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Unveiling Soil Moisture: Techniques and Insights for Precision Measurement

Srijayee Hazra[1] and Subhadeep Mandal[2*]

[1]Department of Soil Science and Agricultural Chemistry, Uttar Banga Krishi Viswavidyalaya,
Pundibari, Cooch Behar, West Bengal 736165
[2]Carbon GIS Scientist, Equilibrium, Bangalore, Karnataka 560001

Abstract

Soil moisture is a critical factor in agricultural productivity, influencing irrigation, crop health and overall yield. In India, where agriculture is highly dependent on monsoon rainfall, soil moisture variability poses significant challenges, especially during droughts, affecting crop growth and food security. Accurate quantification of soil moisture is essential for effective water management, particularly in regions with fluctuating moisture levels. Both traditional and modern techniques are vital for capturing this variability. Combining these approaches ensures precise moisture estimation, supporting better decision-making for irrigation scheduling, crop stress monitoring and adaptive farming strategies, ultimately enhancing agricultural resilience.

Keywords: Indian agriculture, Precision agriculture, Quantification, Soil moisture

Introduction

Soil moisture, a vital component of the Earth's hydrological cycle, plays a fundamental role in supporting plant growth, regulating water fluxes and maintaining ecosystem balance. Although it constitutes only ~0.05% of the Earth's freshwater resources, soil moisture is indispensable for sustaining soil microorganisms and ensuring overall ecosystem health (Robinson et al. 2019). In agricultural ecosystems, soil moisture intricately governs nutrient availability, directly influencing crop productivity and resilience.

However, growing pressure on water resources poses significant challenges to sustainable agriculture. Population growth and land-use changes have caused the average cropland per person to decline from 0.41 hectares in 1961 to 0.25 hectares by 2015, with projections suggesting a further drop to 0.20 hectares by 2050 (Hens and Quynh, 2016). This trend, coupled with climate variability, particularly droughts, has exacerbated the vulnerability of agricultural systems, as seen in India, where approximately 35 million hectares of crops were damaged by hydro-meteorological events between 2015 and 2021 (Kumar et al. 2022). These issues underscore the increasing fragility of water resources, emphasizing the need for proactive management to ensure sustainable agricultural

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production. Given these challenges, this article explores methods and implications for accurately quantifying soil moisture to address the increasing risks to Indian agriculture and food security.

Background: Relevance to Indian agriculture

Nearly a third of India's land is susceptible to soil moisture deficits, impacting irrigation, crop planning, and agricultural productivity. This variability is crucial for addressing drought challenges, as soil moisture influences crop yields and food security. In 2023, about 32.8% of India's land, experienced negative soil moisture anomalies, indicating vulnerability to drought. Regions like Rajasthan, Maharashtra and Andhra Pradesh, with semi-arid and drought-prone climates, frequently face moisture deficits (Gupta et al. 2024). Conversely, 47.7% of the land had higher-than-average soil moisture, leading to flooding risks. This variability underscores the need for region-specific water management. During the monsoon, areas like Rayalaseema, parts of Tamil Nadu and northern Karnataka saw deficient rainfall, worsening dry conditions, while states like Punjab benefited from positive soil moisture anomalies, supporting robust crop production. Thus, accurately quantifying soil moisture is crucial for addressing the escalating risks to Indian agriculture.

Factors affecting Soil Moisture

Soil moisture quantification is challenging due to the spatiotemporal variability influenced by multiple factors, including climate, topography, soil properties, vegetation and land use (Vereecken et al. 2014). Climate, being the most critical, directly affects moisture through precipitation and evapotranspiration, while temperature and solar radiation indirectly influence moisture dynamics. Solar radiation and temperature regulate heat flux and soil ionic composition, influencing moisture release, redistribution. Topography further complicates the picture by affecting seepage, drainage, and runoff, with steep slopes promoting faster lateral water movement compared to flat terrains. Soil properties, such as texture, organic matter content, and macroporosity, also play significant roles, influencing moisture retention, infiltration, and drainage. Additionally, vegetation and land-use types impact plant processes that affect infiltration, runoff, and evapotranspiration, with more noticeable effects during the growing season. Given the complex and interrelated nature of these factors, relying on a single method for soil moisture quantification is both challenging and insufficient, as each driver exhibits its own spatial and temporal variations. By integrating various methods, a more comprehensive and accurate understanding of soil moisture can be achieved, capturing variations across different scales and conditions.

Estimation Techniques of Soil Moisture

Traditional Soil Moisture Estimation Techniques

To address this variability and enhance the accuracy of soil moisture estimates, various techniques have been used to estimate soil moisture, broadly classified into (i) Direct Methods, which provide a direct measure of soil water content by manually assessing the soil's relative wetness through weight differences, and (ii) Indirect Methods, which estimate soil water content by evaluating the response of soil properties to different variables under field or laboratory conditions. Both classical methods (e.g., gravimetric method) and modern techniques (e.g., tensiometers, neutron scattering, time domain reflectometry (TDR), capacitance sensors, machine learning/artificial intelligence, remote sensing) are commonly applied in field and laboratory settings. These methods, summarized in Table 1, highlight their principle and applications.

Advanced Soil Moisture Estimation Techniques

Modern techniques include satellite-derived soil moisture data (SMOS, SMAP, MODIS, Sentinel 1 etc.) and soil simulation software such as RETC and HYDRUS-1D. Satellite-derived data allows for real-time, large-scale soil moisture monitoring; for example, MODIS-based indices integrate soil moisture and vegetation health indicators to enhance the accuracy of drought assessments, particularly in regions like Odisha (Satapathy et al. 2021). HYDRUS-1D simulates one-dimensional water flow and solute transport in unsaturated soils, offering insights into irrigation needs and crop stress at a localized level (van Genuchten, 1980). These modern techniques allow for the precise monitoring of crop stress and soil moisture across large areas, which is difficult with traditional methods that rely on manual measurements or small-scale observations. Combining remote sensing data, with soil simulation tools like RETC for analyzing soil-water characteristic curves, enhances the ability to predict water availability, evapotranspiration and crop stress in real time.

Table 1. Overview of traditional soil moisture measurement techniques

Methods	Principle	Depth (cm)	Advantage	Limitation	Measurement*
Gravimetric technique	Measure weight difference between moist and dry soil samples.	Any depth	High accuracy, direct measurement	Labor-intensive, small spatial coverage	GMC
Neutron scattering probe	Measures hydrogen content in soil by emitting neutrons and detecting scattered radiation.	< 30	Quick, non-destructive	Sensitive to soil type, requires calibration	VMC

TDR (Time Domain Reflectometry)	Measures soil moisture by analysing the time it takes for an electromagnetic pulse to travel through the soil.	30-60	High precision, real-time measurement	Expensive, requires calibration	VMC
Capacitance sensor	Measures soil moisture by detecting changes in the dielectric constant of the soil.	20-50	Real-time, easy to use	Sensitive to soil texture, requires calibration	VMC
Gypsum resistance block	Measures the resistance of a block of gypsum to the flow of current, which is influenced by soil moisture.	10-30	Simple, inexpensive	Sensitive to soil salinity and temperature changes	MP
Tensiometer	Measures the tension of water in the soil, indicating soil moisture.	15-60	Reliable for low-moisture conditions	Requires maintenance, not suitable for dry soils	MP
Pressure membrane apparatus	Uses air pressure to extract water from a soil sample and measure the moisture content.	0-100	Accurate, wide depth range	Time-consuming, requires sample preparation	MP
Tension table	Similar to pressure membrane but uses a suction table to measure soil water retention at different tensions.	0-30	Accurate for field conditions	Labour-intensive, limited to small soil samples	MP

*Abbreviation: GMC = Gravimetric Moisture Content; VMC = Volumetric Moisture Content; MP = Matric Potential

Conclusion

Soil moisture monitoring is critical for Indian agriculture, where water management is challenged by diverse climates, soils and irrigation practices. As agricultural demands increase and irrigation infrastructure expands, precision techniques like real-time monitoring and variable rate irrigation (VRI) are key to optimizing water use and improving crop yields. Integrating satellite data, soil simulation and sensors provides a comprehensive view of soil moisture. However, accuracy issues persist due to environmental and soil variations, requiring ongoing research to refine methods. In India, where agriculture relies on monsoons and faces water scarcity, precise soil moisture estimation is essential for efficient water use, reducing crop stress and ensuring food security and sustainability. Thus, combining advanced technologies with traditional practices can help to build resilient agricultural systems in the face of the climate change.

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