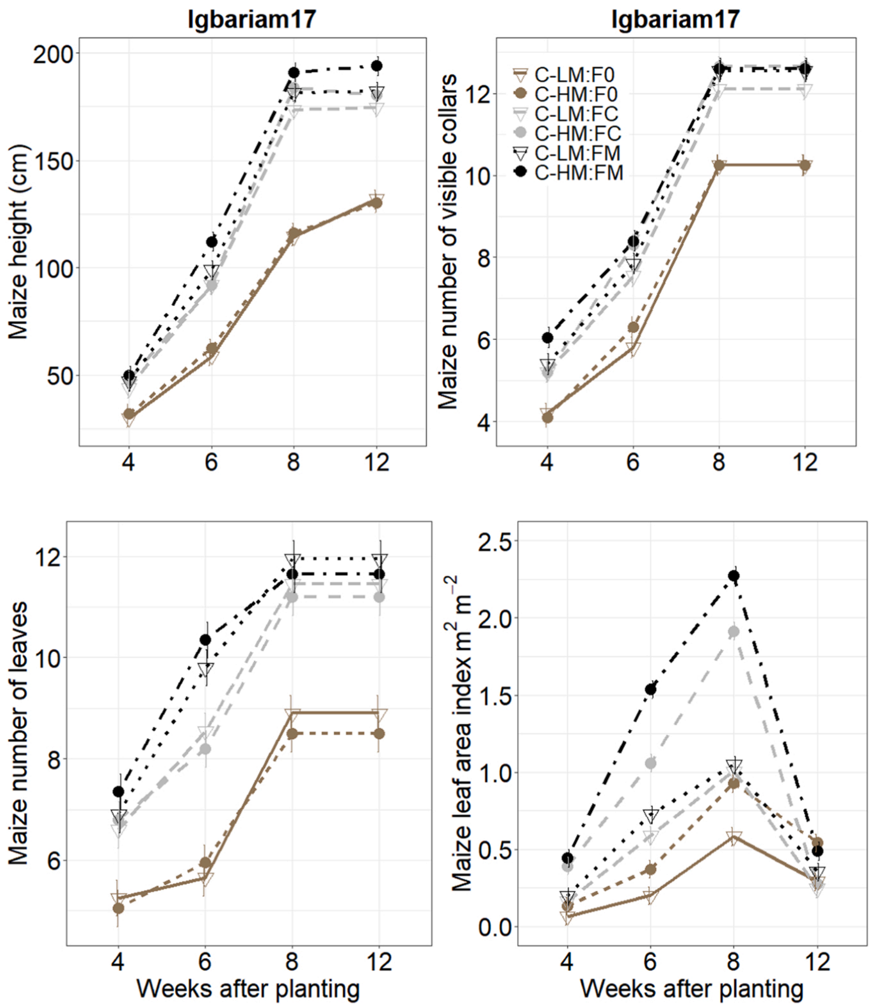


**Fig. 2.** Maize height, visible collars, leaf production, and leaf area index over time as affected by maize planting density and NPK application in cassava-maize intercropping systems at Igbariam17 in 2017. **C:** cassava at 12,500 $ha^{-1}$; **LM:** low density maize (20,000 $ha^{-1}$); **HM:** high density maize (40,000 $ha^{-1}$); **F0**: no fertilizer applied; **FM:** fertilizer application at 90 kg N $ha^{-1}$, 20 kg P $ha^{-1}$ and 37 kg K $ha^{-1}$; **FC:** fertilizer application at 75 kg N $ha^{-1}$, 20 kg P $ha^{-1}$ and 90 kg K $ha^{-1}$. Error bars represent standard errors of the mean.

and diameter were at their maximum at 24 WAP. Leaf production and canopy area peaked at 12 WAP and declined afterward (Fig. 4). The trend was similar at Igbariam18 except that canopy volume observation until 36 WAP showed that this parameter increased again after declining at 24 WAP (Fig. 5). Regardless of maize density, all the parameters we measured were highest at sole cropping (Fig. 5).

Out of all the possible interaction effects, only the interaction between maize density and fertilizer was significant for canopy volume in 2018 (Igbariam18); maize density and sampling time for all the parameters in 2018; and fertilizer regime and sampling time for all the parameters in both years (Table 5). Canopy volume was higher in the cassava fertilizer regime than in maize fertilizer in sole and intercropping treatments. Similarly, stem length, stem girth, leaf production, and canopy volume were higher in sole cropping than intercropping; the poorest of the parameters were observed in the high maize density intercropping (Igbariam18 data). At 24 WAP, stem diameter and stem length were highest in the maize fertilizer regime at Igbariam17. In 2018 (at Igbariam18), no apparent differences were observed for the parameters between both fertilizer regimes. Averaged across treatments, leaf production and canopy area declined after 12 WAP in 2017 (Fig. 4). Our results from 2018 showed that canopy volume would later increase by 36 WAP (Fig. 5).

The one-time point cassava growth and development results at 12 WAP from 2018 showed effects of maize density and fertilizer at all locations (Table 5). Canopy area was largest in sole plots followed by intercropping at low maize density (Supplementary Fig. B1). Regardless of maize density at all the locations, canopy area was larger in the maize fertilizer regime than in the cassava fertilizer regime. No fertilizer application resulted in the least canopy area. No significant effect of maize density on stem length was observed at Ikom18 and Otukpo18, which was not the case at Igbariam18 and Omogho18 (Supplementary Fig. B2). Regardless of maize density across cropping systems and at all the locations, stem length was highest in the maize fertilizer regime. In general, response to fertilizer was least at Omogho18. Leaf production per plant was significantly highest at all locations in the maize fertilizer regime in sole cropping. In intercropping situations, leaf production was highest at low maize density in the cassava fertilizer at Igbariam18 and Ikom18. At Omogho18 and Otukpo18, leaf production was highest at low maize density in the maize fertilizer regime. Stem diameter was highest at sole cropping in the maize fertilizer regime at all the locations. Between the maize densities, the FM regime resulted in the highest stem diameter at LM density at Igbariam18, Omogho18, and Otukpo18. The least stem diameter was observed at high maize density in the FC regime at Otukpo18.

### *3.3. Combined cassava and maize biomasses response to maize density and fertilizer regime*

There were effects of maize density and fertilizer on the combined intercrop biomass (Table 5). Our results showed that yield was higher ($p < 0.05$) in the C-HM than C-LM in both years (Supplementary Fig. C2). Biomass yield was least without fertilizer application (F0) and was increased with fertilizer application in both years. The combined intercrop biomass response to fertilizer was comparable between the

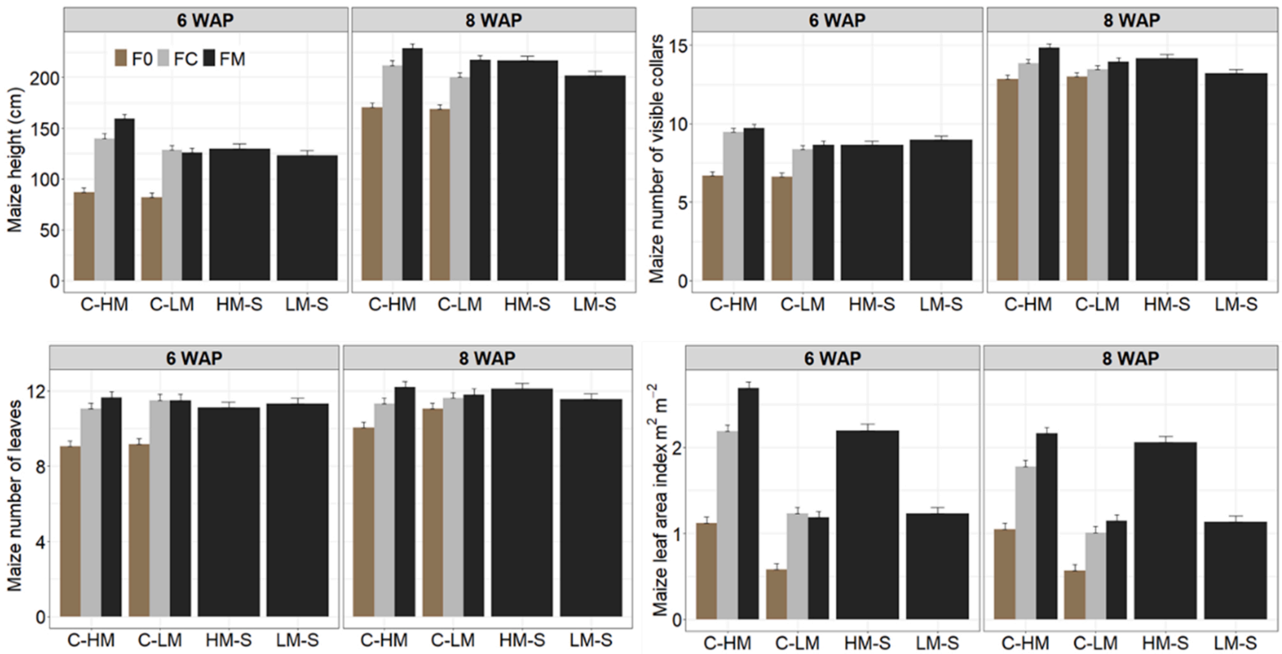


**Fig. 3.** Maize height, visible collars, leaf production, and leaf area index at 6 and 8 weeks after planting (WAP) as affected by maize planting density, and NPK application in cassava-maize intercropping systems at Igbariam18 in 2018. **C:** cassava at 12,500 ha$^{-1}$; **S:** sole crop; **LM:** low density maize (20,000 ha$^{-1}$); **HM:** high density maize (40,000 ha$^{-1}$); **F0**: no fertilizer applied; **FM:** fertilizer application at 90 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 37 kg K ha$^{-1}$; **FC:** fertilizer application at 75 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 90 kg K ha$^{-1}$. Error bars represent standard errors of the mean.

two fertilizer regimes. It increased with crop age and was highest at 12 WAP in both years. The maize fertilizer regime resulted in the highest intercrop biomass yield (1179 g DM m$^{-2}$), which was not statistically different when compared with the yield in the cassava fertilizer regime (1081 g DM m$^{-2}$). Similarly, in 2018, the FM and FC regimes resulted in high but statistically equal biomass yields of 1406 and 1331 g DM m$^{-2}$, respectively compared with no fertilizer application (F0: 660 g DM$^{-2}$).

### 3.4. Effects of maize density and fertilizer regime on IPAR

The percentage of IPAR was affected by maize density and fertilizer in both years (Table 5). IPAR was 5% lower ($p < 0.001$) in 2017 than in 2018 (Fig. 6). Average IPAR was 70% in 2017 and 75% in 2018. Without fertilizer application (F0), IPAR was higher at high maize density compared with low maize density by 4% at Igbariam17 and 2% at Igbariam18. With fertilizer application, IPAR increased by 7% at Igbariam17 and 5% at Igbariam18. IPAR was highest at 8 WAP, dropped to the lowest in the 13th WAP at Igbariam17 (Fig. 6). The treatments of low maize density had lower IPAR values than their high maize density counterparts, with exceptions in 2018 at 12 and 13 WAP. At Igbariam17, IPAR was in the following ranking: 8 (80%) > 4 (68%) > 12 WAP (62%); the ranking was 8 (82%) > 12 (78%) > 4 WAP (69%) at Igbariam18. Important to note is that 12 WAP coincided with the onset of the dry season in 2017.

### 3.5. Effects of maize density and fertilizer regime on RUE

The RUE was graphically derived for both sites (Igbariam17 and Igbariam18) (Fig. 8). The derived RUE was 0.6 g DM MJ$^{-1}$ IPAR ($r^2 = 0.82$) for C-LM:F0 and 0.5 g DM MJ$^{-1}$ IPAR ($r^2 = 0.90$) for C-HM:F0 in 2017 (Igbariam17). RUE increased to 0.8 g DM MJ$^{-1}$ IPAR ($r^2 = 0.98$) each at C-LM:FM and C-HM:FM at Igbariam17 (Fig. 8). RUE was highest at Igbariam18 compared to Igbariam17 largely due to better biomass production, especially with fertilizer application. RUE at Igbariam18 was 0.5 g DM MJ$^{-1}$ IPAR ($r^2 = 0.96$) in C-LM:F0 and 0.4 g DM MJ$^{-1}$ IPAR ($r^2 = 0.93$) in C-HM:F0. However, when fertilizer was applied, RUE was highest; 0.9 g DM MJ$^{-1}$ IPAR ($r^2 = 0.98$) in C-LM:FM and 1.0 g DM MJ$^{-1}$ IPAR ($r^2 = 0.99$) in C-HM:FM at Igbariam18 (Fig. 8). In general, it was observed that the RUE varied between 0.2 and 1.0, 0.5–2.0, and 1.0–3.0 g DM MJ$^{-1}$ IPAR at 4, 8, and 12 WAP, respectively. The smallest RUE at every sampling time was observed in the C-HM:F0.

### 3.6. Effects of maize density and fertilizer regime on volumetric soil moisture content

There was an effect of maize density and fertilizer on volumetric soil moisture content (VMC) in both years (Table 5). At 20 and 50 cm, VMC was higher at Igbariam18 than Igbariam17 by 28% and 25%, corresponding to 0.11 and 0.14 m$^3$ water per m$^3$ of soil, respectively (Fig. 8).

Volumetric soil moisture content at 20 cm was higher ($p < 0.001$) by 11.4% (0.03 m$^3$ m$^{-3}$) in the high maize density (0.17 m$^3$ m$^{-3}$) treatment relative to low maize density (0.13 m$^3$ m$^{-3}$) at Igbariam17 (Table 5). At 50 cm, the reverse was however the case; a VMC 1.3% higher (by 0.006 m$^3$ m$^{-3}$) was observed at low maize density (0.22 m$^3$ m$^{-3}$) compared with at high maize density (0.21 m$^3$ m$^{-3}$). Maize density effect on VMC at Igbariam18 was exactly the opposite of Igbariam17; VMC was significantly higher at 20 cm in the low maize density (0.33 m$^3$ m$^{-3}$) treatment compared with the high maize density (0.32 m$^3$ m$^{-3}$). At 50 cm, VMC was higher in the high maize density (0.41 m$^3$ m$^{-3}$) treatment than in the low maize density (0.36 m$^3$ m$^{-3}$) (Fig. 8).

The maize fertilizer regime resulted in higher ($p < 0.01$) VMC at all depths compared with the control treatment of no fertilizer application at Igbariam17. At Igbariam18, VMC was higher ($p < 0.001$) in the control treatment at 20 cm (0.34 m$^3$ m$^{-3}$) than in the maize fertilizer regime (0.31 m$^3$ m$^{-3}$). No fertilizer effect ($p = 0.18$) was observed on VMC at 50 cm (Fig. 8) at Igbariam18. Soil VMC declined as time progressed, reaching all-time lowest at 24 WAP at Igbariam17 (Fig. 8). The trend was different at Igbariam18, especially at 20 cm where VMC was relatively highest at 12 WAP (Fig. 8). This period coincided with the onset of the second rainfall peak in the season after maize harvest in 2018 at Igbariam18.

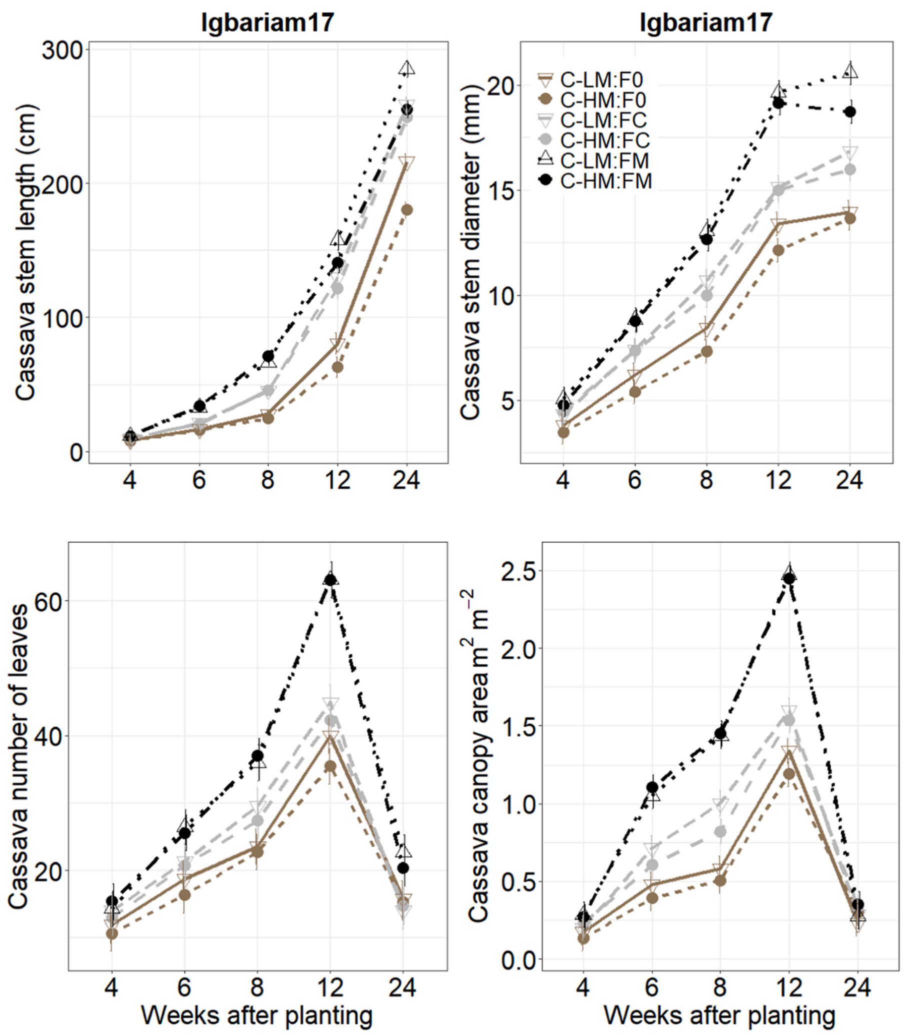


**Fig. 4.** Cassava stem length, stem diameter, leaf production, and canopy area over time, as affected by maize planting density and NPK application in cassava-maize intercropping system at Igbariam17. **C:** cassava at 12,500 ha$^{-1}$; **LM:** low density maize (20,000 ha$^{-1}$); **HM:** high density maize (40,000 ha$^{-1}$); **F0:** no fertilizer applied; **FM:** fertilizer application at 90 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 37 kg K ha$^{-1}$; **FC:** fertilizer application at 75 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 90 kg K ha$^{-1}$. Error bars represent standard errors of the mean.

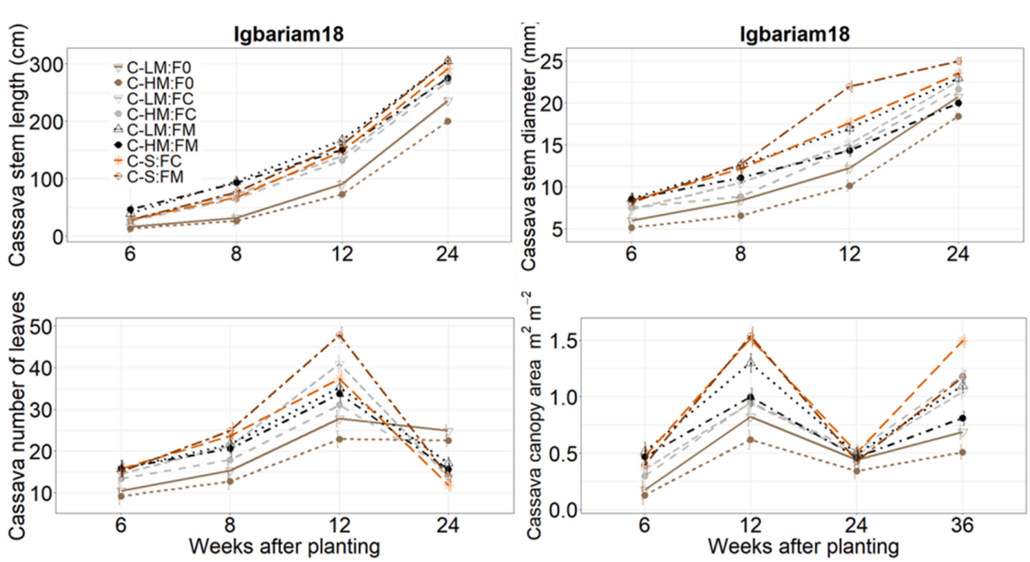


**Fig. 5.** Cassava stem length, stem diameter, leaf production, and canopy area over time, as affected by maize planting density and NPK application in cassava-maize intercropping system at Igbariam18. **C:** cassava at 12,500 ha$^{-1}$; S: sole crop; **LM:** low density maize (20,000 ha$^{-1}$); **HM:** high density maize (40,000 ha$^{-1}$); **F0:** no fertilizer applied; **FM:** fertilizer application at 90 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 37 kg K ha$^{-1}$; **FC:** fertilizer application at 75 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 90 kg K ha$^{-1}$. Error bars represent standard errors of the mean.

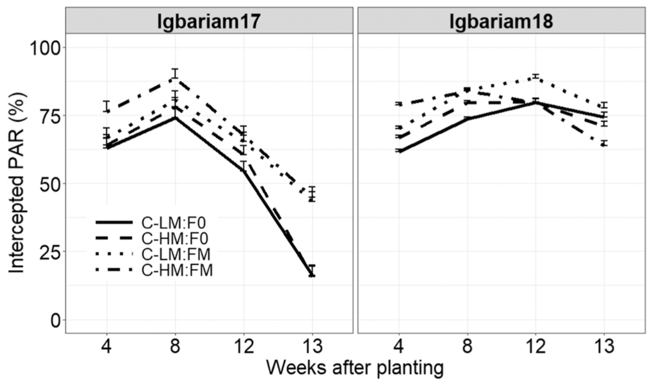


**Fig. 6.** Intercepted PAR over time, as affected by maize planting density and NPK application in cassava-maize intercropping system at Igbariam in Igbariam17 and Igbariam18. **C:** cassava at 12,500 $ha^{-1}$; **LM:** low density maize (20,000 $ha^{-1}$); **HM:** high density maize (40,000 $ha^{-1}$); **F0:** no fertilizer applied; **FM:** fertilizer application at 90 kg N $ha^{-1}$, 20 kg P $ha^{-1}$ and 37 kg K $ha^{-1}$. Error bars represent standard errors of the mean.

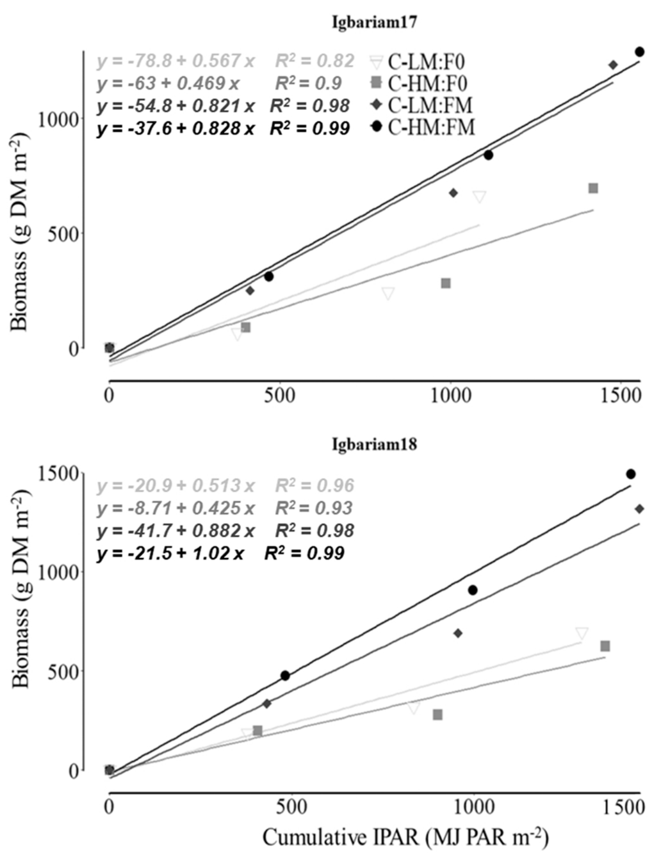


**Fig. 7.** Relationship between the combined cassava and maize biomass yields over time, the cumulative amount of IPAR, and the regression lines indicating radiation use efficiencies (RUE = the slope of the lines) for each intercrop treatment in cassava-maize intercropping systems at Igbariam17 and Igbariam18 in 2017 and 2018. **C:** cassava at 12,500 $ha^{-1}$; **LM:** low density maize (20,000 $ha^{-1}$); **HM:** high density maize (40,000 $ha^{-1}$); **F0:** no fertilizer applied; **FM:** fertilizer application at 90 kg N $ha^{-1}$, 20 kg P $ha^{-1}$ and 37 kg K $ha^{-1}$.

### *3.7. Response of maize grain and cassava storage root yields to maize density and fertilizer regime*

Grain yield was highest in the high maize density treatments at all the locations in both years. Grain yields were very low at Omogho, and yield across treatments was highest at Otukpo and comparable to yields from Ikom17 and Igbariam17 in 2017 (Fig. 9). In 2018, yields were comparable at Igbariam18 and Otukpo18, and lower at Ikom18. The maize yield (cobs) at Omogho for 2018 was pilfered before we could harvest it. The maize fertilizer regime resulted in the highest grain yields at all maize densities at all locations. Yields were generally poor at Omogho17; here no yield difference was observed between the cassava fertilizer regime and the control with no fertilizer applied (F0). However, a yield response ($p < 0.05$) was obtained in the maize fertilizer regime (Fig. 9). At Ikom17, the cassava fertilizer regime resulted in the highest grain yield at low maize density but not at high maize density.

Maize density did not affect cassava storage root DM yield at all the locations in 2017 (Table 5). In 2018, yields were higher ($p < 0.01$) in sole cropping than in intercropping (Fig. 10). Averaged across fertilizer regimes, fertilizer application resulted in highest storage root (DM) yield across locations in both years. In most cases in 2017, except at Igbariam17 in C-LM, yields in the cassava fertilizer regime were higher than yields in the maize fartilizer regime. A similar fertilizer response was observed in 2018 at Igbariam18 and Omogho18 across cropping systems. However, yields in the maize fertilizer regime were higher than yields in the cassava fertilizer regime in C-S and C-LM at Ikom18 and Otukpo18. Intercropping reduced storage root yield relative to sole cropping by 10% (2 Mg DM $ha^{-1}$) each at Igbariam18 and Omogho18, and by 11% (2 Mg DM $ha^{-1}$) at Ikom18 and 33% (5 Mg DM $ha^{-1}$) at Otukpo18. The average yield in sole cropped treatments was 9 Mg DM $ha^{-1}$ each at Igbariam18 and Ikom18, and 7 Mg DM $ha^{-1}$ at Omogho18 and 10 Mg DM $ha^{-1}$ Otukpo18 (Fig. 10). Averaged across fertilizer regime and intercropping systems in 2017, yield was highest at Ikom17 (10.4 Mg DM $ha^{-1}$), followed by Igbariam17 (9.4 Mg DM $ha^{-1}$), and poorest, at Omogho17 (4 Mg DM $ha^{-1}$). The 2018 ranking was in the order: Igbariam18 (7 Mg DM $ha^{-1}$) = Ikom18 (7 Mg DM $ha^{-1}$) > Otukpo18 (6 Mg DM $ha^{-1}$) > Omogho18 (5 Mg DM $ha^{-1}$).

## 4. Discussion

The objective of this study was to assess how different maize densities and fertilizer regimes affect IPAR, RUE, VMC, and yields of cassava and maize in cassava-maize intercropping systems in southern Nigeria. Rainfall distribution in both years was adequate for the establishment and growth of cassava (Akinbile et al., 2019) and maize (Brouwer and Heibloem, 1986) in all the studied agro-ecologies. Although the soil textural classes (Table 1) and pH range (4.2–6.9) is within the requirement for cassava and maize production, the SOC, N, P, and K levels of the experimental sites (Table 4) were all below the minimum requirements for cassava and maize production (Howeler, 2002; Nájera et al., 2015).

### *4.1. Effect of maize density and fertilizer regime on IPAR*

Our findings on IPAR corroborates a report by Olasantan et al. (1996) that higher IPAR in cassava-maize intercropping systems between 4 and 12 WAP compared with sole cropping was attributed to the maize rather than cassava which had a low average LAI of 0.5 $m^2\ m^{-2}$. In this study, the largest cassava canopy area was observed at 12 WAP; at a time IPAR had started to decline (Fig. 6). Also in agreement with the results of this study was a report by Cenpukdee and Fukai (1992) that cassava canopy was very low between 30 and 50 days after planting (~

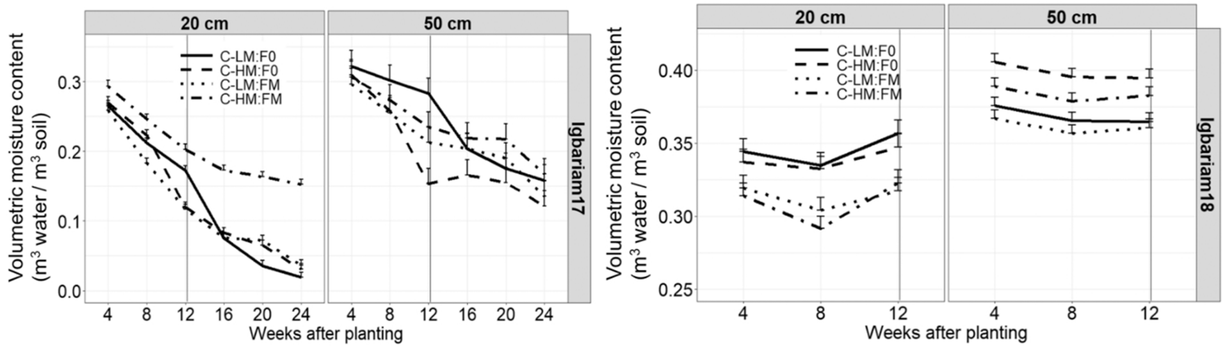


**Fig. 8.** Soil volumetric water content over time and depths as affected by maize planting density and NPK application in cassava-maize intercropping systems at Igbariam17 and Ignariam18. **C:** cassava at 12,500 ha$^{-1}$; **LM:** low density maize (20,000 ha$^{-1}$); **HM:** high density maize (40,000 ha$^{-1}$); **F0:** no fertilizer applied; **FM:** fertilizer application at 90 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 37 kg K ha$^{-1}$. Error bars represent standard errors of the mean. The vertical line shows the day of maize harvest.

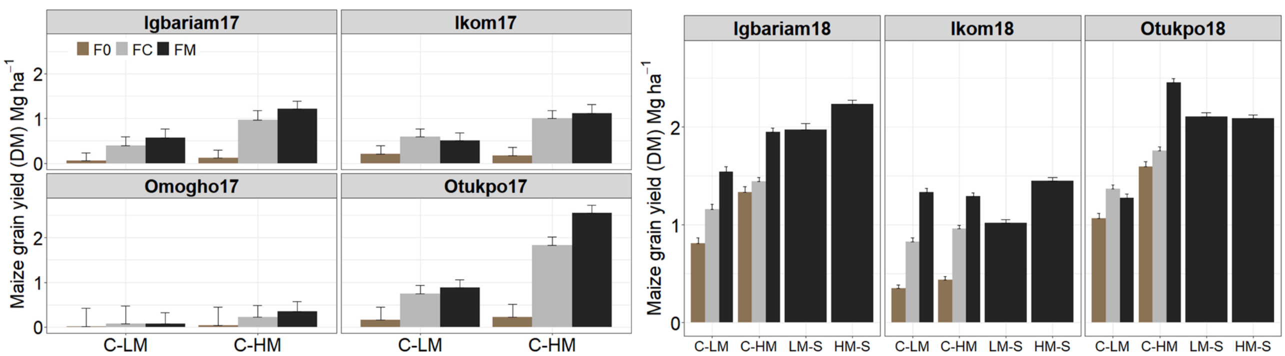


**Fig. 9.** Maize grain yield as affected by maize planting density and NPK application in cassava-maize cropping systems at Igbariam, Ikom, Omogho, and Otukpo in 2017 and 2018 (except Omogho due to trial pilferage). **C:** cassava at 12,500 ha$^{-1}$; **LM:** low density maize (20,000 ha$^{-1}$); **HM:** high density maize (40,000 ha$^{-1}$); **S:** sole crop; **F0:** no fertilizer applied; **FM:** fertilizer application at 90 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 37 kg K ha$^{-1}$; **FC:** fertilizer application at 75 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 90 kg K ha$^{-1}$. Error bars represent standard errors of the mean.

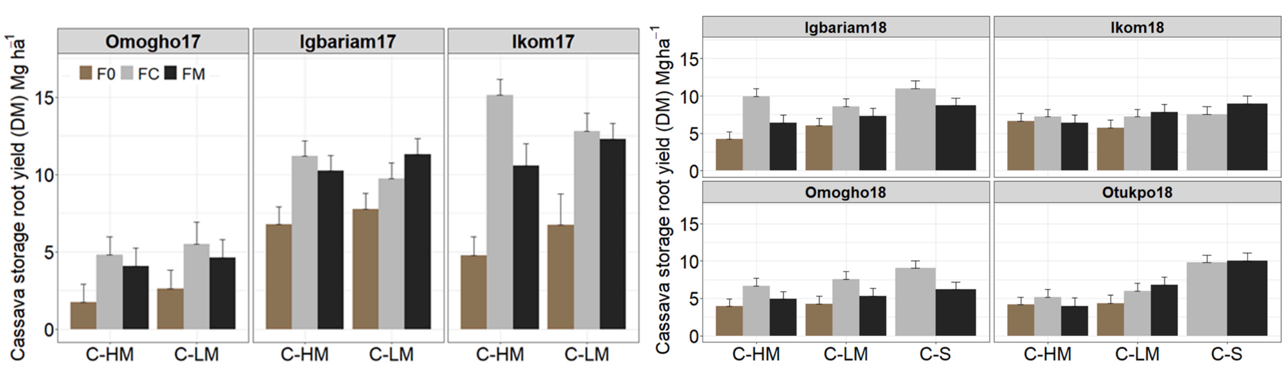


**Fig. 10.** Cassava storage root yield (in DM) as affected by maize planting density and NPK application in cassava-maize cropping systems at Igbariam, Ikom, Omogho, and Otukpo in 2017 (except Otukpo due to trial pilferage) and 2018. **C:** cassava at 12,500 ha$^{-1}$; **LM:** low density maize (20,000 ha$^{-1}$); **HM:** high density maize (40,000 ha$^{-1}$); **S:** sole crop; **F0:** no fertilizer applied; **FM:** fertilizer application at 90 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 37 kg K ha$^{-1}$; **FC:** fertilizer application at 75 kg N ha$^{-1}$, 20 kg P ha$^{-1}$ and 90 kg K ha$^{-1}$. Error bars represent standard errors of the mean.

4–8 WAP) in intercropping with pigeon pea, leading to about 95% of the light being intercepted by the pigeon pea component. Following maize stalk removal after cobs harvest and by 12 WAP, crop biomass reduced in the plots and the amount of photosynthetically active radiation (PAR) lost to the ground had increased. PAR lost to the ground after maize harvest was higher in 2017 (Igbariam17) than in 2018 (Igbariam18) because of better cassava growth and development in 2018. In 2017, the crops experienced drought after maize harvest. The removal of the maize crop also led to the observed IPAR interchange at 12 and 13 WAP between the high and low maize density intercropping treatments in 2018, when IPAR in the low maize density surpassed IPAR in the high maize density treatments. The evident and longer negative effect of maize on cassava even at low density in 2017 than in 2018 could be attributed to moisture rather than nutrient scarcity. Our result agrees with the reports that planting or intercropping cassava at high-density results in reduced growth and development of cassava which affects the amount of IPAR by the crop (Joseph et al., 2018; Silva et al., 2013).

Furthermore, the moisture stress in 2017 at Igbariam17 which resulted in lesser biomass production than in 2018 (Igbariam18) was because of late planting. The 2017 experiment was established in mid-August while that of 2018 was established in early June. At Igbariam, Awka North local government area of Anambra state rain starts late and ends relatively early. The VMC results of our experimental sites showed that soil moisture at all measured depths was lower at Igbariam17 than Igbariam18 (Fig. 8), evidence that indeed, moisture was the major factor that limited crop growth in 2017 at Igbariam17. This observation highlights the importance of moisture availability to plants during the early stages of growth and development as reported by Armstrong (2020). The differences in plant population $m^{-2}$ in our study also explains the effect of high planting density on above-ground biomass: whereas 5.25 plants $m^{-2}$ were established in the C-HM treatments (1.25 cassava and 4.0 maize plants $m^{-2}$), there were 3.25 plants $m^{-2}$ in the C-LM treatments (2 cassava and 1.25 maize plants $m^{-2}$). The implication of this is that a better ground cover was achieved in the C-HM treatments. Although without fertilizer application the above-ground cassava biomass yield was smaller in high maize density intercropping than in low maize density intercropping, the combined biomass yields of both crops was higher at high density intercropping than at low density. Thus, the contributions from high maize density at intercropping situations increased the overall plant biomass production that led to the highest canopy cover resulted in the highest IPAR (Fig. 6). Whereas IPAR is increased with increasing plant density (Tao et al., 2018), a higher IPAR and use efficiency is achieved by the adoption of cultural practice that modifies the crop canopies via optimal plant population density (Chapera, Mudada, and Mapuranga, 2020; Muoneke, 2007; Muoneke and Asiegbu, 1997).

### 4.2. *Effect of maize density and fertilizer regime on RUE*

In both years, radiation use efficiency was higher in C-LM:F0 than C-HM:F0 (Fig. 7). This result corroborates a report by Tao et al. (2018) that high plant population density does not always result in high radiation use efficiency. Considering the growth morphology of both crops, with the maize canopy occupying mostly the upper strata and cassava the lower strata in the canopy arrangement, it was perhaps that light penetration down the canopy was reduced at high maize density intercropping, thus subjecting the cassava to reduced quantity and quality PAR throughout the intercrop period. The shading effect might have resulted in the poorer performance of cassava growth and DM production without fertilizer at intercropping with the high maize density planting than at low density. Cassava contributing on average 58% of the combined intercrop biomass yield in C-LM:F0 compared with the average of 42% in C-HM:F0 is a confirmation that its growth and development was affected more negatively at high than low density intercropping. The findings are in agreement with the report by Sinclair and Sheehy (1999) that more erect leaves (as in maize and rice compared to cassava) would result in greater leaf area receiving the light intensity required for crop canopies to maintain leaves, prevent senescence and abscission. Conversely, a more prostrate leaf (as with cassava compared to maize) prevents more light interception at the lower strata in the canopy. At high population densities, the prostrate leaf pattern is particularly detrimental for leaf maintenance and results in a poor RUE (Purcell et al., 2002) in either sole cropping or intercropping. It is interesting to note that indeed at intercropping maize plants at high density without fertilizer application were more than twice as tall as the companion cassava plants. It is important to note is that data for RUE assessment covered only the periods cassava was still at the formative stage (< 4 months).

The other possible reason for a lower RUE at C-HM:F0 compared with C-LM:F0 is the soil nutrient status of our experimental sites (Table 4). As discussed above, the soil nutrient statuses of our sites were poor so that at high population densities there was a stronger intra- and interspecific competition for the available nutrients. The situation was perhaps ameliorated by fertilizer application which then resulted in better crop development and higher RUE at C-HM:FM than C-LM:FM. Similar to our findings that nutrient supply under nutrient-limited conditions increases RUE even at a high planting density, Mandal and Sinha (2004) reported a positive effect of fertilizer application on crop canopy development and by extension light interception (Rosati et al., 2001). Averaged across maize density and years, fertilizer application resulted in a 45% higher biomass yield than no fertilizer application. Kermah et al. (2017) also reported high biomass yield because of better soil fertility status. Similarly, Olasantan et al., (1996, 1994) reported higher cassava and maize above-ground biomass production with fertilizer application in cassava-maize intercropping. Indeed, nutrient supply particularly N contributes to increased RUE; a result which has been documented for cassava (Ezui et al., 2017), maize (Ahmadi et al., 2018), and other field crops (Purcell et al., 2002; Sinclair and Horie, 1989).

### 4.3. *Effect of maize density and fertilizer regime on VMC*

The differences in VMC trend between Igbariam17 and Igbariam18 were perhaps because of different seasons of the establishment. Whereas Igbariam17 was established late-season towards the end of the rain, Igbariam18 was established mid-season when in the peak of rain. By 12 WAP, the Igbariam17 trial received 468 mm.i.e., 4 mm of rain per day (equivalent to 0.004 $m^3$ $m^{-3}$), the Igbariam18 trail received 1136 mm.i.e., 13 mm per day (equivalent to 0.013 $m^3$ $m^{-3}$). Soils of both sites have similar physicochemical properties and belong to the sandy loam textural class. Thus VMC was most likely not influenced differently by water infiltration and holding characteristics at both sites. The contrasting VMC at both sites particularly by 12 WAP at comparable depths was likely a function of rain volume rather than management. The frequent rain observed at Igbariam18 is associated with low potential evaporation (~ 1.2 mm $day^{-1}$), and infrequent rain at Igbariam17 is associated with high potential evaporation (> 3 mm $day^{-1}$) (Yunusa et al., 1993).

Exactly 468 mm of rain was recorded at Igbariam17 between 0 and 12 WAP. This amount is considered a little less than the minimum water requirement (500 mm) for maize production (Brouwer and Heibloem, 1986). However, this did not cause significant differences in maize development between both years. When plant demand for water exceeds supply, they make more conservative use of available water to minimize stress to continue metabolic activities (Horton and Hart, 1998). According to a report by El-Sharkawy (2007), cassava can slowly extract water from deep soils, a characteristic of paramount importance in seasonally dry and semiarid environments where deeply stored water needs to be tapped. Therefore, we hypothesized that the cassava, a shrub and a deep-rooted (>3.2 m) plant (Adiele et al., 2020), was hydraulic lifting water from the deeper soil layer to the upper 0–50 cm layer at Igbariam17 when moisture was scarce. Hydraulic lift is a characteristic of deep-rooted (2.2 m) shrubs grown in arid and semi-arid conditions (Horton and Hart, 1998). It is a process by which some deep-rooted plants take in water (~ 1 L $m^{-2}$ per night) from lower soil layers and exude the same into the upper and drier soil layer thereby benefiting both the crop and neighboring plants (Richards and Caldwell, 1987). This mechanism can buffer plants against water stress during seasonal water deficit and might be the process that sustained maize development at Igbariam17 despite the low rain. This could be the reason for the observed similarity in maize performance between both years and the high VMC at 20 and 50 cm at high density planting particularly in 2017.

It is a general principle that a denser canopy should withdraw and transpire more volume of water (Ogindo, 2003), however, evaporation becomes lower because a dense canopy reduces net radiation absorbed by the soil surface, therefore, the energy available for soil surface evaporation (Walker and Ogindo, 2003). Hydraulically lifted water is only beneficial to plants if a significant amount of the lifted water is not lost via evaporation (Passioura, 1988). A denser leaf canopy in C-HM:FM than C-LM:FM might have facilitated the humidification of the air around the canopy, reduced evaporative demand, and water loss from both the soil, middle, and lower leaf surfaces. Evaporation forms a substantial source of water loss from cropping systems; however, maize LAI exceeding 2 has been found to significantly prevent soil evaporation losses beneath canopies (Al-Kaisi et al., 1989). Therefore, in addition to LAI > 2 we obtained for maize at high density, the largest cassava canopy area was also obtained with fertilizer application regardless of maize density. Walker and Ogindo (2003) reported that early leaf area index or canopy development is an important plant attribute that contributes to water-saving through soil surface canopy cover. This could also explain the high VMC at high planting density with fertilizer application compared with low density in our study.

### *4.4. Effect of maize density and fertilizer regime on grain and storage root yields*

Maize planting at high density and fertilizer application increase maize productivity (Morales-Ruiz et al., 2016; Sarmento et al., 2020). Maize, unlike rice and wheat, does not produce reliable tillers to achieve an increase in population per hill. Maize would rather compensate for the number of tillers by an increased number of plants $m^{-2}$ and cobs per plant. Regardless of fertilizer regime, high maize density planting resulted in the highest LAI in both years (Figs. 2 and 3), an effect that contributed to high IPAR (Fig. 6) and effectively to increased biomass production due to a higher assimilate production. At high maize density, more maize cobs per unit area were produced, which resulted in high grain yield (Fig. 9). Similar effects of high planting density with fertilizer application on yields have been reported for maize (Joseph et al., 2018; Morales-Ruiz et al., 2016; Sarmento et al., 2020; Watiki et al., 1993), cassava (Ayoola and Makinde, 2008; Silva et al., 2013) and peanut (Suprapto et al., 2012). Fertilizer application was found to increase cassava productivity and reduced the negative effect of maize competition compared with no fertilizer application in our study. Results that corroborate previous reports by Nwokoro et al. (2021) in cassava-maize intercropping systems and Onasanya et al. (2021) in cassava mono-cropping. Also in agreement with the findings of this study are the reports by Adiele et al. (2020) on the positive effects of fertilizer application on cassava storage root yields in Nigeria; Democratic Republic of Congo (Munyahali et al., 2017; Pypers et al., 2011); Togo (Ezui et al., 2017); and in Kenya and Uganda (Fermont et al., 2010). Regardless of maize density, grain yield was generally higher in the maize fertilizer regime than cassava fertilizer in both years across locations (Fig. 9). The storage root yield was generally higher in the cassava fertilizer regime than in the maize fertilizer regime at most locations (Fig. 10). However, at Ikom18 and Otukpo18 where storage root yields in the maize fertilizer regime were higher in low maize density intercropping and sole cassava than in the cassava fertilizer regime could be because of better response to N at low than high planting density. It might have been that N uptake by the maize crop during maize growth and development was higher in the high maize density intercropping than the low maize density intercropping. This implies that N rather than k is the most limiting nutrient at both sites. A higher N ratio in the maize fertilizer regime and K in the cassava fertilizer regime was specifically used to target yield increases on maize and cassava, respectively. This is most likely the reason behind the largely observed high yield response of cassava to the cassava fertilizer regime and maize to the maize fertilizer regime. These results are in agreement with what was found in the literature on cassava (Adiele et al., 2020; Ezui et al., 2017; Howeler, 2002; Sanchez, 2019) and maize (Sanchez, 2019; Setiyono et al., 2010; Sharifi and Taghizadeh, 2009). Cassava is a carbohydrate producer; therefore it requires a high amount of K. Adequate K nutrition is important for starch synthesis and translocation. It is also reported to increase cassava resistance to anthracnose (IFA, 1992). According to a report by Howeler (2015), potassium plays a special role in carbohydrate production and translocation for storage root initiation and bulking (Howeler, 2015). As a result, high K nutrition and uptake are required to maintain high cassava storage root yield (Howeler, 2002), a report that corroborates the findings of this study. This also affirms the report that K deficiency becomes the most limiting nutritional constraint if cassava is grown repeatedly without adequate K fertilization (Howeler, 2015). On the other hand, stover production in maize, assimilates synthesis and translocation to the ear (sink) for grain filling depends largely on N availability, uptake, and utilization (Asibi et al., 2019). N accumulation in maize shoots promotes assimilate partitioning to reproductive sinks at flowering, a process that results in high grain yields at adequate N fertilization on N limited fields (Uhart and Andrade, 1995; Nenova et al., 2019).

Intercropping did not negatively affect grain yield at Otukpo18; however, yields were higher in sole cropping than intercropping by 8% (0.2 Mg $ha^{-1}$) at Ikom18 and 18% (0.6 Mg $ha^{-1}$) at Igbariam18. Storage root yield reduction by intercropping was 10–11% corresponding to 2 Mg DM $ha^{-1}$ each at Igbariam18, Omogho18, Ikom18, and 33% (5 Mg DM $ha^{-1}$) at Otukpo18. The higher reduction in cassava yield than maize by intercropping could be attributed to the better competitive ability of maize. Similarly, Olasantan et al. (1996) reported delayed storage root initiation and bulking which resulted in reduced storage root yield in cassava-maize intercropping due to competition by maize. The higher percentage storage root yield reduction at Otukpo18 than other locations can be attributed to the lower amount of rain at the site that lasted for a shorter period throughout cassava growth (Fig. 1). Adiele et al. (2020) reported a similar observation in the same location relative to other locations where rain was higher and lasted longer during cassava growth. Both cassava and maize yields are reduced at intercropping relative to their respective sole crop yields. Indeed, it is not uncommon that cassava yield is affected more than the maize at intercropping according to other research reports (Adeniyan, 2014; Joseph et al., 2018; Olasantan, 1988, 1996, 1997).

## 5. Conclusion

Increasing maize planting density from 20,000 to 40,000 plants $ha^{-1}$ in cassava-maize intercropping and fertilizer application on nutrient-limited soils of southern Nigeria improve the productivity of the system. It is recommended that 12,500 cassava plants $ha^{-1}$ be intercropped with 40,000 maize plants $ha^{-1}$ to improve incident solar radiation capture on fertile fields. On nutrient-limited fields similar to our study fields, maize should be planted at 20,000 plants $ha^{-1}$. Otherwise, the system should be managed with 90 kg N, 20 kg P, and 37 kg K $ha^{-1}$ at 40,000 maize plants $ha^{-1}$ to achieve improvements in solar radiation capture, use efficiency, and better soil moisture retention to increase grain productivity in the system, especially in a late-season planting. If higher cassava storage root rather than maize grain yield is desired, the maize should be planted at 20,000 plants $ha^{-1}$, especially on nutrient-limited fields, or the intercrop be managed with 75 kg N, 20 kg P, and 90 kg K $ha^{-1}$ when maize is planted at 40,000 plants $ha^{-1}$. We, therefore, recommend further studies to (1) understand fully the effects of maize density and fertilizer application (until final cassava storage root harvest) on soil moisture dynamics, radiation interception, and use efficiency, especially in late-season planting, (2) study modified fertilizer rates in the system after maize harvest on cassava storage root yield improvement, and (3) assess the profitability of the system under modified fertilizer rates.

## CRediT authorship contribution statement

**Charles Chigemezu Nwokoro:** Investigation, Data curation, Writing – original draft. **Christine Kreye:** Conceptualization, Data curation, Methodology, Investigation, Supervision, Writing – review & editing, Funding acquisition, Project coordination Nigeria. **Magdalena Necpalova:** Methodology, Supervision, Writing – review & editing. **Olojede Adeyemi:** Supervision, Investigation, Writing – review & editing, Project administration. **Barthel Matti:** Methodology, Writing – review & editing. **Stefan Hauser:** Data curation, Methodology, Investigation, Writing – review & editing, Funding acquisition, Project administration. **Pieter Pypers:** Conceptualization, Investigation, Funding acquisition, Project lead. **Johan Six:** Conceptualization, Data curation, Methodology, Investigation, Supervision, Writing – review & editing, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2022.108550.

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