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Soil moisture bibliometrics in Brazil: Estimations using remote sensing

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R E S U M O

Soil moisture plays a critical role in the hydrological cycle, ecosystem productivity, and climate regulation. This study presents a bibliometric analysis of soil moisture estimation using remote sensing in Brazil, based on 99 scientific articles published between 1995 and 2024. The analysis reveals increasing scientific production, particularly after 2010, and highlights recurring themes such as MODIS, SMAP, energy balance, and agricultural drought. Although research has advanced in recent years, it remains uneven across Brazil's biomes and limited in the application of advanced tools such as machine learning. The findings suggest that remote sensing has become a strategic tool for monitoring soil moisture, with growing importance for climate change adaptation and water resource management. By identifying knowledge gaps and thematic trends, this work contributes to a more integrated and regionally relevant research agenda, supporting sustainable land and water use across South America.

Key-words: Research trends, Scientific mapping, GIS, Climate change, Water resources.

Bibliometria da umidade do solo no Brasil: Estimativas usando sensoriamento remoto

RESUMO

A umidade do solo desempenha um papel fundamental no ciclo hidrológico, na produtividade do ecossistema e na regulação do clima. Este estudo apresenta uma análise bibliométrica da estimativa da umidade do solo usando sensoriamento remoto no Brasil, com base em 99 artigos científicos publicados entre 1995 e 2024. A análise revela o aumento da produção científica, principalmente após 2010, e destaca temas recorrentes como MODIS, SMAP, balanço de energia e seca agrícola. Embora a pesquisa tenha avançado nos últimos anos, ela continua desigual nos biomas do Brasil e limitada na aplicação de ferramentas avançadas, como o aprendizado de máquina. Os resultados sugerem que o sensoriamento remoto se tornou uma ferramenta estratégica para o monitoramento da umidade do solo, com importância crescente para a adaptação às mudanças climáticas e a gestão de recursos hídricos. Ao identificar lacunas de conhecimento e tendências temáticas, este trabalho contribui para uma agenda de pesquisa mais integrada e regionalmente relevante, apoiando o uso sustentável da terra e da água em toda a América do Sul.

Palavras-chave: Tendencias de pesquisa, Mapeamento científico, SIG, Mudanças climáticas, Recursos hídricos.

Introduction

Soil moisture is a fundamental component of the Earth system, exerting a direct influence on the hydrological cycle, surface energy balance, biogeochemical processes, and primary productivity (McColl et al., 2017; Seneviratne et al., 2010; Srivastava, 2017). By regulating key processes such as infiltration, evapotranspiration, surface runoff, and groundwater recharge, soil moisture plays a central role in ecosystem functioning, food security, and water resource management (Soylu & Bras, 2021; Wang et al., 2019). As an integrative variable at the interface between the land surface and the atmosphere, soil moisture links hydrological, climatic, and ecological dynamics across multiple spatial and temporal scales.

Beyond its hydrological relevance, soil moisture acts as a key state variable controlling land–atmosphere interactions by regulating exchanges of water, energy, and carbon across the soil–plant–atmosphere continuum. Variability in soil moisture governs surface energy partitioning through the modulation of sensible and latent heat fluxes, directly influencing land surface temperature and the development of heat extremes (Rahmati et al., 2024). As a fundamental reservoir for terrestrial water, soil moisture establishes the boundary conditions for water movement and energy fluxes between the land surface and the atmosphere (Legates et al., 2011). In addition to its role in water and energy exchanges, soil moisture variability exerts a dominant control on terrestrial carbon dynamics, accounting for up to 90% of the interannual variability in global land carbon uptake through its regulation of plant productivity and ecosystem respiration (Humphrey et al., 2021).

These coupled processes directly affect boundary-layer development, precipitation–evapotranspiration feedbacks, and atmospheric circulation patterns, particularly in regions characterized by strong climatic seasonality. Soil moisture influences cloud formation and precipitation by controlling evapotranspiration rates and the availability of atmospheric water vapor, thereby shaping local and regional circulation regimes (Rahmati et al., 2024). Evapotranspiration alone can contribute between 10% and 30% of the atmospheric moisture over continental regions, reinforcing the role of soil moisture as a key driver of land–atmosphere feedbacks and climate variability (Legates et al., 2011). Consequently, changes in soil moisture conditions can either amplify or dampen climate extremes, highlighting its central importance in climate system analyses and land–atmosphere coupling studies (Seneviratne et al., 2006; Seneviratne & Koster, 2012).

From a watershed perspective, soil moisture determines infiltration capacity, runoff generation mechanisms, and groundwater recharge, serving as a primary control on hydrological responses to rainfall events. Antecedent soil moisture conditions dictate whether runoff generation occurs through infiltration-excess (Hortonian) or saturation-excess processes, directly influencing flood magnitude, peak discharge, and runoff timing at the catchment scale (Legates et al., 2011). By regulating infiltration, vertical redistribution, and subsurface flow pathways, soil moisture also plays a critical role in aquifer recharge and streamflow sustainment during dry periods (Rahmati et al., 2024). Prolonged soil moisture deficits, in turn, contribute to the onset, severity, and persistence of hydrological droughts, linking short-term soil processes to long-term water availability (Robock, 2003).

In agricultural systems, soil moisture regulates crop water availability, root development, nutrient uptake, and yield stability, particularly under water-limited conditions. Recent bibliometric analyses identify crop yield and water use efficiency as major research hotspots, underscoring the direct relationship between soil moisture dynamics, food security, and sustainable agricultural production (Cai et al., 2023). By controlling plant physiological processes and rooting depth, soil moisture serves as a critical indicator for agricultural drought monitoring and irrigation management, especially in semi-arid and seasonally dry regions (Rahmati et al., 2024). For these reasons, soil moisture is widely recognized as an essential variable for drought monitoring, watershed management, agricultural planning, and climate resilience assessments across multiple spatial and temporal scales.

Soil moisture is also closely linked to the occurrence, intensity, and predictability of extreme events such as droughts, floods, and landslides, particularly in tropical and subtropical regions that exhibit pronounced spatial and temporal variability (Aditama et al., 2023; Whiteley et al., 2019). In agricultural contexts, continuous soil moisture monitoring is essential for mitigating productivity losses caused by both water stress and excess moisture. However, in situ soil moisture measurements remain spatially sparse, temporally discontinuous, and strongly influenced by soil heterogeneity and local-scale variability. These limitations are further exacerbated by the low density and uneven distribution of monitoring networks, especially in large and environmentally diverse countries (Colliander et al., 2017; Sekertekin et al., 2020a).

Brazil represents a particularly challenging context for soil moisture monitoring due to its continental dimensions and pronounced climatic, pedological, and ecological heterogeneity. The country encompasses a wide range of climatic regimes, from humid equatorial conditions in the Amazon to semi-arid environments in the Northeast, in addition to extensive tropical savannas, wetlands, grasslands, and highly fragmented forest systems. This environmental diversity is accompanied by marked variability in soil types, land-use systems, vegetation structure, and hydrological functioning across Brazilian biomes, which strongly influences soil moisture dynamics (De Castro et al., 2016; de Queiroz et al., 2020; de Sousa et al., 2022). As a consequence, point-scale soil moisture observations often fail to adequately represent spatial patterns and regional dynamics, limiting their applicability for national-scale analyses and large-area hydrological assessments (Dari et al., 2019; Robinson et al., 2008; Vergopolan et al., 2022; Yu et al., 2024).

In this context, remote sensing has emerged as a strategic and indispensable tool for soil moisture assessment in Brazil. Satellite-based observations provide spatially continuous, repetitive, and temporally consistent measurements, enabling soil moisture monitoring across large and environmentally heterogeneous regions where dense ground-based networks are not feasible (Al-Yaari et al., 2019; Babaeian et al., 2019; Ma et al., 2019). Remote sensing approaches allow soil moisture information to be integrated into a wide range of applications, including drought monitoring, agricultural management, hydrological modeling, disaster risk reduction, and climate change adaptation, effectively overcoming the spatial limitations inherent to in situ observations (Babaeian et al., 2019; Kumar et al., 2025; Xu et al., 2020).

Passive microwave missions, such as the Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) satellites, estimate soil moisture based on the sensitivity of microwave brightness temperatures to soil dielectric properties. These missions have generated unprecedented global soil moisture datasets with relatively high temporal resolution, proving particularly valuable for climate studies, large-scale hydrological modeling, and drought monitoring (Entekhabi et al., 2010; Colliander et al., 2017). Nevertheless, their relatively coarse spatial resolution and sensitivity to vegetation cover and surface roughness limit their performance in heterogeneous landscapes and complex land-use mosaics, such as those commonly found in Brazil (Al-Yaari et al., 2019; Peng et al., 2021).

Active microwave systems, particularly Synthetic Aperture Radar (SAR) sensors, offer higher spatial resolution and enhanced sensitivity to surface conditions. Variations in SAR backscatter are strongly controlled by changes in soil dielectric properties, making these sensors suitable for detailed spatial analyses at field to watershed scales (Bhogapurapu et al., 2022; Shen et al., 2023. In Brazil, SAR-based approaches have been applied in agricultural areas, floodplains, wetlands, and forested regions, demonstrating their potential for spatially explicit soil moisture mapping (Duarte et al., 2024). However, signal saturation under dense vegetation, complex surface scattering mechanisms, and the interaction between soil moisture and vegetation structure continue to pose significant methodological challenges, particularly in tropical forest and savanna environments (Ningthoujam et al., 2017; Shi et al., 2025).

Optical and thermal remote sensing techniques provide indirect estimates of soil moisture through vegetation indices, land surface temperature, and surface energy balance models. Sensors such as MODIS and Landsat are widely used to infer soil moisture dynamics via evapotranspiration estimates and vegetation stress indicators, benefiting from relatively high spatial resolution (Bezerra et al., 2022; De Castro Teixeira et al., 2017). However, in tropical regions like Brazil, the effectiveness of these approaches is often constrained by frequent cloud cover and atmospheric interference, which reduce data availability and compromise temporal continuity, limiting their applicability for operational soil moisture monitoring (Seneviratne et al., 2013).

Despite substantial international advances in soil moisture research and the existence of consolidated bibliometric analyses at the global scale (Cai et al., 2023), similar assessments remain scarce in the Brazilian context. This gap hampers the systematic identification of national research trends, dominant methodologies, thematic priorities, and unresolved challenges. Given Brazil's environmental diversity, climatic vulnerability, and strategic importance in global food production and water resources, understanding the evolution and structure of soil moisture research within the country is both scientifically and societally relevant.

Bibliometric analysis provides a robust methodological framework for identifying scientific patterns, emerging themes, and research opportunities through the systematic examination of academic literature (Bornmann & Marx, 2018). When combined with a critical perspective, bibliometrics enables not only the quantification of scientific production but also the interpretation of its theoretical contributions and practical implications.

Within this context, the present study conducts a critical bibliometric analysis of Brazilian scientific production on soil moisture estimation using remote sensing. The objectives are to identify temporal trends, dominant research themes, key applications, and methodological gaps, as well as to examine the spatial distribution of studies across Brazilian biomes. By synthesizing existing knowledge and highlighting research gaps, this study contributes to a better understanding of soil moisture research dynamics in Brazil and supports broader discussions on climate resilience, hydrological modeling, and sustainable development in South America, aligning national priorities with global environmental challenges.

Materials and methods

A bibliometric analysis was conducted based on studies on the use of remote sensing to estimate soil moisture in Brazil. The bibliographic search in the scientific literature was carried out in the SCI-Expanded database of the Web of Science in November 2024. The following query was used to select articles: ALL=("Remote sensing") AND TS=("soil moisture") AND TS=(Brazil) (Figure 1). The option to use ALL in remote sensing was aimed at expanding the search for articles, since many authors may use terms related to remote sensing tools, such as the names of the satellites used, instead of the specific term remote sensing. The use of ALL makes it possible to find records containing the term anywhere in the complete record, including, for example, in the title of the journal. TS (Topic Search) restricts the search to the title, abstract and author keywords, ensuring that the articles selected are directly related to soil moisture and Brazil.

The information extracted from the articles included the year of publication, authors, thematic categories, journal names, number of citations, keywords and countries of origin. This data was obtained using the bibliometrix library in the R software. The impact factor of the journals was obtained from the InCites Journal Citation Reports (JCR) for 2023.

The authors' main keywords and plus words were analyzed using the R bibliometrix library. To ensure consistency in the results, synonyms were unified and compound terms were standardized, such as soil-moisture, which was corrected to soil moisture, before the articles were analyzed.

Results and discussion

Temporal evolution of soil moisture research in Brazil

A total of 99 articles were selected, published between 1995 and 2024 (Figure 2A). The first publication on the subject was in 1995 in the Amazon region on the use of radars to detect flooding in floodplain forests (Wang et al., 1995). Although scientific production has not followed a continuous pattern and has shown variations over the years, there has been an increase in publications since 2010. This pattern follows the trend observed internationally (Cai et al., 2023), but with a lag in relation to countries such as China, the United States and India. A recurring limiting factor in Brazilian literature is the scarcity of in situ data for sensor calibration and validation, which has a direct impact on the robustness of studies.

In the 1990's there were indications that satellite-based synthetic aperture radar (SAR) sensors had the potential to offer an estimate of the soil surface's volumetric moisture content (θs). The SAR backscatter detected by these orbiting sensors is directly linked to the dielectric constant. Thus, an increase in soil moisture content significantly altered the dielectric constant, resulting in a strong sensitivity of the SAR signal to soil moisture. The first studies, carried out between 1995 and 2004, focused on the indirect estimation of soil moisture, using missions such as LANDSAT-TM, JERS-1, ERS-1 or radars in the Amazon rainforest region, southeast and northeast Brazil (Grover et al., 1999; Kux & Máximo, 1998; Sano et al., 1998; Seyler et al., 1998; Soares Galvão & Vitorello, 1998; Y. Wang et al., 1995). One of the first articles published on the subject used radar to detect floods in floodplain forests, based on the change in the dielectric properties of the soil due to the presence of water.

This change directly impacts the way radar waves are reflected and scattered by the surface. The study showed that soil moisture in non-flooded forests influences the ratio between the radar return signal from flooded and non-flooded areas. As soil moisture increases in a non-flooded forest, this ratio decreases, as the dielectric properties of the soil become more similar to those of a flooded soil, making it difficult to distinguish between the two conditions.

In 1982, Landsat 4 began operating, incorporating the TM (Thematic Mapper) sensor, specially designed to help with research into natural resources. The ERS-1 and ERS-2 satellites were subsequently launched on July 17, 1991 and

April 21, 1995, respectively. Both satellites were equipped with a Synthetic Aperture Radar (SAR). In 1992, the JERS-1 satellite was launched by the then National Space Development Agency of Japan (NASDA). The JERS mission represented a significant investment by Japan in global environmental monitoring.

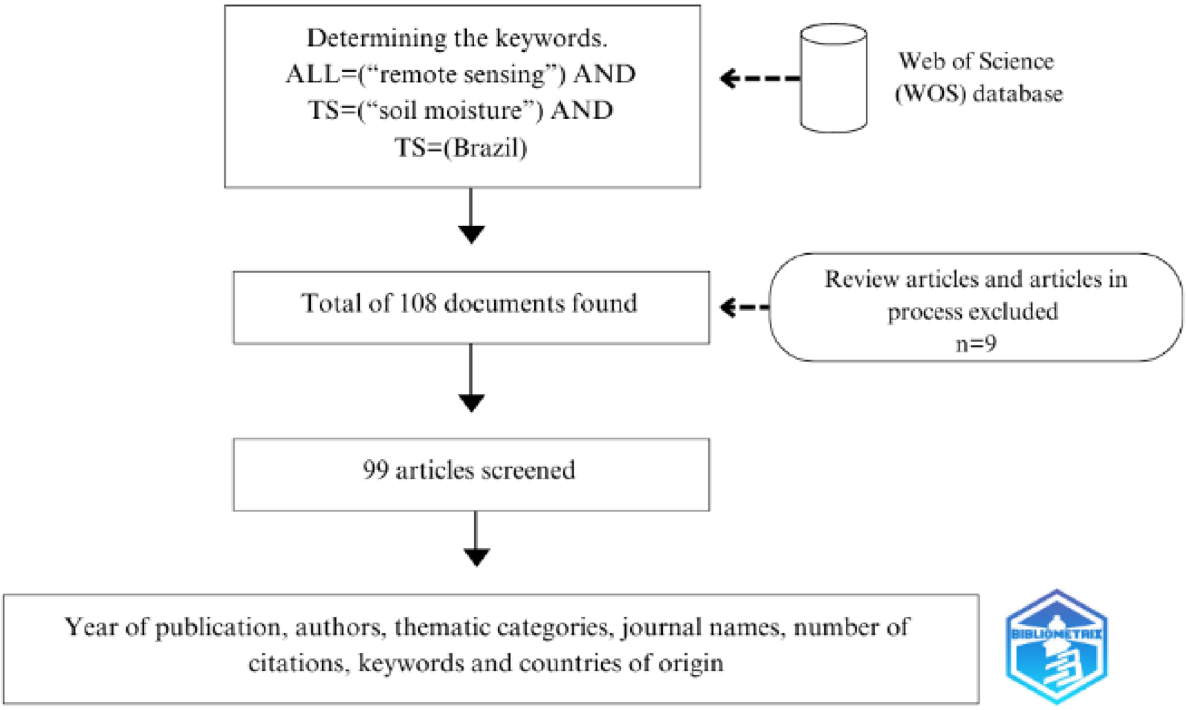

Figure 1 - Step by step of searching articles in the bibliometrics.

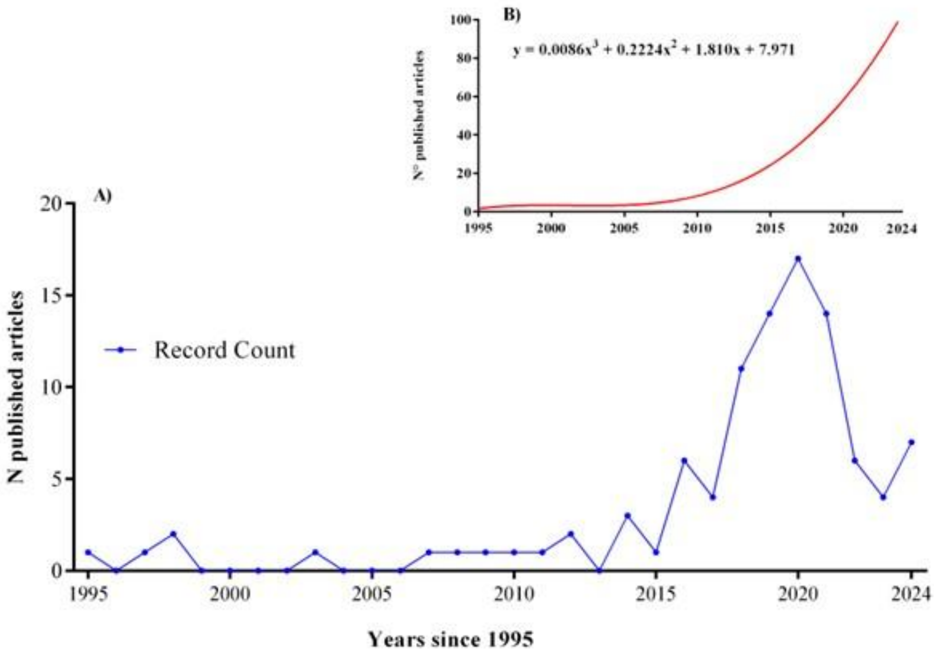

Figure 2 -Publication output performance of soil moisture estimation by remote sensing in Brazil 1995 to 2024. Variables: N = numbers.

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Citation dynamics and scientific impact

Figure 3 illustrates the variations in the citation status of articles published on research into soil moisture estimates in Brazil via remote sensing between 1995 and 2024. The Total Citations per Article (TCP) reflects the relationship between the total number of citations and the number of articles published in a given year, while the Total Citations per Article per Year (TCCP) is obtained by dividing the TCP by the number of years since the publication of each article.

In Figure 3, the TCP shows peaks and valleys, showing that the popularity and impact of soil moisture research can vary significantly from one year to the next. These oscillations can be influenced by various factors, such as relevant scientific discoveries, technological advances or extreme weather events. A notable example occurred between 2015 and 2016, when Brazil faced an extreme drought. During this period, the articles with the highest TCCP and TCP were concentrated on drought-related topics. In addition, TCPP follows the same trend as TCP, reinforcing the idea that the immediate influence of research can fluctuate over time. Both metrics, TCPP and TCCP, show an increase since 2020, suggesting that, despite variations in the immediate impact of research, the average quality of articles and their long-term impact have been growing gradually.

The 99 articles analyzed were published in 22 journals. The four most productive journals accounted for 37% of the total number of publications (Table 1). The journal Remote Sensing stood out as the most productive, with 17 articles published, followed by Remote Sensing of Environment and Remote Sensing Applications-Society and Environment. The journal with the highest number of citations (TC) was Remote Sensing of Environment, followed by Remote Sensing Applications-Society and Environment. In terms of Impact Factor (IF), Remote Sensing of Environment had the highest value (11.1) and Water the lowest (3). In general, the four most productive journals are focused on geoprocessing and remote sensing.

To assess the impact of journals, the metrics TC (Total Citations), IF (Impact Factor) and H-index are often used. The H-index reflects both the productivity and impact of a journal, indicating the highest number H for which there are H articles cited at least H times. For example, if a journal has 10 articles cited at least 10 times, its H-index is 10. Figure 3 shows the 10 journals with the highest H indexes.

The journal *Remote Sensing* has the highest H index (Figure 4), closely followed by *Remote Sensing of Environment*, which has a slightly lower value. Both stand out as the most influential, indicating that their articles are widely cited and have a major impact on the local scientific community. The other journals follow a decreasing order of impact. This prominence of the two main journals reinforces the relevance of remote sensing and its applications in various areas, such as the environment and agriculture. In addition, the high H-index of these publications suggests that local research in this field has high quality and international recognition, and is often used as a reference by other researchers.

The global patterns identified by Cai et al. (2023) provide an important framework for contextualizing Brazil's position within international soil moisture research. Their analysis highlights the consolidation of soil moisture as a key variable in studies related to ecosystem functioning, climate variability, and environmental change, driven by advances in remote sensing, data integration, and modeling approaches. In this global context, the results of the present bibliometric analysis indicate that Brazil has established itself as a relevant contributor to soil moisture research, reflecting the strategic importance of this variable for a country characterized by strong climatic gradients, diverse biomes, and recurrent hydroclimatic extremes.

Table 1 - Top 4 more productive journals (1995-2022). Variables TP=Total publications, TC= Times Cited, IF= Impact factor 2023*

Journal	TP	TC	IF
Remote Sensing	17	518	4.2
Remote Sensing of Environment	11	983	11.1
Remote Sensing Applications-Society and Environment	6	97	3.8
Water	2	56	3.0

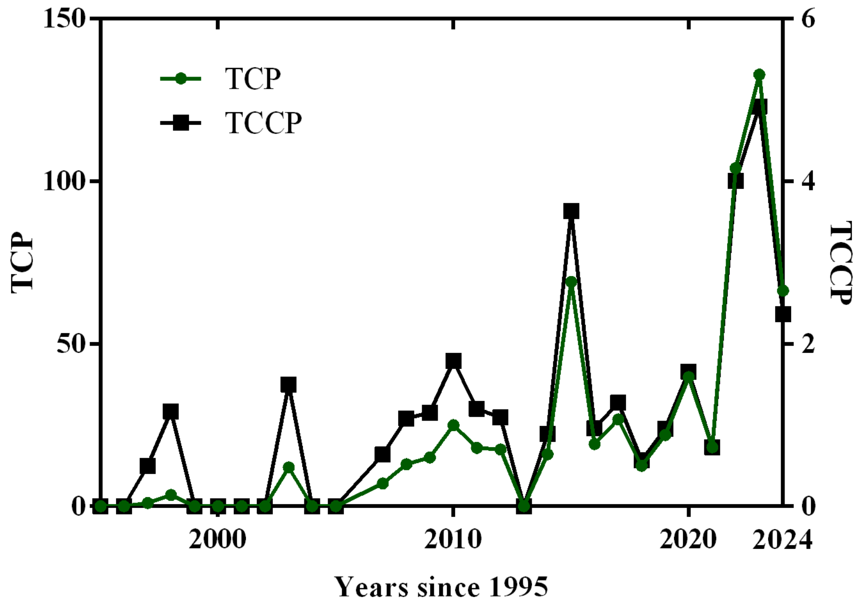

Figure 3 - Average citations per article and changes in TCP and TCPP on soil moisture estimation by remote sensing in Brazil from 1995 to 2024.

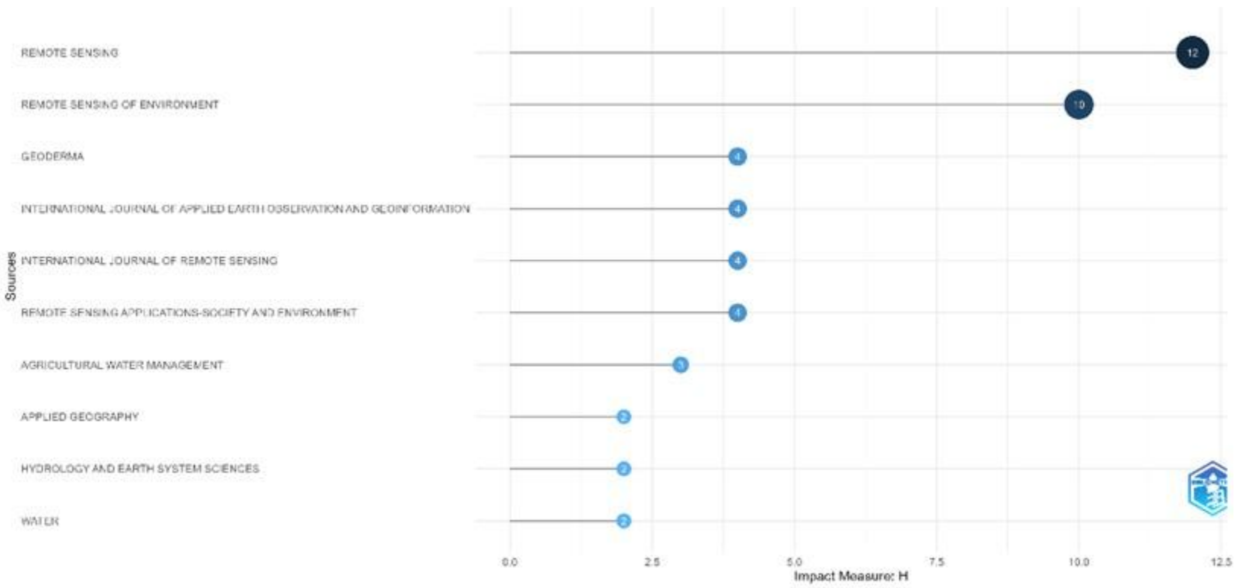

Figure 4 - Sources' Local Impact on soil moisture estimation by remote sensing in Brazil from 1995 to 2024.

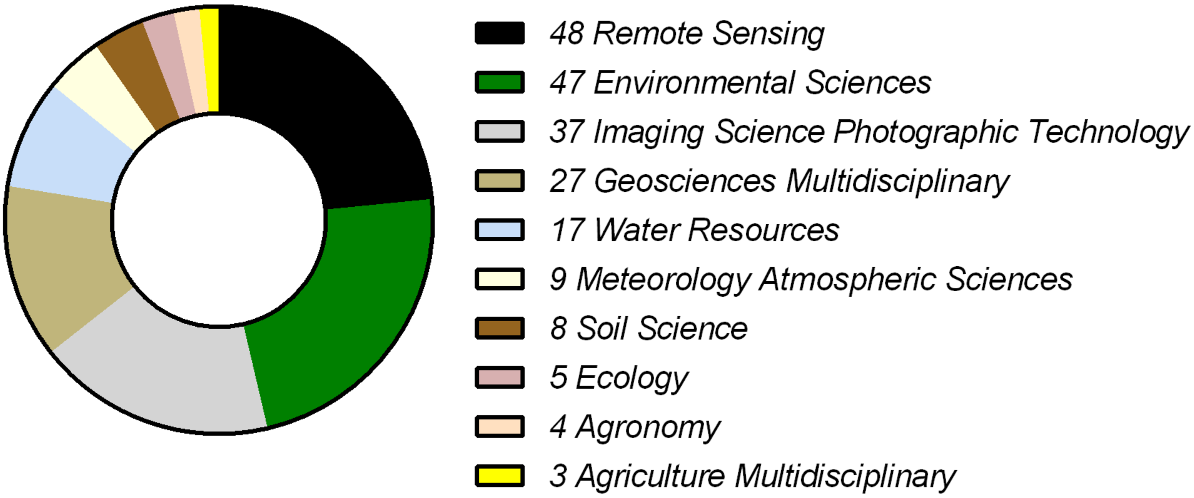

Figure 5- Distribution of top 10 subject categories Web of Science on soil moisture estimation by remote sensing in Brazil from 1995 to 2024.

However, when examined in light of the leadership and collaboration patterns discussed by Cai et al. (2023), the Brazilian research landscape reveals important structural challenges. While the United States is characterized by broad and well-integrated international collaboration networks, and China by rapid scientific expansion supported by strong domestic cooperation, Brazil occupies an intermediate position. Although Brazilian institutions participate in international research networks, collaboration remains uneven and often project-specific, limiting the consolidation of long-term partnerships and the translation of scientific advances into operational soil moisture products. Strengthening international collaboration, improving data infrastructure, and enhancing integration between academic research and operational agencies emerge as key strategies for increasing the global impact and applicability of Brazilian soil moisture research.

The results of the *Web of Science* study categories show that soil moisture estimates are a priority topic discussed by *Remote Sensing*, with 48 records classified in this research area, followed by *Environmental Sciences* (Figure 5). This leadership reflects the growing interest of the scientific community in studying and tackling environmental issues such as climate change, environmental degradation and the sustainable use of natural resources, including soil moisture.

Figure 5 highlights the strong connection between soil moisture research and the Sustainable Development Goals (SDGs), emphasizing the climate change adaptation (SDG 13). In this context, the integration of different scientific disciplines is essential for developing sustainable solutions, directly linking soil moisture management practices to environmental preservation and global sustainability targets.

Monitoring soil moisture is vital for climate forecasting, water management and adapting ecosystems to climate change, as well as improving plant growth, mitigating drought and promoting agricultural sustainability (Babaeian et al., 2019; Bhuvaneswari et al., 2019). In climate forecasting, for example, the incorporation of soil moisture estimates into atmospheric models has improved the accuracy of weather projections, reducing uncertainties. The coupling between soil moisture and precipitation is essential for accurate weather forecasts, especially in regions with complex terrain or under specific climatic conditions (Rodríguez-Fernández et al., 2019) . The Assimilation of soil moisture data from sources such as SMOS and SMAP into models such as ECMWF (European Centre for Medium Range Weather Forecasts) and KIM (Korean Integrated Model) has significantly improved forecasts, especially in areas with little in situ data situ (Kwon et al., 2024; Wehbe et al., 2020; H. Zhang et al., 2020).

In water resource management, soil moisture has been used to estimate groundwater recharge, providing greater precision when integrated with water balance models, evapotranspiration and soil characteristics. The use of inverse modeling, combined with pedotransfer data, helps to reduce uncertainties and improve the representation of water infiltration and storage processes in the subsoil (Mathias et al., 2017; T. Wang et al., 2016).

For agriculture, the incorporation of remote sensing products into crop growth model improves the estimation of soil moisture, allowing for more accurate monitoring of agricultural drought (Zhou et al., 2022). As soil moisture is an essential factor for agricultural production, its reduction during periods of drought is directly associated with a drop in crop yields (Modanesi et al., 2020).

Spatial distribution of soil moisture studies in Brazil

The spatial distribution of the 99 analyzed articles reveals a strong regional concentration of soil moisture–related studies in Brazil (Figure 6). The Caatinga and the Brazilian semiarid region account for the largest share of publications, with 22 articles, followed by the Cerrado (17 articles) and the Atlantic Forest (15 articles). The Amazon biome is represented by 11 articles, while southern Brazil, including the Pampa, comprises 9 articles, and the Pantanal is addressed in only 4 articles. In addition, 21 studies were conducted at national, multi biome, or global scales, treating Brazil as an integrated unit or comparing multiple biomes. This spatial pattern highlights an uneven distribution of scientific production, closely associated with regions where soil moisture exerts stronger control over key environmental processes.

In semi-arid environments, particularly in the Caatinga, the high concentration of studies is directly linked to the role of soil moisture as the primary limiting factor for vegetation productivity, water security, and the occurrence of agricultural droughts. Research in this region predominantly focuses on the validation of remote sensing products (SMOS and SMAP), the monitoring of spatiotemporal soil moisture variability, and evapotranspiration estimation, especially across northeastern Brazil. In the Cerrado, soil moisture is frequently associated with carbon stock dynamics, pasture degradation, and fire susceptibility, serving as a key variable in land-use management analyses and CO_2 emission assessments. In the Atlantic Forest, studies emphasize the importance of antecedent soil moisture in triggering landslides, intensifying extreme events in urbanized areas, and regulating the water balance in intensive agricultural systems.

In the Amazon biome, the identified studies reinforce the role of soil moisture in controlling water, energy, and carbon exchanges, as well as the dynamics of seasonally flooded areas, which are often investigated using radar-based sensors. In contrast, the Pantanal and the Pampa remain clearly underrepresented despite their high hydrological sensitivity. While the presence of national- or multi biome-scale studies reflects recognition of soil moisture as an integrative variable across different climatic and ecological domains, it also underscores the lack of localized investigations within specific biomes. Thus, the spatial distribution map not only highlights the central role of soil moisture in the analyzed environmental processes but also reveals important geographical research gaps that should be addressed by future studies.

Beyond spatial patterns, the literature reveals a clear thematic orientation, with soil moisture research strongly linked to drought monitoring, agricultural productivity, vegetation dynamics, and water resource management. In Brazil, challenges such as high rainfall variability and recurrent prolonged droughts impose significant constraints on water management (Marengo & Bernasconi, 2015), making the optimization of water use in agriculture essential to ensure productivity and reduce socio-economic impacts. Studies applying indices such as the Soil Moisture Agricultural Drought Index (SMADI) in Pernambuco have demonstrated significant correlations between drought severity and crop productivity for crops such as maize and sorghum (Souza et al., 2021). Complementarily, the Soil Moisture Index (SMI) has been used to assess short-term agricultural risk, reinforcing the role of soil moisture as an early indicator of water stress (Zeri et al., 2018).

Analyses of soil moisture variability across Brazilian biomes indicate contrasting trends. The Caatinga, for instance, exhibited the most severe decline in soil moisture between 2009 and 2015, whereas the Pampa and Pantanal biomes showed positive trends over the same period (Ribeiro et al., 2021). These findings are critical for informing soil conservation strategies and climate adaptation planning. In the Brazilian semiarid region, agricultural productivity has been shown to correlate more strongly with rainfall than with surface soil moisture, indicating that practices aimed at increasing water retention within the root zone are fundamental for mitigating drought impacts (Rossato et al., 2017). In this context, the use of SMOS satellite data has improved crop yield estimates under dry conditions (White et al., 2020).

The relationship between soil moisture and vegetation dynamics is widely explored through spectral indices such as NDVI, EVI, and VHI. Areas with higher soil moisture availability tend to exhibit healthier vegetation and higher index values, whereas drought conditions lead to significant reductions. The EVI, in particular, incorporates the blue band to correct for atmospheric effects, making it more robust than NDVI in densely vegetated areas and avoiding saturation under humid conditions (Risso et al., 2009; Leivas et al., 2022). In the Amazonas state, the Vegetation Health Index (VHI) showed marked declines between 2001 and 2018 during drought periods, indicating moderate to extreme drought conditions driven by soil moisture deficits and elevated air temperatures (Vilanova et al., 2020). Similarly, in the Central Atlantic Forest Corridor, EVI exhibited a negative trend associated with declining soil moisture, accompanied by increased fire occurrence in agricultural areas during extreme climate events (de Santana et al., 2020).

Hot topics and frontiers

Figure 7 shows a strategic map that organizes the themes of our research into four quadrants, based on centrality and density, providing information on the critical points of the research. This map was drawn up using the 200 keywords most used by the authors. Centrality indicates the degree to which a topic is connected to other clusters, while density measures the level of cohesion within the cluster, assessing how closely related the keywords are.

Each circle in the diagram represents a topic, identified by the most frequent keyword, with the size of the circle increasing as the frequency of that keyword increases. The first quadrant (top right) shows a driving theme, well-developed and crucial to the field of research. The second quadrant (top left) contains a niche theme, characterized by being highly specialized, with a restricted number of researchers. The third quadrant (bottom left) identifies an emerging theme, which is either on the rise or in decline. Finally, the fourth quadrant (bottom right) represents fundamental topics, with high centrality and low density.

Our research offers an integrated view of the complex thematic network involving remote sensing, soil moisture and its impacts on natural and socio-economic systems. Figure 7 highlights a dynamic scenario, with consolidated and emerging themes connected by the common goal of tackling contemporary environmental challenges. The prevalence of themes related to remote sensing, such as MODIS, Sentinel-2 and Google Earth Engine, reflects the importance of these technologies for monitoring crucial variables, especially soil moisture. This parameter is vital in several areas, from precision agriculture to water management. The prominence of soil moisture, evidenced in topics such as evapotranspiration, energy balance and drought, reaffirms its relevance to understanding hydrological and ecological processes that affect productivity, vegetation and extreme events. The growing incorporation of machine learning and digital soil mapping points to the use of advanced tools for processing large volumes of data to support decisions

Most studies on soil moisture use remote sensing, as in situ assessments are limited to specific points and do not capture regional heterogeneity (Colliander et al., 2017; Sekertekin et al., 2020). Despite the limitations of in situ sensors, such as calibration and dependence on soil and climate, remote sensing overcomes these barriers, offering comprehensive and accurate monitoring (Negrón-Juárez et al., 2020; Pereira et al., 2022).

Remote sensing is one of the main driving themes of our research (Figure 7) and is an essential tool that uses satellite images to obtain detailed information about the earth's surface. Its various applications include estimating crop yields, using vegetation indices, detecting water stress, assessing soil moisture, monitoring natural disasters and other important parameters for agriculture and the environment. In the context of Brazil, remote sensing becomes even more relevant due to the country's vast territorial extension and great environmental diversity. In addition, the ability to predict future events, such as agricultural productivity or deforestation, represents a significant advantage of this technology, contributing to more accurate and efficient decision-making

Another driving theme of our research is soil moisture, an essential parameter for agriculture, which can be monitored using remote sensing, which also makes it possible to analyze the reflectance of the earth's surface. This data is used to infer plant health and the presence of water, as pointed out by (Seneviratne et al., 2010; D. Zhang & Zhou, 2016). Water availability plays a crucial role not only in agriculture, but also in environmental preservation and the socio-economic development of a region

The strategic diagram of publications related to remote sensing–based soil moisture estimation (Figure 7) confirms the central role of remote sensing and soil moisture as driving themes within Brazilian scientific production between 1995 and 2024. These themes exhibit high centrality and density, indicating both strong internal development and significant connections with other research topics. This positioning suggests that remote sensing–based soil moisture studies form the structural backbone of the national literature, supporting a wide range of methodological and applied investigations.

At the same time, the diagram highlights the emergence of new methodological frontiers associated with data-driven approaches, particularly machine learning and cloud-based platforms. These topics appear as emerging or transversal themes, signaling their growing importance but also their incomplete consolidation within the Brazilian research landscape.

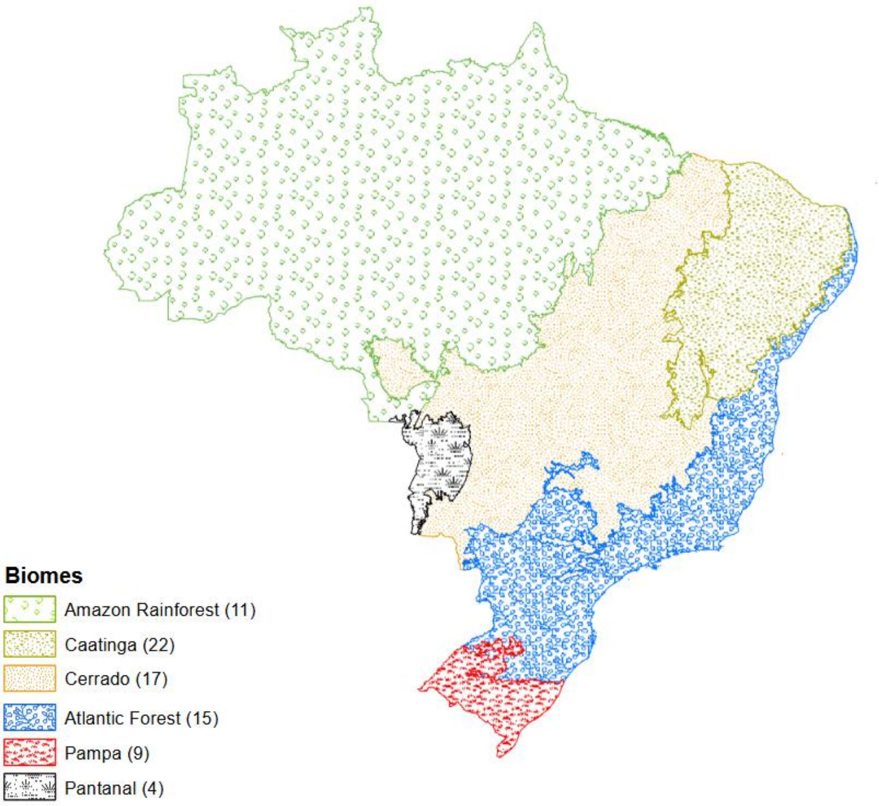

Figure 6 - Distribution of soil moisture papers across Brazilian biomes.

Emerging technologies: machine learning and cloud-based platforms

Among the emerging themes identified in the strategic diagram, machine learning and cloud-based platforms represent important research frontiers for soil moisture estimation. Data-driven approaches, including random forests, neural networks, and hybrid physical–statistical models, have demonstrated strong potential for improving soil moisture retrieval accuracy by integrating multi-source data. These methods are particularly suited to handling non-linear relationships between soil moisture and remote sensing variables.

When compared to international research trends, Brazilian studies show a delayed adoption of advanced analytical frameworks. While countries such as the United States, China, and several European nations increasingly employ artificial intelligence for operational soil moisture products, Brazilian applications are predominantly exploratory (Cai et al.,2023). This gap reflects structural challenges, including sparse in situ observations, limited long-term datasets, and reduced integration between academic research and operational agencies.

Despite their global dissemination, the application of machine learning techniques in Brazilian soil moisture studies remains limited. Most existing studies rely on conventional empirical or physically based models, often constrained by data availability and computational resources. Cloud platforms such as Google Earth Engine have expanded access to large datasets, yet their integration with local calibration data and national monitoring networks is still incipient.

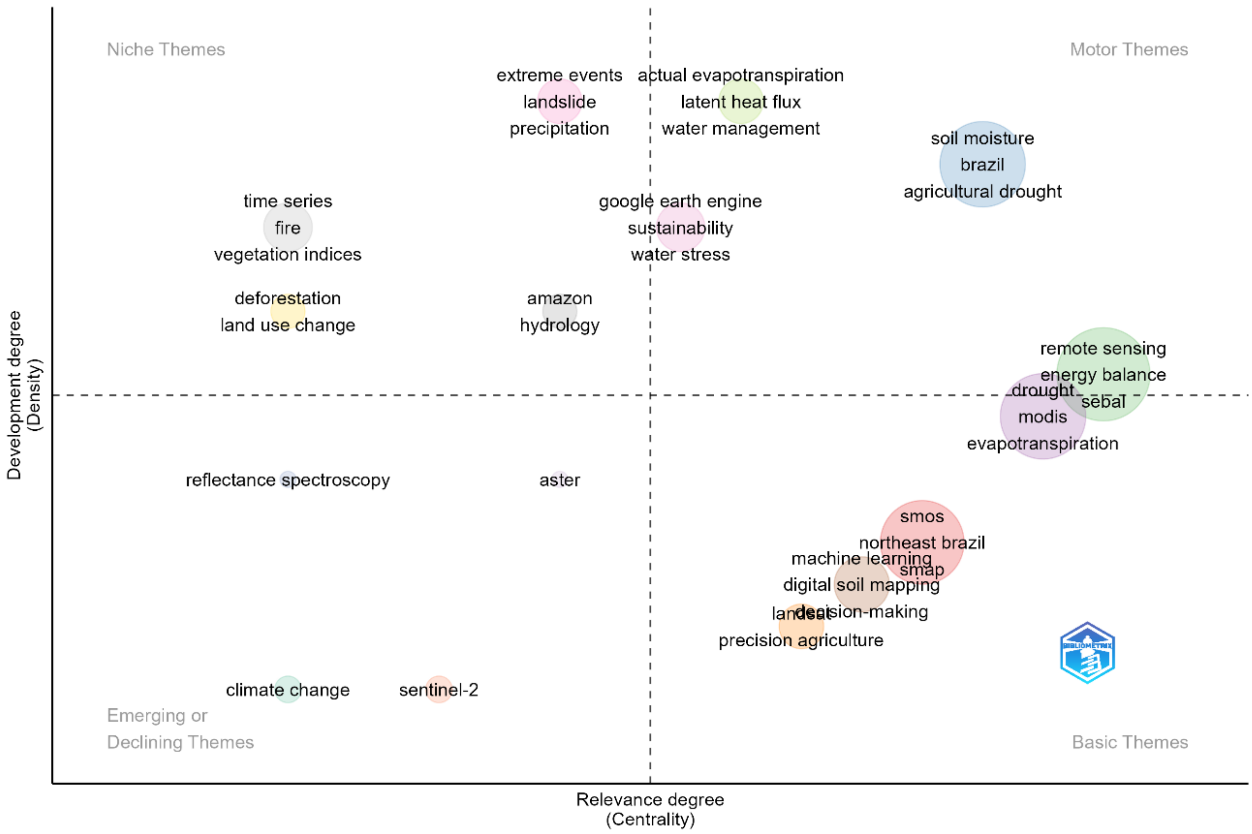

Figure 7- Strategic diagram of publications related to remote sensing soil moisture estimates from 1995 to 2024

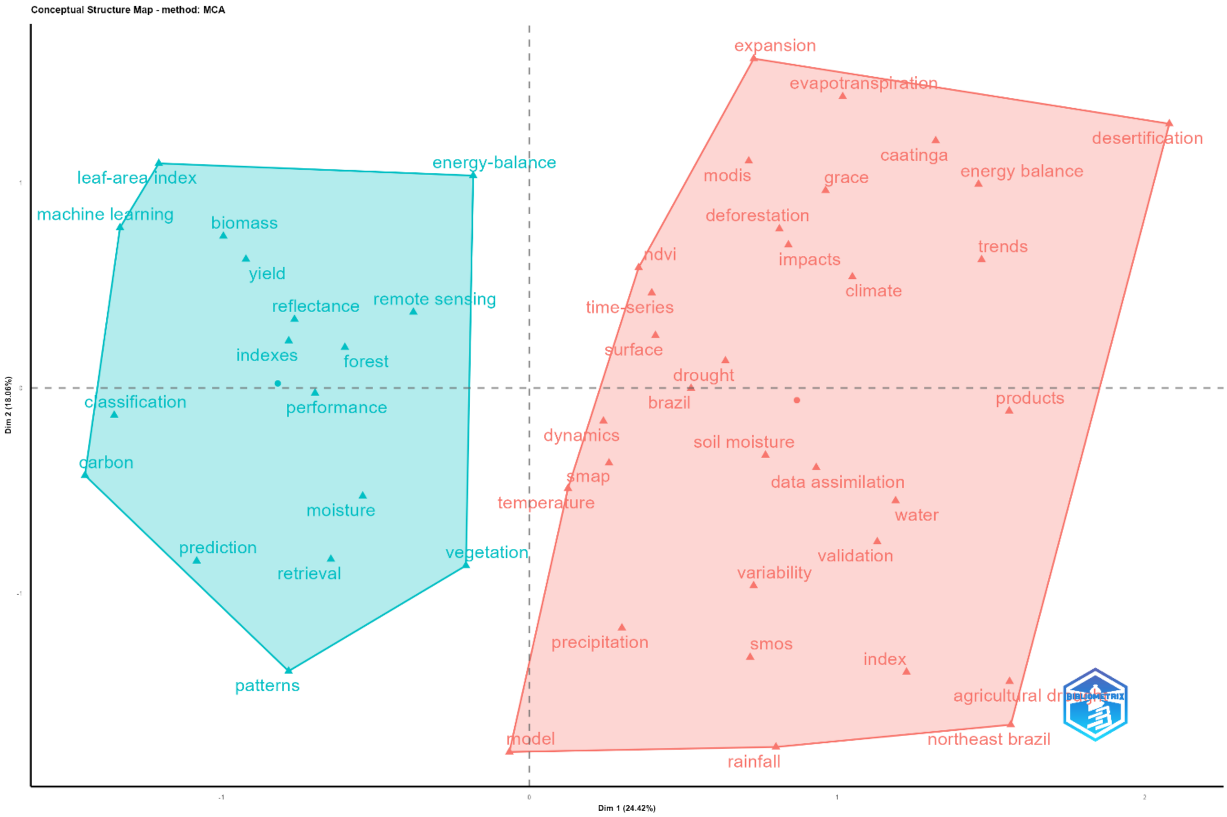

Figure 8 - Conceptual structure map of research on soil moisture in Brazil based on Multiple Correspondence Analysis (MCA) from 1995 to 2024.

Figure 8 presents the conceptual structure map of author keywords obtained through Multiple Correspondence Analysis (MCA), highlighting the thematic organization of Brazilian scientific production on soil moisture estimation using remote sensing. Two major thematic clusters are clearly distinguished along Dimension 1 (24.42%), which represents the primary gradient structuring the literature.

On the left side of the axis, keywords related to methodological and computational approaches are concentrated, including *machine learning*, *classification*, *prediction*, *performance*, and *remote sensing*. This cluster reflects a body of studies focused on the development, evaluation, and optimization of analytical techniques for estimating soil moisture and related biophysical variables. The presence of terms such as *reflectance*, *indexes*, *leaf area index*, *biomass*, and *yield* indicates a strong emphasis on optical remote sensing data and vegetation-based proxies, frequently combined with data-driven models to capture spatial patterns and improve estimation accuracy under heterogeneous land-cover and soil conditions.

In contrast, the cluster located on the right side of the conceptual map aggregates keywords associated with environmental, hydrological, and climatic applications, such as *soil moisture*, *drought*, *precipitation*, *climate*, *evapotranspiration*, and *energy balance*, along with widely used satellite products including *MODIS*, *SMAP*, and *SMOS*. The recurrence of region-specific terms such as *Brazil*, *Northeast Brazil*, and *Caatinga* underscores the applied nature of this research, which is strongly oriented toward understanding soil moisture dynamics in regions characterized by high climatic variability and environmental vulnerability. This thematic group encompasses studies that employ soil moisture as a key variable for monitoring agricultural drought, assessing climate change impacts, analyzing water and energy exchanges, and investigating desertification processes (dos Santos Araujo et al., 2024; Paredes-Trejo & Barbosa, 2017).

The close association between *soil moisture*, *precipitation*, and *drought* reinforces the central role of soil moisture in regulating ecosystem responses and agricultural productivity, particularly in semi-arid environments where water availability is the main limiting factor.

Keywords positioned near the center of the conceptual space, such as *vegetation*, *energy balance*, *temperature*, and *time series*, indicate a transitional thematic zone that links methodological developments with applied environmental studies. These terms represent integrative processes that are fundamental to both modeling frameworks and the interpretation of land–atmosphere interactions. However, the relatively clear separation between the two clusters suggests that, despite parallel advances, the integration of advanced data-driven methods—especially machine learning and pattern-recognition techniques—into operational environmental and climate applications remains limited within the Brazilian literature.

This thematic gap highlights the need for future research that explicitly bridges methodological innovation with applied objectives, such as soil moisture forecasting, data assimilation in hydrological and climate models, and decision-support systems for water resource management and drought mitigation. Strengthening this integration is particularly critical for vulnerable biomes such as the Caatinga, where sparse in situ observations, strong climatic seasonality, and increasing anthropogenic pressures demand robust, scalable, and application-oriented monitoring approaches.

Challenges and research gaps in soil moisture studies in Brazil

Despite the growing scientific output revealed by the present bibliometric analysis, soil moisture research in Brazil still faces several persistent challenges that reflect, but also amplify, limitations observed at the global scale. One of the main constraints identified in this study is the low density of in situ monitoring networks, which restricts sensor calibration, validation, and long-term assessments. This limitation is particularly critical in complex and heterogeneous biomes where soil moisture dynamics are poorly represented by coarse-resolution global products (Peng et al., 2021). Similar challenges have been reported in global assessments of the field, which highlight the difficulty of simultaneously achieving high accuracy, long temporal coverage, high spatial resolution, and global consistency in soil moisture datasets (Cai et al., 2023).

In line with the global trends identified in the literature, the results of this study indicate that technological integration is a key pathway for advancing soil moisture research in Brazil. The combined use of remote sensing, artificial intelligence, and advanced computational resources offers promising opportunities to overcome data limitations and improve spatial and temporal representation (Lamichhane et al., 2025; Montzka et al., 2026). However, as evidenced by the Brazilian literature, the practical application of machine learning techniques remains largely exploratory, with few studies focusing on local validation or adaptation to specific ecosystems such as the Caatinga and Pantanal. This pattern mirrors global observations that, despite rapid methodological advances, the operational implementation of data-driven approaches is still uneven and strongly dependent on data availability and infrastructure.

Another critical gap highlighted by the Brazilian results concerns the limited translation of scientific advances into operational tools and public policy frameworks. Although soil moisture information is widely recognized as essential for drought mitigation, agricultural zoning, and water allocation, few national studies explicitly link remote sensing–based products to decision-making processes. This disconnect between scientific production and environmental governance has also been identified as a broader challenge in the international literature, reinforcing the need for approaches that bridge methodological innovation with applied management contexts (Juhola et al., 2024; Räsänen et al., 2024).

Taken together, the results indicate that Brazilian soil moisture research broadly follows international trends, while exhibiting context-specific constraints related to data infrastructure, ecosystem diversity, and governance structures.

These findings point to critical research questions for future investigations, including how machine learning models can be effectively integrated with climate data for operational soil moisture forecasting, and how global remote sensing products can be adapted to Brazil's diverse soil and climate conditions. By addressing these challenges, Brazilian research has the potential to strengthen its international relevance and contribute more effectively to operational solutions for climate adaptation, food security, and sustainable water management.

These trends point to new scientific questions that are essential for future research, such as:

- How to integrate machine learning models with climate data for operational soil moisture forecasting?

- What are the best methods for adapting global remote sensing products to Brazil's specific soil and climate conditions?

Thus, this section not only highlights the most relevant current issues, but also suggests ways to overcome challenges and increase the impact of Brazilian research on the international stage.

Conclusion

Our study highlights the increasing relevance of remote sensing in soil moisture monitoring in Brazil, especially in the context of environmental variability and agricultural sustainability. The bibliometric analysis revealed a marked growth in publications since 2010, reflecting not only a rising scientific interest but also the strategic importance of this topic for understanding ecosystem dynamics and managing natural resources.

The concentration of studies within the categories of Environmental Sciences and Remote Despite these advances, important gaps remain. Research is still unevenly distributed across Brazil's diverse biomes, and practical applications, particularly those informing public policies on drought mitigation, agricultural zoning, or water allocation, are underdeveloped. Moreover, the use of advanced tools such as machine learning and cloud-based platforms like Google Earth Engine remains limited in scope and depth.

To address these challenges, future research should prioritize the following: (1) the integration of multi-source data—including satellite, drone, and ground-based observations—to improve spatial and temporal resolution; (2) the coupling of remote sensing outputs with hydrological and climate models to enhance predictive capacity; and (3) the development of methodologies tailored to Brazil's edaphoclimatic heterogeneity.

In summary, this study reinforces the essential role of remote sensing in advancing our understanding of soil moisture dynamics in Brazil, with implications that extend to broader South American contexts. By highlighting current trends, knowledge gaps, and methodological challenges, it supports a more strategic, interdisciplinary, and operationally relevant research agenda. Such efforts are vital for enhancing climate resilience, optimizing agricultural water use, and supporting evidence-based policies for drought mitigation and environmental conservation throughout the continent.

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