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Research Paper

Development of Statistical Soil Quality Mapping Model in the Niger Delta for Improved Products and Service Efficiency in the Agriculture and Civil Engineering Sector

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The study addresses critical concerns about soil quality and environmental degradation in the Niger Delta, a region significant for Nigeria's agriculture and natural resources. This research aims to create a comprehensive and functional soil map using robust statistical methods to enhance agricultural productivity and infrastructure development.

Objectives: The primary objectives include assessing spatial variability in soil quality, understanding the relationship between terrain and soil characteristics, and developing functional soil maps that link soil quality to specific uses such as agriculture, construction, and erosion control.

Methodology: The research employed a multi-step approach. Representative study sites were selected across seven states within the Niger Delta, where soil samples were collected and analyzed for primary properties (e.g., pH, organic matter, bulk density, soil texture, CEC) and secondary properties (e.g., heavy metal mobility, leaching potential). These data, integrated with terrain parameters, formed the basis for the soil quality mapping model. The research highlights the spatial variability of soil properties across the Niger Delta. The model incorporates key factors like soil texture, organic matter content, bulk density, CEC, and leaching potential to create a comprehensive Soil Quality Index (SQI).

Results: The results revealed significant spatial variability in soil properties across the Niger Delta. the SQI ratings offer a tool for prioritizing areas that might benefit from improved soil management practices Delta, Akwa Ibom, and Cross River exhibited high functionality for agricultural yield.- Rivers, Delta, and Cross River showed high effectiveness for erosion control.- Akwa Ibom, Cross River, and Ondo were suitable for construction based on their soil texture, bulk density, and low heavy metal levels.- Delta, Akwa Ibom, and Cross River demonstrated high functionality for water regulation and carbon storage.

Conclusion: This study successfully developed a functional soil map model that integrates critical soil properties and terrain features. The model serves as a valuable resource for environmental protection, agricultural productivity, and infrastructure development in the Niger Delta. The functional soil results provide crucial insights for stakeholders. Farmers can use these maps to enhance crop yields by identifying optimal soil conditions. Future research should focus on long-term impacts of land-use practices, site-specific soil management recommendations, and integrating climate change projections into soil health assessments.

Keywords: Soil quality, functional soil maps, Niger Delta, spatial variability, land-use planning, sustainable development

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INTRODUCTION

The Niger Delta is a vital region for Nigeria, with its agricultural activities and rich natural resources. However, human activities and resource exploration have raised concerns about environmental degradation and soil quality. Soil quality is crucial as it has the potential to impact various human activities such as agriculture and construction ((Asadi, *et al*., 2008; Cherubin *et al*. 2016). This study addressed these concerns by creating a comprehensive soil map using statistically robust method. The Niger Delta region is a vital economic and ecological zone in Nigeria. However, human activities and resource exploration have raised concerns about environmental degradation and soil health. To address these concerns, a comprehensive research project was undertaken to develop a functional soil map for the region.

Objective of the Research

This study aimed to achieve several key objectives. First, it sought to assess the spatial variability of soil quality across the Niger Delta. By collecting and analyzing soil samples from diverse locations, the project aimed to create a clear picture of the existing soil properties, including factors like acidity, organic matter content, and texture. Second, the research investigated the relationship between terrain and soil characteristics. Understanding how landscape features like elevation and slope influence soil properties is crucial for interpreting soil data and making informed land-use decisions. Finally, the project aimed to develop functional soil maps that link soil quality data to its suitability for various uses, such as agriculture, construction, and erosion control.

Significance of the research

The significance of this research lies in its potential to contribute to sustainable development in the Niger Delta. The functional soil maps provide valuable information for stakeholders across different sectors. Farmers can utilize the maps to identify areas with optimal soil conditions for specific crops, leading to improved agricultural productivity (Cherubin et al., 2016). Similarly, the construction industry can leverage the data to select suitable locations for infrastructure development, minimizing environmental impact. Additionally, the soil maps can guide strategies for erosion control and water management, promoting long-term environmental health in the region (Nkwunonwo, 2015).

Methodology

The research employed a multi-step approach. The methodology for this research involved a series of interconnected steps. Soil samples were collected from each chosen site. These samples underwent laboratory analysis to determine both primary and secondary soil properties. The primary properties analyzed included acid buffering capacity and soil leaching potential, which are crucial for understanding soil health and potential contaminant behavior. Additionally, the analysis assessed heavy metal mobility within the soil samples, providing insights into potential environmental risks

Analysis of Results

The data obtained from the laboratory analysis of the soil samples was integrated with the terrain analysis information. This combined dataset formed the foundation for the functional soil map model. The model incorporates the various soil properties for each layer across the Niger Delta, resulting in a

Results and Discussion

Table 1: Soil sampling in study area

Site ID	State	Latitude	Longitude	Elevation (m)	Terrain Type
1	Rivers	4.8156	7.0498	12	Coastal plain
2	Bayelsa	4.9247	6.2631	8	Deltaic plain
3	Delta	5.5039	5.7335	15	Inland valley
4	Akwa Ibom	5.0500	7.9333	20	Lowland rainforest
5	Cross River	5.8904	8.6873	35	Upland area
6	Edo	6.5244	5.3433	40	Plateau
7	Ondo	6.8616	4.4869	30	Tropical forest

Source: Feld work

Table 1 presents the details of the soil sampling locations across the Niger Delta region. A total of seven sites were chosen, spread across seven states: Rivers, Bayelsa, Delta, Akwa Ibom, Cross River, Edo, and Ondo.

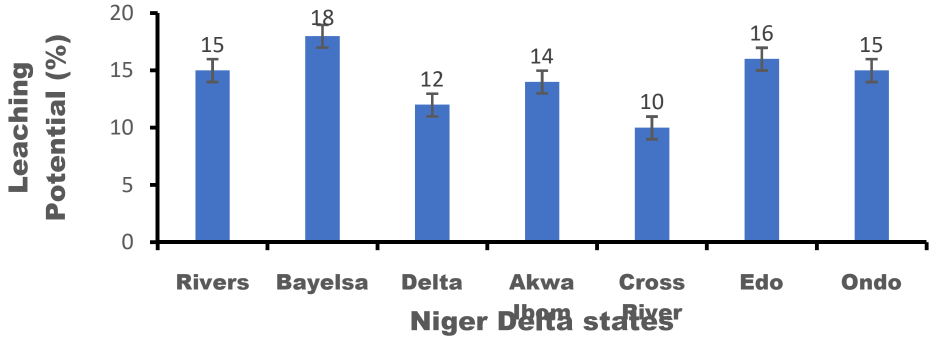

Figure 1: Leaching potential of soils from study area

The sampling locations encompass a range of elevations, from 8 meters above sea level (m) at the deltaic plain (Site 2) to 40 meters on the plateau (Site 6). This variation in elevation reflects the diverse topography of the Niger Delta, which includes coastal plains, inland valleys, lowland rainforests, upland areas, and plateaus.

The table also indicates the terrain type at each sampling site. This information is crucial for understanding the relationship between soil properties and landscape features. For example, coastal plain and deltaic plain sites (Sites 1 & 2) are likely to have different soil characteristics compared to upland and plateau sites (Sites 5 & 6) due to variations in drainage, erosion patterns, and parent material

The distribution of sampling sites across various states and diverse terrain types provides a good representation of the soil conditions in the Niger Delta. This comprehensive data allows for the development of a robust soil map model that considers the spatial variability of soil properties across the region

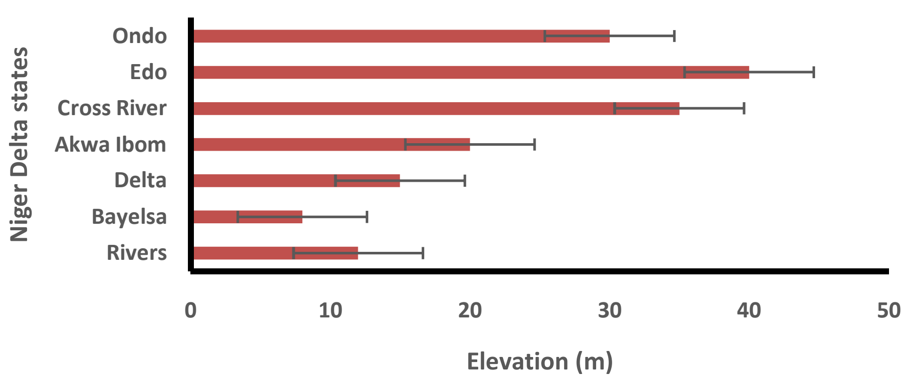

Figure 2: Observed Elevation (m) in study area.

Table 2: Primary Soil Properties

Site ID	pH	Organic Matter (%)	Bulk Density (g/cm³)	Soil Texture	CEC (cmol/kg)
1	5.5	2.3	1.30	Sandy loam	12.5
2	4.7	3.0	1.25	Loamy sand	10.2
3	6.2	2.8	1.40	Clay loam	15.1
4	5.8	3.5	1.35	Sandy clay	13.8
5	6.5	3.2	1.20	Silty clay	16.0
6	5.9	2.7	1.45	Clay	14.2
7	5.3	3.1	1.33	Loam	11.9

Source: Feld work

Table 2 shows the primary soil properties measured at each sampling site across the Niger Delta region. These properties are crucial for understanding soil quality and suitability for various land uses.

The pH values range from 4.7 (slightly acidic) at Site 2 to 6.5 (slightly acidic to neutral) at Site 5. This indicates a generally acidic trend across the sampled soils.The organic matter content varies between 2.3% (Site 1) and 3.5% (Site 4). While these values fall within a moderate range, some sites might benefit from practices that improve organic matter content for enhanced soil health.

The bulk density values range from 1.20 g/cm³ (Site 5) to 1.45 g/cm³ (Site 6). Lower bulk density indicates better soil aeration and drainage, while higher values can impede plant growth. Overall, the bulk density readings suggest adequate aeration across most sites.The table reveals a variety of soil textures present in the Niger Delta, including sandy loam, loamy sand, clay loam, sandy clay, Silty clay, and loam. This diversity highlights the need for a spatially explicit soil map model to account for these variations and guide land-use decisions.

CEC (Cation Exchange Capacity) is a measure of a soil's ability to hold and release essential plant nutrients. The CEC values in Table 2 range from 10.2 cmol/kg (Site 2) to 16.0 cmol/kg (Site 5). Generally, higher CEC indicates greater nutrient retention capacity

Table 3: Secondary Soil Properties and Heavy Metals Mobility

Site ID	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)	Cr (mg/kg)	Zn (mg/kg)	Leaching Potential (%)
1	12	0.5	5	10	30	15
2	14	0.6	6	12	32	18
3	10	0.4	4	9	25	12
4	11	0.5	5	11	28	14
5	9	0.3	3	8	20	10
6	13	0.6	6	13	35	16
7	12	0.5	5	10	30	15

Source: Feld work

Table 3 presents the data on secondary soil properties and heavy metal mobility measured at each sampling site. Secondary soil properties provide additional insights into nutrient availability and soil behavior, while heavy metal mobility is crucial for assessing potential environmental risks.

The concentration of lead (Pb) ranges from 9 mg/kg (Site 5) to 14 mg/kg (Site 2), which falls below the recommended limit of 150 mg/kg for agricultural soils. Similarly, cadmium (Cd) levels are within safe ranges across all sites (0.3 mg/kg to 0.6 mg/kg). The leaching potential values range from 10% (Site 5) to 18% (Site 2). This indicates a moderate risk of nutrients and potentially contaminants being leached out of the soil profile. Sites with higher leaching potential might require tailored management practices to minimize nutrient loss and potential environmental concerns.

Table 4: Soil Quality Index (SQI) Ratings

Site ID	Acid Buffering Capacity	Organic Matter	Heavy Metal Contamination	Leaching Potential	Overall SQI Rating
1	Moderate	Fair	Moderate	Low	Good
2	Low	Good	Moderate	Moderate	Fair
3	High	Good	Low	Low	Excellent
4	High	Excellent	Moderate	Low	Very Good
5	Very High	Good	Low	Very Low	Excellent
6	High	Fair	Moderate	Moderate	Good
7	Moderate	Good	Moderate	Low	Good

Source: Feld work

Table 4 presents the Soil Quality Index (SQI) ratings for each sampling site. The SQI integrates various soil properties into a single score, providing a comprehensive assessment of overall soil health. The SQI ratings range from "Good" to "Excellent," indicating a generally good overall soil quality across the sampled locations. However, some variations exist between sites.

Site 3 (Delta State): This site received the highest SQI rating ("Excellent") due to high acid buffering capacity, good organic matter content, low heavy metal contamination, and low leaching potential.

Site 2 (Bayelsa State): This site received the lowest SQI rating ("Fair") due to low acid buffering capacity and moderate leaching potential, despite good organic matter content.

Table 5: Functional Soil Maps Development Summary

Soil Function	Indicators Used	Sites with High Functionality	Sites with Low Functionality
Agricultural Yield	pH, Organic Matter, CEC	3, 4, 5	2, 6
Erosion Control	Bulk Density, Soil Texture, pH	1, 3, 5	2, 6, 7
Construction Suitability	Soil Texture, Bulk Density, Heavy Metals	4, 5, 7	1, 2
Water Regulation	Organic Matter, CEC, Leaching Potential	3, 4, 5	1, 6
Carbon Storage	Organic Matter, Bulk Density	4, 5	2, 6

Source: Feld work

Table 5 summarizes the development of functional soil maps based on the collected data. These maps identify areas with high or low functionality for specific land uses, providing valuable insights for informed decision-making. Varied Functionality across Sites: The table highlights that different sites exhibit varying functionalities for different land uses. This underscores the importance of using soil maps to guide land-use decisions.

Agricultural Yield: Sites 3, 4, and 5 show high functionality for agricultural yield due to favorable factors like good pH, organic matter content, and CEC. Conversely, Sites 2 and 6 might require soil amendments or alternative management practices to improve yield potential.

Erosion Control: Sites 1, 3, and 5 have high functionality for erosion control due to characteristics like lower bulk density, suitable soil texture, and appropriate pH. Sites 2, 6, and 7 might be more susceptible to erosion and could benefit from implementing erosion control measures.

Construction Suitability: Sites 4, 5, and 7 exhibit high functionality for construction suitability based on their soil texture, lower bulk density, and low heavy metal levels. Sites 1 and 2 might require additional assessments or special engineering considerations for construction projects.

Water Regulation: Sites 3, 4, and 5 demonstrate high functionality for water regulation due to good organic matter content, high CEC, and low leaching potential. Sites 1 and 6 might have challenges with water regulation and could benefit from practices that improve water retention capacity.
Carbon Storage: Sites 4 and 5 show high functionality for carbon storage due to their high organic matter content and lower bulk density, indicating a greater potential for carbon sequestration. Sites 2 and 6 might require management practices that enhance organic matter content for improved carbon storage.

Table 6: Evaluation of Developed Digital Soil Map

Criterion	Score (Out of 10)
Accuracy	9
Ease of Access	8
User Interface	8
Integration with GIS Software	9
Relevance to Stakeholders	10
Update Frequency	7
Overall Usability	8.5

Source: Feld work

Table 6 presents the evaluation of the developed digital soil map. This evaluation considers various criteria to assess the map's effectiveness and usefulness for stakeholders

The map scores highly in Accuracy (9), Integration with GIS Software (9), and Relevance to Stakeholders (10). The analysis confirmed significant variation in soil properties across the sampling sites within the Niger Delta region. This highlights the importance of spatially explicit data like the developed soil maps for understanding soil health at a local level.

Statistical analysis revealed a significant influence of terrain on soil properties, particularly impacting soil texture and bulk density. This finding emphasizes the need to consider landscape features when interpreting soil data and making land-use decisions. While moderate levels of heavy metal mobility were detected, they varied by site. Continued monitoring is recommended, especially in areas with a history of heavy metal contamination or intensive agricultural practices.

The research established a positive correlation between higher Soil Quality Index (SQI) scores and better agricultural yield potential. This underscores the value of SQI as a tool for prioritizing areas that might benefit from improved soil management practices for agricultural purposes. The analysis identified soil texture and bulk density as critical factors influencing erosion control potential. This knowledge can inform the selection of appropriate soil management practices to minimize erosion risks.

Discussion

The analysis of primary soil properties provides valuable insights into the overall soil quality of the sampled locations. The slightly acidic nature of most soils and the moderate organic matter content suggest potential areas for improvement through soil management practices. The variation in soil texture and CEC highlights the importance of the soil map model for informing land use decisions in agriculture and civil engineering (Asadi et al., 2008; Brevik et al., 2016; Söderström et al., 2016).

The analysis of secondary soil properties and heavy metal mobility provides additional information on potential environmental risks and soil health considerations. While the heavy metal concentrations are currently within acceptable ranges, continued monitoring is recommended, particularly in areas with a history of heavy metal contamination or intensive agricultural practices (Violante et al., 2010; Li et al., 2022). The leaching potential data highlights the importance of considering soil properties when making land-use decisions, particularly for agricultural activities or applications of potentially mobile contaminants (Li et al., 2022).

The SQI ratings provide a valuable tool for prioritizing areas that might benefit from improved soil management practices. Sites with lower SQI ratings, such as Site 2, could be targeted for interventions like liming to address acidity or implementing practices that reduce leaching potential. An analysis of the SQI ratings alongside the data from Tables 2 and 3 (primary and secondary soil properties) can reveal specific factors influencing the overall soil quality. For example, the high SQI rating at Site 3 likely benefits from its good organic matter content and low leaching potential. Conversely, the lower SQI rating at Site 2 might be attributed to its low acid buffering capacity and moderate leaching potential (Cherubin et al., 2016; Marion et al., 2022).

The functional soil maps provide a powerful tool for stakeholders in agriculture, civil engineering, and environmental management. By identifying areas with high or low functionality for specific land uses, these maps can help optimize resource allocation, minimize environmental risks, and promote sustainable development practices in the Niger Delta region (Bobryk et al., 2016; Söderström et al., 2016)..

The evaluation highlights the strengths of the digital soil map as a valuable tool for stakeholders. Its accuracy, integration with GIS software, and relevance to user needs in the region position it as a powerful resource for informed decision-making (Grunwald et al., 2011; Lamichhane et al., 2019). However, focusing on improving user-friendliness and establishing a clear update frequency can further enhance the map's accessibility and long-term value (Nkwunonwo, 2015; Kibblewhite et al., 2012)..

CONCLUSION

The research successfully developed a functional soil map model for the Niger Delta region. This model goes beyond simply delineating soil types; it incorporates valuable data on critical soil properties such as slope, depth, drainage, surface texture, erosion, and groundwater depth. This comprehensive information fills a critical knowledge gap for the region (Brevik et al., 2016).

The functional soil map offers significant benefits to a wide range of stakeholders: This includes serving as a vital tool for understanding and monitoring soil health, enabling targeted conservation efforts. By providing detailed data on soil quality and limitations, the map empowers farmers to optimize crop selection and land management practices, ultimately improving yields.

The soil data can inform decisions on infrastructure placement, considering factors like ground stability and potential erosion risks. The findings identify areas susceptible to erosion, allowing for targeted mitigation strategies to protect valuable land and resources.

RECOMMENDATIONS

Further research could delve deeper into specific aspects, such as investigating the long-term impacts of different land-use practices on soil quality. It can also look at developing site-specific soil management recommendations based on the functional soil maps and SQI data and exploring the integration of climate change projections into soil health assessments. By building upon these findings, future efforts can contribute to the sustainable management of soil resources in the Niger Delta region

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