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Development of Geophysical Moisture Measurement Methods for Soil Moisture Mapping at Agricultural Field Scale within the Framework of Digital Irrigation

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ABSTRACT

This bibliographic analysis provides a comprehensive overview of contemporary non-invasive technologies for soil mapping, with a particular focus on their implications for agricultural management, agroecology, and food security. We explored the advantages and limitations of remote and proximal sensing methods for soil moisture assessment. Recent advancements in geophysical moisture measurement techniques, such as electromagnetic induction and ground-penetrating radar, are examined in light of their effectiveness for soil moisture mapping at agricultural field scales. The critical need for reliable technologies to accurately map soil moisture content is emphasized, as precise moisture assessment is vital for optimizing agricultural practices and enhancing crop yields. This research is especially pertinent in the context of climate change, where the frequency and severity of droughts are increasing, necessitating improved water resource management strategies. By facilitating targeted irrigation practices and enabling the cultivation of higher yields with reduced inputs, these innovative technologies play a pivotal role in promoting sustainable land management and bolstering agroecological resilience. Furthermore, this study highlights recent findings from key reviews in the field, which provide insights into the integration of digital technologies in precision agriculture. Ultimately, this analysis underscores the essential role of advanced soil mapping methods in addressing challenges related to resource allocation and food production, thereby reinforcing global food security.

Keywords: Soil cover, Soil moisture measurement, Mapping, Digital irrigated agriculture

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INTRODUCTION

Trends driven by an increasing global population observed and projected climate changes (Seneviratne et al., 2010), and the digital transformation of established production, technologies-particularly in agriculture (Rodriguez-Alvarez et al., 2009; Vereecken et al., 2014; Zeyliger & Ermolaeva, 2016; Scholz et al., 2018) have significantly heightened the demand for accuracy and reliability in information regarding the soil moisture content (Mujumdar, 2006; Bláhová et al., 2024).

One critical area of study where the spatial distribution patterns and temporal dynamics dominate the physical and biological phenomenons occurring in the Earth's subsurface is soil hydrology, also known as Hydropedology (Lin et al., 2006). This field is underpinned by the theory of hierarchical multi-level systems (Mesarovich et al., 1970), which serves as a framework for integrating several fundamental scientific disciplines: landscape science (Dyakonov, 1991; Puzachenko et al., 2002), soil science (Kozlovsky & Goryachkin, 1996; Karpachevsky, 1997; Kozlovsky, 2003), soil physics (Globus, 1969; Michurin, 1975; Voronin, 1986), and land hydrology (Velikanov, 1964; Antipov & Korytny, 1985; Kuchment et al., 1989). This interdisciplinary approach aims to investigate the water regime of soil cover with a focus on precision crop management and agroecology.

To achieve this aim, methods for studying hierarchical systems are employed. Those specifically linking measurement results and modeling with the spatial scale of geophysical surveys, as well as with the characteristics of relief, soil and vegetation cover of the underlying layer

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(Allen et al., 2009). In this actively developing interdisciplinary scientific direction, characteristics of moisture content (the product of soil moisture content and its volume) are examined from the perspective of the relevance of measurements conducted using geophysical methods with varying resolutions, ranging from several centimeters (Stagnitti et al., 1999) to several kilometers or more, and characteristic temporal ranges from seconds to years (Nielson et al., 2021; Robinson et al., 2008).

Information about soil moisture content addresses numerous theoretical and practical challenges. It is essential for enhancing our understanding of mass transfer processes within the porous structure of the soil-ground layer (Vereecken et al., 2008), as well as related heat exchange processes growth, and development of plants within a complex that links the soil-ground layer with vegetation cover and the atmospheric boundary layer (Topp, 2003; Robinson et al., 2008; Bogena et al., 2015; Rudolph et al., 2015).

The practical implications of utilizing data on soil moisture content extend to optimizing existing agricultural practices and developing innovative technologies rooted in the principles of digital agriculture (Adams & Cook, 1997; Ammar et al., 2024; Blackmore et al., 2006; Bramley, 2009). This research aims to enhance food security while promoting sustainable agricultural management by focusing on precision farming techniques and agroecological practices. Ultimately, the objective is to provide actionable insights that empower farmers to make informed decisions based on precise soil moisture data, thereby ensuring effective resource management and contributing to global food security in the face of climate crisis.

Electromagnetic Soil Moisture Measurement

Electromagnetic soil moisture (SM) measurement methods are widely used to assess moisture content in different porous materials, including soils. These methods are classified as geophysical techniques for studying porous media of natural or anthropogenic origin. Other established methods for indirectly estimating SM include neutron moisture measurement, tensiometry, and conductometry which are primarily utilized in scientific research (Globus, 1987; Shock et al., 2016).

The physical principle for SM measurement relies on the significant differences in dielectric properties between the pore solution and the organic-mineral framework of the porous medium. The advantages of SM measurement methods include a) rapid and continuous measurements, b) adaptability to long-term monitoring conditions, and c) automation of measurements and data transmission. These benefits facilitate the development of novel devices and monitoring networks or adapt existing instrumentation to meet the specific requirements of research and agricultural projects (Kremer, 2002; Kaatze, 2010; Kaatze, 2012). The following are types of electromagnetic soil moisture measurement methods.

Invasive Methods of Electromagnetic Soil Moisture Measurement

In most cases, invasive methods are employed to profile SM. These methods rely on sensors placed within the soil medium that measure either capacitive characteristics or the speed of reflected electromagnetic impulses, such as Time Domain Reflectometry (TDR) (Topp et al., 1984; Topp et al., 1996; Topp et al., 2003; Zatinatskii et al., 2007; Cataldo et al., 2009; Doo et al., 2009; Scheuermann et al., 2010; Skierucha et al., 2012; Zhu et al., 2012; He et al., 2021). The results from these measurements (Fig. 1) provide SM values in relatively small sampling volumes, typically ranging from several centimeters to several decimeters in all three spatial dimensions. Moving these sensors along the soil profile or establishing a network of vertically arranged sensors (referred to as SM profiling) makes it possible to obtain detailed SM values for individual layers (Ermolaeva & Zeiliguer, 2010).

When operated correctly, stationary invasive profilers can yield reliable layered data on SM with high frequency over extended periods and under varying weather conditions. However, there are notable disadvantages associated with using SM profilers for area monitoring, including a) spatial resolution dependence on the density of profiler installation and b) uncertainties arising during spatial extrapolation/interpolation of measurement results, particularly when installations are sparse.

Non-Invasive Electromagnetic Methods for Soil Moisture Measurement

In parallel with invasive geophysical techniques, non-invasive methods for measuring SM are being actively developed, focusing on assessing low-amplitude electromagnetic field characteristics. Prominent examples of these methods include Ground Penetrating Radar (GPR) (Fig. 2a) systems (Ulaby et al., 1996; Inman et al., 2002; Huisman et al., 2003; Annan, 2005; Jonard et al., 2011) and Electromagnetic Induction (EMI) systems (Huisman et al., 2003; Klotzsche et al., 2018; Zeiliger & Tuluzakov, 2013).

GPR systems, which utilize active probing, and EMI devices (Fig. 2a) both fall under the category of instruments employing non-invasive electromagnetic methods. These tools allow for collecting soil moisture data with relatively high spatial resolution, suitable for measurement depths comparable to the root zones of most agricultural crops. A modified version of the EMI method enables layered moisture content measurements (Zeiliger & Tuluzakov, 2013).

However, the results obtained from GPR surveys can be sensitive to the characteristics of underlying layers (Das et al., 2011). A set of empirical models has been developed (D'Urso & Mario, 2006), which necessitates calibration in the studied area. A similar limitation applies to EMI systems, where pore solutions' chemical composition and concentration highly influence readings. The characteristic sizes of volumes measured using GPR and EMI techniques can range from several decimeters to several meters horizontally and vertically (Annan, 2005). These characteristics classify GPR and EMI methods as non-invasive profiling techniques for assessing SM based on electromagnetic measurements.

The movement of measuring devices for non-invasive profiling of SM on mobile platforms allows for varied

Fig. 1: FieldScout TDR 350 Soil Moisture Meter (a) and Portable soil sampler Drill & Drop by Sentek (b) devices

Fig. 2: Ground Penetrating Radar (GPR) – OKO-150 (a) and Ground Conductivity Meters EM38MK-2 from Geonix (b).

movement trajectories to achieve comprehensive coverage of the monitoring area with the required data resolution. Consequently, data measurement arrays can be obtained for relatively large areas, and survey routes can be flexibly adjusted based on soil and vegetation characteristics. Moreover, integrating parallel driving systems on self-propelled devices facilitates automation through Global Navigation Satellite System (GNSS) technology, making such surveys independent of time constraints.

Despite their advantages, non-invasive SM profiling methods have several drawbacks: a) relatively high cost, b) dependence on weather conditions, and c) lower resolution than invasive moisture profiling. To enhance the resolution of non-invasive profiling methods along the soil profile, ongoing research explores their combined use with other techniques, such as passive microwave radiometry (Jonard et al., 2011), non-invasive electromagnetic induction (Inman et al., 2002) and invasive profilometry (Zeiliger & Tuluzakov, 2013). Recent advancements in machine learning are also being integrated to improve the accuracy and efficiency of SM estimation.

In this context, the characteristic sizes of sampling zones in the horizontal direction can vary from several meters to several kilometers in a stationary state. This extensive range is primarily influenced by the altitude of the recording platform, where the receiving antenna is situated above the ground surface. Additionally, a critical dimension in measurements using synthetic aperture radar (SAR) is the depth from the surface, which typically ranges from several centimeters and is largely dependent on the granulometric properties of the upper soil layer (Franceschelli et al., 2020).

The characteristic sizes associated with sampling zones in SAR methods position them as a subcategory of non-invasive single-layer techniques. The deployment of advanced measuring equipment on space platforms facilitates the acquisition of nearly seamless coverage of SM content in the upper layer, regardless of weather conditions. This capability allows for high temporal repeatability at lower resolutions or medium repeatability with relatively high spatial resolution.

Another method within this subcategory of non-invasive geophysical single-layer SM measurement techniques is the active measurement approach utilizing signals from Global Navigation Satellite Systems (GNSS), such as GPS and GLONASS (Katzberg et al., 2006; Larson et al., 2008; Larson et al., 2008; Cataldo et al., 2009; Rodriguez-Alvarez et al., 2009; Larson et al., 2010; Rodriguez-Alvarez et al., 2011; Muzalevskiy & Mironov, 2012; Larson & Small, 2013; Chew et al., 2014; Shulga et al., 2016; Muzalevsky & Mikhailov, 2018; Muzalevskiy & Zeyliger, 2021; Zeyliger et al., 2021a). This GNSS moisture measurement technique is grounded in the correlation between the amplitude and phase of descending and reflected signals from GNSS systems and the moisture content of the upper soil layer (Inman et al., 2002; Larson et al., 2010; Overeem et al., 2011; Bogena et al., 2015; Feng & Astin, 2015; Kiseleva et al., 2018; Yang et al., 2024).

While the GNSS moisture measurement method shares certain advantages and disadvantages with previously discussed techniques such as GPR and EMI, it also offers two notable benefits. Firstly, it enables nearly continuous and universal measurements wherever GNSS signals are accessible. Secondly, it allows for the potential deployment of corresponding devices on Unmanned Aerial Vehicles (UAVs), thereby enhancing flexibility and operational efficiency in monitoring soil moisture across diverse landscapes.

Thermal Infrared Soil Moisture Measurement

In recent years, advancements in thermal infrared (TIR) imaging techniques have opened new avenues for assessing SM content in agricultural contexts. These geophysical methods leverage actual evapotranspiration (ETa) from the underlying plant cover layer to evaluate the SM availability in the root zone, which is critical for understanding crop responses to water stress (Feddes, 1987; Dobrachev et al., 1988; Golovanov, 1993; Zeyliger et al., 2019). Researchers can gain insights into their water demand and optimize irrigation practices by analyzing how crops react to varying SM content.

For the joint interpretation of such data, hydrometeorological monitoring data and data from remote sensing (RS) are involved (Bastiaanssen et al., 2005). The subsequent interpretation of this data through agrohydrological models enables a more nuanced understanding of how SM correlates with the evaporation rates of agricultural crops throughout their growing season (Zeiliger et al., 2021b). This allows for a precise evaluation of SM that is readily available for uptake by plant root systems.

One of the key advantages of SM measurement using TIR data is its focus on quantifying available SM to crops rather than merely assessing total SM content within the soil profile. This specificity makes the method particularly relevant for digital agriculture, facilitating real-time decision-making in irrigation management and resource allocation (Zeyliger & Ermolaeva, 2013).

However, this method has notable limitations compared to other noninvasive SM profiling techniques. The spatial resolution provided by current TIR sensors is generally lower, which may affect the granularity of the data collected. Additionally, the effectiveness of these measurements can be significantly influenced by weather conditions, which can hinder consistent data acquisition (Carlson & Petropoulos 2019).

In summary, while SM measurement using TIR data presents a promising approach for enhancing agricultural water management, ongoing improvements in RS technology and methodologies are essential to mitigate its constraints and fully harness its potential in modern farming practices.

Requirements for Root Zone Moisture Data for Practical Implementation of Digital Irrigated Agriculture Technologies

The diversity of soil cover significantly influences the spatial variability of hydrochemical and thermal-physical regimes within soils (Puzachenko et al., 2002; Zatinatskii et al., 2007). This spatial variability in energy and mass transfer processes within soil cover can be observed across various scales, from the micro-level of pore spaces (Voronin, 1986) up to watershed levels (Antipov & Korytny, 1985; Robinson et al., 2008). At the scale of agricultural fields, where natural soil formation factors interact with anthropogenic influences, this variability manifests as distinct growth patterns in cultivated crops, leading to variations in yield (Samsonova et al., 2010; Zhelezova & Samsonova, 2014; Zhelezova et al., 2014).

To address the spatial heterogeneity of soil cover within individual agricultural fields, precision agriculture technologies are being developed and implemented (Yakushev, 2002, 2007; Samsonova et al., 2010; Zeyliger, 2010; Belenkov et al., 2011; Yakushev, 2016; Ammar et al., 2024). These technologies are grounded in research that explores the biophysical and chemical processes occurring in the subsurface layers of the Earth, aiming to establish nature-like anthropogenic systems for efficiently utilizing energy, soil, mineral, and water resources.

A notable characteristic of many processes occurring within the soil cover during the irrigation of crops is the intensification of the water transfer process during the warm season, along with the associated transport process. The dynamics of this intensification are closely related to irrigation technologies and their regional and local applications.

Irrigation of large-scale agricultural plantings is recognized as a highly efficient technology, predicated on the idealized concept of uniform water distribution across the entire non-irrigated area. However, findings from spatial-temporal analyses have informed the development of a concept centered on non-uniform, spatially differentiated irrigation (SDI) within quasi-homogeneous contours in irrigated fields Zeyliger, 2010; Zeiliger et al., 2012). These technologies are grounded in scientific research that explores the biophysical and chemical processes occurring in the subsurface layers, aiming to establish nature-like anthropogenic systems for efficiently utilizing energy, soil, mineral, and water resources.

According to the technological framework established for SDI, each sprinkler's operation mode in the irrigation system is managed by an onboard microprocessor. This microprocessor utilizes a GNSS antenna to monitor the position of sprinklers within the irrigated field. Adherence to the specified norms and intensities outlined in the technological map, generates commands for the drivers responsible for controlling sprinkler operations (Zeyliger, 2010). This system allows for real-time adjustments to irrigation practices based on identified contours.

Ultimately, by adjusting irrigation norms and intensity, this approach reduces the impediments associated with conventional uniform irrigation technology. The benefits include: a) increased crop yields; b) enhanced efficiency in water use by agricultural crops; c) reduced operational cost related to irrigation; d) diminished negative impacts of irrigation on land and water, and ecosystems; and e) prevention of irrigated land’s degradation.

Integrated Use of Electromagnetic Soil Moisture Measurement Methods and Technologies at the Level of Irrigated Agricultural Fields

Technological maps for implementing SDI rely on spatial data concerning SM in the root zone (Sadler et al., 2000; Khose & Mailapalli, 2024). Current research focuses on acquiring this spatial data through geophysical methods, specifically EMI and TIR measurements of soil cover.

The limitations of utilizing equipped stationary wells for SM measurement become apparent during the spatial interpretation of data obtained from these wells. Depending on the distances between sprinklers, the service area for a single irrigation machine can range from 50 to 200m^2. Consequently, establishing a sufficiently dense monitoring network is often necessary to derive reliable SM content values within each service zone based on profile measurements. This requirement entails significant capital and operational expenditures. Furthermore, installing stationary wells within agricultural fields complicates farming operations and may lead to their decommissioning due to damage (Ratshiedana et al., 2023).

The use of portable invasive SM measuring devices currently necessitates considerable time investment and substantial manual labor for implementation across expansive agricultural fields. The application of robotic devices remains limited, primarily due to insufficient research aimed at developing designs for such measuring instruments, which in turn hampers assessments of their reliability and economic viability (Khose & Mailapalli, 2024).

In contrast, non-invasive SM measurement employs devices mounted on mobile terrestrial or aerial platforms. As these devices traverse or hover above the Earth's surface, they capture values related to the electromagnetic field and the corresponding coordinates of measurement points. The localized data sets generated through this process undergo interpretation during subsequent processing with specialized computational tools, resulting in maps that depict layered SM content. A significant advantage of non-invasive EMI methods over invasive techniques is their adaptability, allowing for spatial resolution adjustments that meet the requirements for creating technological maps. However, non-invasive methods also present challenges, including the necessity for local calibration and difficulties associated with maneuvering over crops.

Applying methods based on TIR measuring for assessing SM in underlying layers demands a comprehensive set of ground data, including topography, soil cover, sowing dates, growth phases, meteorological data, and thermal imaging information of the monitored area. Automating these processes is essential to effectively implement data collection, processing, and subsequent integration into a geospatial database using specialized software.

Moreover, integrating machine learning algorithms into this framework can significantly enhance data interpretation and predictive analytics. By leveraging machine learning techniques, researchers can improve the accuracy of SM content predictions and optimize irrigation strategies based on real-time data.

Conclusion

Currently, there are no methodologies capable of generating sufficiently comprehensive datasets for the effective implementation of irrigation of agrocenosis utilizing modern digital technologies. Although significant strides have been made in the digital transformation of agriculture, yet substantial challenges persist in producing adequate datasets for practical applications. Addressing these challenges will necessitate ongoing research and development efforts to enhance data collection technologies and their seamless integration into resource management systems. Creating technological maps for spatially differentiated irrigation requires a holistic approach to soil moisture measurement. By integrating invasive methods, such as soil probes, with non-invasive techniques like electromagnetic sensors, we can accurately assess soil moisture levels across various soil depths. This multifaceted strategy is crucial for comprehensively understanding the spatial variability of soil moisture content within agrocenosis. Enhancing spatial SM data at the scale of agricultural fields through the comprehensive application of electromagnetic SM measurement methods represents an emerging knowledge domain. This area demands interdisciplinary research and field studies incorporating aerospace monitoring and advanced computer modeling techniques.

Furthermore, the incorporation of machine learning algorithms into this framework can significantly augment data interpretation and predictive analytics. This integration streamlines decision-making processes and promotes a more sustainable approach to water resource management in irrigated agriculture.

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