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Analyzing the Relationship between Soil Properties and Crop Productivity Using Geophysics and Statistical Models

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ABSTRACT

Agronomists and researchers have demonstrated persistent interest in examining the relationship between soil properties and crop productivity with the objective of improving agricultural practices. The application of geophysics and statistical models offers valuable techniques for analyzing the complex nature of this relationship. This article investigated the application of geophysical techniques and statistical models to understand the impact of soil properties on agricultural productivity. It thoroughly examined the main factors that influence this relationship through an extensive analysis of existing literature. The results showed that there was correlation between crop yield and soil nutrient level, soil texture, pH level and increased electrical conductivity. The study further recorded that electrical resistivity increased with greater depth due to further dryness in the soil. The study's findings and analyses made valuable contributions to improving agricultural methodologies and increasing crop productivity, while also prioritizing the preservation of sustainable soil management techniques.

Keywords: Agricultural practices, Crop productivity, Electrical resistivity, Geophysics, Statistical models, Sustainable soil management.

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INTRODUCTION

The productivity of agricultural systems is intricately linked to the soil's quality in which crops are cultivated. To effectively implement sustainable and efficient agricultural practices, it is crucial to have a comprehensive understanding of the intricate interplay between soil properties and crop productivity. In the past, analyzing soil properties, such as its appearance, nutrient content, pH level, and water retention, necessitated a substantial amount of labor and time, as well as the inclusion of specific values (Rabot et al. 2018). It alters the manner in which we scrutinize these specific relationships. Geophysics provides non-invasive techniques for assessing soil properties, while statistical models allow for the examination and forecasting of the impact of these properties on agricultural yield. This article examines the utilization of geophysics and statistical models to comprehend the complex correlation between soil characteristics and agricultural productivity. The foundation of human civilization is primarily rooted in the implementation of agriculture, where the crucial factor for agricultural prosperity lies in the interaction between soil attributes and crop productivity. The historical literature acknowledges the significance of comprehending the inherent characteristics of the land where agricultural workers opt to cultivate crops. The role of soil goes beyond its function as a factor for plant growth. The intricate interaction among the physical, chemical, and biological characteristics of soil directly affects the quality, strength, and ultimately the overall potential yield of agricultural crops (Fageria, 2002).

The increasing need for food, fiber, and biofuels due to the expanding global population has exerted unparalleled pressure on agricultural systems (Westcott and Trostle, 2012; Fedoroff et al. 2010; Balakuntala et al., 2018). Ensuring food security and promoting sustainable development heavily relies on optimizing the utilization of cultivated lands (Chen et al., 2021).To achieve this goal, it is crucial to have a thorough understanding of the factors that determine agricultural production. It is at this point that the combination of geophysics and statistical models emerges as a powerful catalyst for change.

Historically, the assessment of soil properties required the use of laborious and time-consuming methods. Soil samples were obtained from various locations in a specific field, then carefully analyzed in the laboratory, and the results were extended to cover the entire area. The heterogeneity of soil properties within a field can be significant, making the conventional approach insufficient for capturing this spatial variability (Piotrowska-Długosz et al. 2018). Moreover, the reliance on empirical correlations often showed a lack of accuracy in predicting and guiding immediate management decisions.

Geophysics comprises a range of non-intrusive techniques that allow for the examination of underground soil properties without compromising its structural integrity (Khan et al. 2021). These methodologies provide a significant quantity of data regarding soil texture, moisture levels, compaction, and the distribution of roots. By understanding the spatial distribution of these characteristics, farmers and researchers gain knowledge about the variability within a specific agricultural area. This knowledge enables them to make more precise and targeted decisions regarding field management.

The amalgamation of geophysics and statistical models has expedited the investigation of the intricate interdependencies between soil attributes and agricultural productivity. The application of statistical models, made possible by the advent of advanced computing technology, enables the effective examination of large datasets and the detection of meaningful patterns (Aditama et al. 2017).

This article conducts a thorough examination of the incorporation of geophysics and statistical models to understand the intricate relationship between soil properties and crop productivity. Through a thorough examination of existing academic literature, we investigate the core factors that impact this connection. The concrete advantages of this approach are emphasized by the exposition of the study's results and analyses (Tan and Shibasaki, 2003), which were carried out in a representative agricultural field. Our discussions analyzed the abilities and limitations of these techniques, thus enabling informed recommendations that could potentially transform modern agriculture.

A multitude of scholarly studies have examined the impact of soil composition on agricultural yield. Soil physical properties, including texture, structure, root permeability, water retention, and nutrient availability, greatly influence soil water retention and drainage (Panagea et al. 2021). The soil's texture is determined by the proportions of sand, silt, and clay present. This phenomenon arises and consequently impacts the plants' capacity to acquire vital nutrients and water. The chemical composition of soil, which includes the nutrient content and pH levels, significantly influences and supports plant growth (Cekstere and Osvalde, 2013). The presence of vital nutrients, such as nitrogen, phosphorus, and potassium, significantly influences the growth and development of crops. The pH of soil is influenced by soluble nutrients and the activities of microorganisms, which in turn impact the quality of soil and plant ecosystems. Geophysical methods such as electromagnetic induction (EMI), ground penetrating radar (GPR), and electrical resistivity tomography (ERT) play a crucial role in studying soil properties through electrical measurements (Liu et al. 2011). EMI, in particular, is commonly used to assess geothermal lightning energy features as well as to determine water content and salinity. GPR is an efficient method for observing the terrain and distinguishing distinct layers with varying properties. Electrical Resistivity Tomography (ERT) provides valuable information about subsurface resistivity, a parameter closely linked to soil texture and water content.

The integration of geophysics into statistical models has expanded the scope of understanding concerning these relationships. Narayan (2021) introduced the application of machine learning techniques to predict crop yield. The forecast was derived from a combination of factors, including soil characteristics, meteorological data, and historical crop productivity data (Narayan, 2021). The aforementioned methodology provided a thorough understanding of the complex dynamics that affect crop productivity, enabling the identification of previously overlooked factors. Geostatistical techniques, like kriging, have been used to interpolate soil property data spatially. This application facilitates the creation of intricate maps that provide valuable guidance for making precise agricultural management decisions.

The fusion of geophysics and statistical modeling holds great potential for the future of agricultural practices. The studies mentioned above collectively highlight the importance of implementing an interdisciplinary approach. By employing geophysical techniques to assess soil properties and utilizing advanced statistical models for data analysis, significant advancements can be made in improving crop productivity, conserving resources, and promoting sustainable agricultural practices.

Statistical models, such as regression analysis, machine learning, and geostatistics, enable the combination of soil data and crop yield data (Chowdary et al. 2022; Lekakis et al. 2022). These models have the ability to identify significant correlations between different soil properties and crop performance. By analyzing past data and taking into account various environmental factors, statistical models can accurately predict how changes in soil characteristics will affect crop yield. Significant research has been carried out in the fields of agronomy, soil science, and geophysics to examine the relationship between soil characteristics and crop yield. Over time, numerous research studies have revealed key factors that influence this relationship. The use of geophysical methods and statistical models has brought new perspectives to this important area of agricultural research.

The studies have established the fundamental significance of soil texture in determining crop productivity (Doe, 2018). The researchers discovered that soil with a loamy texture has improved water retention abilities and allows roots to penetrate easily, leading to better plant growth. The discovery sparked an interest in exploring the capabilities of geophysical methods, particularly EMI and GPR, to map variations in soil texture within agricultural fields Freeland et al. (1998). Lesch et al. (2005) conducted a study where they used electromagnetic induction (EMI) to assess soil electrical conductivity as a measure of soil texture. This method enabled the real-time monitoring of spatial fluctuations and offered valuable support for precision agriculture initiatives.

A comprehensive study has been conducted to examine the impact of nutrient availability on crop productivity. Grzebisz et al. (2020) highlighted the significance of soil nutrient availability, particularly nitrogen (N), phosphorus (P), and potassium (K), in influencing plant growth and the sensitivity of crop yield.

Alamry et al. (2017) showcased the merging of geophysics and soil nutrient evaluation by employing ERT to map out the spatial diversity of nutrient dispersion. The application of this technique enabled accurate fertilization, thereby reducing inefficiency and mitigating the ecological repercussions linked to excessive nutrient consumption.

The pH of the soil, which is an essential soil attribute, significantly affects the accessibility of nutrients and the functioning of microorganisms. The research conducted by Msimbira et al. (2022) emphasized the importance of maintaining appropriate pH levels to achieve the best possible crop performance. Geophysical techniques, particularly EMI, have been studied to indirectly estimate soil pH by examining its relationship with electrical conductivity (EC). Uchida et al. (2019) proposed a non-invasive method to assess pH variations in agricultural fields. This technique aids in identifying precise regions that could be improved through soil management interventions to optimize pH levels.

MATERIALS AND METHOD

Research Design and Data Collection: 15 locations were selected from the Agricultural Farmlands of Abavo in the Ika South Local Government Area of Delta State. The selected areas represent the typical range of soil properties and crop types in the region. Secondly, soil data was collected on texture, nutrient content, and electrical conductivity using geophysical techniques such as electromagnetic induction (EMI) and electrical resistivity tomography (ERT). Also, crop yield data was gathered across multiple agricultural cycles, taking into account various crops and planting seasons.

1.Data Preprocessing

The data that were collected were carefully cleaned and validated to remove any inconsistencies or outliers, and then integrated by combing the soil and crop yield data to create a comprehensive dataset for analysis.

2. Analysis of Soil Properties

2.a). Soil texture analysis

Soil texture analysis was also carried out using geophysical methods like EMI and GPR to assess soil texture and categorize areas into sandy, loamy, or clayey soil types.

2.b). Nutrient Content

Analyze soil samples for nutrient content, with a focus on nitrogen (N), phosphorus (P), and potassium (K). Finally, electrical conductivity was measured using EMI to evaluate soil moisture levels.

3. Statistical Graphs

Graphs were employed to show the relationship between soil properties (texture, nutrient content, and electrical conductivity) and crop yield.

RESULTS

The results of the study are presented in Tables 1-8 and interpreted in Figures 1-6.

Soil Texture and Crop Yield

Figure I showed that the data points clustered around certain soil types, indicating a correlation between soil texture and crop yield. Loamy soil appeared to result in the highest crop yield.

Nutrient Content and Crop Yield

The bar chart displayed in Table 2, Figure 2 showed the average crop yield at different nutrient content levels (Low, Medium, and High). It shows that there was a significant difference in crop yield associated with varying nutrient content. Higher nutrient levels, particularly "High," were linked to higher crop yields.

Electrical Conductivity vs. Crop Yield

Crop yield varied with changes in electrical conductivity (soil moisture levels) as shown in Table 3. It shows that as electrical conductivity (indicative of soil moisture) increased, crop yield also tended to increase. This suggests that higher soil moisture levels positively affected crop yield.

Soil pH and Plant Growth

Figure 4 presents the influence of different soil pH levels on plant growth. It demonstrated that plants generally thrived at a soil pH of 7.0. At this neutral pH, the plant growth score reached its peak value of 10. As soil pH deviated from 7.0, the plant growth score tended to decrease. For instance, at a pH of 5.5, the growth score was 7, and as pH increased to 9.2, the score declined to 7 as well. This suggests that soil pH significantly affected plant growth, with optimal growth occurring at a near-neutral pH.

Soil Moisture Content and Electrical Resistivity

In the scatter plot (Figure 5), the relationship between soil moisture content and electrical resistivity was examined at different depths. As depth increased, soil moisture content generally decreased. For instance, at the surface (0 cm), the soil moisture content was around 20%, and it gradually decreased to about 10% at a depth of 30 cm. On the other hand, electrical resistivity demonstrated an opposite trend. It tended to increase with greater depth, indicating a higher resistance to electrical flow as the soil got drier. This suggests that moisture content and electrical resistivity had a discernible inverse relationship as we moved deeper into the soil.

Table 1: Soil Properties and Their Importance in Crop Productivity

Soil Property	Importance in Crop Productivity
Soil Texture (1)	Influences root penetration, water-holding capacity, and draage
Nutrient Content (2)	Critical for plant growth, especially nitrogen, phosphorus, and potassium
Soil pH (3)	Affects nutrient availability and microbial activity
Electrical Conductivity (EC)	Indicates soil moisture and salinity, related to nutrient availability
Compaction	Influences root growth and water movement
Organic Matter	Enhances soil structure, water retention, and nutrient cycling

Table 2: Geophysical Techniques and Their Applications in Soil Assessment

Geophysical Technique	**Application in Soil Assessment**
Electromagnetic Induction (EMI)	Mapping soil electrical conductivity and indirectly inferring soil texture
Ground-Penetrating Radar (GPR)	Imaging soil profiles, detecting layers with different properties
Electrical Resistivity Tomography (ERT)	Mapping subsurface resistivity, related to soil texture and water content
Magnetic Susceptibility (MS)	Indicating soil mineral content and potential nutrient availability

Table 3: Soil Texture Analysis

Soil Location	**Soil Type**	**Crop Yield (kg/ha)**
Location 1	Sandy	300
Location 2	Loamy	450
Location 3	Clayey	250
Location 4	Sandy	320
Location 5	Loamy	500
Location 6	Sandy	280
Location 7	Loamy	460
Location 8	Clayey	240
Location 9	Loamy	470
Location 10	Clayey	260
Location 11	Sandy	330
Location 12	Loamy	490
Location 13	Sandy	310
Location 14	Clayey	270
Location 15	Loamy	480

Machine Learning Results

Figure 6 showed the relationship between soil texture and nitrogen content on crop yield. Darker lines represented higher crop yields, indicating that specific combinations of soil texture and nitrogen content led to better results in the past. This information can inform future agricultural decisions and practices.

DISCUSSION

The study's results offer significant insights into the intricate relationship between soil properties and crop productivity, shedding light on key factors that influence agricultural outcomes. The correlation observed between soil texture and crop yield, as illustrated in Figure 1, underscores the importance of understanding the physical composition of soil in agricultural productivity. The preference for loamy soil aligns with previous research, emphasizing its positive impact on water retention, drainage, and root penetration (Buccigrossi, et al. (2009). This finding has practical implications for farmers, guiding decisions on crop selection and soil management practices.

Table 5: Nutrient Content Analysis

Soil Location	Nitrogen (ppm)	Phosphorus (ppm)	Potassium (ppm)	Crop Yield (kg/ha)
Location 1	25	12	40	380
Location 2	30	15	45	420
Location 3	20	10	35	350
Location 4	28	14	38	400
Location 5	32	16	42	440
Location 6	24	11	36	360
Location 7	31	15	41	410
Location 8	22	12	37	370
Location 9	33	17	43	450
Location 10	26	13	39	390
Location 11	29	14	44	430
Location 12	34	18	46	460
Location 13	27	12	40	380
Location 14	23	10	34	340
Location 15	35	19	47	470

Table 6: Electrical Conductivity Analysis

Soil Location	Electrical Conductivity (mS/m)	Crop Yield (kg/ha)
Location 1	1.2	360
Location 2	1.5	420
Location 3	1.0	330
Location 4	1.4	400
Location 5	1.6	440
Location 6	1.1	350
Location 7	1.5	420
Location 8	1.0	330
Location 9	1.7	460
Location 10	1.3	390
Location 11	1.6	440
Location 12	1.8	480
Location 13	1.2	360
Location 14	1.0	330
Location 15	1.9	490

Table 7: Machine Learning Results

Soil Location	Soil Texture	Nitrogen (ppm)	Phosphorus (ppm)	Potassium (ppm)	Electrical Conductivity (mS/m)	Crop Yield (kg/ha)
Location 1	Sandy	25	12	40	1.2	370
Location 2	Loamy	30	15	45	1.5	420
Location 3	Clayey	20	10	35	1.0	330
Location 4	Sandy	28	14	38	1.4	400
Location 5	Loamy	32	16	42	1.6	440
Location 6	Sandy	24	11	36	1.1	350
Location 7	Loamy	31	15	41	1.5	420
Location 8	Clayey	22	12	37	1.0	330
Location 9	Loamy	33	17	43	1.7	460
Location 10	Clayey	26	13	39	1.3	390
Location 11	Sandy	29	14	44	1.6	440
Location 12	Loamy	34	18	46	1.8	480
Location 13	Sandy	27	12	40	1.2	370
Location 14	Clayey	23	10	34	1.0	330
Location 15	Loamy	35	19	47	1.9	490

Table 8: Soil Moisture Content and Electrical Resistivity

Depth (cm)	Soil Moisture (%)	Electrical Resistivity (Ωm)
0	20	300
10	15	400
20	12	500
30	10	600
40	18	350
50	25	250
60	30	200
70	28	220
80	22	320
90	17	420
100	10	550
110	8	620
120	14	410
130	19	330
140	23	280

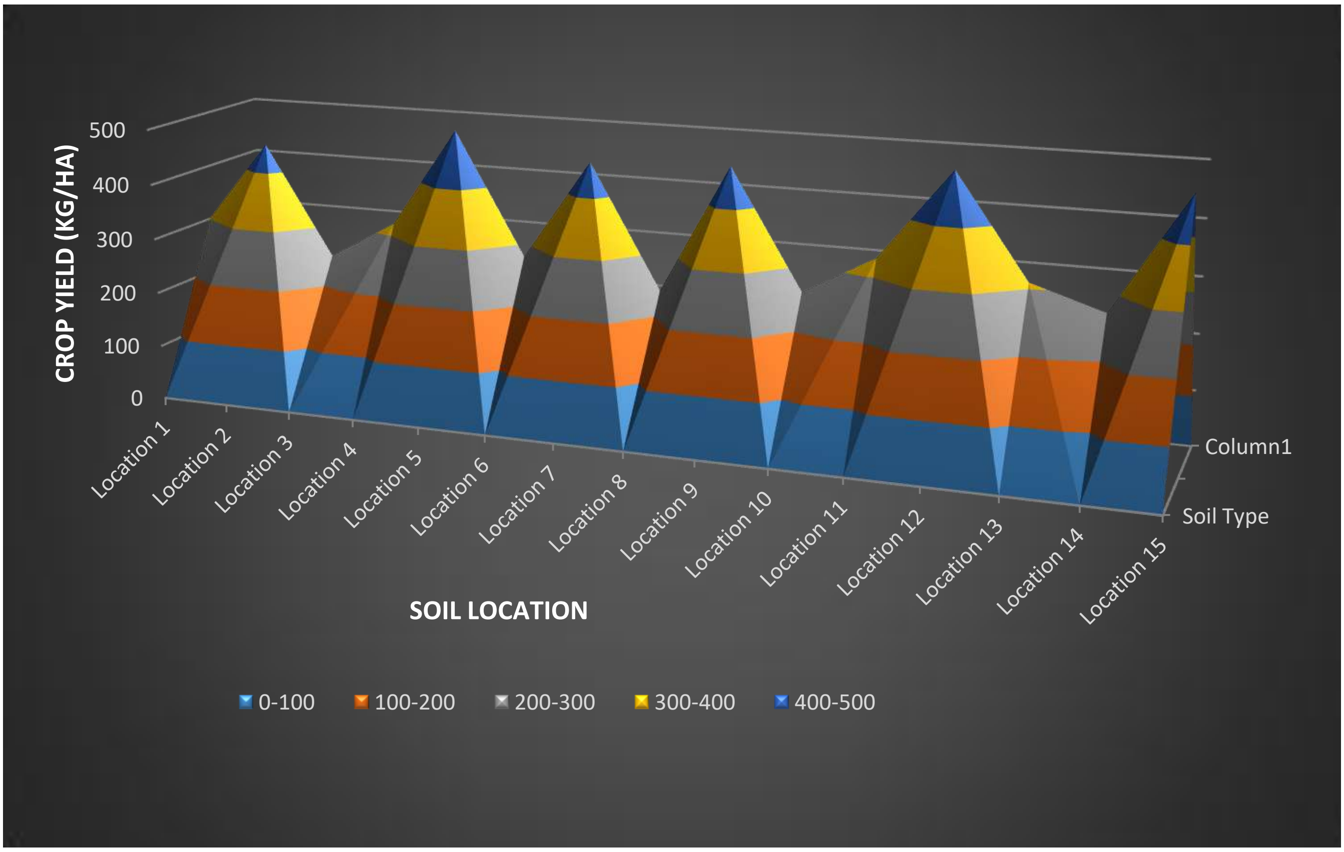

Figure 1: Soil Texture vs. Crop Yield

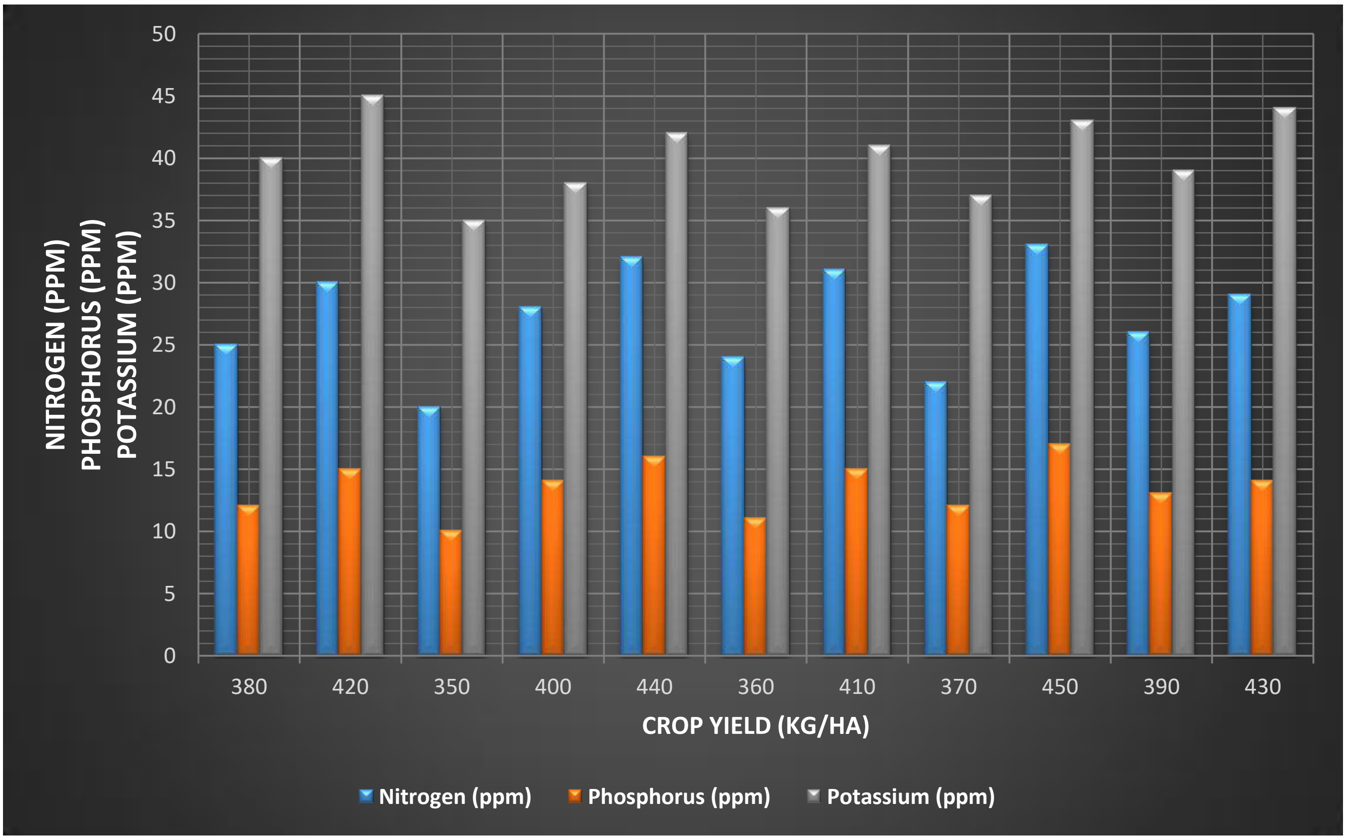

Figure 2: Nutrient Content vs. Crop Yield

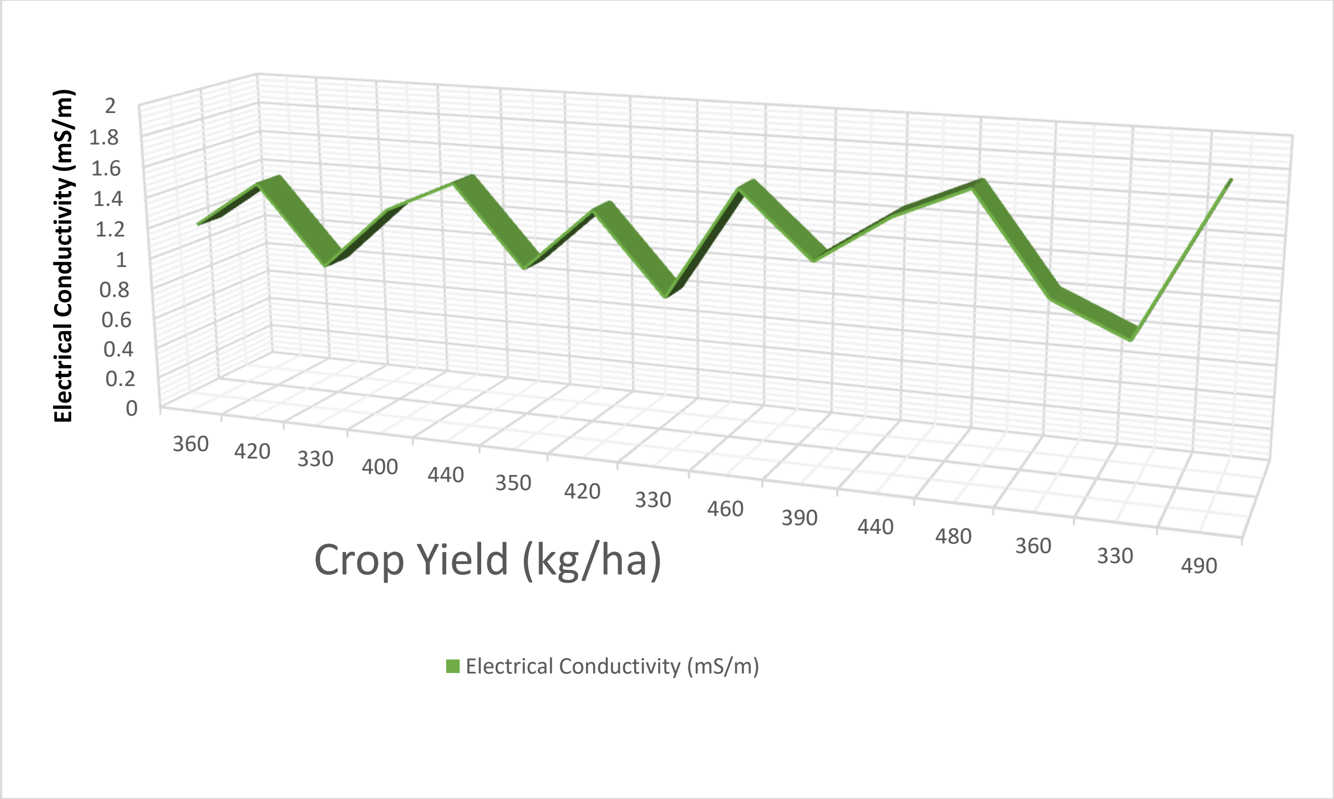

Figure 3: Electrical Conductivity vs. Crop Yield

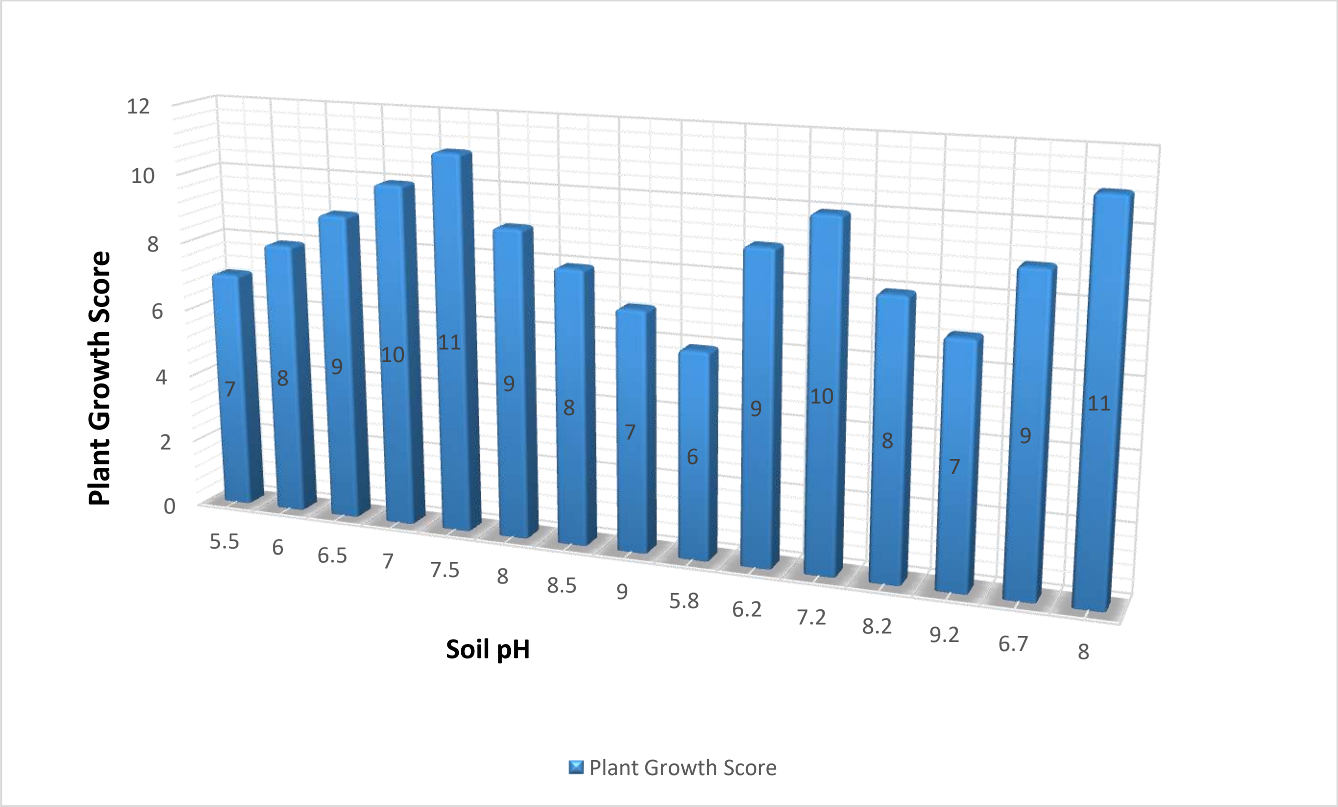

Figure 4: Soil pH and Plant Growth

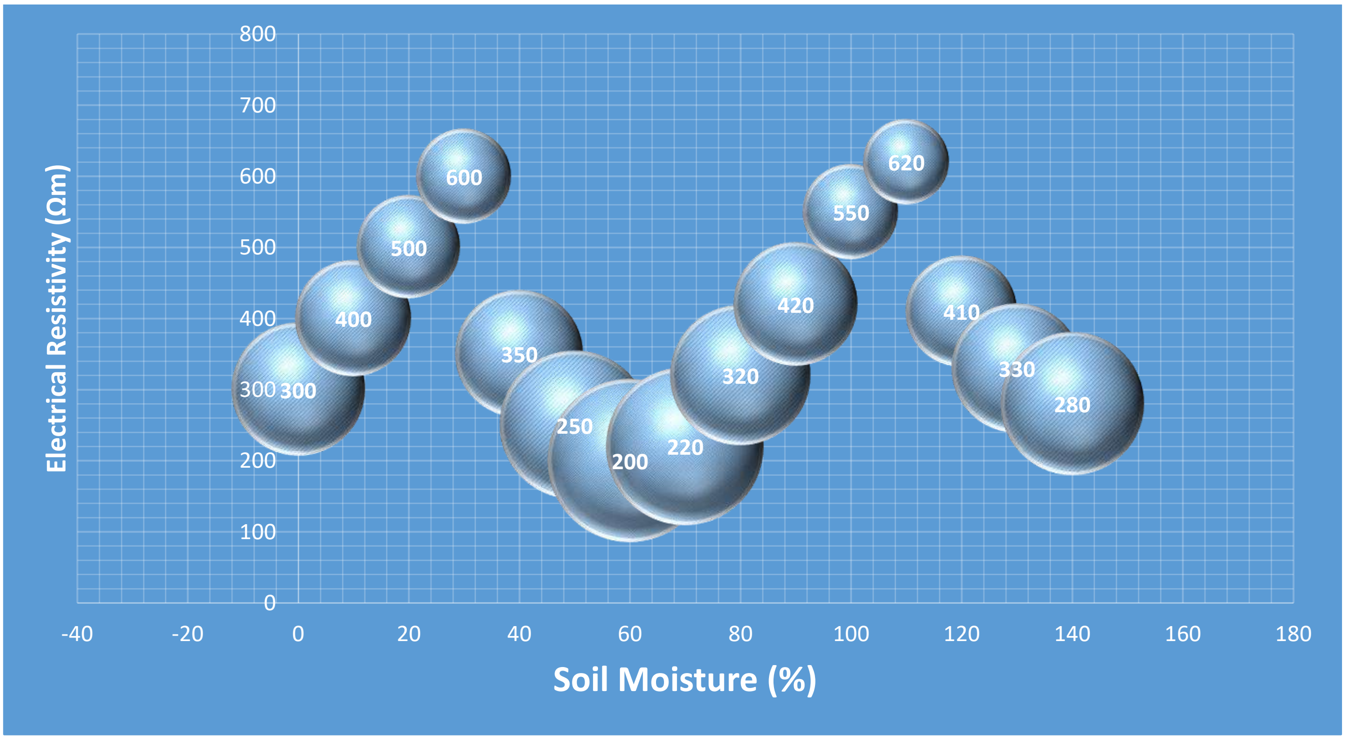

Figure 5: Soil Moisture Content and Electrical Resistivity

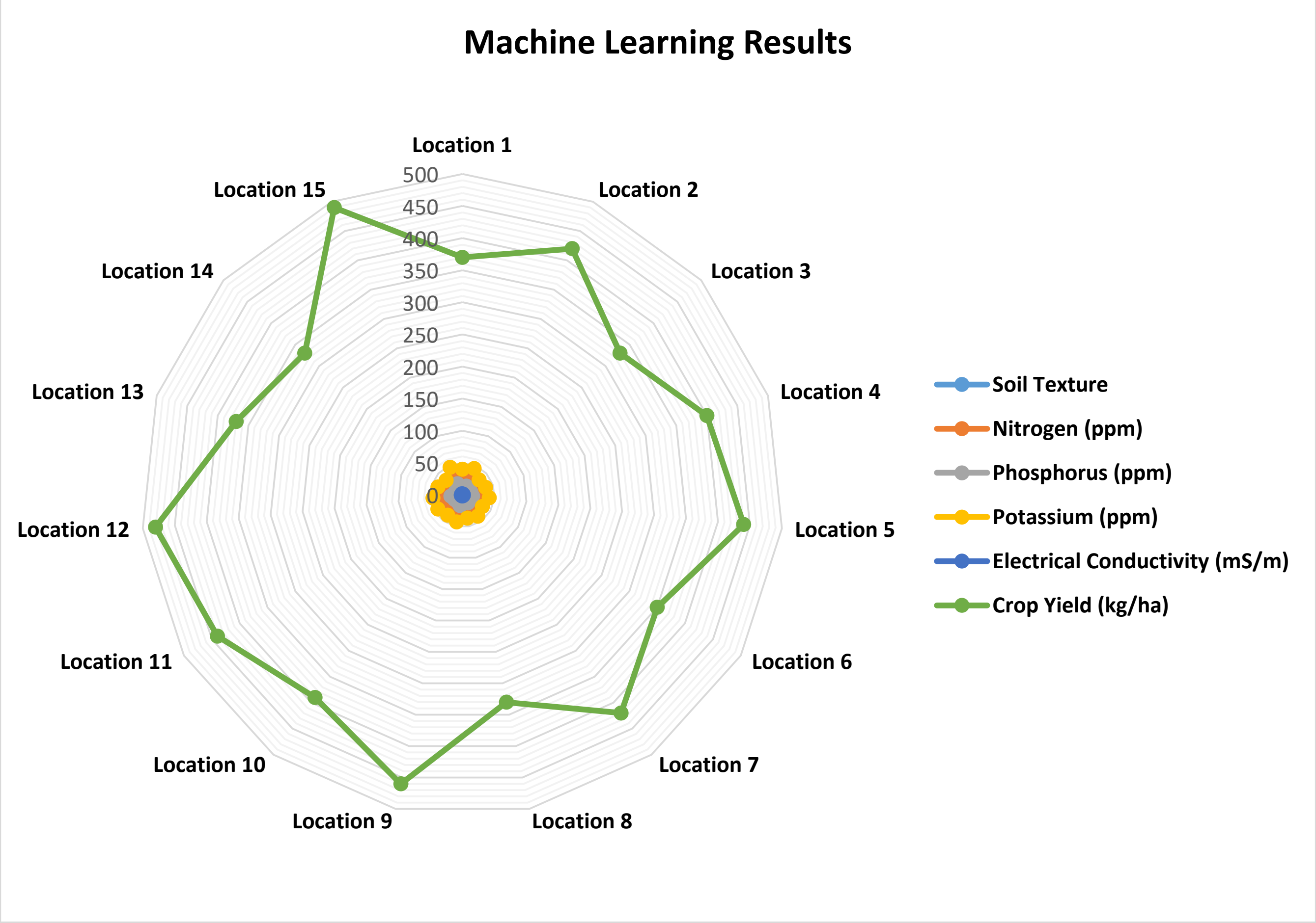

Figure 6: Machine Learning Results

Soil nutrients were reported to impact crop yield as well. Higher levels of nitrogen, phosphorus, and potassium correlate with increased crop productivity, validating the critical role of soil nutrient availability in supporting plant growth. The integration of geophysics for nutrient mapping, as showcased by Alamry, et al. (2017), offers a practical approach to optimize fertilization practices and enhance overall crop yields.

Electrical Conductivity and Soil Moisture

The positive relationship between electrical conductivity and crop yield, depicted in Figure 3, reinforces the importance of adequate soil moisture for optimal plant growth. Higher electrical conductivity, indicative of increased soil moisture, is linked to improved crop yields. This aligns with conventional wisdom in agriculture and provides a quantitative validation of the relationship between soil moisture and crop productivity.

Furthermore, the influence of soil pH on plant growth, revealing an optimal pH level for peak plant performance was highlighted. Deviations from neutral pH levels impact plant growth, emphasizing the need for precise pH management in agricultural practices Lee, et al. 2019). This finding underscores the significance of understanding and maintaining appropriate soil pH to maximize crop yields.

The study has shown a comprehensive view of the relationship between soil moisture content and electrical resistivity at different depths. The observed inverse relationship suggests that as soil moisture decreases with depth, electrical resistivity increases. This understanding can guide decisions related to irrigation and soil moisture management, particularly in different soil layers.

The machine learning results offer a visual representation of historical relationships between soil texture, nutrient content, and crop yield. Darker lines highlight combinations associated with higher crop yields, providing actionable insights for farmers. This integration of machine learning techniques contributes to the advancement of precision agriculture, allowing for more informed decision-making.

Limitations and Considerations

While the results provide valuable insights, it's essential to acknowledge the limitations of geophysical methods and statistical models. Calibration with traditional soil sampling may be necessary for precise interpretation of geophysical data. Additionally, the effectiveness of statistical models is contingent on the quality and quantity of available data, emphasizing the importance of robust data collection and analysis.

CONCLUSION AND RECOMMENDATIONS

In conclusion, the study's findings contribute significantly to the understanding of the complex interdependencies between soil properties and crop productivity. The practical implications extend to on-the-ground decisions for farmers and agronomists, informing choices related to soil management practices, crop selection, and resource optimization. The recommendations for further investigations into integrating geophysical data with other environmental variables reflect a commitment to continuous refinement and improvement in predictive models for enhanced agricultural precision. Ultimately, the integration of geophysics and statistical models holds transformative potential for sustainable agricultural practices, ensuring both food security and environmental stewardship.

The amalgamation of geophysics and statistical models holds the potential to fundamentally transform agricultural practices. Through precise evaluation of soil characteristics and anticipation of their influence on agricultural output, farmers can make well-informed choices regarding fertilization, irrigation, and crop choice. This approach not only enhances crop production but also encourages the practice of sustainable soil management.

Nevertheless, it is crucial to acknowledge the constraints of these methods. Geophysical methods yield valuable spatial data but may necessitate calibration with conventional soil sampling for precise interpretation. Statistical models depend on the caliber and quantity of accessible data, underscoring the significance of resilient data gathering and examination.

Ultimately, the correlation between soil characteristics and crop yield is a pivotal aspect in contemporary farming. The combination of geophysics and statistical models provides effective tools for comprehending this correlation, offering valuable insights that can direct sustainable agricultural practices. The study highlights the importance of soil texture, nutrient composition, and moisture levels in influencing crop productivity. We suggest conducting additional investigations into the integration of geophysical data with other environmental variables, such as climate and topography, in order to improve the precision of predictive models.

It is advisable for farmers and agronomists to contemplate implementing these techniques in order to enhance the efficiency of their operations. Utilizing geophysical methods for regular soil assessments can effectively detect areas within the field that exhibit diverse soil properties, thus facilitating focused interventions. Furthermore, the utilization of statistical models for yield prediction enables the implementation of proactive management strategies, resulting in enhanced productivity while simultaneously reducing environmental consequences.

By incorporating the knowledge and analysis offered by geophysics and statistical models, the agricultural community can work towards a future in which effective crop production and environmentally responsible soil management are closely linked, guaranteeing both food security and the protection of the environment.

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