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SPATIAL STUDIES ON GINGER AND PIGEON PEA-BASED AGROFORESTRY SYSTEMS AND IMPLICATIONS FOR CARBON SEQUESTRATION AND SOIL NUTRIENT RECAPITALIZATION IN UMUDIKE, SOUTHEAST NIGERIA

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ABSTRACT

This spatial study on ginger and pigeon pea-based agroforestry systems assessed the impacts of location and agroforestry systems on soil health and carbon sequestration in southeastern Nigeria. A split-plot design experiment with four replications was employed, using location as the main plot and agroforestry production systems as subplots. Three locations (Olokoro, Western Farm NRCRI Umudike, and Eastern Farm NRCRI Umudike) and four ginger production systems—Ginger-Pigeon Pea Alley System (GPAS), Ginger-Pigeon Pea Scatter System (GPSS), Sole Ginger Unmulched (SGU), and Sole Ginger with Mulch (SGM)—were evaluated. The experiment utilized 2m x 5m plots, with ginger planted at 20cm x 20cm spacing and pigeon pea at 20cm x 40cm spacing. Ginger was introduced 2 months after the planting of pigeon pea. Results indicated significant location effects on initial soil pH, organic carbon, and nitrogen levels, with Olokoro Farm showing the highest soil organic matter (26.2 g/kg). Agroforestry systems significantly improved soil health, with GPAS and GPSS increasing soil organic matter by 15% and 12%, respectively. Carbon sequestration ranged from 14.2 t/ha (SGU) to 25.1 t/ha (GPAS). The study specifically highlighted the efficacy of the ginger-pigeon pea alley system (GPAS) and mulching in promoting soil health and enhancing carbon sequestration. Furthermore, integrating ginger and pigeon pea into alley or scatter systems enhanced ecosystem services, reduced soil erosion, and improved biodiversity.

Keywords: Agroforestry, Ginger, Pigeon Pea, Location-Specific, Soil Health, Carbon Sequestration

INTRODUCTION

Agroforestry systems have emerged as a vital strategy for mitigating climate change, enhancing biodiversity, and promoting sustainable agriculture in tropical regions. By integrating trees into agricultural landscapes, agroforestry systems can sequester significant amounts of carbon dioxide, improve soil fertility, and enhance ecosystem services (Nair et al., 2021; IPCC, 2022). In Nigeria, where agricultural expansion and deforestation are major environmental concerns, agroforestry systems offer a promising approach for achieving sustainable development goals (Adeola et al., 2020). Climate change poses a significant threat to ginger production in Nigeria, and deforestation is a major driver of the climate crisis. Soil degradation, rising temperatures, loss of vegetation, changing precipitation patterns, erosion, and nutrient depletion are challenges that ginger farmers face, particularly in tropical regions with high rainfall and intensive agricultural practices Akinyemi and Olniyi,2014; IPCC, 2022)

Ginger (*Zingiber officinale*) and pigeon pea (*Cajanus cajan*) are two crops widely cultivated in Southeast Nigeria. Ginger is a valuable spice crop that provides income for smallholder farmers, while pigeon pea is a leguminous crop that enhances soil fertility through nitrogen fixation (Onyemelukwe and Obasi, 2019; Ezeaku and Okechukwu, 2020). There is a significant research gap in ginger-pigeon pea intercropping, and integrating these crops into agroforestry systems could potentially enhance carbon sequestration, improve soil nutrient recapitalization, and promote sustainable agriculture in the region.

The study examined the spatial dynamics of ginger and pigeon pea-based agroforestry systems in Umudike, Southeast Nigeria, with a focus on carbon sequestration and soil nutrient recapitalization. By combining field experiments and spatial analysis, this research provided insights into the potential of ginger-pigeon pea agroforestry systems to mitigate climate change, enhance ecosystem services, and promote sustainable agriculture in the region.

MATERIALS AND METHODS

Study site, location and description

The study was conducted at the Western and Eastern experimental fields of National Root Crops Research Institute, Umudike in Ikwuano Local Government area of Abia state, which lies between Latitude 5^0 28^1 and 5^0 30'N and between Longitude 7^0 31^1 and 7^0 33'E: and Olokoro autonomous community in Umuahia south Local Government Area of Abia state, South-East Nigeria. The area lies between Latitude 5^0 25′ and 5^0 39′ N and Longitude. 7^0 24′ E and 7^0 33′ E). Rainfall within this area is over 2000 mm annually. The climate within the study location is in the humid tropical region with lowland rainforest vegetation. The study site has a low fertility status and is susceptible to soil erosion and drought stress (NRCRI, 2008).

Land preparation and input collection

Ginger rhizomes (yellow ginger-Umu Gin 1) were sourced from the ginger programme, National Root Crops Research Institute, Umudike, while pigeon pea seeds were sourced from the National Seed Service, Umudike station. The experimental sites in the 3 locations were prepared mechanically using a tractor, while the ridges were later converted manually to seed beds of 2m x 5m.

Experimental design

The experiment adopted spatial replication in the three locations (Eastern farm Umuairigha, Western farm Umudike, in Ikwuano local government area of Abia state, and Olokoro farm) in Umuahia South local government area of Abia state, southeast Nigeria. The treatments consisted of four production systems: Ginger Pigeon pea alley cropping (GPAS), Ginger pigeon pea Scatter tree system (GPSS), Sole ginger with mulch (SGM), and Sole ginger without mulch (SGU

Plot size, planting distance and plant population

The experiment was conducted on a plot size of 2m x 5m, where ginger and pigeon peas were planted 20cm apart. Pigeon peas were planted at a seed rate of 600 stands per 10m², equivalent to 600,000 plants per hectare, while ginger was planted at a rate of 250 plants per 10m², or 250,000 plants per hectare. The planting schedule for the 2023/2024 season consisted of pigeon peas being planted in March, followed by the introduction of ginger two months later in May. The Ginger-Pigeon Pea Alley System (GPAS) featured three hedge rows of pigeon pea, forming two alleys where ginger was planted at 20cm intervals. In contrast, the Ginger-Pigeon Pea Scatter System (GPSS) involved establishing pigeon pea stands 40cm apart, with ginger introduced in a scattered arrangement between two pigeon pea stands

Data collection and soil sampling.

Composite soil samples collection before and after treatment introduction using soil auger and soil core at 10-30 cm depth and samples were processed and analyzed to determine the soil texture (Particle size distribution), Bulk density, total porosity, moisture content at field capacity, Moisture content at wilting point and Available moisture, soil Ph., N, P, K, Ca, Mg, Na, ECEC, BS, soil carbon and Carbon sequestration

Laboratory/ statistical analysis

Soil samples collected from the field were air-dried at room temperature and crushed gently with a wooden roller and sieved with a 2-mm sieve. Particle size distribution was analyzed following the modified hydrometer method (Gee and Or, 2002), using sodium hexametaphosphate (Calgon) as a dispersant. Total N was determined by the micro Kjedahl wet oxidation method (Brenner, 1996) while available P was determined by Bray - 2 method (Bray and Kurtz, 1945). Organic carbon was determined by the method of Nelson and Sommers (1982). The data obtained were converted to organic matter by multiplying by 1.724. Soil pH was determined in a soil: distilled water ratio of 1:2.5 using Beckman's Zeromatic pH meter (Thomas, 1996). Exchangeable bases were extracted with neutral 1N ammonium acetate (NH_4OAc) solution. Ca and Mg were determined by EDTA titration, while K and Na were determined using flame photometry. Exchangeable acidity (EA) was determined by KCl extraction following the procedure of Mclean (1982). Effective cation exchange capacity (ECEC) was obtained by the summation of total exchangeable bases (Ca, Mg, K, and Na) and EA. Base saturation was calculated as a quotient obtained after dividing total exchangeable bases by ECEC, multiplied by 100.

Final soil mean data obtained from the 2023/2024 seasons were processed and later subjected to Analysis of Variance (ANOVA) to assess whether there are statistically significant differences in carbon sequestration and soil nutrients, and treatment means were separated using the least significant differences at a 0.05 level of probability

RESULTS AND DISCUSSION

The soil analysis reveals distinct characteristics that affect soil fertility, water-holding capacity, and crop productivity. The soils range from Loamy Sand (LS) at Olokoro to Sandy Loam (SL) at NRCRI Eastern and Western Farms, indicating varying textures. Olokoro has the highest sand content, while NRCRI Western Farm has the lowest. NRCRI Eastern Farm has the highest silt content, while NRCRI Western Farm has the highest clay content, tied with NRCRI Eastern Farm. The pH levels across all sites are acidic, ranging from 4.50 at NRCRI Eastern Farm to 4.90 at NRCRI Western Farm. Phosphorus content varies, with Olokoro having the highest level and NRCRI Western Farm the lowest. Nitrogen levels differ significantly, with NRCRI Western Farm having the highest content and NRCRI Eastern Farm the lowest. Organic carbon and organic matter content are highest at Olokoro. Exchangeable cations and acidity also showed variations. Calcium content is highest at Olokoro and lowest at NRCRI Eastern Farm. Magnesium levels are relatively consistent across sites. Potassium availability is highest at NRCRI Western Farm and lowest at NRCRI Eastern Farm. Sodium content is highest at Olokoro. Exchangeable acidity and effective cation exchange capacity are highest at NRCRI Eastern Farm, while base saturation is highest at Olokoro.

Generally, Olokoro's soil has a sandier texture, higher phosphorus and organic matter content, and higher base saturation. NRCRI Eastern Farm has a more acidic pH and lower nitrogen content. NRCRI Western Farm has a higher nitrogen content and potassium availability. Understanding these soil characteristics across the three sites is crucial for optimizing crop yield under an intercrop situation

Table 1. The Initial physical and chemical properties of the Experimental sites

SOIL PARAMETERS	NRCRI Eastern Farm	OLOKORO	NRCRI WESTERN FARM
SAND (g/kg)	793.0	878.0	748.0
SILT (g/kg)	77.00	57.00	127.0
CLAY	125.0	65.0	125.0
TEXTURE	SL	LS	SL
PH ($H_2$0	4.50	4.80	4,90
P (g/kg)	29.40	22.60	17.90
N (g/kg)	1.54	3.36	2.24
O C(g/kg)	17.86	12.16	21.28
OM (g/kg)	30.79	20.96	36.68
Ca (Cmol/kg)	3.20	4.40	2.80
Mg (Cmol/kg)	1.20	1.20	1.20
K (Cmol/kg)	0.163	0.301	0.137
Na (Cmol/kg)	0.276	0.424	0.320
EA (Cmol/kg)	1.68	0.64	1,44
ECEC (Cmol/kg)	6.319	6.965	5.897
BS (%)	74.22	90.81	75.58

Effect of treatments on soil physical and chemical properties across all locations

The results presented in Table 2 showed the effects of location, agro-forestry systems across 3 locations, and their interaction on selected soil physico-chemical properties of a Ginger-pigeon pea-based agroforestry. The study's findings have significant implications for sustainable agriculture, soil conservation, and environmental management

Location Effects

The data shows that location significantly affects soil physico-chemical properties. Olokoro farm demonstrated better soil fertility indicators, including higher total nitrogen (TN), available phosphorus (Av. P), exchangeable potassium (Exch. K), and organic carbon (OC) compared to the Eastern and Western farms. This suggests that Olokoro Farm's soil has a higher potential for crop production and sustainability (Brady and Weil, 2018). The higher soil pH at Olokoro farm indicates a relatively higher soil alkalinity, which may be beneficial for certain crops but could also lead to nutrient deficiencies.

According to Lal (2019), soil degradation is a significant contributor to inadequate human nutrition. Therefore, understanding the location-specific effects on soil fertility is crucial for developing sustainable agricultural practices. The Eastern farm, Umudike, had the lowest soil pH, indicating acidic soil conditions. This may require careful management to mitigate potential aluminum toxicity and nutrient deficiencies.

Agroforestry System Effects

The agro-forestry systems also had a significant effect on soil physico-chemical properties. The Ginger-Pigeon Pea Alley System (GPAS) and Ginger-Pigeon Pea Scatter System (GPSS) showed improved soil fertility indicators compared to the Sole Ginger without Mulch (SGU) system. GPAS demonstrated higher available phosphorus and organic carbon, while GPSS had higher total nitrogen. These findings suggest that integrating ginger and pigeon pea in alley or scatter systems can enhance soil fertility and sustainability (Palm et al., 2018).

The Sole Ginger with Mulch (SGM) system showed intermediate values for most soil properties, indicating a moderate level of soil fertility. This emphasizes the importance of mulching in maintaining soil health. Mulching can help reduce soil erosion, improve soil moisture retention, and increase organic carbon content (Ekeledo and Chukwu, 2023).

Location X Agro-forestry Interaction Effects

The interaction effects between location and agro-forestry system revealed significant differences in soil physico-chemical properties. Olokoro Farm X GPAS had higher available phosphorus and organic carbon compared to Eastern Farm X GPAS. This suggests that the GPAS system is more effective in improving soil fertility at the Olokoro farm. Similarly, Olokoro farm X GPSS had higher total nitrogen compared to Eastern farm X GPSS.

Implications for Sustainable Agriculture

Findings from the study have significant implications for sustainable agriculture and soil conservation. The results highlight the importance of considering location-specific factors when designing agroforestry systems. Integrating ginger and pigeon pea in alley or scatter systems can enhance soil fertility and sustainability. Mulching is also essential for maintaining soil health.

Farmers and agricultural practitioners can use these findings to develop location-specific strategies for improving soil fertility and sustainability. By adopting sustainable agricultural practices, farmers can reduce soil degradation, improve crop yields, and contribute to food security (Lal, 2019).

Table 2. Effect of location, Agro-forestry system and location x Agro-forestry interaction on selected soil physico-chemical properties of a ginger/pigeon pea farm at Umudike.

Treatment	Soil pH	TN (g/kg)	Av.P (mg/kg)	Exch. K (Cmol/kg)	OC (g/kg)	SAW (mm)	TP (%)
Location effect							
Eastern farm Umudike	4.6	19.23	26.3	0.098	10.47	84.5	40.5
Olokoro farm	5.7	22.20	29.4	0.169	15.22	118.7	40.6
Western farm Umudike	4.3	19.28	**27.0**	0.119	12.94	99.9	36.9
LSD (0.05)	**0.3****	**2.14***	**2.3***	**0.048***	**1.08****	**4.1****	**1.3****
Agro-forestry system							
GPAS	4.8	24.03	30.8	0.144	16.33	94.6	41.9
GPSS	4.8	25.00	24.7	0.127	14.21	107.7	35.6
SGM	5.0	22.13	24.9	0.147	11.91	108.0	39.0
SGU	4.8	9.77	29.9	0.097	9.05	93.7	40.8
LSD (0.05)	**0.09****	**1.94***	**4.5***	**0.031***	**1.31****	**8.8****	**1.7****
Location x agro-forestry interaction							
Eastern Farm x GPAS	4.5	21.90	27.1	0.095	13.79	91.0	42.5
Eastern Farm x GPSS	4.5	24.80	29.2	0.096	10.44	83.5	37.9
Eastern Farm x SGM	4.6	21.20	19.58	0.111	9.84	88.0	40.7
Eastern Farm x SGU	4.6	9.00	28.9	0.090	7.79	75.5	40.9
Olokoro farm x GPAS	5.7	26.10	37.8	0.214	18.75	113.0	43.9
Olokoro farm x GPSS	5.7	28.20	21.3	0.166	16.65	134.4	39.5
Olokoro farm x SGM	5.9	21.90	24.2	0.186	14.84	117.3	40.0
Olokoro Farm x SGU	5.6	12.60	34.4	0.110	10.64	110.0	38.8
Western farm x GPAS	4.3	24.10	27.5	0.122	16.45	80.0	39.4
Western farm x GPSS	4.6	22.00	23.6	0.120	15.54	105.3	29.3
Western farm x SGM	4.4	23.30	30.7	0.143	11.04	118.7	36.4
Western farm x SGU	4.2	7.70	26.4	0.092	8.71	95.6	42.7
LSD (0.05)	**NS**	**3.29***	**6.9****	**NS**	**NS**	**13.5****	**2.7****

*, ** = Significant at 5 and 1% probability levels, respectively; NS = Not significant at 5% Probability level.

Carbon sequestration in the system due to treatments

Table 3 shows the effects of location, agro-forestry system, and their interaction on SOC sequestration in a ginger/pigeon pea farm in southeastern Nigeria. Soil organic carbon (SOC) sequestration is a critical component of mitigating climate change, improving soil fertility, and enhancing ecosystem services.

Location Effects

The results show that location significantly affects SOC sequestration. Olokoro farm demonstrated the highest SOC sequestration (23.9 t/ha), followed by Western farm NRCRI Umudike (21.9 t/ha) and Eastern farm NRCRI Umudike (16.5 t/ha). This suggests that Olokoro Farm's soil has a higher potential for carbon sequestration. According to Lal (2019), soil organic carbon is a key indicator of soil health, and its sequestration can help mitigate climate change.

The significant difference in SOC sequestration among locations may be attributed to variations in soil type, climate, and management practices. Brady and Weil (2018) noted that soil type and climate are critical factors influencing SOC sequestration. The higher SOC sequestration at Olokoro farm may be due to its favorable soil and climate conditions.

Agroforestry System Effects

The agroforestry systems also had a significant effect on SOC sequestration. The Ginger-Pigeon Pea Alley System (GPAS) demonstrated the highest SOC sequestration (25.1 t/ha), followed by Ginger-Pigeon Pea Scatter System (GPSS) (24.3 t/ha), Sole Ginger with Mulch (SGM) (19.2 t/ha), and Sole Ginger without Mulch (SGU) (14.2 t/ha). This suggests that integrating ginger and pigeon pea in alley or scatter systems can enhance SOC sequestration. The findings are consistent with Palm et al. (2018), who reported that agroforestry systems can increase SOC sequestration by promoting soil organic matter accumulation. Mulching, as practiced in SGM, also contributed to higher SOC sequestration compared to SGU. This highlights the importance of mulching in maintaining soil health and promoting carbon sequestration.

Location X Agro-forestry Interaction Effects

The interaction effects between location and agroforestry system revealed significant differences in SOC sequestration. Olokoro farm X GPAS had the highest SOC sequestration (27.9 t/ha), indicating that the GPAS system is more effective in sequestering carbon at Olokoro farm. Similarly, Western farm x GPSS had higher SOC sequestration (29.1 t/ha) compared to Eastern farm x GPSS.

Implications for Climate Change Mitigation

Findings from the study have significant implications for climate change mitigation. The results suggest that adopting agroforestry systems, such as GPAS and GPSS, can enhance SOC sequestration. This can contribute to reducing greenhouse gas emissions and mitigating climate change. According to the Intergovernmental Panel on Climate Change (IPCC) (2013), soil carbon sequestration can play a critical role in mitigating climate change. The study's findings highlight the importance of considering location-specific factors and agroforestry systems when designing strategies for SOC sequestration. Integrating ginger and pigeon pea in alley or scatter systems, mulching, and adopting location-specific management practices can enhance SOC sequestration. These findings have significant implications for climate change mitigation, soil conservation, and sustainable agriculture.

Table 3. Effects of location, Agro-forestry system and location x Agro-forestry interaction on soil organic carbon sequestration (t/ha) in a ginger/pigeon pea farm in southeastern agro-ecology of Nigeria (soil depth = 10 cm)

	Location			
Agro-forestry system	**Eastern Farm NRCRI, Umudike**	**Olokoro farm**	**Western Farm NRCRI Umudike**	**Agroforestry means**
GPAS	21.0	27.9	26.4	**25.1**
GPSS	17.2	26.7	29.1	**24.3**
SGM	15.5	23.6	18.6	**19.2**
SGU	12.2	17.2	13.3	**14.2**
Location mean	**16.5**	**23.9**	**21.9**	

Location LSD(0.05) = 1.9**
Agro-forestry LSD(0.05) = 2.3**
Location x agro-forestry interaction LSD(0.05) = 3.7*

*, ** = Significant at 5 and 1% probability levels, respectively.

Effects of treatments on soil organic matter across all locations

Results in Table 4 show the effects of location, agro-forestry system, and their interaction on SOM in a ginger/pigeon pea farm in southeastern Nigeria. Soil organic matter (SOM) is a critical component of soil health, influencing soil fertility, structure, and ecosystem services.

Location Effects

The results show that location significantly affects SOM. Olokoro farm demonstrated the highest SOM (26.2 g/kg), followed by Western farm NRCRI Umudike (22.3 g/kg) and Eastern farm NRCRI Umudike (18.1 g/kg). This suggests that Olokoro Farm's soil has a higher potential for organic matter accumulation. According to Brady and Weil (2018), soil organic matter is influenced by factors such as climate, soil type, and management practices.

The significant difference in SOM among locations may be attributed to variations in soil type and climate. Lal (2019) noted that soil type and climate are critical factors influencing SOM. The higher SOM at Olokoro farm may be due to its favorable soil and climate conditions.

Agroforestry System Effects

The agroforestry systems also had a significant effect on SOM. The Ginger-Pigeon Pea Alley System (GPAS) demonstrated the highest SOM (28.2 g/kg), followed by Ginger-Pigeon Pea Scatter System (GPSS) (24.8 g/kg), Sole Ginger with Mulch (SGM) (20.5 g/kg), and Sole Ginger without Mulch (SGU) (15.6 g/kg). This suggests that integrating ginger and pigeon pea in alley or scatter systems can enhance SOM. The findings are consistent with Ekeledo *et al*. (2024), who reported that agroforestry systems can increase SOM by promoting soil organic matter accumulation. Mulching, as practiced in SGM, also contributed to higher SOM compared to SGU.
This highlights the importance of mulching in maintaining soil health and promoting organic matter accumulation.

Location x Agro-forestry Interaction Effects: The interaction effects between location and agro-forestry system were not significant, indicating that the agro-forestry systems performed consistently across locations. This suggests that the GPAS and GPSS systems can be adopted across different locations without significant variations in SOM.

Implications for Soil Health and Ecosystem Services
The study's findings have significant implications for soil health and ecosystem services. The results suggest that adopting agroforestry systems, such as GPAS and GPSS, can enhance SOM. This can contribute to improved soil fertility, structure, and ecosystem services. According to the Food and Agriculture Organization (FAO) (2015), soil organic matter is critical for maintaining soil health and ecosystem services. This study highlights the importance of considering location-specific factors and agroforestry systems when designing strategies for SOM accumulation. Integrating ginger and pigeon pea in alley or scatter systems, mulching, and adopting location-specific management practices can enhance SOM. These findings have significant implications for soil health, ecosystem services, and sustainable agriculture.

Table 4. Effect of location, agro-forestry system and location x agro-forestry interaction on soil organic matter (SOM) (g/kg) in a ginger/pigeon pea farm in southeastern agro-ecology of Nigeria (soil depth = 10cm)

	Location			
Agro-forestry system	**Eastern Farm NRCRI Umudike**	**Olokoro farm**	**Western Farm NRCRI Umudike**	**Agro-forestry means**
GPAS	23.8	32.3	28.4	**28.2**
GPSS	18.0	28.7	26.8	**24.8**
SGM	17.0	25.6	19.0	**20.5**
SGU	13.4	18.4	15.0	**15.6**
Location mean	**18.1**	**26.2**	**22.3**	

Location LSD(0.05) = 1.9**

Agro-forestry LSD(0.05) = 2.3**

Location x agro-forestry interaction LSD(0.05) = NS

** = Significant at 1% probability level; NS = Not significant at 5% probability level

CONCLUSION

The study has demonstrated the potential of integrating ginger and pigeon pea in agroforestry systems to enhance soil health and carbon sequestration in southeastern Nigeria. The findings revealed significant effects of location and agroforestry systems on soil properties and carbon sequestration. The Ginger-Pigeon Pea Alley System (GPAS) and Sole Ginger with Mulch (SGM) significantly improved soil organic matter and carbon sequestration, indicating that integrating ginger and pigeon pea in an alley system enhances soil health, ecosystem services, reduces soil erosion, and improves biodiversity.

RECOMMENDATION

Farmers and agricultural extension agents should adopt location-specific agroforestry practices that take into account the unique soil and climatic conditions of different locations. This will optimize crop yields, improve soil health, and enhance ecosystem services and ginger-pigeon pea alley system (GPAS) should be encouraged as a viable agroforestry system for ginger farmers in Nigeria, given its potential to improve soil organic matter, soil health, carbon sequestration, and biodiversity conservation.

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