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HARNESSING ELECTRICAL RESISTIVITY FOR PRECISION AGRICULTURE: ADVANCES AND CHALLENGES IN GEOPHYSICAL APPROACHES FOR SOIL AND WATER OPTIMIZATION

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Abstract

The integration of resistivity methodologies in agricultural sciences has emerged as an indispensable tool for optimizing soil characterization, moisture assessment, and salinity management. Electrical resistivity techniques, including Electrical Resistivity Tomography (ERT) and Electromagnetic Induction (EMI), offer profound insights into subsurface heterogeneities, facilitating data-driven precision agriculture. The application of resistivity surveys enables real-time evaluation of soil hydrodynamics, enhancing irrigation efficiency and mitigating excessive water usage. Additionally, resistivity-based mapping delineates salinity gradients, aiding in the formulation of targeted soil remediation strategies. However, the precision of these techniques is often impeded by inherent soil variability, mineralogical composition, and external environmental fluctuations. Despite the sophisticated advancements in geophysical instrumentation, challenges persist regarding cost-effectiveness, accessibility for small-scale agrarian communities, and the integration of resistivity data with contemporary remote sensing and artificial intelligence frameworks. Addressing these challenges necessitates a multidisciplinary approach that amalgamates geophysics, agronomy, and computational analytics to refine predictive modeling capabilities. This review systematically evaluates the state-of-the-art resistivity applications in agriculture, synthesizing global research advancements to delineate their efficacy and limitations. Furthermore, it underscores the imperative need for technological refinements that enhance user accessibility and operational feasibility. By bridging the existing knowledge gaps, future research endeavors must prioritize scalable and economically viable resistivity-based solutions, ensuring their practical deployment in sustainable agricultural.

Keyword: ***Precision Agricultural Electrical Resistivity, Geophysical Approach, Soil and Air Optimization***

Introduction

Agricultural sustainability depends significantly on efficient soil and water management strategies. Traditional techniques for assessing soil quality and moisture content often require labor-intensive sampling and provide limited spatial data (Corwin & Lesch, 2005). In recent years, geophysical methods such as electrical resistivity imaging have emerged as powerful tools in agricultural sciences, enabling precise and non-invasive mapping of subsurface conditions (Samouëlian et al., 2005). These techniques provide crucial insights into soil moisture distribution, salinity levels, and subsurface water reserves, all of which are vital for optimizing agricultural productivity and addressing climate-related challenges (Lück et al., 2009). Resistivity-based assessments rely on measuring the ability of soil to conduct electrical currents, which varies with moisture content, soil texture, organic matter, and salinity (Michot et al., 2003). By utilizing techniques like Electrical Resistivity Tomography (ERT) and Electromagnetic Induction (EMI), researchers can obtain high-resolution subsurface profiles that enhance precision farming practices (Doolittle & Brevik, 2014). These advancements facilitate informed decision-making in irrigation management, soil conservation, and crop health monitoring, ultimately

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reducing environmental degradation and resource wastage (Abu-Hassanein et al., 1996). One of the primary applications of resistivity in agriculture is in optimizing irrigation practices. Water availability and distribution significantly impact crop growth, and traditional irrigation methods often lead to inefficiencies due to uneven water application (Robinson et al., 2008). By employing resistivity-based soil moisture mapping, farmers can precisely identify water-stressed areas and optimize irrigation schedules, leading to improved water-use efficiency (Friedman, 2005). Additionally, these techniques assist in monitoring soil salinity, a critical concern in arid and semi-arid regions where excessive salt accumulation hampers crop productivity (Rhoades et al., 1999).

Apart from water management, resistivity techniques are increasingly used to assess soil compaction and root zone characteristics. Root development plays a crucial role in nutrient absorption and plant stability, and soil compaction can restrict root growth and limit access to essential nutrients (Whalley et al., 2008). Through non-invasive imaging, resistivity surveys can map root zones, helping agronomists develop targeted soil management strategies to improve plant health and yield (Dalton, 1995). Furthermore, resistivity imaging aids in groundwater exploration and monitoring, particularly in drought-prone regions where efficient water resource management is essential (Scanlon et al., 2012). The integration of resistivity methods into modern agricultural practices aligns with global efforts toward sustainable farming. As climate change intensifies challenges related to soil degradation, water shortages, and declining crop yields, the need for innovative, data-driven approaches has become more pressing (Hatfield & Prueger, 2015). The combination of geophysical surveys with advanced data analytics and machine learning models holds great promise for improving precision agriculture and enhancing food security (McBratney et al., 2005).

Fundamental Principles of Resistivity in Agriculture

Electrical resistivity is a geophysical property of soil that determines its ability to conduct electrical current. It is influenced by factors such as moisture content, soil texture, salinity, temperature, and organic matter. The resistivity of agricultural soils is primarily controlled by the presence of water and dissolved ions, making it a reliable indicator for soil health and water management applications.

Measurement Techniques

Soil resistivity measurement is an essential tool for assessing a variety of soil properties that are crucial for agricultural and environmental management. Different methods are employed to measure the resistivity of soil, each offering distinct advantages in terms of resolution, depth penetration, and application scope. These techniques range from non-invasive imaging methods to traditional electrode-based configurations, and they provide valuable data for understanding soil moisture, salinity, compaction, and other important parameters. The following sections elaborate on the most commonly used techniques for measuring soil resistivity: Electrical Resistivity Tomography (ERT), Electromagnetic Induction (EMI), and traditional electrode arrays such as the Wenner and Schlumberger configurations.

1. Electrical Resistivity Tomography (ERT)

Electrical Resistivity Tomography (ERT) is a sophisticated, non-invasive geophysical technique widely used to map subsurface soil properties. This method is particularly useful in agriculture for assessing soil moisture distribution, detecting compaction zones, mapping salinity levels, and identifying the heterogeneity of the soil profile at various depths. The basic principle of ERT involves the injection of electrical current into the ground through a series of electrodes, and the subsequent measurement of the resulting voltage differences. These measurements are then used to calculate the resistivity of the soil at different depths, producing a 2D or 3D resistivity profile. ERT has several key advantages over other resistivity measurement techniques. It provides high spatial resolution and can produce detailed images of subsurface soil properties at a range of depths. Moreover, the data obtained from ERT surveys is continuous and spatially distributed, making it an excellent tool for large-scale studies and precision agriculture applications. The ability to map soil conditions across an entire field enables farmers to make informed decisions regarding irrigation, salinity management, and soil treatment.

In the context of agriculture, ERT has been extensively used for monitoring soil moisture. Since water significantly influences the resistivity of the soil, variations in soil moisture lead to distinct resistivity patterns that can be visualized using ERT. This makes it a powerful tool for precision irrigation, where farmers can identify areas of the field that are overly dry or overly saturated, allowing them to adjust irrigation practices accordingly. ERT is also highly effective for detecting compacted soil layers, which can hinder root growth and affect plant health. By identifying such zones, farmers can implement targeted soil treatment measures to improve soil aeration and root penetration.

One of the most significant advancements in ERT is its ability to produce time-lapse images, which allows for monitoring changes in soil properties over time. This dynamic approach is particularly useful for studying the effects of agricultural practices, such as irrigation, fertilization, and tillage, on soil structure and moisture content. As a result, ERT is becoming an indispensable tool in agricultural research and practice.

2. Electromagnetic Induction (EMI)

Electromagnetic Induction (EMI) is another popular method for measuring soil conductivity and resistivity. Unlike ERT, EMI does not require direct contact with the soil, making it a more convenient and faster technique for large-scale surveys. In EMI, a transmitter generates an alternating electromagnetic field that induces eddy currents in the ground. The induced currents interact with the soil and produce secondary electromagnetic fields that are measured by a receiver. These measurements are used to estimate the electrical conductivity of the soil, which is inversely related to the soil's resistivity.

EMI has several advantages over traditional resistivity methods, especially in terms of its speed and ability to cover large areas. Since EMI does not require physical contact with the soil, it can be used to survey fields quickly, often at walking speed, making it ideal for large-scale precision agriculture. This is particularly useful for farmers who need to survey large areas of land for soil conditions, such as soil salinity or moisture content, without the need for labor-intensive sampling. The main application of EMI in agriculture is in the mapping of soil conductivity, which provides valuable information about soil texture, moisture content, and salinity. Soil conductivity is influenced by several factors, including the presence of water and salts, which both decrease resistivity and increase conductivity.

Therefore, EMI can be used to detect areas of the field that are more saline, helping farmers manage irrigation practices and reduce the adverse effects of salinity on crops. EMI is also useful for detecting variations in soil texture and structure, which can affect root development and nutrient uptake. For example, areas with high clay content tend to have higher conductivity, while sandy soils exhibit lower conductivity. This information can be used to guide precision farming practices, such as adjusting fertilizer application rates or irrigation schedules based on the specific needs of different soil types within a field. Furthermore, EMI is advantageous because it can be used in a variety of environmental conditions and over different types of terrain. It is a relatively cost-effective method for large-scale mapping, as it requires fewer labor resources and is less time-consuming compared to methods that involve direct sampling.

3. Wenner and Schlumberger Arrays

The Wenner and Schlumberger arrays are traditional techniques used to measure soil resistivity and are widely employed in soil physics studies and groundwater exploration. These methods involve the use of four electrodes that are arranged in specific configurations on the surface of the soil. The electrodes are placed in a linear array, with two electrodes used to inject current into the soil and the other two to measure the resulting potential difference. The resistivity of the soil is then calculated based on the measured voltage and the distance between the electrodes.

The **Wenner array** consists of four electrodes placed at equal intervals along a straight line. The current is injected through the outer two electrodes, and the voltage is measured across the inner two electrodes. This configuration provides a simple and effective method for measuring soil resistivity at relatively shallow depths. It is particularly useful for small-scale surveys, such as studies of soil compaction or mapping of shallow groundwater levels. The primary advantage of the Wenner array is its simplicity and ease of use, making it an ideal tool for basic soil resistivity measurements.

The **Schlumberger array**, on the other hand, has a similar configuration but with a different electrode spacing arrangement. The inner two electrodes are placed closer together, while the outer electrodes are spaced farther apart. This allows the Schlumberger array to provide deeper penetration compared to the Wenner array, making it more suitable for surveys that require data from greater depths, such as groundwater exploration or subsoil characterization.

While both the Wenner and Schlumberger arrays provide valuable resistivity data, they have some limitations compared to more advanced techniques like ERT and EMI. One of the main drawbacks is that these methods are typically more labor-intensive, as they require the manual placement of electrodes and measurements at multiple locations. Additionally, the data obtained from these arrays is usually limited to specific points in the soil and does not provide the continuous, high-resolution images offered by methods like ERT.

Despite these limitations, the Wenner and Schlumberger arrays remain widely used in agricultural and environmental studies due to their relatively low cost and straightforward implementation. They are particularly effective in applications where high-resolution mapping is not required, or when data needs to be obtained at a limited number of locations.

Applications of Resistivity in Agriculture

Resistivity techniques have emerged as a significant tool in agricultural research and practice, offering non-invasive methods to assess and manage various soil and environmental conditions that are critical to crop production. Electrical resistivity methods involve measuring the resistance of the soil to the flow of electrical current, which is influenced by several factors such as moisture content, salinity, texture, and compaction. The growing interest in these methods stems from their efficiency, cost-effectiveness, and ability to provide real-time, high-resolution data over large areas. This research explores the key applications of resistivity in agriculture, particularly in soil moisture monitoring, salinity detection and management, precision irrigation, root zone characterization, and groundwater exploration.

1. Soil Moisture Monitoring

Soil moisture plays a pivotal role in crop growth, influencing water availability, nutrient uptake, and overall plant health. Maintaining an optimal moisture level is essential for sustainable agricultural practices, particularly in areas subject to varying precipitation patterns or drought. Electrical resistivity surveys are particularly effective for monitoring soil moisture because moisture significantly influences the soil's electrical conductivity. The relationship between resistivity and moisture is based on the fact that water has a relatively low resistivity compared to dry soil. Therefore, high resistivity readings generally indicate dry conditions, while lower resistivity values suggest areas with higher moisture content. By conducting resistivity surveys, farmers and agronomists can obtain detailed maps of soil moisture variations across a given field. This information is invaluable for monitoring soil moisture levels across different depths, ensuring that irrigation is applied more precisely where needed and preventing both over-irrigation and under-irrigation. Several studies have demonstrated the utility of resistivity methods in monitoring soil moisture in different agricultural environments. For instance, in vineyards, resistivity measurements have been used to assess water availability in the root zone and optimize irrigation schedules. Similarly, in row crop farming, resistivity surveys help detect variations in moisture content at various soil depths, guiding irrigation decisions and reducing water wastage.

2. Salinity Detection and Management

Soil salinity is a major concern in many agricultural regions, particularly in areas with arid and semi-arid climates where irrigation practices may exacerbate the salinity problem. High levels of salinity can negatively affect plant growth by disrupting nutrient uptake and reducing soil permeability. In extreme cases, salinity can render the soil unsuitable for most crops, leading to land degradation and reduced agricultural productivity.

Resistivity surveys are highly effective in detecting soil salinity, as salt ions in the soil enhance its electrical conductivity. As a result, areas with high salinity levels will exhibit lower resistivity values compared to areas with lower salinity. By mapping the spatial distribution of electrical conductivity in the soil, resistivity methods allow farmers to identify saline hotspots within a field. This spatial variability in salinity can then be targeted for soil management practices, such as applying amendments or adjusting irrigation strategies to reduce salinity buildup.

One of the key advantages of using resistivity for salinity detection is its ability to provide real-time, high-resolution data over large areas. Traditional methods of salinity measurement, such as collecting soil samples and conducting laboratory tests, are time-consuming and can only provide data for discrete points. In contrast, resistivity surveys can cover an entire field quickly and efficiently, providing a comprehensive view of the salinity distribution. This information allows farmers to implement precise salinity management techniques, such as leaching with fresh water or applying gypsum to improve soil structure.

3. Precision Irrigation and Water Conservation

The global demand for water resources is increasing, making water conservation an essential component of sustainable agriculture. Precision irrigation, which involves applying water only to areas that require it, has emerged as a key strategy for optimizing water use in agriculture. Electrical resistivity methods play a crucial role in this process by providing detailed information on soil moisture distribution, helping farmers optimize irrigation schedules and minimize water wastage. By conducting resistivity surveys, farmers can map out areas with varying moisture levels and adjust irrigation accordingly. For instance, if resistivity data indicates that certain parts of a field have higher moisture content, these areas can be irrigated less frequently or with reduced water volume. Conversely, areas with lower moisture levels can be irrigated more intensively. This targeted approach ensures that crops receive the necessary water without the risk of over-irrigation, which can lead to waterlogging and soil degradation. In addition to improving water efficiency, precision irrigation also promotes better crop health and productivity. Plants receive adequate moisture for optimal growth, leading to more efficient nutrient uptake and reduced water stress. Several studies have shown that integrating resistivity data into irrigation management systems can increase water use efficiency and improve crop yields. For example, a study on cotton farming demonstrated that resistivity-based irrigation systems resulted in significant water savings while maintaining or even improving crop productivity.

4. Root Zone Characterization

Understanding the characteristics of the root zone is essential for improving soil conditions and optimizing crop growth. The root zone is the portion of soil in which plant roots are concentrated, and it directly influences nutrient and water uptake. Factors such as soil compaction, texture, and aeration affect the ability of roots to penetrate the soil and access necessary resources. Resistivity surveys provide valuable insights into the structure of the root zone by measuring variations in electrical conductivity at different depths. In compacted soils, the resistivity tends to be higher because the reduced pore spaces restrict the movement of water and ions. Conversely, in aerated soils, the resistivity is lower due to the higher moisture content and greater pore space. By mapping these resistivity variations, it is possible to differentiate between compacted and aerated soil layers, offering insights into root zone structure and its suitability for plant growth. This information is vital for improving soil aeration and enhancing root penetration. For example, if resistivity data indicates compacted layers in the root zone, farmers can take corrective actions such as tilling, deep plowing, or using soil conditioners to improve soil structure. These practices promote better root growth and nutrient uptake, ultimately enhancing crop productivity. Additionally, resistivity methods can help monitor the effects of soil amendments and tillage practices over time, providing feedback on the success of these interventions.

5. Groundwater Exploration

In regions facing water scarcity, locating groundwater reserves is a critical task for ensuring a reliable water supply for irrigation. Resistivity surveys are widely used for groundwater exploration because the presence of water significantly affects the electrical resistivity of the soil. In general, areas with higher resistivity correspond to less saturated zones, while lower resistivity values are indicative of groundwater presence. Resistivity methods, such as electrical resistivity tomography (ERT), can be used to map the subsurface and identify potential groundwater reserves in agricultural regions. These surveys provide a non-invasive way to assess the depth, extent, and quality of groundwater resources. In addition, resistivity surveys can be used to monitor changes in groundwater levels over time, helping farmers manage their water resources more effectively and sustainably. Several case studies have demonstrated the effectiveness of resistivity methods for groundwater exploration in agriculture. For example, resistivity surveys in arid regions of India have been used to identify groundwater sources for irrigation, reducing dependence on surface water and improving water security for farmers. In regions where groundwater depletion is a concern, resistivity surveys can help identify areas with sustainable water resources, ensuring that irrigation practices do not deplete local aquifers.

Challenges and Limitations

Despite its numerous advantages, the application of resistivity in agriculture faces certain challenges:

- **Soil Heterogeneity**: Variability in soil composition affects resistivity readings, requiring advanced data processing techniques for accurate interpretation.
- **Instrument Sensitivity**: External factors such as temperature fluctuations and soil mineralogy can influence measurements.
- **Cost and Expertise**: High-resolution resistivity surveys require specialized equipment and trained personnel, making them less accessible for small-scale farmers.

Research Gap and Future Directions

While resistivity techniques have demonstrated significant potential in agriculture, there remain several research gaps that need to be addressed:

1. **Integration with Remote Sensing and AI**: Combining resistivity surveys with remote sensing technologies and artificial intelligence can enhance data interpretation and provide real-time decision-making tools for farmers.
2. **Long-term Soil Health Monitoring**: More studies are needed to establish standardized protocols for using resistivity to monitor soil health trends over extended periods.
3. **Impact of Climate Change on Soil Resistivity**: Investigating how changing climate conditions affect soil electrical properties will be crucial for adapting resistivity applications to future agricultural challenges.

Discussion

The application of resistivity techniques in agriculture has gained considerable traction due to its ability to provide non-invasive, high-resolution insights into soil and water management. The use of electrical resistivity methods, including Electrical Resistivity Tomography (ERT) and Electromagnetic Induction (EMI), has significantly improved the efficiency of precision farming by enabling real-time monitoring of soil conditions. However, despite its growing importance, several challenges persist, necessitating further research and technological advancements. One of the major advantages of resistivity-based assessments is their role in optimizing irrigation strategies. With the increasing global water crisis, efficient water use is critical for agricultural sustainability. Studies have demonstrated that resistivity imaging can accurately map soil moisture variations, allowing farmers to tailor irrigation schedules to specific field conditions. This reduces water wastage and enhances crop productivity. Additionally, soil salinity, which remains a significant concern in arid and semi-arid regions, can be effectively detected and managed using resistivity methods. By identifying saline patches at an early stage, appropriate soil remediation measures can be employed to prevent long-term degradation.

Another critical aspect of resistivity applications is its utility in understanding soil compaction and root development. Soil compaction negatively impacts plant growth by restricting root penetration and reducing nutrient availability. Resistivity surveys provide valuable data on subsurface structures, enabling agronomists to assess soil health and implement corrective measures such as deep tillage or organic amendments to enhance soil aeration. Despite these advantages, several limitations hinder the widespread adoption of resistivity techniques in agriculture. One primary challenge is soil heterogeneity, which can introduce variability in resistivity readings. Differences in soil composition, mineral content, and temperature fluctuations may affect measurement accuracy. Additionally, the initial cost of equipment and the need for technical expertise pose barriers to small-scale farmers, particularly in developing countries. Future research should focus on improving cost-effective, user-friendly resistivity tools that can be integrated into precision agriculture practices without requiring extensive technical knowledge. There is a need for greater integration of resistivity techniques with emerging technologies such as remote sensing, artificial intelligence, and machine learning. Combining resistivity data with satellite imagery and predictive analytics could enhance the accuracy of soil assessments and provide farmers with real-time decision-making tools. This multidisciplinary approach has the potential to revolutionize agricultural management by increasing efficiency and sustainability.

Conclusions

The use of resistivity techniques in agriculture represents a promising advancement in precision farming and sustainable land management. The ability to non-invasively assess soil moisture, salinity, compaction, and groundwater availability offers numerous benefits for improving crop productivity and resource efficiency. However, while resistivity methods have demonstrated substantial potential, challenges such as cost, technical expertise, and data variability must be addressed to facilitate broader adoption. Future advancements should focus on the development of affordable and portable resistivity measurement tools, ensuring accessibility for small-scale farmers. Additionally, integrating resistivity with modern data analytics and remote sensing technologies will further enhance its applicability in precision agriculture. Addressing these research gaps will contribute to more effective and sustainable agricultural practices, ultimately improving global food security and resource conservation.

REFERENCES

1. Abu-Hassanein, Z. S., Benson, C. H., & Blotz, L. R. (1996). Electrical resistivity of compacted clays. *Journal of Geotechnical Engineering*, 122(5), 397-406.
2. Corwin, D. L., & Lesch, S. M. (2005). Apparent soil electrical conductivity measurements in agriculture. *Computers and Electronics in Agriculture*, 46(1-3), 11-43.
3. Dalton, F. N. (1995). In-situ root-zone soil moisture sensing. *Agricultural Water Management*, 28(3), 299-306.
4. Doolittle, J. A., & Brevik, E. C. (2014). The use of electromagnetic induction techniques in soils research. *Geoderma*, 223, 33-45.
5. Friedman, S. P. (2005). Soil properties influencing apparent electrical conductivity. *Journal of Environmental and Engineering Geophysics*, 10(2), 143-157.
6. Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, 10, 4-10.
7. Lück, E., Harms, J., & Scholz, M. (2009). Electrical resistivity tomography for precision agriculture. *Precision Agriculture Journal*, 11(2), 233-250.
8. McBratney, A. B., Whelan, B. M., & Ancev, T. (2005). Future directions of precision agriculture. *Precision Agriculture*, 6(1), 7-23.
9. Michot, D., Benderitter, Y., Dorigny, A., & Nicoullaud, B. (2003). Soil water content estimation using electrical resistivity. *Soil Science Society of America Journal*, 67(3), 593-601.
10. Rhoades, J. D., Kandiah, A., & Mashali, A. M. (1999). The use of saline waters for crop production. *FAO Irrigation and Drainage Paper*, 48, 1-133.
11. Robinson, D. A., Jones, S. B., Wraith, J. M., Or, D., & Friedman, S. P. (2008). A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. *Vadose Zone Journal*, 7(2), 586-601.
12. Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., & Richard, G. (2005). Electrical resistivity survey in soil science: A review. *Soil and Tillage Research*, 83(2), 173-193.
13. Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences*, 109(24), 9320-9325.
14. Whalley, W. R., Binley, A., Watts, C. W., Shanahan, P., Dodd, I. C., Ober, E. S., & Ashton, R. W. (2008). The evaluation of soil structure using electrical resistivity. *Soil Science Society of America Journal*, 72(2), 442-450.