



Pigeonpea (*Cajanus cajan*) and white yam (*Dioscorea rotundata*) cropping system: Improved resource use and productivity in Ghana



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ABSTRACT

Yam production along the West African yam belt is challenged with deteriorating soil fertility and unavailability of stakes, resulting in decreased yam productivity, and farmers' livelihood. This study evaluated resource use and yam productivity in pigeonpea-yam cropping systems in Ghana's forest and forest-savannah transition zones from 2017 through 2019 cropping seasons. Pigeonpea was established either in an alley or as a border during the 2017 cropping season, while yam was cultivated in 2018 and 2019. A split-plot design of cropping system (yam planted in alleys of pigeonpea—PA; yam planted with pigeonpea as a border—PB and sole yam) as main-plot treatments and chemical fertilizer (0–0–0; 23–23–30; 45–45–60 N-P₂O₅-K₂O kg ha⁻¹) as subplot treatments were used for the study. Productivity data on pigeonpea and yam were collected. The results revealed significantly higher leafy biomass and correspondent higher N content and N due to fixation in PA fields than PB fields in both locations and seasons. The presence of the pigeonpea and its biomass resulted in a significant suppression of ridge erosion and weeds, while soil moisture and nutrients improved, resulting in increased yam tuber productivity than in sole yam production. Further, planting yam with pigeonpea and half (23–23–30 N-P₂O₅-K₂O kg ha⁻¹) the recommended fertilizer rate significantly improved tuber yield and productivity than planting sole yam with full recommended fertilizer level in both locations and seasons. Promoting and adopting the pigeonpea-yam cropping system could sustain soil fertility, provide readily available stakes to address the constraint of deforestation and land degradation associated with yam production.

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1. Introduction

The world population is projected to increase from 7.8 billion to 9.6 billion by 2050. Therefore, increasing and sustaining food production per unit area on limited land resources is imperative (Bahar et al., 2020; Rahmann et al., 2020). Mesfin and Markos (2019) observed that implementing innovative climate-smart technologies in agriculture accessible and affordable to smallholder farmers would be the way forward. Although known for its vital role in rural households, yam production also supplies food and generates income through ware yam consumption and marketing. However, yam production faces the

challenge of soil fertility decline and scarcity of stakes for yams to climb on for sunlight (Ennin et al., 2014).

Yam takes up heavy nutrients from the soil, resulting in a high export of the major nutrients of nitrogen, phosphorus and potassium. This is evidence of the rapid decline of yam tuber yields upon the second year of cropping on the same piece of land (Frossard et al., 2017; Neina, 2021). To cope with the heavy nutrients demanded by yam, farmers move to new lands every year, searching for fertile lands and stakes for yams to climb, resulting in land degradation and deforestation. The practice of shifting cultivation, coupled with the increasing human population, has led to pressure on arable lands and forests in the yam growing communities (Ennin et al., 2014; Frossard et al., 2017). The fallow period and available fertile lands keep reducing while yam fields are getting farther and more difficult to access. Traditional slash-and-burn cultivation has been identified as a major contributing factor to deforestation in Ghana (Asamoah et al., 2020). Soil improvement with fertilizer

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and manure has been suggested to address this situation. However, the increasing and high cost of fertilizers make it difficult for resource-poor farmers to access and use fertilizer on their farms. Also, the use of fertilizer alone has been observed not to promote good soil biological activities and health (Bitew and Alemayehu, 2017; Singh, 2018). Traditional organic materials such as crop residue and animal manure have been a cheaper source of nutrition for crop production. However, they are bulky, and availability in reasonable quantities in most cases is also limited to offer a reasonable alternative (Agegnehu and Amede, 2017; Bationo and Waswa, 2011; Diby et al., 2011).

The option of integrated soil fertility management (ISFM), which combines inorganic fertilizer and organic matter for sustainable crop production, is being promoted to intensify food production (Pypers et al., 2011; Sinclair and Vadez, 2012). Legume crops and trees/shrubs have been observed to fix nitrogen through Biological Nitrogen Fixation (BNF) for the benefit of associated crops and, therefore, can be adopted for sustainable yam production (Chianu et al., 2011; Iannetta et al., 2016; Liu et al., 2011). The legume shrub – pigeonpea (*C. cajan* [L] Millsp.) can be integrated into yam cultivation for soil nutrients management and sustainable intensification of yam production. Pigeonpea is an important grain legume and income source in most semi-arid tropics, where the grains are exported mainly to India (Kaoneka et al., 2016; Walker et al., 2015). Smallholder farmers generally cultivate it as a sole, mixed, intercrop, or ratoon crop (cut yearly and allowed to re-grow) under a rainfed system. Although pigeonpea is a novel legume shrub in West Africa, it has shown multipurpose promise of improving soil aggregation, organic matter, and soil fertility upon incorporation into the soil its biomass (Adjei-Nsiah, 2012; Smith et al., 2016). Its biomass fixes more N per unit area than other major crop legumes used in cropping systems (Mhango et al., 2017; Mhango et al., 2020; Kwena et al., 2019). Pigeonpea has been observed to return large quantities of residue to the soil for productive use of the subsequent crop and minimize soil organic carbon loss (Adjei-Nsiah, 2012; Costa et al., 2021). In a participatory farmer trial in Ghana, farmers preferred using pigeonpea to improve their soil fertility than mucuna (*Mucuna pruriens*) because pigeonpea provided immediate benefits both as food and cash crop (Adjei-Nsiah, 2012). Thus, pigeonpea could play a positive role in food security.

The grains of pigeonpea can serve as an additional source of income and nutrition for smallholder farmers. The grains are nutritionally well balanced and are an excellent source of protein, carbohydrates, and high vitamins A and C (Talari and Shakappa, 2018). It can also be an easier source of fodder for livestock (Ayele et al., 2012). To introduce pigeonpea into yam production systems in Ghana, there is the need to evaluate the above and belowground competition between the two crops so appropriate measures can be taken to improve yam productivity. Besides, there is limited information on the specific impact of integrating pigeonpea into the yam cropping system and its implications on yam productivity in West Africa. This field evaluation is a part of a more extensive study to assist yam farmers in integrating pigeonpea into yam production in Ghana to improve soil fertility, income, and livelihoods. This study aimed to investigate BNF and resource use in pigeonpea-yam cropping system and its implications on yam productivity. This would serve as a recommendation guide in the introduction of pigeonpea into yam cropping systems in Ghana and along the West African yam belt.

2. Materials and methods

2.1. Site description

The study was conducted on a 13–15 year continuously cropped field with maize and cowpea in rotation at Fumesua (6° 41' N, 1° 28' W) and Ejura (7° 23' N, 1° 21' W) in the forest and forest-savannah transition zones of Ghana respectively (Fig. 1). Fumesua soils are Ferric Acrisols, Asuasi series with greyish brown sandy clay loam topsoil.

Ejura soils are Ferric Lixisol; Ejura series with a thick top layer of fine sandy loam (Effland et al., 2009). The rainfall and temperature of both locations during the study period are shown in Fig. 2.

2.2. Experimental design

The treatments were arranged in a split-plot design with three replications. Pigeonpea-yam cropping system (yam in an alley of pigeonpea – PA, yam in pigeonpea as a border – PB, and no pigeonpea/sole yam) was the main plot. The subplot of fertilizer levels consisted of full-rate – 45–45–60 kg ha⁻¹ N-P₂O₅-K₂O (Recommended by the CSIR-Crops Research Institute, Ghana); half-rate – 23–23–30 N-P₂O₅-K₂O kg ha⁻¹ and no fertilizer (Ennin et al., 2014). A sole pigeonpea/no yam field was established adjacent to each replicate to compare the productivity of the systems. Also, maize was planted adjacent to each replicate to serve as a reference plant for the determination of BNF by the pigeonpea. The combination of the pigeonpea and yams on the plots followed the replacement or substitutive approach with a row/ridges for yams substituted for pigeonpea either within the yam ridges or around the border of the field for PA and PB plant fields, respectively (Figs. S1 & S2).

A total pigeonpea population of 5931 plants ha⁻¹ (about 27% of the sole pigeonpea population), each were planted on PA and PB fields at one per stand. The pigeonpea used was a late-maturing type (after eight months), whiles “Pona”, a premium *D. rotundata* local yam accession, was used. The pigeonpea was planted as a perennial in the pigeonpea-yam cropping system whiles the yam was an annual crop and planted on a yearly basis. The fields were tractor ploughed, and pigeonpea was planted in the first and second weeks of May 2017 at Fumesua and Ejura, respectively. The yams were planted on ridges in both locations for the pigeonpea in the alley and pigeonpea as border/live fence and sole yam (No pigeonpea) during the 2018 and 2019 cropping seasons, the last week of April and the first week of May for Fumesua and Ejura respectively. On the pigeonpea in alley fields, we followed the design indicated in Fig. S1. Yam sett was treated with 120 g Conti-Zeb' 5' (mancozeb 80%), a fungicide and 80 mL of Dursban (480 g L⁻¹ chlorpyrifos), an insecticide in 15 L mL of water (Aighevi et al., 2015).

Two rows/ridges of yams were planted at 1.2 and 0.8 m inter and intra-row, respectively, to achieve a population of 7177 yams ha⁻¹ within the alleys of pigeonpea with a population of 5931 plants ha⁻¹. Pigeonpea biomass was pruned twice before yam vines climbed the pigeonpea each season, and biomass was applied on the ridges for each cropping system at both locations. The pigeonpea alleys served as live stakes for yams to climb for sunlight, with stake heights ranging between 2 and 2.4 m (Figs. S1 & S2). On the pigeonpea as border field, two rows of pigeonpea were planted at three sides of the field at 1.2 and 0.5 m inter and intra-row, respectively, to achieve a population of 5931 plants ha⁻¹. Ridges were constructed in the space within the pigeonpea fence, and yams planted at 1.2 and 0.8 m inter and intra-row, respectively, to achieve a population of 7177 yams ha⁻¹. Stakes were cut from the thick stems of the pigeonpea from the border for staking the yams. Stake height ranged between 0.8 and 1.2 m (Figs. S1 & S2). On the sole yam field, yams were planted on ridges at 1.2 and 0.8 m inter and intra-rows, respectively, to achieve a population of 10,416 yams ha⁻¹ (Figs. S1 & S2) whiles the sole pigeonpea field had pigeonpea planted in rows at 0.9 and 0.5 m inter and intra-row to achieve a population of 22,222 plants ha⁻¹. Bamboo stakes were purchased and transported to the no pigeonpea/sole yam fields for staking. Stake height ranged between 2 and 2.5 m (Figs. S1 & S2). Ridges were about 40–45 cm high at planting for all treatments. Eight weeks after planting, yam stands were refilled for all treatments to ensure the optimum population. The subplot treatment of inorganic fertilizer was applied in split on the ridges per yam stand at 5–6 and 12 weeks after planting in both locations and years.

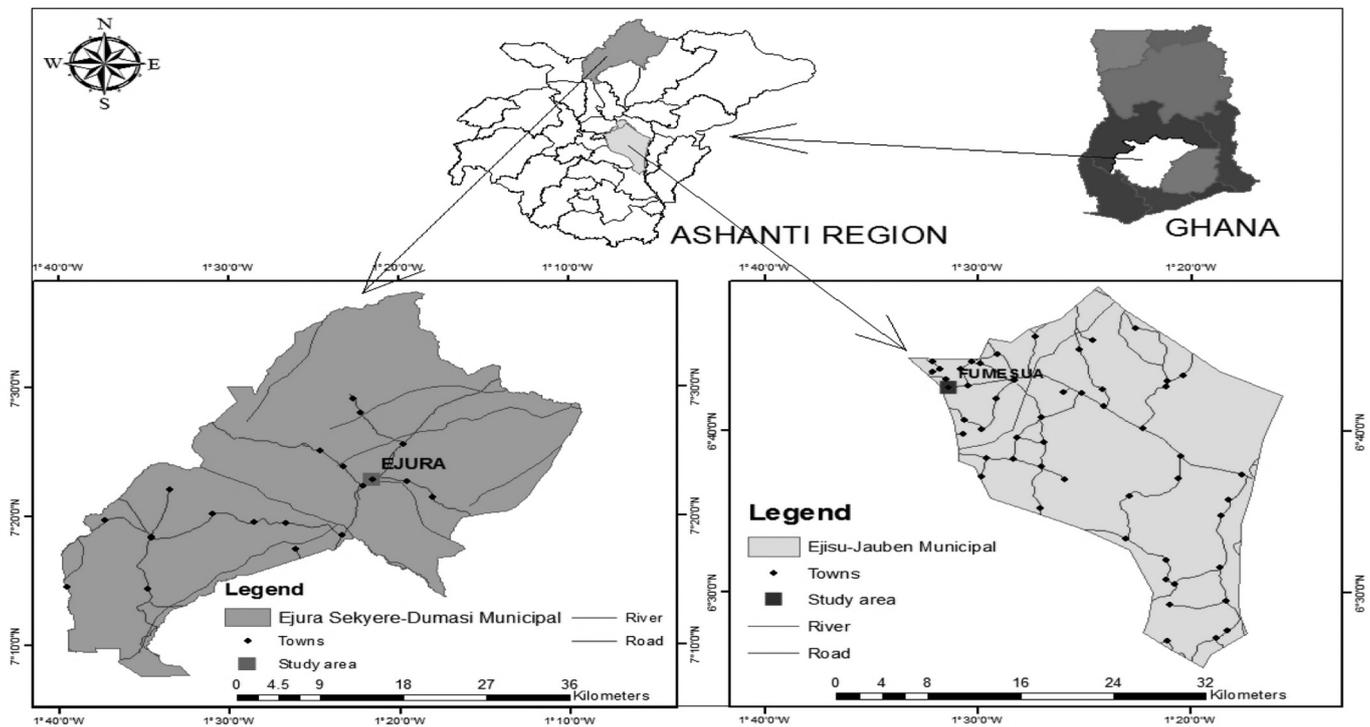


Fig. 1. Map of Ghana showing Ejura and Fumesua study areas in the Ashanti region.

2.3. Data collection

Data were collected on growth, biomass yield and grain yield of the pigeonpea. Stand count (stand establishment), growth and yield component were taken for the yam. Data were also collected on sunlight reaching above the canopy of the cropping system, soil moisture and nutrients below ground, weed pressure (biomass) and height (erosion) of ridges were taken for each cropping system. This was to be able to monitor above and below the ground competition for sunlight, moisture and nutrients in the cropping systems.

2.3.1. Soil analysis

Composite soil samples consisting of nine (9) random subsamples from each plot/treatment were mixed together, and a sample was pulled to represent that treatment and depth. The samples were collected during the planting of pigeonpea, planting of yam, and harvesting yam at random on the ridges for all cropping seasons. Soil analysis was conducted at the CSIR-Soil Research Institute, Kumasi, for total nitrogen (N), pH, organic carbon, phosphorus, and potassium measured at 0–20 and 20–40 cm on the ridges (Table S1). Total N was determined using the Kjeldahl method (Sáez-Plaza et al., 2013), and soil pH was measured

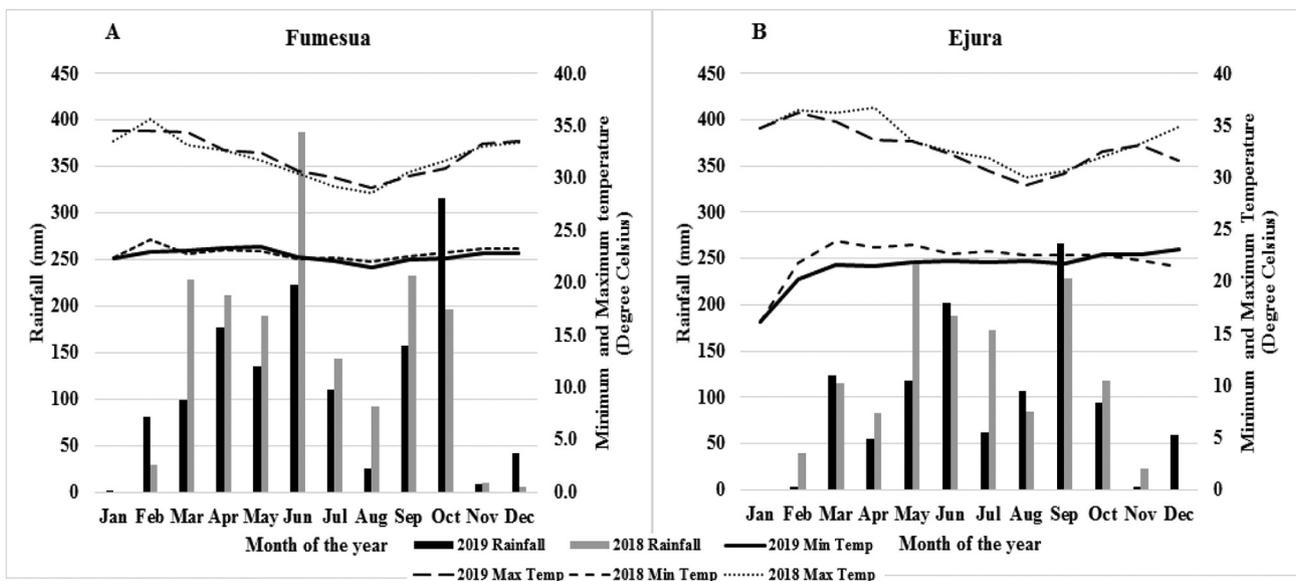


Fig. 2. Rainfall, maximum and minimum temperatures for 2018 and 2019 of the study areas of Fumesua (A), and Ejura (B). Source: Data from the Ghana Meteorological Agency (GMA), 2019.

using a pH meter (1:2.5, soil:H₂O), while soil organic carbon (SOC) was measured using the Walkley and Black approach (Jha et al., 2014). The available P in soil was determined using the Bray method 1 (Bray and Kurtz, 1945) and the available K in the soil using the flame photometric method (Toth and Prince, 1949). The ammonium acetate method determined exchangeable cations and Cation Exchange Capacity (CEC) (Black, 1986).

2.3.2. Installation of access tubes for soil moisture monitoring

Each cropping system's soil moisture was measured and monitored bi-weekly using a Time Domain Reflectometry (TDR) approach with a PR2/6 soil profile probe device from Delta-T Devices (Delta-T Devices Ltd., Cambridge, UK). The soil probe (PR2/6) allowed monitoring of the soil profile to a depth of 1 m with six separate rings enabling soil moisture monitoring at 0–100, 100–200, 200–300, 300–400, 400–600, and 600–1000 mm. Upon inserting the tubes, the probe emits an electromagnetic field around each measuring ring, which penetrates the soil to record moisture readings for each depth (Delta-T Devices Ltd., Cambridge, UK). Two access tubes were inserted at random on ridges in the central row of each cropping system (Fig. S1). The access tubes for each treatment were open, and the PR2/6 probe was inserted bi-weekly to record the percentage of moisture for the six depths for each cropping system. The soil moisture data were used to evaluate the belowground competition for water and nutrients in each treatment.

2.3.3. Weed biomass determination

To understand the weed pressure resulting from each cropping system, a quadrant of 1.2 × 1 m was placed at random three times on each field 8–9 weeks after planting the yam. The weeds within the area were carefully removed, and fresh weight was taken. Fresh weed samples were then dried in an oven at 75 °C until a constant weight was obtained for dry weight determination. Fresh weed weights were converted from the sub-sample fresh weights to dry weights using the fresh to dry weight conversion factor.

2.3.4. Determination of Biological Nitrogen Fixation (BNF) of pigeonpea biomass

The pigeonpea and maize reference dried leafy biomass was subsampled and weighed into capsules and sent to the stable isotope facility at UC Davis to determine $\delta^{15}\text{N}$ and %N. Maize served as the non-N-fixing reference plant. The BNF was calculated using the natural abundance method by Unkovich et al. (2008) (Eq. 1).

$$\% \text{Ndfa} = \frac{(\delta^{15}\text{N maize} - \delta^{15}\text{N pigeonpea}) \times 100}{(\delta^{15}\text{N maize} - B)} \quad (1)$$

where %Ndfa – the percentage of N due to BNF; $\delta^{15}\text{N}$ – the natural abundance of maize or pigeonpea biomass; B – the smallest weighted value of reference crop.

2.3.5. Sunlight on yam leave and chlorophyll content monitoring

A photosynq multispeQ device V1.0 was used to monitor photosynthetic-related parameters such as light intensity and leaf chlorophyll content on a bi-weekly basis on the yam leaves (Kuhlgert et al., 2016). After establishing yam on the stakes (9–10) Weeks after planting, fresh and fully developed young yam leaves on each treatment's central rows were selected bi-weekly on three strata of the stakes [Above canopy (AC) Mid of canopy (MC), and Below canopy (BC)] for monitoring. The yams' stake height ranged between 0.8 and 1.2, 2–2.4, and 2–2.5 m for pigeonpea as a border, pigeonpea in an alley, and sole yam fields, respectively. These stake heights influenced MC position on the stakes used for the monitoring. For the above canopy level, young and fully developed apical yam leaves were used at the top of the stakes. Young and fully developed yam leaves at an average height

of 1.1, 1.2, and 0.7 m were monitored at mid-canopy for pigeonpea in an alley, sole yam, and pigeonpea as a border, respectively. Young and fully developed yam leaves on the ridges of all the treatments were used for monitoring light, reaching the belowground canopy. The device also recorded leaf chlorophyll content alongside the light intensity. The leaf chlorophyll content indicates the health of the plant and N usage by the plants in the soil.

2.3.6. Yam yield and land equivalent ratio (LER) determination

Yam tuber yields were determined by harvesting the central rows of each treatment, and adjacent stands were harvested as a replacement in case of loss of stand within the central rows (Fig. S1). For each treatment, both total and sub-sample fresh weights were taken in the field. The fresh tuber weight for each treatment was converted to a hectare basis. The LER was determined following the approach of Bybee-Finley and Ryan (2018), Eqs. 2, 2.1 and 2.2.

$$\text{LER} = \text{Partial LER of yam} + \text{Partial LER of pigeonpea} \quad (2)$$

$$\text{Partial LER of yam} = \frac{\text{Yield of yam in intercrop}}{\text{Yield of yam in monocrop}} \quad (2.1)$$

$$\text{Partial LER of pigeonpea} = \frac{\text{Yield of pigeonpea in intercrop}}{\text{Yield of pigeonpea in monocrop}} \quad (2.2)$$

2.4. Statistical analysis

An analysis of variance (ANOVA) at 5% significant level ($P \leq 0.05$) of the SAS, 9.4 version was used to analyze the data collected on sunlight intensity on the yam leaves, percentage of soil moisture along with the soil profile, yam stand establishment, pruned pigeonpea biomass applied on ridges, and the yam yield components. All data parameters met the Shapiro Wilk normality and Levenes' homogeneity tests before the ANOVA test. PROC MIXED of cropping system and fertilizer level as fixed effects with block, location, and year as random effects were used. The effect of the cropping system, location, and year was tested on total pigeonpea pruned biomass, biomass N yield, N-fixation, yam stand establishment, sunlight intensity on yam leaves, and weed pressure in a three-way ANOVA. Using the cropping system, fertilizer level as fixed factors and location and year as random factors, a four-way ANOVA was used to test the effect on yam yield components and yam leaf chlorophyll content. Where treatment means differ significantly, the standard error of the difference between means (SED) at a 5% significance level was used to separate the means.

3. Results

3.1. Soil characteristics

Irrespective of the timing of soil sampling, the soils at Ejura showed better indications of fertility (pH and Effective Cation Exchange Capacity, ECEC) than Fumesua soils (Table S1). Fumesua soils were generally very strongly acidic (pH 4.4–5.2), while Ejura soils were closer to neutral (pH 6.6–7.9). Ejura soils are lixisols known to be less weathered, have deeper topsoil, and are more fertile than the acidic acrisols found in Fumesua. The introduction of the pigeonpea and application of its biomass on the ridges did increase N (Nitrogen), P (Phosphorus), and the availability of other nutrients, improving ECEC in the soil of both locations and years. Also, P was high at harvest on Fumesua soils than Ejura soils (Table S1).

3.2. Yam stands and establishment

Yam stands, and the establishment was significantly influenced by the cropping system in both locations and years. Irrespective of the location,

yam planted in PA had a significantly higher number of stands and establishments at the field for both locations and years. Generally, sole yam fields recorded the worst field establishment in both locations and years (Fig. 3).

3.3. N yield and N – fixation of applied leafy biomass

Cropping system significantly influenced the leafy biomass production of pigeonpea in both locations and years. Pigeonpea stands at harvest were similar for the cropping systems in 2018 but significantly reduced for all the cropping systems in 2019. PA produced significantly higher leafy biomass in 2018 than in the 2019 cropping seasons, irrespective of the location. Leafy biomass applied on the PA field resulted in an N yield of 51.10 and 76.45 kg ha⁻¹ at Fumesua and Ejura, respectively, for the 2018 cropping season. In 2019, on PA fields, the N yield reduced significantly to 25.44 and 30.05 kg ha⁻¹ for Fumesua and Ejura, respectively. Similar trends were observed on the PB fields with the applied biomass N yield of 36.08 and 65.72 kg ha⁻¹ at Fumesua and Ejura, respectively, for the 2018 cropping season compared to N yield of 20.10 and 22.86 kg ha⁻¹ in Fumesua and Ejura respectively for the 2019 cropping season. High N due to fixation of 27.06 (52.95%) and 49.2 kg ha⁻¹ (62.35%) were observed for Fumesua and Ejura, respectively, in PA. While PB had N fixation of 17.99 (49.86%) and 34.05 kg ha⁻¹ (51.81%) at Fumesua and Ejura, respectively, in the 2018 cropping season. N due to fixation reduced to 16.30 (64.07%) and 19.25 kg ha⁻¹ (64.06%) for PA and 10.34 (51.44%) and 11.69 kg ha⁻¹ (51.14%) for PB at Fumesua and Ejura respectively for the 2019 cropping season (Table 1).

3.4. Above ground competition for sunlight

There was no significant interaction between location, cropping system, and year and their two-way interactions. Cropping system significantly influenced the light intensity on the yam leaves in both locations and years. Generally, the light intensity observed on yam leaves at MC of PB and sole yam was similar to the light intensity on PA's yam leaves at AC in both locations across the years. Also, the light intensity on yam

leaves at BC of PB and sole yam were significantly higher than the light intensity on yam leaves at MC of PA fields (Fig. 4).

3.5. Stake and ridge height at harvest

Interaction between location and cropping system significantly influenced the stake height and the ridge height at harvest of yam (Table 2). The bamboos used in the sole yam field at both locations and years had an average height of 2.33 and 2.63 m, in line with the optimum stake height of 3 m recommended by Ennin et al. (2014) for yam production. The stake height in PA depended on the height of the pigeonpea. Thus, a live-stake pigeonpea with an average height of 2.17 and 2.31 m was used at Fumesua and Ejura, respectively. The PB field's stake height was the lowest due to shorter pigeonpea stem cuttings used as stakes from the borders, with an average height of 0.98 and 1.12 m at Fumesua and Ejura, respectively (Table 2).

3.6. Chlorophyll content of yam leaves

A significant interaction was observed between pigeonpea-yam cropping system and fertilizer rate on the chlorophyll content of yam leaves in both locations and years. The average leaf chlorophyll content was better at Ejura (B) than Fumesua (A). Generally, at no fertilizer and half fertilizer rate (23–23–30 N-P₂O₅-K₂O kg ha⁻¹), leaf chlorophyll content followed the order of PA > PB > sole yam. At full fertilizer rate (45–45–60 N-P₂O₅-K₂O kg ha⁻¹), it followed an order of PA = PB > sole yam and PA > PB > sole yam in Fumesua and Ejura, respectively (Fig. 5).

3.7. Below ground competition for water

The presence of the pigeonpea and the biomass on the field influenced the moisture on the ridges (0–40 cm). PA fields generally had the highest moisture content, followed by PB, and the lowest in the sole yam field in both locations and years. Sole yam field had a high percentage of soil moisture below 400 cm compared to yam planted in PA and PB fields in both locations and years (Fig. S3). Thus, soil moisture was available in

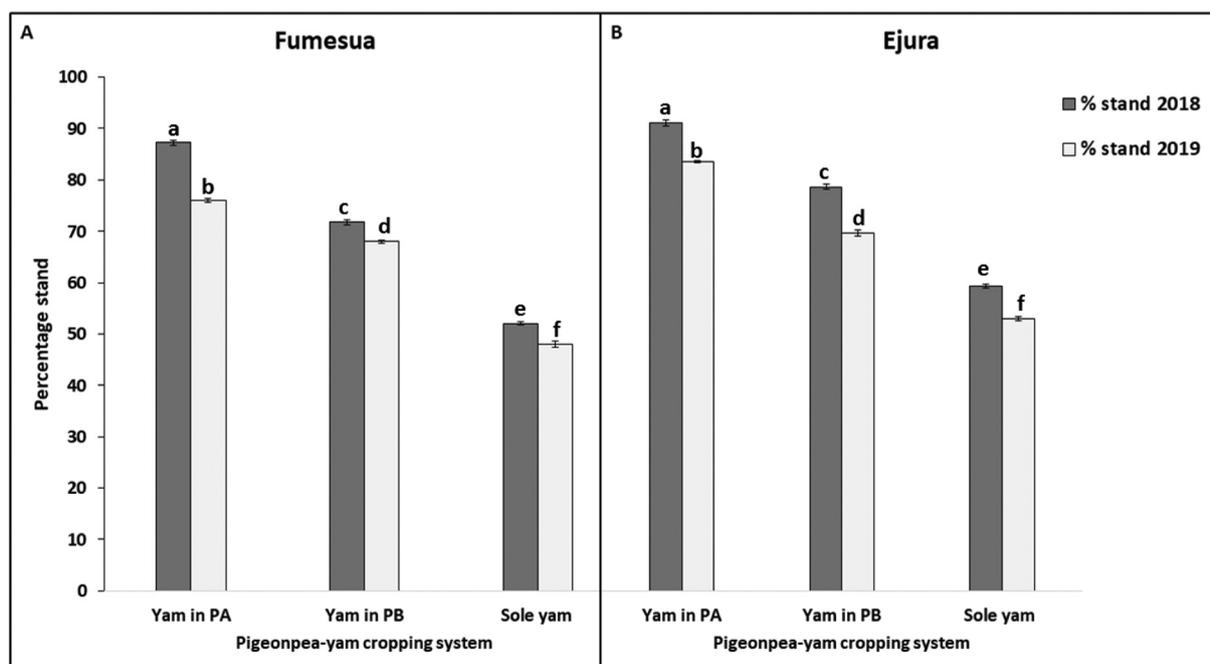


Fig. 3. Percentage yam stand, two months after planting yam at Fumesua (A) and Ejura (B) for the 2018 and 2019 cropping season. PA – pigeonpea in alley; PB – pigeonpea as border. Error bars represent SED of cropping system means at 5% significant ($P \leq 0.05$).

Table 1
Total dry matter of pigeonpea biomass applied on ridges in the cropping system, nitrogen (N) yield and N due to fixation as influenced by cropping system for 2018 and 2019 cropping season.

Location	Pigeonpea-yam cropping system	Population density at harvest ha ⁻¹		Total leafy biomass added (t ha ⁻¹)		N content of biomass (kg ha ⁻¹)		N due to fixation (kg ha ⁻¹)	
		2018	2019	2018	2019	2018	2019	2018	2019
Fumesua	Yam in PA	5910 ^a ± 29.08	4712 ^b ± 103.52	2.41 ^c ± 0.07	1.06 ^c ± 0.04	51.10 ^c ± 9.57	25.44 ^c ± 1.17	27.06 ^c ± 13.89	16.30 ^c ± 1.16
	Yam in PB	5871 ^a ± 49.93	4613 ^b ± 188.37	2.13 ^d ± 0.05	0.91 ^d ± 0.01	36.08 ^d ± 6.93	20.10 ^d ± 0.64	17.99 ^d ± 7.76	10.34 ^d ± 2.91
Ejura	Yam in PA	5914 ^a ± 28.87	4837 ^a ± 49.50	3.57 ^a ± 0.05	1.25 ^a ± 0.05	76.45 ^a ± 26.07	30.05 ^a ± 1.06	49.20 ^a ± 8.59	19.25 ^a ± 1.25
	Yam in PB	5881 ^a ± 49.98	4638 ^b ± 50.01	3.19 ^b ± 0.09	1.04 ^b ± 0.03	65.72 ^b ± 19.93	22.86 ^b ± 0.64	34.05 ^b ± 12.76	11.69 ^b ± 2.9

PA – pigeonpea in alley; PB – pigeonpea as a border. Means followed by the same letter in each year do not significantly differ from each other at 5% significant level ($P \leq 0.05$). ± and value beside each mean represent the standard deviation (SD) of the mean.

the ridges for the growth and development of yam during the growing season on PA, followed by PB with worse soil moisture availability on the ridges of the sole yam field for both years and locations.

3.8. Weed pressure in the cropping system

Weed pressure was significantly influenced by the pigeonpea-yam cropping system. Weed biomass was significantly lower in yam planted in PA fields, followed by yam in PB fields, with the sole yam field recording the highest weed pressure in both locations and years. Generally, weed pressure was high for all the cropping systems in 2019 than in the 2018 cropping season and higher at Ejura (B) than Fumesua (A) for both cropping seasons (Fig. 6).

3.9. Resource use and yam productivity

Significant interactions between location, year, cropping system, and fertilizer was observed in the yam tuber yields. Generally, yam yield was higher at Ejura (C & D) than Fumesua (A & B) and in the 2018 (A & C) cropping season than in the 2019 (B & D) cropping season as shown in Fig. 7. Also, fertilizer application generally improved yield except in sole yam fields and especially in the 2019 cropping season. A

significantly lower yield was observed for the sole yam field with no and half fertilizer rate for both locations and cropping season. Generally, across locations and years, tuber yields were higher and similar for planting yam in PA with half fertilizer rate (23–23–30 N-P₂O₅-K₂O kg ha⁻¹) and full fertilizer rate (45–45–60 P₂O₅-K₂O kg ha⁻¹) than tuber yield on PB and sole yam fields (Fig. 7).

The LER was influenced significantly by the cropping system in both locations and years. The relative yield of yam in all the cropping systems was more than one (1), while the pigeonpea was less than 1 for both locations and years. More than 1 LER were recorded for all the intercropping systems with yam in PA, recording the highest LER than yam in PB for both locations and years (Table S2). The Pearson correlation indicates the factors that explain the increase in yam tuber components. Total pigeonpea biomass applied and ridge height significantly and directly contributed about $R^2 = 77\%$; $R^2 = 53\%$ and $R^2 = 66\%$; $R^2 = 54\%$ to yam tuber yield stands at Fumesua and Ejura, respectively across the two cropping seasons. The leaf chlorophyll content explains 61 and 30% of the tuber yield per stand at Fumesua and Ejura, respectively. However, a significant inverse relationship was observed between the yam yield components and the total sunlight reaching the yam leaves in both locations across the two seasons (Fig. 8).

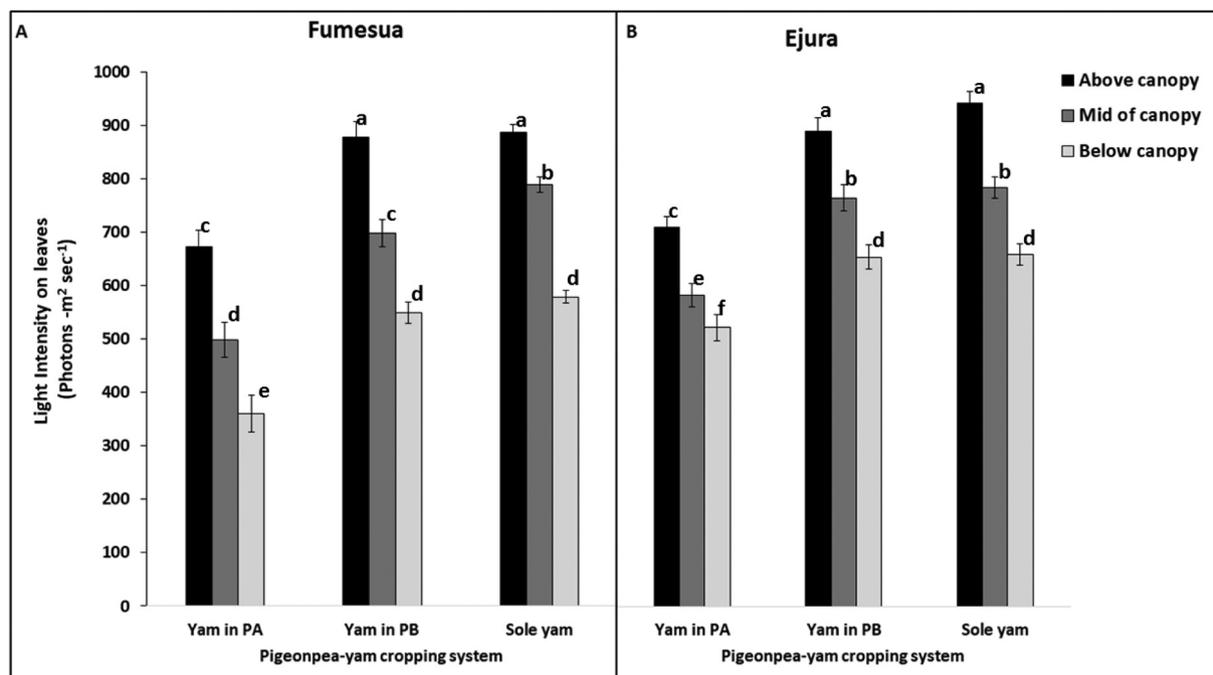


Fig. 4. Average bi-weekly (8–28 weeks after planting) sunlight photon reaching yam leaves in pigeonpea-yam cropping system at Fumesua (A) and Ejura (B) across 2018 and 2019 cropping seasons. PA – pigeonpea in alley; PB – pigeonpea as border. Error bars represent SED of sunlight reaching a canopy level across seasons at 5% significant level ($P \leq 0.05$).

Table 2

Stake and ridge height at harvest of yam in cropping systems at Fumesua and Ejura across 2018 and 2019 cropping seasons.

Location	Cropping system	Stake height at harvest (m)	Ridge height at harvest (m)
Fumesua	Yam in PA	2.17 ^b ± 0.61	0.34 ^a ± 0.07
	Yam in PB	0.98 ^c ± 0.65	0.27 ^b ± 0.08
	Sole Yam	2.33 ^a ± 0.59	0.20 ^c ± 0.07
Ejura	Yam in PA	2.31 ^b ± 0.64	0.38 ^a ± 0.06
	Yam in PB	1.12 ^c ± 0.67	0.32 ^b ± 0.09
	Sole Yam	2.63 ^a ± 0.65	0.23 ^c ± 0.07

PA – pigeonpea in alley; PB – pigeonpea as a border. Means followed by the same alphabet in each location do not significantly differ from each other at 5% significant level ($P \leq 0.05$). ± and value beside each mean represent Standard Deviation (SD) for each cropping system across seasons.

4. Discussion

4.1. Yam sprout rate and establishment

The observed significantly higher stand establishment for planting yam in the PA at Fumesua (A) and Ejura (B) for both cropping seasons could be attributed to the shade provided by the pigeonpea and its biomass during the sprouting of the yams. Even in the 2019 cropping season, when pigeonpea biomass was reduced at both locations, yam sprouting, and establishment were significantly better on PA and PB fields than the sole yam fields (Fig. 3). Thus, shade provided by the pigeonpea canopy and biomass on the ridges reduces direct heat from the sun and moisture loss from the ridges creating a suitable medium for the yam sprouting and yields. Agbede et al. (2014) observed that mulching in yam is essential for the growth and development of yams. Soil nutritional improvement due to mulch and the mulch's ability to control the soil temperature and moisture for the benefit of the yam was demonstrated using *Tithonia* and *Chromoleana* mulch. Plant biomass for mulching yam resulted in the reduction of soil temperature along the depth of the ridges or mound for the benefit of the yam tuber resulting in improved yields and profit (Agbede et al., 2014; Akinola and Owombo, 2012). This suggests that reducing soil temperature and conserving soil moisture, especially in the tropics, might

prevent seed yam rot and subsequent death during planting. Shading and biomass from the pruning of legume shrubs such as pigeonpea would play a vital role in yam production.

4.2. Nitrogen and other nutrient contributions of pigeonpea in the system

The generally high pigeonpea biomass production in Ejura than Fumesua, irrespective of the similar stands, could be attributed to the lxisols found at Ejura, which are less weathered and more fertile than the acidic acrisols found at Fumesua. Thus, the Ejura fertile soils supported more growth and pigeonpea biomass production at Ejura than Fumesua. Similar stands were observed for PA and PB in 2018. PA had higher stands in 2019 and produced significantly higher biomass compared to the PB fields (Table 1). This observation could be attributed to the less space and high intra-specific competition for resources by the pigeonpea of the PB field. PB fields had all pigeonpea population crowded at three borders of the field planted at 1.2×0.5 m, while the pigeonpea in an alley field had pigeonpea planted 3.6×0.5 m. The planting distances imply while the intra-specific competition for above ground (Sunlight) and below ground (soil nutrients and water) resources were high among the pigeonpea stands in PB fields, the intra-specific stand competition was minimal in the PA field. As such, the PA would have had almost all resources for the growth and accumulation of biomass. Several studies have made similar observations. Kaur and Saini (2018), observed that planting determinate pigeonpea at a wider row spacing of 0.6 m resulted in a significantly high yield attribute than planting at a row spacing of 0.5 and 0.45 m. The PA field's high leafy biomass than PB fields, contributed significantly higher N yield and N-fixation for both locations and years. Significant reduction in the number of stands and leafy biomass in both locations for the 2019 cropping season resulted in significantly lower N yield and N-fixation (Table 1). N-fixation depends significantly on the total biomass yield and total N yield of the biomass (Mhango et al., 2020; Tamagno et al., 2018).

Mhango et al. (2017) observed that high biomass production of pigeonpea, especially in good rainfall years, resulted in high N-fixation. The significant reduction in the number of stands, leafy biomass, N yield, and N-fixation by PA and PB in both locations in the 2019 cropping season might be due to the pruning effect from the

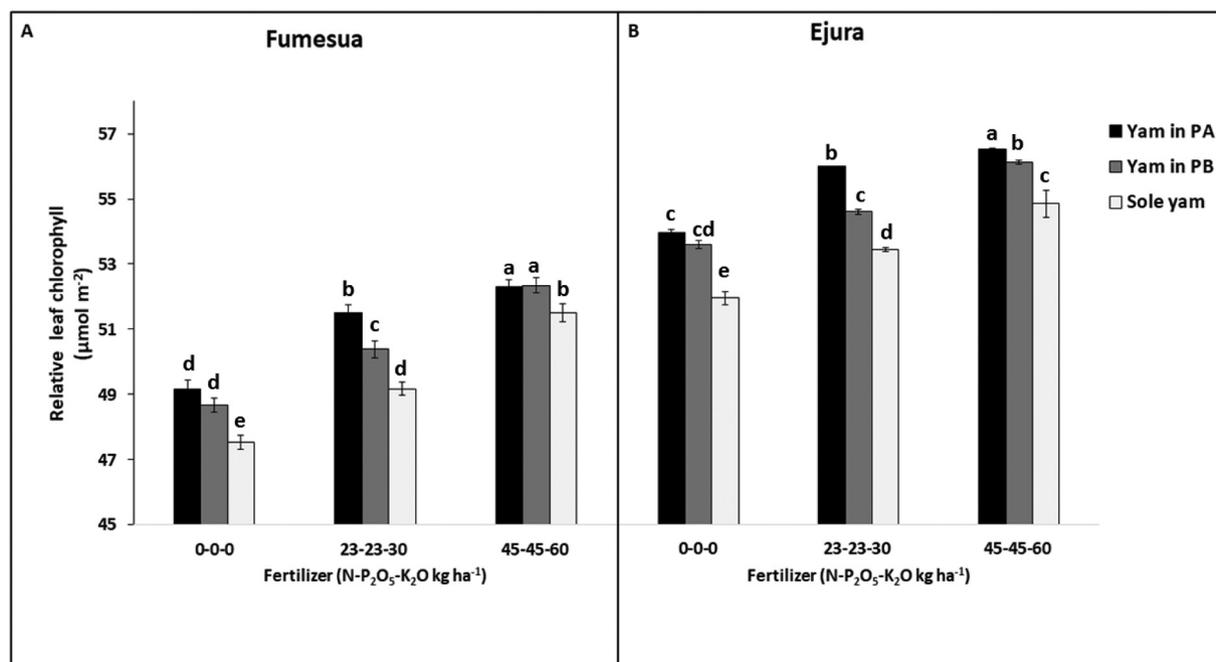


Fig. 5. Average biweekly leaf chlorophyll content of yam in pigeonpea-yam cropping system at Fumesua (A) and Ejura (B) across the 2018 and 2019 cropping season. PA – pigeonpea in alley; PB – pigeonpea as a border. Error bars represent SED of the cropping system mean across seasons at 5% significant level ($P \leq 0.05$).

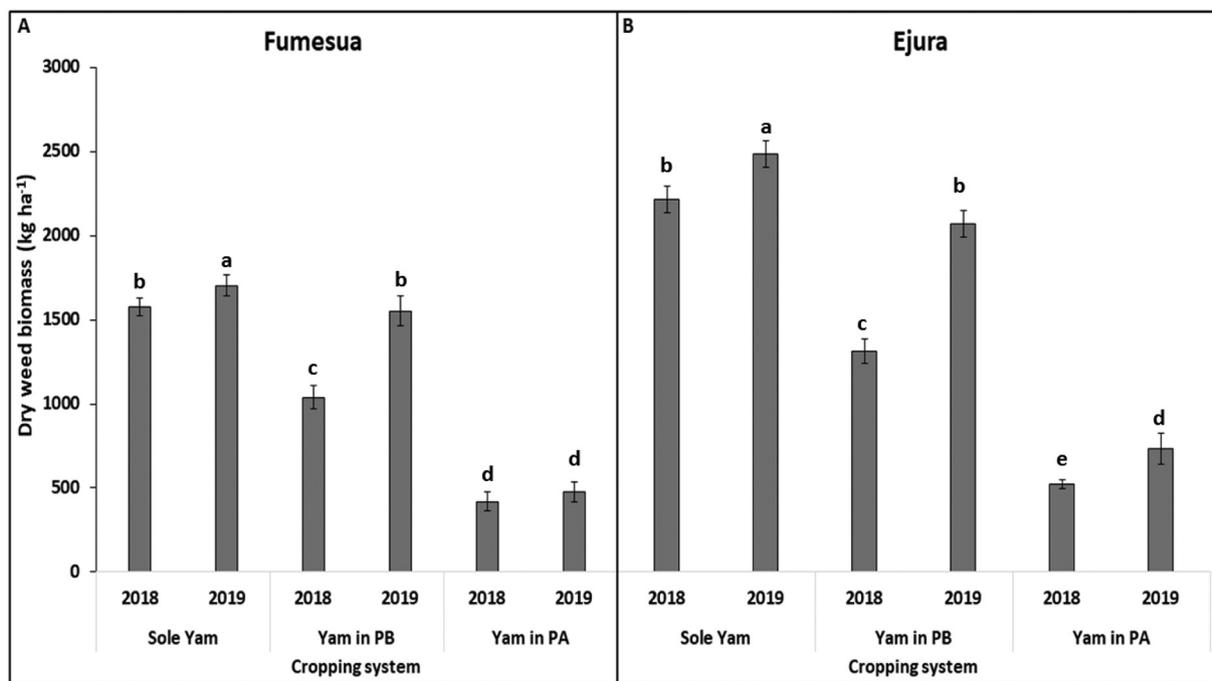


Fig. 6. Weed pressure eight weeks after planting in the pigeonpea-yam cropping system at Fumesua (A) and Ejura (B) for the 2018 and 2019 cropping season. Error bars represent the SED of means of the cropping system at 5% significant level ($P \leq 0.05$). PA – pigeonpea in alley, PB – pigeonpea as border.

2018 cropping season (Table 1). Severely pruning of pigeonpea significantly reduced the survival and yield of pigeonpea cropping system. Letty et al. (2021), observed pruning height affected biomass production. Pruning at the height of 90 cm resulted in a significantly higher branching than others. Thus, the need to further pay attention to the pruning and management of the pigeonpea in the pigeonpea-yam cropping system to ensure sustainable biomass production. Pigeonpea can produce root exudates, enabling it to efficiently take up P from the

soil into its biomass to benefit associated crops (Krishnappa and Aftab Hussain, 2014). This observation is in line with the general improvement in phosphorus (P) and cation exchange capacity on the ridges upon applying pigeonpea biomass (Table S1). Gerland et al. (2017), indicated improved soil nutrient including P with the presence of pigeonpea in a cropping system. Thus, the inclusion of pigeonpea in the cropping system, especially in the tropics, would be a strategic option for efficient P cycling to benefit associated crops.

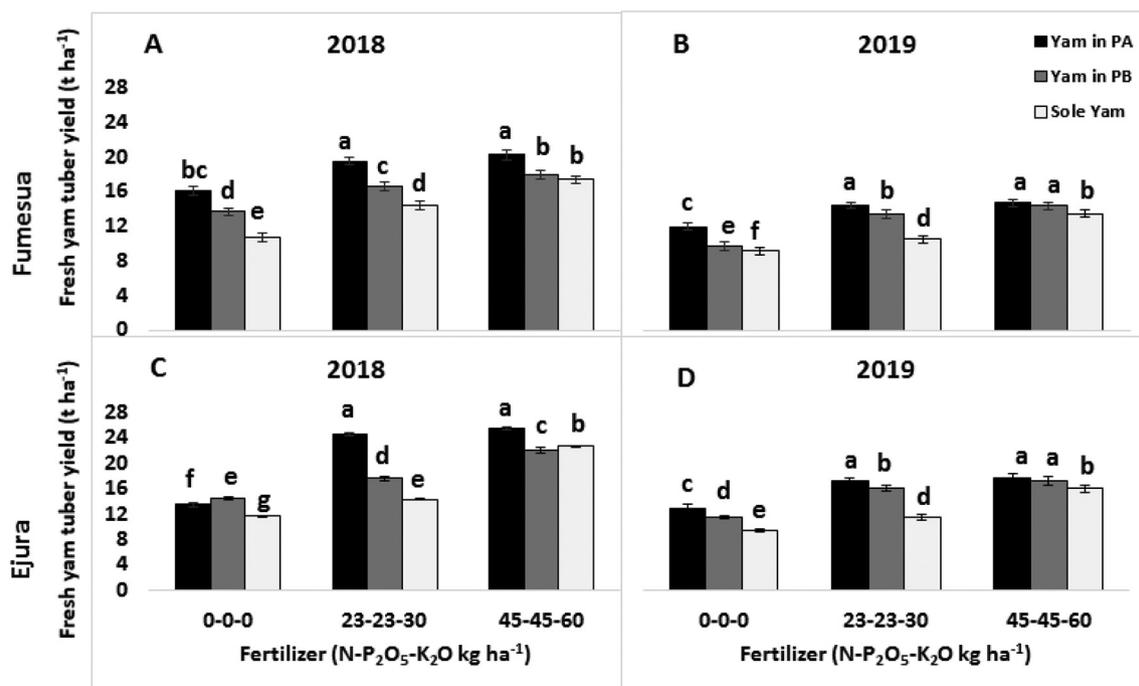


Fig. 7. Fresh yam tuber yield in a pigeonpea-yam cropping system for 2018 (A) and 2019 (B) cropping seasons at Fumesua and for 2018 (C) and 2019 (D) cropping seasons at Ejura. PA and PB are pigeonpea in alley and pigeonpea as a border, respectively. Error bars represent the SED of cropping systems.

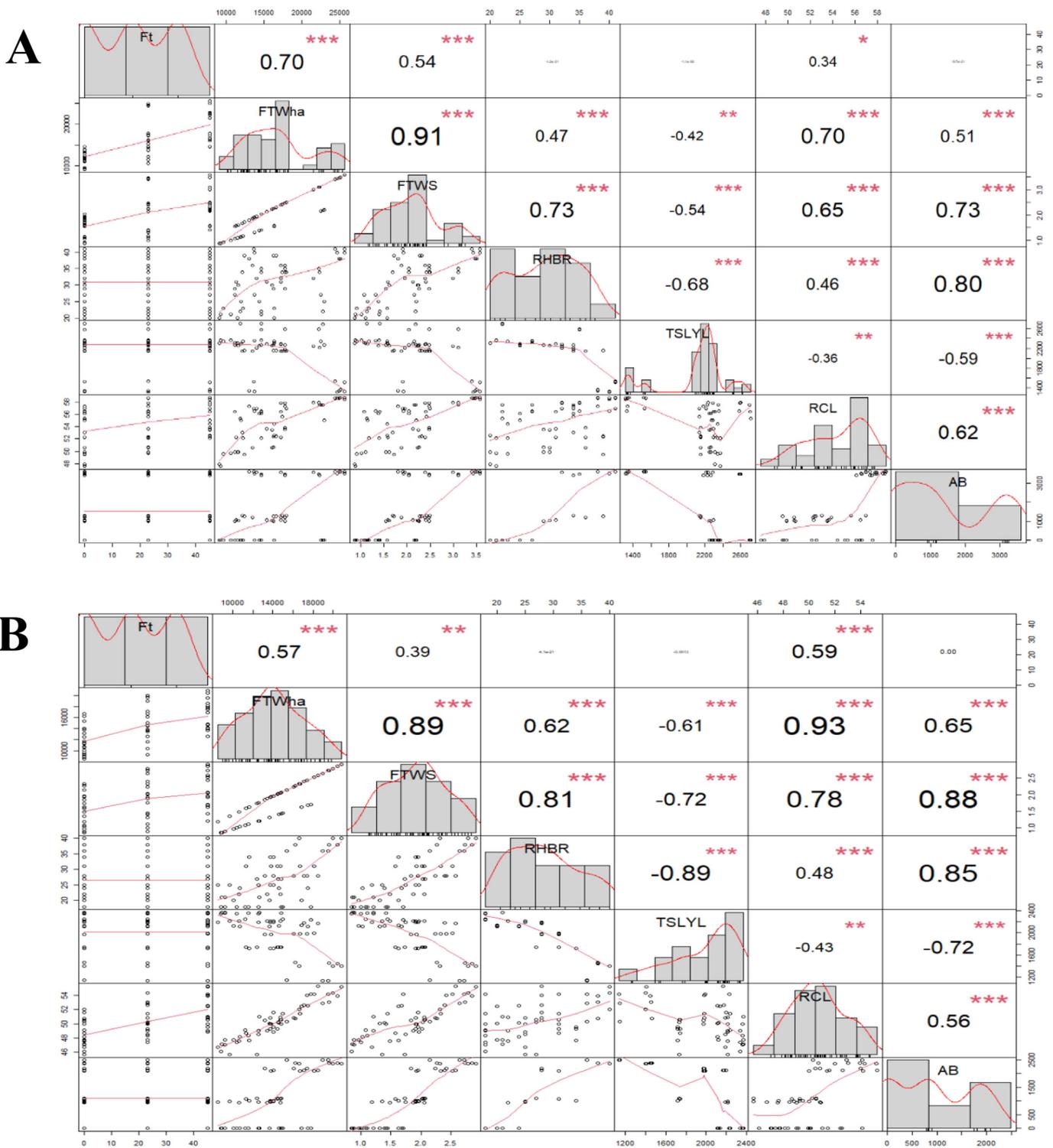


Fig. 8. Pearson correlation of tuber yield components, sunlight intensity and ridge height at Fumesua (A) and Ejura (B) across 2018 and 2019 cropping seasons. **Correlation is significant at 1% level ($P \leq 0.01$) (2-tailed). *Correlation is significant at 5% level ($P \leq 0.05$) (2-tailed). Ft – fertilizer level; FTWha – fresh tuber yield per hectare; FTWS – fresh tuber yield per stand; RHBR – ridge height before re-shaping; TSLYL – total sunlight on yam leaves; RCL – chlorophyll of leaves; AB – total biomass applied as pruning.

4.3. Resources use and implication on yam productivity in the cropping system

Leaf chlorophyll content and tuber yield of yam were influenced significantly by the interaction between the cropping system and fertilizer in both locations and years. The generally high leaf chlorophyll content and tuber yields at Ejura (B) as compared to Fumesua (A) could be

accounted for by the more fertile lixisols at Ejura, which supported plant growth and development than the acidic acrisols found at Fumesua (Figs. 5 and 7). Soils with a pH between 6 and 7, such as in Ejura, are suitable for yam and most food production. ECEC improved whiles P was reduced at harvest in Ejura soils than Fumesua soils suggesting better uptake of nutrients and P in Ejura soils (pH 6.4–6.8) than in strongly acidic soils of Fumesua (4.4–5.3, Table S1).

The presence of the pigeonpea, especially in yam planted in PA fields, did shade the yam leaves resulting in significantly lower sunlight photons reaching the yam leaves in both locations and years (Fig. 4). This suggests reduced sunlight on yam leaves as a result of the pigeonpea in the pigeonpea-yam cropping system. However, the shading from the pigeonpea positively resulted in soil moisture conservation, reduced ridge erosion, and reduction in weed pressure (Table 2; Figs. S3 & 6). Thus, the generally significantly higher tuber yields recorded in 2018 (A & C) than the 2019 (B & D) cropping season could be attributed to the corresponding high pigeonpea biomass produced in 2018 cropping season than the 2019 cropping season (Table 1; Fig. 7). Yam in PB fields received similar sunlight photons as the sole yam fields, resulting in generally similar sunlight reaching the leaves at various canopy levels compared to sole yam in both locations and years (Fig. 4). However, the shading effect of the pigeonpea on the yam in PA did not reduce yam productivity but instead enhanced the yam yields (Figs. 4 and 8). Significantly higher tuber yields recorded for the yam planted in PA than PB and sole yam in both locations and years indicates the positive effect of the shade and biomass provided by the pigeonpea.

Yam is a climber and C3 plant species which upon receiving 50% of the required light intensity, becomes saturated, making yams tolerant to shade and operate under full photosynthetic potential in the moderate shade by increasing their leaf size and chlorophyll content as an adaptation strategy (Blomme et al., 2020; Sawitri and Primananda, 2020). Also, environmental conditions such as high-temperature increase oxygenation reactions along the photorespiratory pathway, causing about 25–30% losses in carbon fixation, especially C3 plants (Raines, 2011). Thus, the moderate shading provided by the pigeonpea in the alley might have reduced temperature and improved photosynthetic efficiency resulting in the high productivity of yams in PA fields than the yam in PB fields and sole yam fields. Improvement in nutrient assimilation and cocoa productivity under moderate shade observed by Abdulai et al. (2018), and Asare et al. (2017) are in line with this study. Arrangement of agroforestry tree and intercropping with maize – a C4 plant, enhanced productivity (Sileshi et al., 2012), suggesting similar radiative use efficiency of maize as in sole maize cropping system. Thus, the tree component's shading did not significantly affect the quality of photons needed for the maize productivity.

Stakes for the yam vines to climb are important for yam productivity (Ennin et al., 2014). Yam planted in PA and PB had 2.1–2.3 m live-stake, and 0.9–1.1 m cut stakes, respectively, from the pigeonpea to climb for enough sunlight (Table 2). Unlike yam, pigeonpea has a deep taproot system (Singh et al., 2019, 2020) and an ability to improve the availability of soil nutrients, primarily N and P, for the benefit of the associated cropping system (Gerland et al., 2017; Smith et al., 2016). These attributes of pigeonpea created a beneficial microenvironment facilitating the use of resources to benefit the yam in the pigeonpea-yam cropping system. Similar chlorophyll content of the yams and corresponding yam tuber yields, especially yam in PA fields with half fertilizer (23–23–30 kg ha⁻¹ N-P₂O₅-K₂O) and full (45–45–60 kg ha⁻¹ N-P₂O₅-K₂O) fertilizer rates were observed for both locations and years. These results suggest that the half fertilizer rate could meet the yam's nutrient requirement in the presence of the pigeonpea leafy biomass. Even where no fertilizer was applied, yam yields were relatively better with the pigeonpea biomass's presence on either yam in PA or PB than sole yam fields (Fig. 7). Liu et al. (2021) made a similar observation when pigeonpea biomass and fertilizer were used in yam cultivation. It resulted in reduced soil organic matter loss and improved yam productivity.

The major contributing factor for the significantly higher total tuber yield from the yam pigeonpea intercropped fields (PA and PB) is as a result of the corresponding significantly higher yield per stand compared to the sole yam fields (Figs. 7 and 8). Several studies have observed that the availability of moisture is not only crucial for sprouting and establishment during the early stages of the roots and tuber crops but also vital for bulking larger tubers (Ennin et al., 2014; Eruola et al., 2012).

Yam, unlike cassava, does not penetrate its roots in the soil before bulking, and as such, the tuber expansion, size, shape, and quality are dependent on the soil medium. Agbede et al. (2014) observed that organic matter on yams would prevent erosion of the medium in which the yam is bulking, increase infiltration and water conservation, and improve microbial activity to enhance yam tuber bulking and yield. Thus, the size of the bulking medium has a more pronounced influence on yam tuber yield per stand; preventing it from erosion would improve productivity.

Although re-shaping of the ridges was conducted one and two times for PB and sole yam fields, respectively, no re-shaping was needed in PA fields. The PA fields had a ridge height of 0.34–0.38 m, while the PB fields had a ridge height of 0.26–0.32 m at the time of harvest in comparison to a ridge height of 0.19–0.23 m in the sole yam fields in both locations and years (Table 2). These results suggest that the pigeonpea and biomass on the PA fields protected the ridges from eroding. The significant positive influence of applied pigeonpea biomass and ridge height on the yam tuber yield component (Fig. 8) indicates the vital role of pigeonpea in a pigeonpea-yam integrated system. Thus, the presence of the pigeonpea would provide shade, reduced erosion of ridges, improve infiltration, conserve moisture, reduce weed pressure, and improve soil nutrition on the ridges resulting in improved yam tuber yield per stand of the associated yam crop.

Yam production along the West African yam belt is far below potential yield, achieving just about 10 t ha⁻¹ yields compared to a potential of about 50 t ha⁻¹ across all yam varieties, and increase in yam production along the West African yam belt are mainly as a result of an increase in the area under yam cultivation (Frossard et al., 2017; Neina, 2021). Thus, yam production in Ghana, just like other West African countries, increase as the area under yam cultivation increase. These observations suggest yam would continue to contribute to land degradation and deforestation if improved technologies are not employed to sustain its production on continuously cropped fields, which farmers under normal circumstances would not prefer for yam production. Integrated soil fertility management, along with farmer options and preferences, has been observed to be the way forward (Frossard et al., 2017). We have demonstrated that the integration of pigeonpea into the yam cropping system would reduce ridge erosion, improve soil nutrients and moisture conservation, thereby sustaining yam's productivity even on the continuously cropped fields.

5. Conclusion

Integrated soil fertility management with pigeonpea biomass and inorganic fertilizer is a possible option for sustainable yam production to address the constraint of staking acquisition and soil fertility sustenance resulting in deforestation and land degradation associated with yam production. Apart from providing reliable cut-stakes or live-stakes, the pigeonpea biomass and shade reduced ridge erosion, conserved soil moisture, improved yam sprouting, and suppressed weeds. These attributes of the pigeonpea on yam resulted in the facilitation of resources used in the cropping system and enhanced yam's productivity. Growing yam in an alley of pigeonpea with half fertilizer rate (23–23–30 kg ha⁻¹ N-P₂O₅-K₂O) resulted in sustained soil fertility, provided live-stakes for yam vines, and improved yam productivity. Besides, the cultivation of yam with pigeonpea at the borders (equivalent to using about a third of the field for growing pigeonpea) as a reliable source of cut-stakes with half fertilizer rate (23–23–30 kg ha⁻¹ N-P₂O₅-K₂O) also presents an option better than the sole yam cultivation. Therefore, integrated soil fertility management of planting yam with pigeonpea with half the recommended fertilizer rate (23–23–30 kg ha⁻¹ N-P₂O₅-K₂O) could be the way forward for sustainable yam production on continuously cropped fields. However, there would be a need for further studies on the fertilizer rate to ascertain if the half-rate (23–23–30 kg ha⁻¹ N-P₂O₅-K₂O) can be further reduced without affecting the productivity and returns on the

yam. Economic analysis of the pigeonpea-yam cropping system options would be needed to ascertain each cropping system option's profitability. Future research on pruned height, and frequency of pruning the pigeonpea to ensure a sustainable biomass supply will be needed. Pursuing and providing answers to the above research areas would result in an informed decision on making the pigeonpea-yam a sustainable yam production option attractive to especially smallholder farmers. Thus, land degradation and deforestation associated with yam production along the West African yam could be addressed.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aaos.2022.05.001>.

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