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Original Article

Spatial soil variability and precision management strategies for optimizing maize productivity in Kwara State, Nigeria

OPEN ACCESS

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ABSTRACT

Abstract

Agriculture is critical to the economies of most states in Nigeria, Kwara included, with maize being an important food crop. However, geographic variation in soil qualities and inconsistencies in maize yields across the states are becoming increasingly concerning. The spatial variability of major soil physical and biological properties in Asa and Moro Local Government Areas (LGAs) was investigated utilizing a cross-sectional design, current Geographic Information Systems (GIS), and geostatistical approaches. Soil samples were collected at 70 geo-referenced locations and analyzed for texture, bulk density, porosity, moisture content, microbial biomass, and organic carbon. Data were mapped using ArcGIS 10.7 to assess spatial trends and identify management zones. The results revealed significant differences between the two LGAs. Asa LGA had higher moisture content (46.74%), porosity (49%), organic carbon (1.6%), and phosphorus (24.5 mg/kg) but lower pH (5.4 in water; 4.5 in $CaCl_2$) and higher erosion risks. Moro LGA, by contrast, showed higher pH (6.4 in water; 5.3 in $CaCl_2$), bulk density (1.29 gcm^{-3}), and hydraulic conductivity (23.5 $mmhr^{-1}$). Tailored management strategies, such as lime application in Asa and organic amendments in Moro, are crucial. These findings highlight the need for precision agriculture and site-specific management strategies in addressing soil variability and maximizing resource usage and maize yields in both LGAs.

KEYWORDS: *Erosion control, Hydraulic conductivity, Precision agriculture, Soil biological properties*

INTRODUCTION

Agriculture activities play a significant role in most Nigerian states' economies, Kwara inclusive, with maize serving as a crucial staple crop for both food security and industrial purposes. Olaniyan (2015) reported that maize (*Zea mays* L.) was introduced to West Africa in the 16th century, and is a widely cultivated, temperature-tolerant cereal crop vital to Nigeria's economy. However, there is inconsistent maize yields across the region are causing concern (-1%, 0%, -3% at Asa, Baruten, and Irepodun local government area (LGA) of the State) using production data between 2020 – 2023 among farmers who rely on the crop for a living (Adeboye *et al*., 2020; Ndoye *et al*., 2023). Crop production variability is directly related

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to changes in soil quality, which are frequently disregarded in regular agricultural operations.

Soil properties such as texture, bulk density, porosity, bacterial biomass and diversity, and moisture content are critical soil quality indicators and plant growth, directly influencing root development, water retention, and nutrient availability (Brady & Weil, 2016). According to Cárceles Rodríguez *et al*. (2022), these properties are not uniform across different fields or even within a single farm due to a combination of natural factors (e.g., topography, climate) and human activities (e.g., tillage, irrigation, and crop rotation). This spatial variability means that a uniform approach to soil management—such as applying the same amount of fertilizer and water across all fields—can lead to inefficient resource use and suboptimal maize yields (Webster & Oliver, 2007).

In Kwara State, many farmers use these generalized management strategies, which fail to account for the soil's heterogeneity. This limits maize productivity and accelerates soil degradation (Wegbebu, 2023). Addressing this requires a more detailed understanding of soil variability, which can be achieved using advanced techniques like Geographic Information Systems (GIS) and geostatistical methods. These tools allow researchers and farmers to map soil properties across fields and develop site-specific management practices (Adegbite *et al*., 2019).

Unfortunately, such techniques have been underutilized in this region, resulting in a significant gap in our knowledge of how soil quality affects maize cultivation. Understanding the distribution of these properties will enable the development of tailored soil management strategies, leading to more efficient use of resources, improved maize yields, and sustainable agricultural practices in the region (Tilman *et al*., 2002). The research aim is to assess the spatial variability of soil physical and biological properties in maize-growing farmers' fields in Asa and Moro local government areas (LGA), Kwara State. These properties include texture, bulk density, porosity, bacterial biomass and diversity, and moisture content. By using Geographical Information System (GIS) and geostatistics, we aim to map these properties across LGAs.

MATERIALS AND METHODS

Study Area

Kwara State, Nigeria has sixteen (16) Local Government Areas (Figure 1) and is located in the Southern Guinea savanna belt of the country with areas primarily agricultural, with maize being one of the major crops cultivated (Lawal *et al*., 2009). The State lies within the tropical climate and it is characterized by double rainfall maxima with tropical wet and dry climates with the seasons lasting for about 6 months each with annual rainfall ranging from 1000 to 1500 mm and annual mean temperature ranging between 30° and 34 °C (Oladimeji *et al*., 2015). The study focused on Moro and Asa local governments in Kwara State because of their significant role in maize production, diverse geography, and soil conditions.

Research Design and Soil Sampling

This study followed a cross-sectional research design involving field sampling and laboratory analysis of soil properties. Soil samples were collected from the randomly selected 70 geo-referenced points (35 in each LGA) within the study area, selected to capture variations in soil type, topography, and management practices. A stratified random sampling method was used to ensure that the data captured variability across different strata, such as slopes, flat areas, and vegetative zones.

Samples were collected from the topsoil to a 0 – 20 cm depth, the most critical soil layer for maize root development (Klatka *et al.*, 2019).

Laboratory Analysis

In the laboratory, the following key soil physical properties were analyzed: Soil texture was determined using the hydrometer method, which involves dispersing soil particles in water and measuring their relative settling rates as described by Lal (2019). Bulk density was measured by the core method, where the soil-filled core was dried in an oven at 105°C for 24 hours and then weighed. The bulk density was calculated as the dry weight of the soil divided by the volume of the soil core (Klatka *et al*., 2019). Soil Porosity was calculated based on bulk density, and particle density (assumed to be 2.65 g/cm³ for mineral soils). Soil porosity measures the percentage of void space in the soil, which impacts its ability to hold air and water.The formula used was:

Porosity (P)=(1 - Bulk Density / Particle Density) × 100

(Lal, 2019). Soil moisture content was determined by the gravimetric method. Fresh soil samples were weighed, dried in an oven at 105°C for 24 hours, and reweighed. The moisture content was calculated as the difference in weight before and after drying, expressed as a percentage of the dry soil weight (Adegbite *et al*., 2019). Microbial Biomass Carbon (MBC) was determined using the chloroform fumigation-extraction method using Schimel & Schaeffer (2015) method as modified by Sholeye *et al.* (2021) while the Soil pH was measured in both water and calcium chloride (0.01M $CaCl_2$) using a glass-calomel combined electrode after a 30-minute equilibration period (Lizarralde *et al*., 2021). The organic carbon content was assessed using the method described by Walkley & Black as described by Sholeye *et al.* (2021).

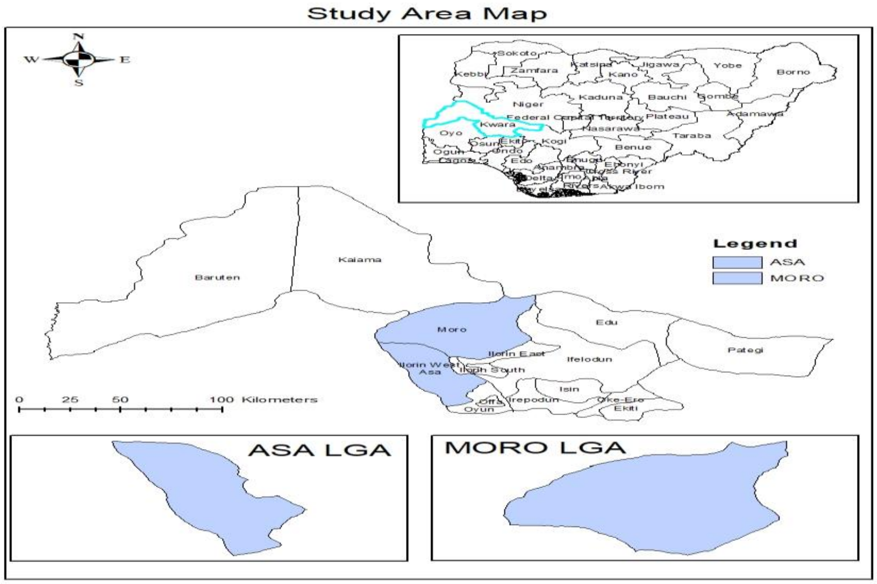

Figure 1. Study Area Map

Data Analysis and Mapping

To analyze the collected data, descriptive statistics (mean, standard deviation) were used to summarize the soil properties with aid of the Jamovi Stastitical software package (2022). The spatial distribution of soil properties was mapped using ArcGIS 10.7 version. This allowed for the visual representation of areas with similar soil characteristics, identifying zones that may require specific management interventions. Geostatistical methods, Kriging, were employed to create continuous surface maps that depict the variability of soil properties across the study area (Longley *et al*., 2015; Kavitha *et al*., 2016). These maps serve as decision-making tools for implementing site-specific soil management practices.

RESULTS AND DISCUSSION

Study Areas' physical and chemical properties

The results presented in Table 1 compare the soil physical and chemical properties between two areas, Asa and Moro LGAs, based on field survey studies of 35 farmers' fields in each study area. The results compared the physical and chemical properties of soils in the study area, Asa and Moro LGAs, highlighting significant differences with implications for maize productivity and soil management.

Physical Properties Analysis

Asa LGA has a higher gravel content (17.33%) than Moro (13.5%); this higher gravel content may restrict root growth and water-holding capacity, which can hinder maize productivity, especially in dry conditions (Ren *et al*., 2019). This finding aligns with Zhang *et al.* (2019) study that affirmed the link between gravel content and reduced soil pore space, limiting water and nutrient retention. The higher moisture content (46.74%) at Asa will provide a more favourable environment for maize, which requires consistent moisture, particularly during critical growth stages (Comas *et al*., 2019). This is related to Liu *et al*. (2016) findings that established water availability is important in sandy soils such as Asa soil with higher water percolation rates. Also, Asa's higher VWC (0.35 m^3/m^3) shows a greater capacity to store water, a beneficial trait for maize growth during dry periods (Chen *et al*., 2016).

The high bulk density in Moro's soil (1.29 kg/m^3) can restrict root penetration and water movement, reducing maize productivity (Brady & Weil, 2016). Asa's lower bulk density (1.19 kg) and higher porosity (49%) suggest a looser structure, beneficial for root development and soil aeration, which aligned with findings of Lal *et al*. (2018) on soil structure and carbon sequstration. Moro soils, with lower moisture content (39.8%) and porosity (42.1%), drain better, reducing waterlogging but limiting water retention during dry periods. Moro's higher bulk density (1.29 g/cm^3) and hydraulic conductivity (23.5 mm/hr) suggest compacted soils and faster water movement, limiting water retention but reducing erosion risk. Both areas have a loamy sand texture, though Moro's higher sand content (84.2%) increases the risk of nutrient leaching.

Moro sandy loam with slightly higher sand content (84.2%) indicates lower nutrient retention capacity, according to a Palta *et al*. (2016) study. Asa's higher silt content (11.7%) may enhance nutrient retention, which can support maize during dry periods aligned with findings by Li *et al*. (2019). Moro's higher HC (23.5 mm/hr) suggests more rapid drainage, which can reduce water retention, particularly during dry periods, necessitating supplementary irrigation to maintain maize productivity (Lal, 2020).

Table 1. Mean of soil physical and chemical properties in the studied area

Parameters	Moro LGAs	Asa LGAs
Soil Physical Properties		
Gravel (%)	13.5	17.33
Moisture Content (%)	39.8	46.74
Bulk Density (kg/m3)	1.29	1.19
Total Porosity (%)	42.1	49.00
Sand (%)	84.2	80.6
Silt (%)	8.0	11.7
Clay (%)	7.8	7.7
Texture	LS	LS
Hydrau. Cond. (mm/hr)	23.5	18.20
VWC (m3/m3)	0.31	0.35
Gravel (%)	13.52	17.33
Soil Chemical Properties		
pH H20	6.4	5.4
pH $CaCl_2$	5.3	4.5
Exchangeable acidity (cmol/ kg)	2.9	1.6
Organic carbon (%)	1.1	1.6
Organic matter (%)	1.8	2.8
Available Phosphorus (mg/kg)	7.6	24.5
Potassium (cmol/kg)	0.12	0.18
Calcium (cmol/kg)	3.0	2.7
Magnesium (cmol/kg)	1.3	2.7
Sodium (cmol/kg)	0.10	0.01

Where Hydrau. Con = Hydraulic conductivity, VWC = Volumetric moisture content

Chemical Properties:

Moro LGA's slightly higher pH (6.4 in water) favours nutrient availability, while Asa's lower pH (5.4) may limit key nutrients like phosphorus and calcium availability (Musinguzi *et al*., 2016). However, Comas *et al* (2019) stated optimal pH levels for maize to be between 5.5 and 7.0. Despite this, Asa soils are potentially fertile, with higher organic carbon (1.6%) and organic matter (2.8%), promoting better nutrient retention, soil structure, and microbial activity. Asa also has higher available phosphorus (24.5 mg/kg), but its low pH could lead to phosphorus fixation, reducing its availability to crops. In contrast, Moro LGA has lower phosphorus (7.6 mg/kg) but higher exchangeable acidity (2.9 cmol/kg), potentially affecting nutrient availability, particularly calcium and magnesium. Asa has higher levels of magnesium (2.7 cmol/kg) and potassium (0.18 cmol/kg), which are crucial for plant growth, while Moro has higher calcium (3.0 cmol/kg) and sodium (0.10 cmol/kg). Elevated sodium in Moro could negatively impact soil structure.

If the soil acidity is managed, the higher moisture content, organic matter, and phosphorus levels in Asa's soil could support higher maize yields. Adjustments, such as liming, could help optimize nutrient availability by correcting the acidic pH. Applying lime can increase pH and improve nutrient availability, as recommended in studies focused on acidic soils by Musinguzi *et al*. (2016). The slightly lower hydraulic conductivity in Asa might be beneficial for maintaining moisture but may require management to avoid waterlogging (Palta *et al*. 2016). These findings align with studies showing that soils with higher moisture retention and organic matter content support better crop resilience under variable climatic conditions (Chenu *et al*., 2019).

Moro's limitations in phosphorus and higher bulk density pose challenges, as studies suggest that low phosphorus and high bulk density can both hinder root development and reduce nutrient availability, affecting maize yield potential (Adegbite *et al*., 2019). Thus, phosphorus fertilization would be essential to improving maize productivity in Moro. Additionally, Moro LGA soils would benefit from organic amendments and phosphorus fertilization. Brady & Weil's (2016) findings show that organic matter addition improves soil structure, water retention, and nutrient cycling, in particular soils. To enhance maize productivity in Kwara State, targeted soil management—such as organic amendments for moisture retention, lime for acidity correction, and nutrient optimization—should focus on Moro's limitations, while Asa's high phosphorus levels suggest further nitrogen-focused studies.

Figure 1 presents the dissolved organic carbon (DOC) concentrations spatial variability trends maps of the Asa and Moro local government areas (LGAs), Kwara State, Nigeria. The spatial variability of DOC concentrations in Asa and Moro LGAs, Kwara State, Nigeria, reveals notable differences in soil organic matter. Asa LGA shows higher DOC levels (165.45–245.02mg/kg) in regions like Afon and Okeso, indicating better soil management, while lower concentrations (112.38–138.91mg/kg) in areas like Alapa suggest soil carbon deficiencies requiring organic amendments. In Moro LGA, higher DOC levels (169.24–176.42 mg/kg) are found in Jeunkunuand Magida, reflecting healthier soil, while northern areas like Bode Saadu have lower DOC (140.5–154.87 mg/kg), signalling a need for improved management.

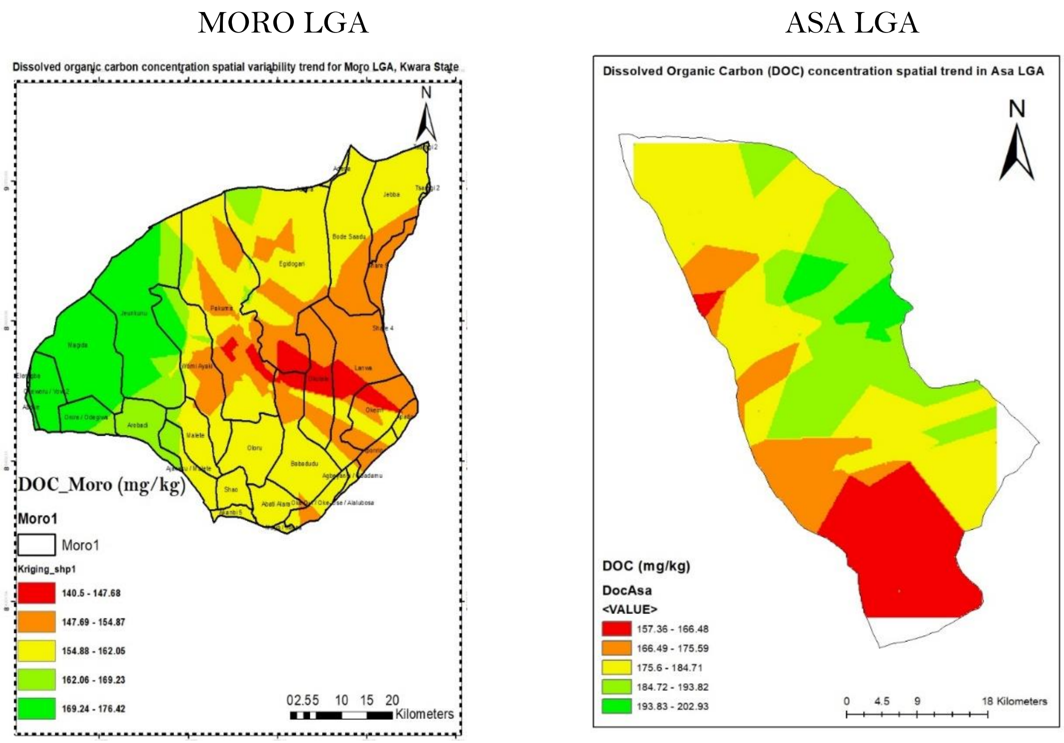

Figure 1. Dissolve carbon concentration spatial variability trend maps of the study area

This variability underscores the need for site-specific soil conservation strategies, including cover cropping, reduced tillage, and organic amendments to enhance soil health and fertility (Lal, 2015; Chenuet al., 2019). Thus, this research support the application of organic inputs to improve nutrient availability, leading to better yields and soil structure as supported by findings from the study of Blanco-Canqui and Ruis (2018). Also, Mazhar *et al*. (2021) believe precision agriculture and location-specific management are essential for maintaining the long-term sustainability of such areas.

Figure 2 shows the microbial biomass carbon (MBC) concentration spatial variability trend maps of Moro and Asa LGAs, Kwara State, Nigeria. The spatial variability of MBC in Moro and Asa LGAs, Kwara State, reveals critical trends in soil health. In Asa LGA, higher MBC levels in northwestern areas like Olorunda and Efue suggest greater microbial activity, supporting nutrient cycling and organic matter decomposition (Hobbie, 2015). In contrast, southeastern areas such as Laduba show lower MBC concentrations, indicating possible soil health concerns. Similarly, in Moro LGA, northeastern regions like Okemi and Share 1 have higher MBC, while southwestern areas, including Magida and Juenkunu, display lower levels, reflecting reduced microbial activity as affirmed by Musilova *et al*. (2016) study.

Regions with low MBC are shown more prone to soil degradation, which impacts soil structure and organic matter retention. Soil conservation practices, such as cover cropping, reduced tillage, and organic amendments, can help improve MBC in these areas (Schimel & Schaeffer, 2015). Higher MBC levels contribute to improved soil health, better crop yields, and resilience against environmental stresses as noted in Sholeye *et al*. (2021) and Lal's (2019) research. Sustainable farming practices, like crop rotation with legumes and using organic fertilizers, can further enhance microbial activity and nutrient cycling which aligns with Larkin *et al*. (2017) study. Adopting these strategies promotes long-term soil fertility, reduces dependence on chemical inputs, and mitigates the impacts of climate change (Gattinger *et al*., 2018).

Figure 3 shows the spatial variability trend maps of soil moisture content in Moro and Asa LGAs of Kwara State.The spatial variability of soil moisture content in Moro and Asa LGAs, Kwara State, presents distinct patterns that have important implications for soil fertility, erosion risks, and sustainable land management.

MORO LGA ASA LGA

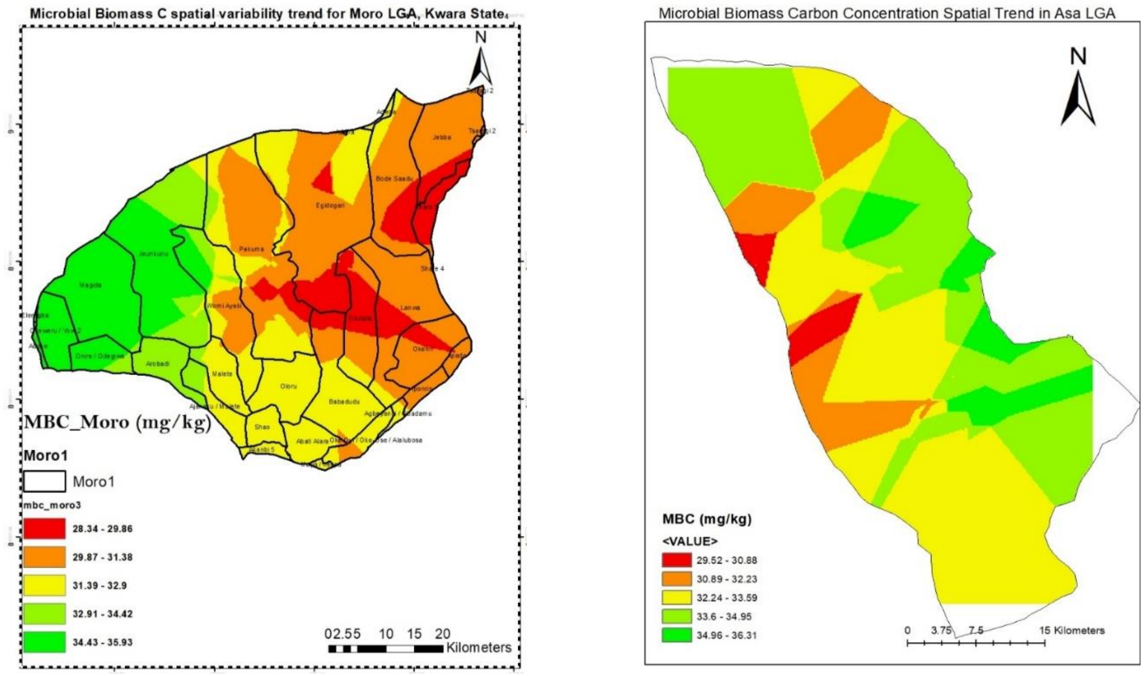

Figure 2. Microbial Biomass concentration spatial variability trend maps of the study area

In Moro LGA, a moisture gradient is observed from dry northern areas (33.75–36.33%) to wetter southern regions (41.49–44.05%). The dry northern areas are susceptible to wind erosion, while the wetter southern regions face a higher risk of water erosion. Asa LGA shows more complexity, with the driest areas (42.2–45.17%) located in the north and southeast, and the wettest areas (51.12–54.08%) in the south. Drier regions are vulnerable to wind erosion, while wetter areas are prone to water erosion.These moisture patterns suggest that tailored land management strategies are necessary. In Moro's drier regions, windbreaks, cover cropping, and water retention techniques can reduce wind erosion risks (Schimel & Schaeffer, 2015). In the wetter areas, contour ploughing and terracing can help prevent water erosion. Asa LGA's diverse moisture distribution requires mulching and vegetative cover in drier areas, and better drainage in wetter zones to avoid waterlogging. These approaches align with precision agriculture practices, which are key to improving soil fertility and long-term agricultural sustainability (Lal, 2019; Gattinger*et al*., 2018).

The spatial variability of soil hydraulic conductivity (Ks) in Moro and Asa LGAs, Kwara State, (Figure 4) reveals critical differences that impact soil conservation, land reclamation, and sustainable agriculture.

In Moro LGA, a southwest-to-northeast gradient in Ks (22.96–24.15 mm/hr) highlights potential challenges. The higher conductivity in the southwest suggests rapid drainage, leading to water loss, which calls for conservation techniques like mulching and reduced tillage to retain moisture. The northeast, with lower conductivity, may face waterlogging, necessitating drainage systems to prevent erosion and enhance soil structure. Precision agriculture, such as planting water-demanding crops in the northeast and drought-tolerant crops in the southwest, can improve outcomes. Asa LGA shows more complex variability, with Ks ranging from 12.18 to 26.24 mm/hr (Sharma, 2007). In southeastern areas, with lower conductivity, practices such as cover cropping and organic matter additions can enhance water retention and reduce erosion risks. In the northern regions, where conductivity is higher, strategies like contour farming and soil conditioners are crucial to prevent excessive drainage.These findings emphasize the need for site-specific management strategies to optimize soil moisture and improve agricultural sustainability, aligning with Zhang *et al*. (2021) on the importance of adapting management practices to varying soil properties.

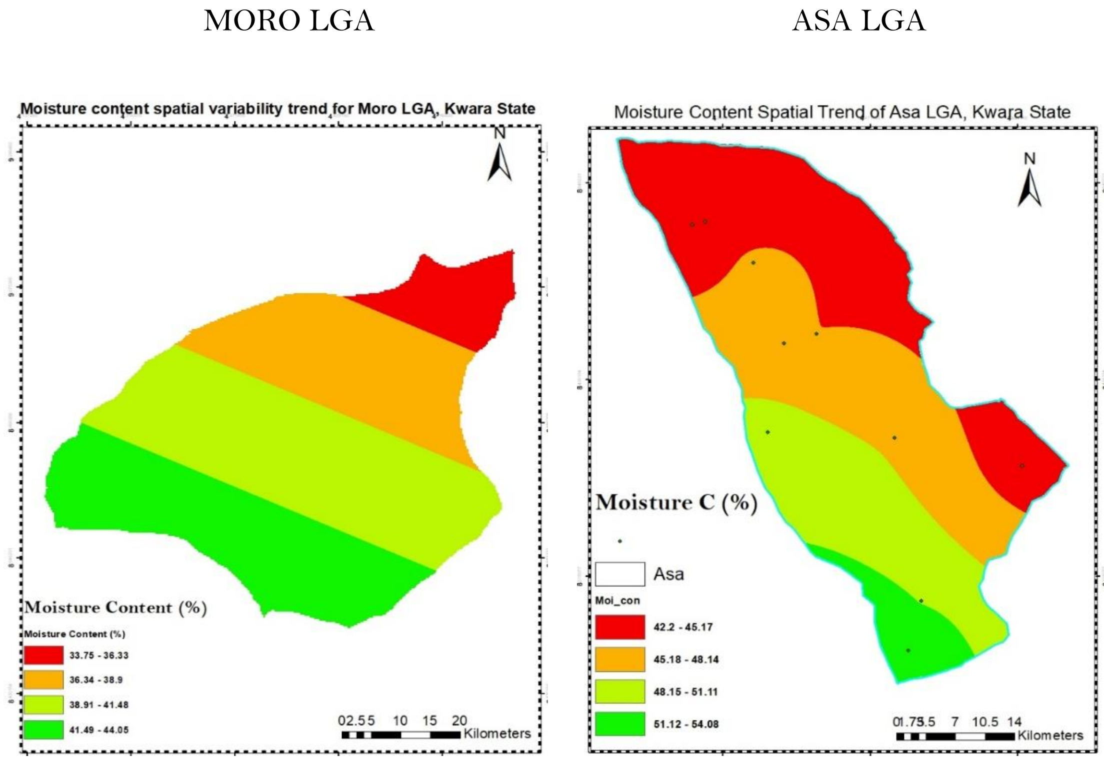

Figure 3. Moisture content spatial variability trend maps of the study area

Figure 5 shows the total porosity spatial variability maps for Asa and Moro LGAs, Kwara State. In Asa LGA, porosity ranges from 46.34% to 53.36%, with the lowest values in the north, where increased runoff and erosion risks are observed. The higher porosity in the south supports better water retention and infiltration. Soil conservation techniques like contour ploughing, terracing, and cover cropping can improve soil structure and reduce runoff in lower-porosity areas. In Moro LGA, porosity ranges from 38.87% to 44.39%, with a northeast-southwest gradient. The northeast's low porosity limits water infiltration and raises erosion risks, requiring soil improvement methods such as organic matter addition and conservation tillage to enhance porosity and soil health. Moro's overall lower porosity compared to Asa LGA indicates a need for more intensive soil management strategies, especially in the northeast.

These spatial variations in porosity highlight the importance of site-specific soil conservation practices, as Asa's southern areas, with higher porosity, may respond better to agricultural initiatives, while Moro's lower porosity regions require targeted improvements. Studies by Ren *et al*. (2019) and Kiani-Harchegani *et al*. (2019) emphasize the link between porosity, water infiltration, and erosion risks. Conservation tillage according to Blanco-Canquiand Rius (2018), and cover crops by Jian *et al*. (2020) are essential for improving soil health and promoting sustainable agriculture which can be applied in both LGAs.

MORO LGA ASA LGA

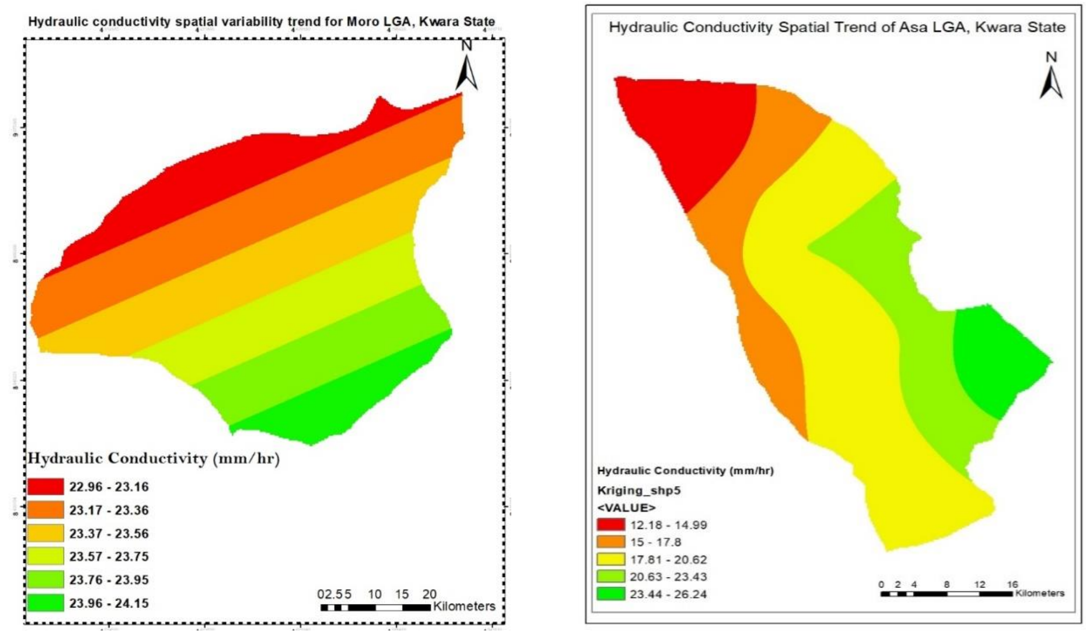

Figure 4. Soil hydraulic conductivity spatial variability trend for the study area

MORO LGA ASA LGA

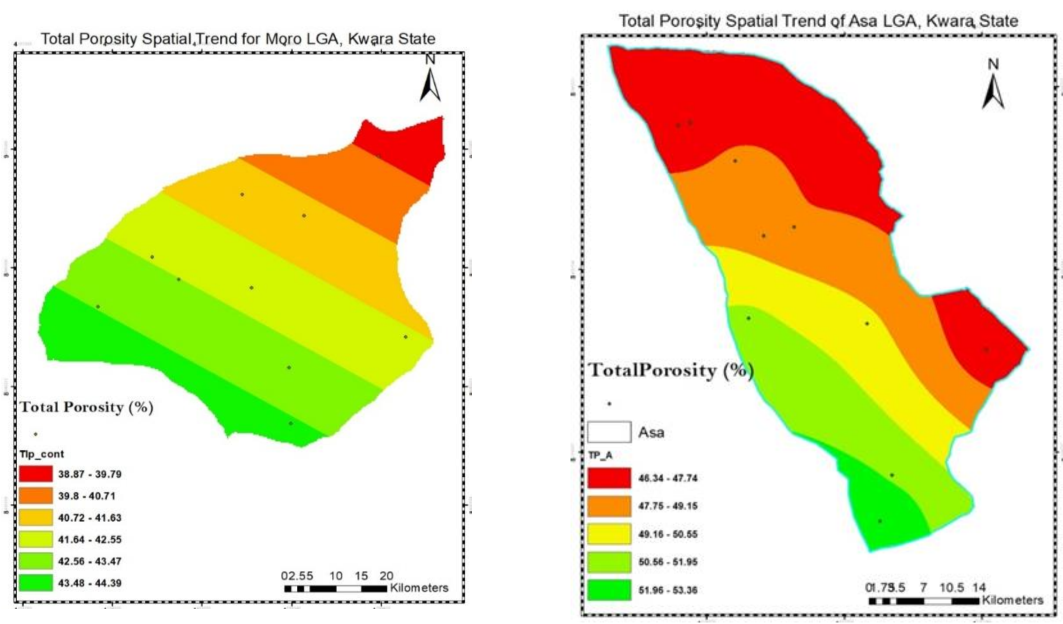

Figure 5. Total porosity spatial variability trend maps of the study area

CONCLUSIONS AND RECOMMENDATION

The study reveals significant soil variability between Asa and Moro LGAs, affecting maize productivity. Asa has higher moisture, organic carbon, and phosphorus but faces erosion and phosphorus fixation due to low pH. Moro's higher pH and bulk density improve drainage but reduce nutrient retention and increase compaction. Tailored management strategies, such as lime application in Asa and organic amendments in Moro, are crucial. Precision agriculture and site-specific practices will optimize yields and enhance sustainable farming in Kwara State.

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Authors' Contributions
Author AAW wrote the manuscript first draft. Authors AAW, AAO & OOJ managed data collection, interpretation of data, Second draft of manuscript, material support, and review of manuscripts and wrote the first draft of the manuscript. Authors AAW, UIY & TTN managed the literature searches. AAW, UIY & AAO managed the development of methodology, data analysis. All authors read and approved the final manuscript.

Ethical Statement
All materials used for this study were approved and confirmed to meet the ethical standard, by the appropriate ethics committee of the Kwara State University, Malete and Kwara State Government. The study was ascertained to be performed under the ethical standards laid down by the Soil Science Society of Nigeria (SSSN).

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