# Soil Moisture–Drought Nexus across Brazil: Identifying Current Issues and Future Perspectives

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**Abstract:** Droughts impact ecosystem activity, water security, and energy production. Recent studies have advanced the understanding of current drought periods and projected expectations for these events in a future of climate change. However, the relationship between droughts and soil moisture (SM)—a key variable in global ecology—remains poorly understood. Therefore, addressing the soil moisture–drought nexus is crucial for water and natural resources management. This endeavor may be particularly challenging in tropical regions like Brazil, a continental-scale country that harbors extensive biodiversity. To bridge this gap, we conducted a state-of-the-art review investigating the soil moisture–drought nexus across Brazil under current and future scenarios. The review findings indicate that SM behavior varies between different Brazilian biomes and regions under water scarcity. Nevertheless, a strong seasonality in SM was detected, suggesting the intensification of drought events in both current and future conditions. Furthermore, several Brazilian crops may become vulnerable in a drier climate, highlighting the urgent need to optimize water use in agriculture while maintaining crop productivity. Given the challenge of water scarcity, it is also essential to adopt strategies that balance agricultural land use with the conservation of natural vegetation, as these often intersect. Based on assessments of the soil moisture–drought nexus with methods ranging from remote sensing products to ground-based data, we concluded that national-scale analyses are valuable for decision-making and resource provision, while field investigations improve the understanding of the physical mechanisms behind land-atmosphere interactions. Our conclusions underscore the necessity of considering soil moisture as an independent variable in future studies, rather than relying on proxies, as it plays a unique role within the climatological and hydrological systems. We believe that the findings of this review can help improve soil water management under drought conditions not only in Brazil but also in Earth's tropical zone as a whole. **DOI: 10.1061/JWRMD5.WRENG-6575.** 

## Introduction

Drought is commonly defined as a water deficit occurring at the land-atmosphere interface (Berg and Sheffield 2018). It indicates a period of drier than normal conditions, referenced against historical water availability data (Stahl et al. 2020). The occurrence of droughts can impact both natural and built environments, resulting in direct or indirect consequences for vegetation dynamics, food and water security, and the overall economy (Freire-González et al. 2017; Lottering et al. 2020; Páscoa et al. 2020; Payus et al. 2020). The intricate nature and far-reaching implications of drought present numerous challenges in terms of monitoring and identification, which are critical endeavors for enhancing drought forecasting and mitigation efforts (Escriva-Bou et al. 2020; Haile et al. 2019; Hao and Singh 2015; Sehgal and Sridhar 2019; Slette et al. 2019). The comprehensive understanding of drought is improved through its categorization into meteorological, agricultural, hydrological, and socioeconomic dimensions. Meteorological drought denotes a deficit in precipitation, agricultural drought pertains to insufficient water supply for vegetation, and hydrological drought is associated with deficits in surface and subsurface water resources. The occurrence of these three forms of drought can culminate in socioeconomic drought, often characterized by the inability to meet societal water-related needs (Van Loon 2015).

While drought has historically been identified solely as a natural hazard, it is increasingly evident that human activities are significantly intertwined with these so-called natural phenomena (Hao and Singh 2015; Van Loon et al. 2016). Consequently, recent studies have introduced the concept of anthropogenic drought, which is frequently linked to the impacts of urbanization, greenhouse gas emissions, and energy production on water shortages (AghaKouchak et al. 2015; Ashraf et al. 2021). This interdisciplinary conceptualization of drought is essential for enhancing the understanding of the interaction between natural variability and human processes, particularly in nonstationary climate conditions (AghaKouchak et al. 2021; Mukherjee et al. 2018). In this context, anthropogenic-induced changes in climate are anticipated to impact both human and natural systems (Muluneh 2021; Vicedo-Cabrera et al. 2021). Moreover, numerous studies have specifically focused on characterizing drought globally in the scenario of climate change (Gu et al. 2022; Li et al. 2021; Pryor et al. 2022).

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Within this context, soil moisture is defined as the water stored in the unsaturated soil zone, also referred to as the vadose zone (Seneviratne et al. 2010). Despite constituting less than 0.01% of the global water stocks (Dingman 2015), soil water storage is an essential variable for improving hydrological studies (Branger and McMillan 2020) and addressing global ecosystem production (Liu et al. 2020). Soil moisture is directly linked to agricultural drought, as it strongly influences crop productivity (Van Loon 2015). However, investigating the relationship between soil moisture and general drought events has proven to be an effective approach for improving water and natural resources management and conservation (Kang et al. 2022; Watson et al. 2022; Zhou et al. 2021).

This is particularly relevant for the Earth's tropical zone, which harbor globally significant ecosystems characterized by extensive biological diversity (Barlow et al. 2018; Harding et al. 2016). The tropical zone surrounds the Equator within the latitudes of the Tropics of Cancer and Capricorn at ±23.5°. In 2014, the tropics were inhabited by 40% of the world's population, a proportion projected to increase to 50% by 2050 (State of the Tropics 2014). This rapid and often unplanned urban growth expected in developing regions, including countries within the tropics, coupled with human activities, can result in habitat loss and decreases in species richness and abundance (Aghamohammadi et al. 2021; Uchôa et al. 2023). Under this scenario, Latin America shelters at least a third of the global biodiversity (Raven et al. 2020), with Brazil standing as the largest country within this region. Consequently, managing this complex human-nature system is particularly challenging in Brazil, a task that may escalate in the future due to the intensification and recurrence of climate extremes in the country (Alves et al. 2020; Avila-Diaz et al. 2020).

Within this context, it is noteworthy that the scientific community has been increasingly contributing to the overall characterization of drought in Brazil (Ballarin et al. 2024; Bevacqua et al. 2021; Cunha et al. 2019). However, there is a lack of studies that summarize the main findings on the relationship between soil water storage and drought events (hereafter referred to as the soil moisture–drought nexus), especially in the complex ecosystems encompassed by tropical regions. Thus, in this study, we conducted a state-of-the-art (SotA) review to investigate the soil moisture–drought nexus across Brazil, based on the most up-to-date published scientific literature. Relying on a six-stage approach to systematically perform the review (Barry et al. 2022), we aimed to identify the current and future feedbacks between droughts and soil moisture, as well as to highlight strategies to improve soil water management during drought conditions in Brazil.

## Methods

To conduct the SotA review, we followed the six-stage approach presented by Barry et al. (2022). The foundations behind this methodology are based on the idea that SotA reviews provide a synthesis that describes, in relation to a certain field of knowledge: (1) where we are now, (2) how we got here, and (3) where we could be going. Following the six-stage methodology, the first step involves defining the initial research questions and the field of inquiry (Stage 1) (Barry et al. 2022). Therefore, we defined the following three initial research questions:

- How are drought events currently related to soil water storage in Brazil?
- What do climatic projections indicate about the future of soil moisture across the Brazilian territory?
- Which strategies could be adopted to improve soil water management in Brazil under drought conditions?

Next, Stage 2 focuses on determining and justifying the timeframe to be considered (Barry et al. 2022). Hence, we defined the IPCC Special Report on Global Warming of 1.5°C, hereafter referred to as SR15, published in October 2018, as the reference point for defining the timeframe in this stage. Overall, the SR15 focuses on reporting the actions needed and the benefits of meeting a global warming target of 1.5°C rather than 2°C above preindustrial levels. This aims to strengthen the global response to the impacts of climate change, further shedding light on sustainable development (IPCC 2018).

The SR15 highlights that climate-related risks for human systems and natural environments are projected to be lower at a global warming of 1.5°C compared to 2°C. Most adaptation requirements will be lower for a 1.5°C target, although mitigation pathways limiting global warming to 1.5°C would still necessitate infrastructure and energy transition, deep emissions reductions, technological innovations, and policy instruments. Moreover, the SR15 indicates that climate models project robust differences in regional climate patterns between the present day and a global warming of 1.5°C, as well as between the 1.5°C and 2°C scenarios. For instance, even though risks from precipitation deficits are projected to be higher at 2°C compared to 1.5°C in some regions, several regional changes in climate are expected to occur with a warming of 1.5°C compared to preindustrial levels. These changes include increases in the intensity or frequency of droughts in some regions (IPCC 2018). Therefore, we have defined the period from 2019 to 2023 as the timeframe to be considered for conducting the SotA review, aligning it with the year following the publication of the SR15. This allowed us to incorporate the most recent advancements concerning the soil moisture–drought nexus in Brazil, while also highlighting key scientific findings in this area that could complement the SR15. Notably, within the 2019–2023 period, we identified studies whose results were related to observations from both the pre-2018 and post-2018 periods, as well as projections for the 21st century.

Stage 3 of the applied methodology involves revising and finalizing the research questions to ensure they properly reflect the chosen timeframe (Barry et al. 2022). We believe that the three scientific questions defined in Stage 1 align with the insights developed in Stage 2. However, considering that international cooperation is an imperative tactic to achieve climate-resilient nations, especially for developing countries and vulnerable regions (IPCC 2018), we recognize the importance of extrapolating the findings identified in the SotA review beyond the Brazilian territory. Therefore, in order to contribute to strategies for a better understanding of the soil moisture–drought nexus in other regions, especially the world's tropics, an additional question was formulated:

- How can the findings of the previous questions shed light on a better comprehension of the soil moisture–drought nexus beyond Brazil?

With all research questions defined, Stage 4 proposes the development of a search strategy (Barry et al. 2022). Thus, our approach was based on searching for published literature indexed in the Web of Science (WoS) and Scopus databases. The search included all source types, and the following search strings were used in both databases:

> [("climate change" OR "global heat*" OR "global warm*") AND ("drought*" OR "defici*" OR "scarc*") AND ("soil moisture" OR "soil water" OR "soil water content" OR "soil water storage" OR "soil moisture content" OR "water content of the soil") AND ("Brazil*")]

The TOPIC field was used in WoS to check for the presence of the aforementioned words in the Title, Abstract, Author Keywords, and Keywords Plus of the literature included in the database. A total of 57 documents were identified through this search in WoS. As for the Scopus platform, the TITLE-ABS-KEY field was applied, which combines the search for the selected words in the Title, Abstract, and Keywords of the documents contained in the database. A total of 48 documents were found with this search.

Following that, we proceeded to identify and eliminate duplicate documents, referring to studies present in both WoS and Scopus. As a result, the database comprised 71 unique documents. Notably, 3 out of the 71 documents lacked full-text availability online and were thus excluded from the analysis. The subsequent step entailed reviewing the title and abstract of each document and selecting literature that closely aligned with the content of the research questions outlined in this SotA review. After reviewing the abstracts of 68 documents, 45 were selected for the following stage, in which the chosen literature is thoroughly analyzed by the authors of the SotA review (Stage 5). Therefore, this step involved reading the full text of the 45 documents. The purpose of this stage is to observe similarities between articles, highlight assumptions that contribute to changes in understanding, identify gaps and the evolution of knowledge, and detect potential directions for future research (Barry et al. 2022), as presented in the "Results and Discussion" section of this study.

The final step (Stage 6) of the six-stage approach proposed by Barry et al. (2022) refers to addressing the subjectivity of the researcher(s) regarding the data interpretation presented in the review. In this study, our aim was to minimize potential subjective bias by conducting literature searches in two widely used databases, namely the Web of Science and Scopus. The searches encompassed the main fields included in both databases, ensuring the inclusion of all relevant documents related to the soil moisture–drought nexus in Brazil. Additionally, the previously described step-by-step strategy of identifying the alignment of the literature, starting with evaluating the title and abstract of each document and later reading the entire article, also contributed to bias minimization. We also believe that defining research questions contributed to a more objective perspective.

## Results and Discussion

We noticed that several articles of this SotA review address the soil moisture–drought concerning Brazilian biomes, along with the division of the country into its federal states and regions. Thus, in the following paragraphs, we provide an overview of the characteristics of Brazil's biomes and present their distribution within the country's five regions (Fig. 1). The SotA review is presented in the subsequent subsections.

Brazil has a population of 203,080,756 (IBGE 2022) and a territorial area of 8,510,821 km$^2$ (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019), making it the largest country in South America. It is divided into 26 states and a Federal District, which together comprise five major regions: North, Northeast, Central-West, Southeast, and South (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). Brazil is home to six main continental biomes: Amazon, Atlantic Forest, Caatinga, Cerrado, Pantanal, and Pampa.

The Amazon is the largest Brazilian biome, covering 49.5% of the national territory (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). According to the Köppen climate classification system, it presents a tropical climate, predominantly

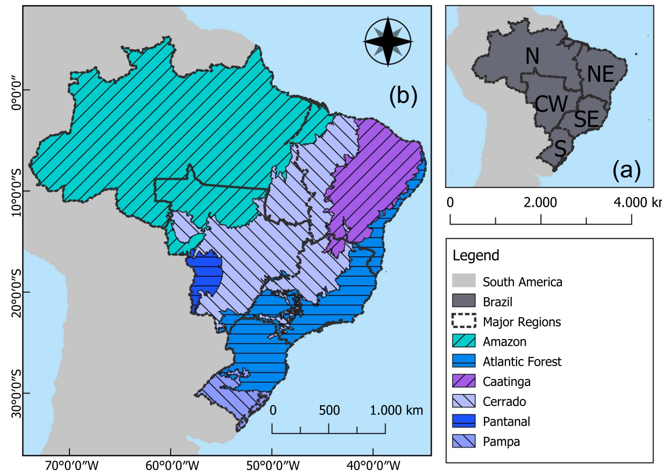


**Fig. 1.** (a) Location map of Brazil with the major regions: North (N), Northeast (NE), Central-West (CW), Southeast (SE), and South (S); and (b) distribution of the Brazilian biomes within the country's major regions. (Base map courtesy of the Brazilian Institute of Geography and Statistics.)

without a dry season (Af) and with a monsoon-type (Am) climate (Alvares et al. 2013). The Amazon is characterized by hot and humid conditions, with heavy rainfall uniformly distributed throughout the year, which can reach annual levels as high as 4,000 mm (Alvares et al. 2013; IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). This biome features predominantly rainforested areas (Overbeck et al. 2015) and is considered the largest biodiversity reserve on the planet (IBGE 2019). The Atlantic Forest biome covers 13.0% of the Brazilian territory and extends throughout the Brazilian eastern Atlantic continental strip (IBGE 2019). The biome features a humid subtropical climate in its southern portion, transitioning to a tropical climate in its central and northeastern regions (Alvares et al. 2013), and it is characterized by rainforested areas (Overbeck et al. 2015). However, due to historically significant development episodes in the country, the Atlantic Forest is now heavily degraded (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019).

The Caatinga is an exclusively Brazilian biome that occupies 10.1% of the national territory (IBGE 2019). The predominant climate is semiarid (BSh type), with annual precipitation normally less than 800 mm (Alvares et al. 2013), while the vegetation commonly consists of dry woodlands (Overbeck et al. 2015). The Caatinga is an unusual semiarid space in a typically tropical country, which is due to a combination of continental equatorial air masses and high-pressure centers that act in the interplateau depressions encompassed within the biome (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). The Cerrado biome is the second largest in Brazil, covering an area corresponding to 23.3% of the country (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019), and is predominantly composed of savanna-type vegetation (Overbeck et al. 2015). The dominant climate is tropical with dry winters (Aw type), characterized by two well-defined seasons—dry and rainy—and annual rainfall that varies between 600 and 2,200 mm (Alvares et al. 2013; IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). The land alterations in the Cerrado have brought significant environmental damage, leading to the classification of this biome as the most endangered savanna on the planet (Ioris et al. 2014).

The Pantanal biome is widely recognized as the largest inland floodplain on the planet, and it is also the smallest Brazilian biome, occupying only 1.8% of the national territory (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). Characterized by wet grassland and savanna landscapes (Overbeck et al. 2015), it boasts a tropical climate with dry winters and hot, humid summers (Aw type) (Alvares et al. 2013). Due to the low permeability soils and negligible slope of the region, just a few months of rainfall are sufficient to seasonally inundate the Pantanal Plain (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). The Pampa is located in the extreme south of Brazil and is the country's second smallest biome, covering an area corresponding to 2.3% of the national territory (IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019). It is characterized by a humid subtropical climate without a dry season and with hot summers (Cfa type) (Alvares et al. 2013). Therefore, it experiences a rainy climate throughout the year, along with the occurrence of polar fronts and negative temperatures during winter, ensuring the presence of typical grasslands from cold and dry climates (Overbeck et al. 2015; IBGE and Coordenação de Recursos Naturais e Estudos Ambientais 2019).

Moreover, from this point forward, we will employ abbreviations to represent recurring variables found within the articles under review. These abbreviations include SM for soil moisture, SWS for soil water storage, P for precipitation (usually indicating rainfall), ET for evapotranspiration, $R_{\text{off}}$ for surface runoff, $T_{\text{surf}}$ for land surface temperature, $T_{\text{air}}$ for air temperature, $T_{\text{soil}}$ for soil temperature, $RH$ for relative air humidity, and WUE for water use efficiency. Further abbreviations will be introduced throughout the text. We did not assign units to the variables as they vary from one study to another, and because we rarely refer to them in quantitative terms. Additionally, any necessary units are indicated throughout the review. Furthermore, based on the articles included in each subsequent section, some generally consistent findings are highlighted first, followed by a detailed presentation of each study's specific contribution.

## *Unveiling Soil-Atmosphere Feedbacks in a Changing Water Balance: The Soil Moisture Perspective*

In general, we observed a prevalence of studies focusing on capturing the temporal and spatial behavior of SM to better understand its relation to drought events' duration and intensity. The assessment of SM trends and temporal evolution reveals that the impact of droughts on soil water availability was not consistent across different Brazilian biomes and regions. Several studies showed a strong effect of climatic conditions on SM, including large-scale circulation mechanisms such as the El Niño–Southern Oscillation (ENSO). As a consequence of these global climate cycles, along with the expected escalation in the variation range of SM in a future climate change scenario, studies evaluating contrasting areas—the Amazon, the Atlantic Forest, and the Caatinga biomes—highlighted strong seasonal behavior of SWS. These coupled soil-atmosphere interactions have also proven to be an important factor in explaining extreme temperatures during drought-heatwave episodes that have recently affected Brazil.

In this context, we also identified the significance of SM to the hydrological system. Specific soil characteristics, such as the water retention capacity and the soil geological formation, were responsible for regulating ET in a drought-affected Atlantic Forest remnant and explain the spatial behavior of drought in the semiarid region, respectively. Moreover, increases in SM in the São Francisco River Basin (SFRB), the main hydrological system in northeastern Brazil, occurring in parallel with a reduction in groundwater levels, suggested an increase in groundwater abstraction. We observed the importance of evaluating SM not only at the land-atmosphere interface but also within the transition from the vadose zone to the saturated zone. Still, we noted that the integration of hydrological variables must be approached with caution in the future, as SM behavior may differ from commonly used approximations, such as $R_{\text{off}}$.

Overall, considering the studies included in this section, the spatial behavior of droughts was primarily investigated at the biome and federative state levels, while few results were ground-based. In this context, we noticed the importance of remote sensing products in providing a broader perspective on drought propagation across Brazil. Similarly, the application of drought indices—such as the water storage deficit index (WSDI)—and the use of computational models—such as the soil and water assessment tool (SWAT)—helped characterize the spatialized impacts of droughts and their effects on SWS.

Moreover, specifically regarding SM trends from 2009 to 2015, the findings from Lopes Ribeiro et al. (2021) revealed that the Caatinga experienced the most significant decline in SM (−4.4% per year), while the Pampa and Pantanal exhibited positive trends (1.6% and 4.3% per year, respectively). The Atlantic Forest, Cerrado, and Amazon regions showed no significant SM trends during the evaluated period (Lopes Ribeiro et al. 2021). In this context, based on remote sensing data sets, Rossi et al. (2023) noted the succession of meteorological and agricultural droughts followed by a hydrological drought in both the 2012 Pampa and 2015 Amazon episodes, suggesting the occurrence of a cascade effect. Conversely, the 2014 Cerrado episode was predominantly affected by a hydrological drought. Despite these variations, the authors highlighted that SM exhibited negative anomalies in all assessed drought episodes (Rossi et al. 2023).

Similarly, Arévalo et al. (2023) reported an increase in the variation range of SM for both the Amazon and Atlantic Forest for the 2022–2050 timeframe. This was associated with the expected increase in the frequency of extreme events and with the intensification of SWS seasonality (Arévalo et al. 2023). On this topic, the spatial and temporal behavior of soil water in the Brazilian Northeast was investigated by de Oliveira Aparecido et al. (2021) using the Thornthwaite and Mather Climatic Water Balance (TM-CWB) method (Thornthwaite and Mather 1955). The authors found distinct seasonal variations in SWS in the region. A highly seasonal and spatial variation in SM was also found by de Oliveira Aparecido et al. (2022a) when evaluating the Maranhão state, northeastern Brazil, with climate change expected to modify the humidity of the state toward a drier condition.

The duration and severity of drought events were evaluated by de Inocêncio et al. (2020) during the 1988–2018 timeframe in the basins of Pernambuco state, northeast Brazil. Using two drought indices based on SM, namely the standardized soil moisture index and soil moisture condition index, they concluded that consecutive years with P below the historical mean increased the magnitude of the droughts. From 2012 onwards, drought events were more pronounced in the basins located in the interior of the state (semiarid region where shallow soils prevail) compared to those in the coastal region (with deeper soils) (de Inocêncio et al. 2020). Soil properties also play a fundamental role in sustaining ET in an Atlantic Forest remnant in southeastern Brazil under drought. Although the forest's physiological mechanisms and the alternation between droughts and near-normal conditions were recognizably important factors, the soils' water-holding capacities were essential for maintaining ET and SWS during scarcity (Guauque-Mellado et al. 2022). These studies shed light on the valuable insights that can be gained by using SM information to better understand water balance components during drought situations. Based on this, we emphasize that national and regional scale investigations are relevant for identifying general trends and obtaining a broader perspective of SM, ultimately aiding decision-making processes and policy adoption.

Furthermore, at the watershed level, Mutti et al. (2022) conducted a long-term (1942–2019) drought evaluation in the SFRB. The results indicated an expansion trend in drought-affected areas from the semiarid lower-middle São Francisco (LMSF) toward the middle and lower São Francisco (MSF and LSF, respectively) areas, in addition to significant trends in the basin's upper region (USF). Nevertheless, this later presented consistent water surpluses due to P during the wet season, which was sufficient to replenish the soil's available water for vegetation. However, in the MSF, the largest area of the basin and the transition zone between the humid subtropical USF and the semiarid LMSF, the wet season was not strong enough to ensure substantial water surpluses (Mutti et al. 2022). Another study in the SFRB was conducted by Paredes-Trejo et al. (2021), who utilized several indices to examine drought, including the soil moisture and ocean salinity-based soil water deficit index (SWDIS) and the WSDI. Similar to Mutti et al. (2022), Paredes-Trejo et al. (2021) observed a drying trend from 1980 to 2015 in portions of the basin equivalent to the MSF and USF regions. However, most recent data from SWDIS and WSDI showed that prolonged drought conditions are reversing. Despite this optimistic perspective, another result was the observed depletion of groundwater levels concurrent with an increase in SM, suggesting an increase in groundwater abstraction mainly for irrigation. This finding highlights the potential degradation of natural resources that can occur as a result of anthropogenic actions on the SFRB, as overexploitation of groundwater can lead to irreversible depletion (Paredes-Trejo et al. 2021).

Moreover, both Paredes-Trejo et al. (2021) and Mutti et al. (2022) observed a relationship between drought and large-scale circulation mechanisms within the SFRB. For instance, drought occurrence in LMSF and LSF regions was driven both by the ENSO and Atlantic Meridional Mode, while the MSF was affected primarily by ENSO (Mutti et al. 2022). Large-scale climatic phenomena were also investigated by de Medeiros Estevam et al. (2020) in a 32-year time series of meteorological data in Rio de Janeiro, southeastern Brazil. The authors concluded that SWS was significantly influenced by global climate cycles, such as the El Niño and La Niña phenomena (de Medeiros Estevam et al. 2020). Therefore, based on the reported results for both the SFRB and Rio de Janeiro, it is noticed that the relevance of examining the effects of natural climatic phenomena simultaneously with human-induced land alterations, in order to improve the comprehension of the nexus between drought and soil water availability. In this context, de Oliveira et al. (2021) analyzed water and carbon fluxes through eddy covariance measurements from 2013 to 2016 in two sites of the Caatinga biome: highly preserved recovering Caatinga vegetation and a recently degraded area with sparse vegetation. The results indicated that the sparse Caatinga had higher annual ET rates than the dense one, suggesting that ET was intensified through deforestation-induced soil water loss in the sparse area (de Oliveira et al. 2021).

Regarding the mitigation of anthropogenic activities, Fontes Júnior and Montenegro (2019) utilized SWAT to analyze the impacts of arboreal Caatinga reforestation on water availability in a representative watershed of the semiarid region. Their findings revealed that Caatinga restoration would foster an increase in SWS and recharge, ultimately enhancing water stocks in the region (Fontes Júnior and Montenegro 2019). Moreover, de Andrade et al. (2019b) examined the effects of incorporating SM data into modeling a predominantly rural watershed in the northeastern region. Despite some associated uncertainty, their results indicate the feasibility of utilizing SM data sets to improve hydrological models. The aforementioned findings indicate strategies to enhance soil water stocks in Brazil, valuable for improving water availability during drought situations. Additionally, they underscore the advances that can be achieved by establishing an interconnection between SM and water balance components in hydrological studies. However, caution must be exercised when using SM as a proxy for other hydrological variables (e.g., $R_{off}$) in the future. This precautionary note stems from observations that robust declines in SM are more widespread compared to P and $R_{off}$ in many parts of the globe, including South America. Based on the application of climate models from Phase Six of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al. 2016) from 2071 to 2100 across a wide range of shared socioeconomic pathways, the 21st-century development and radiative-forcing scenarios (O'Neill et al. 2016), Cook et al. (2020) highlighted the importance of assessing the behavior of the entire hydrological cycle under climate change conditions.

Moreover, during the 2013–2014 summer, southeastern Brazil witnessed exceptional hot $T_{surf}$, leading to several impacts in densely populated areas such as the city of São Paulo. In this context, Geirinhas et al. (2022) found that circulation anomalies did not solely explain the warmer and drier conditions in the region, but also that record-breaking temperatures were promoted by a strong soil moisture-temperature coupled regime. The soil dissection, along with low entrainment of cooler air masses and strong radiative processes, led to a higher-than-normal $T_{surf}$. Additionally, the authors highlighted that SM is becoming more influential in the partitioning of the incoming energy, further indicating that investigating this variable is pivotal to better comprehending soil-atmosphere feedbacks under drier and warmer scenarios (Geirinhas et al. 2022). Under this same context, Libonati et al. (2022) conducted a comprehensive review on compound drought-heatwave events in Brazil. The authors indicated that the 2020 dry season in the Pantanal was characterized by the formation of a coupled soil moisture-temperature regime. The review also showed that drought in the Amazon was associated with high incoming solar radiation and SM deficits, further indicating that soil-atmosphere interactions amplified soil dry-out and extreme temperatures. Overall, the findings reported above can provide guidelines for predicting compound drought-heatwave episodes in the future and adopting adaptive strategies to minimize the related impacts in native land conservation and public health and social issues (Libonati et al. 2022; Geirinhas et al. 2022).

## *Understanding Native Vegetation Functioning in Water Scarcity Conditions by Means of Soil Moisture*

As in the previous section, Brazilian biomes have been extensively studied in the context of the effects of soil water availability on native vegetation functionality, with a particular emphasis on the Amazon and Caatinga biomes. However, in contrast to the previous section, the findings presented here are predominantly based on experimental procedures and field observations. In this scenario, one important focus of these studies was investigating how water availability limitations and temperature increases can impact vegetation behavior. Based on this, some results highlighted that variation in rainfall patterns toward drier conditions represents a limiting factor for vegetation development. In addition, one of the foremost collective contributions within this section to the understanding of the soil moisture–drought nexus was the observation of adaptive mechanisms in several native Brazilian vegetation species in response to water scarcity. In these conditions, SM deficit was a driver of changes in vegetation characteristics.

Besides the prevalence of in situ information, some studies included in this section also used remote sensing data, along with vegetation indices—such as the vegetation health index (VHI) and the normalized multi-band drought index (NMDI)—to characterize SM under drier climate conditions. Based on this, another interesting general result was the strong effect of reduced SM on fire outbreak occurrence. Lastly, we also noted the effectiveness of the autoregressive integrated moving average (ARIMA) model in predicting index behavior, providing valuable insights for the future. Furthermore, the main contributions of each study assessed here are presented below.

In respect to the Amazon biome, the capacity of the Caxiuanã National Forest (CaxNF) trees to adjust their hydraulic system to a 15-year throughfall exclusion experiment was tested (Bittencourt et al. 2020). Because of the absence of interannual P variance at the site, the study reported that the traits associated with both hydraulic safety and efficiency did not adjust to promote the acclimation of the tropical trees exposed to prolonged SM stress. Nevertheless, Bittencourt et al. (2020) concluded that taxonomic diversity played an important role in determining hydraulic strategies and trait relationships across the forest, which can ultimately lead to changes in its composition. Relative to this subject, when short trees are exposed to high light conditions during drought, they can lose leaves to tolerate limited access to deep soil water and stressful leaf environments, as highlighted by Smith et al. (2019). They collected data over a 4-year period at the Tapajós National Forest (TapNF) within the Amazon and concluded that low SM, along with high leaf stress, were responsible for the decrease in leaf area in low canopy surfaces during the dry season.

The future of the extensively studied TapNF was also assessed by Vieira et al. (2023), who investigated the effect of two representative concentration pathways (RCPs), namely the radiative-forcing RCP4.5 and RCP8.5 scenarios (Moss et al. 2010), for the 2071–2100 period in an area of the conservation unit. The results demonstrated that a future drier and warmer climate can constrain plant growth in the TapNF and showed the important role of soil water in the processes embedded in the simulations (Vieira et al. 2023). Similarly, Dantas et al. (2019) investigated how the germination for the year 2055 of three representative tree species of the Caatinga will be affected by limited water availability and increased temperature. They concluded that P rather than $T_{\text{soil}}$ will be the limiting factor for seed germination of the evaluated vegetation (Dantas et al. 2019).

The effects of the expected increase in the duration and frequency of dry spells during the rainy season on the seedling stage of two Cerrado species were investigated by Chaib et al. (2023). Young seedlings of *Tabebuia aurea* and *Qualea grandiflora* were subjected to irrigation at different intervals, leading to the observation of plant-specific responses to the dry spell situations. For instance, root elongation was a priority of *T. aurea* under drought, as deeper roots can reach soil layers with more water. This behavior revealed an effective adaptation strategy of this typical Cerrado species to water scarcity scenarios (Chaib et al. 2023). Furthermore, Ortega Rodriguez et al. (2023) investigated the growth and wood density of the vulnerable *C. fissilis* species in the Jamari National Forest, southern Amazon. The study revealed that *C. fissilis* exhibited wider and denser tree rings during wetter years, and narrower and less dense rings during drier years. This plasticity in wood formation suggested the species' adaptation to long-term drought trends (Ortega Rodriguez et al. 2023). Similarly, Sousa Santos et al. (2020) observed plasticity in a rainfed area of tall coconut palm trees (*Cocos nucifera* L.) on the coast of the northeast region of Brazil. When SM dropped below the permanent wilting point during the dry season, there was a reduction in the photosynthetic rate, indicating stomatal regulation in response to water deficit. The collective findings of Chaib et al. (2023), Ortega Rodriguez et al. (2023), and Sousa Santos et al. (2020) contribute to a deeper understanding of the functional behavior of the investigated species by assessing soil water availability under current and future scenarios. This facilitates the identification of improved strategies for vegetation conservation and management under water scarcity conditions, considering the specific characteristics of both the species and the location under study.

Furthermore, examining the overall vegetation composition of a particular environment, rather than focusing solely on individual species, has also enhanced comprehension of soil-vegetation dynamics in diverse Brazilian landscapes. In this context, Lourenço et al. (2021, 2022) investigated a restinga-protected area, a particular type of coastal humid forest of the Atlantic Forest (Scarano 2009). The site of both studies was composed of plots covering a flooding gradient transition across three forest types: floodable (lower region), intermediate, and dry forests (upper region). The results from Lourenço et al. (2021) showed that parameters related to soil water availability drive important ecological processes in the restinga forest. They observed that soil dryness in the upper region of the study area made the trees converge to smaller body sizes. Conversely, water excess in the lower region favored the occurrence of taller trees (Lourenço et al. 2021). Complementarily, Lourenço et al. (2022) found that trait variation across the same moisture, microtopographic-driven gradient was larger between species than within species. This result suggested habitat specialization accomplished through changes in species composition and abundance (Lourenço et al. 2022). Findings from Lourenço et al. (2021, 2022) highlighted the importance of addressing local variations in soil and moisture variables considering the hydraulic traits of the restinga vegetation, and further provided insights for the future management and conservation of the Atlantic Forest.

Moreover, the combination of leaf and wood traits proved essential in explaining the vegetative behavior of different functional groups within a semiarid riparian forest in the Caatinga, as concluded by da Silva E Teodoro et al. (2022). They observed the prevalence of high wood density species (48%) over low wood density species (9%), which was related to minimizing damage to the plant hydraulic system, as wood density is an important attribute for more efficient soil water exploration. Northeastern Brazil was also studied by Rebello et al. (2020), who found correlations between semiarid vegetation behavior and hydrological variables such as P and SM in large areas affected by drought. The monthly normalized difference vegetation index (NDVI) was calculated for multitemporal images spanning from 2000 to 2015 for the northeastern and southeastern Brazilian regions. In the latter, the duration of drought and the lack of P were not sufficient to impact vegetation greenness or significantly reduce ET within this region. Additionally, the weak correlation between NDVI and P in the Northeast suggested once again the presence of an adaptive mechanism in the Brazilian semiarid regions (Rebello et al. 2020).

Following the methodology from Rebello et al. (2020) and considering the overall studies examined in this SotA review, it is evident that both drought and vegetation indices play a fundamental role in addressing water availability under scarcity conditions. In this context, Vilanova et al. (2020) conducted an assessment of the VHI, in conjunction with variables such as $T_{\text{air}}$, $T_{\text{surf}}$, SM, and fire foci data in the state of Amazonas. The findings indicated a negative correlation between fires and temperature with SM, suggesting that lower temperatures and higher SM potentially reduce





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combustible materials for fire outbreaks. Additionally, the ability of the ARIMA model to forecast the observed VHI within the 2001–2018 timeframe was proven successful (Vilanova et al. 2020). Moreover, between 2001 and 2019, de Oliveira Santos et al. (2021) observed a strong negative correlation of NMDI with different land uses and carbon emissions in the state of Rio de Janeiro, which was associated with increases in fire occurrences. The months with the highest number of fires corresponded to periods with the lowest SM. In addition, the ARIMA model was effective in simulating NMDI for the 2020–2030 period, highlighting the applicability of the drought index for predicting fire risk (de Oliveira Santos et al. 2021). Finally, de Andrade et al. (2019a) investigated the occurrence of fire outbreaks in the state of Rio de Janeiro for the years 2005, 2010, and 2015. By exploring the relationship between soil attributes and meteorological variables, the authors found that, along with $RH$, SM was the variable that most influenced the occurrence of fires (de Andrade et al. 2019a). Based on the aforementioned studies, we emphasize that monitoring SM is imperative for fire prevention, an important strategy toward the preservation of native vegetation and avoidance of land degradation.

## Managing Soil Water Availability under Drought: The Central Role of Agriculture

Since the cultivation of various crops in Brazil is widespread and not restricted to biome and regional boundaries, the studies assessed in this section focused on detailing the specific responses of certain crops and cultivars, such as *Eucalyptus*, sugarcane, and maize, to climatic conditions characterized by water scarcity. In previous sections, we noticed that few studies conducted simulations using the Coupled Model Intercomparison Project—CMIP5 (Moss et al. 2010) and CMIP6 (Eyring et al. 2016)—to investigate the future behavior of soil water content under climate change scenarios. In contrast, this section, which is focused on agriculture, shows a concentration of articles exploring the crop yield and productivity of different typical Brazilian cultivars in the future. Although the results demonstrated variations in crop responses to water deficits, common findings indicated that several cultivars are expected to be negatively impacted by a future drier climate, given the direct effect of droughts on SM. Therefore, in a current and long-standing scenario where Brazil's economy is strongly supported by agriculture, the reviewed literature also enabled raising concerns about the direct and indirect impacts of drought on the country's economic growth. Moreover, several studies were conducted at the plot scale or under field conditions to investigate different ways to optimize water use in agricultural practices. In general, the cultivation of drought-tolerant varieties, the application of appropriate fertilization techniques, and the use of proper irrigation systems are among the approaches emphasized that can mitigate drought stress in agriculture.

As mentioned above, crop yield and productivity were recurrent topics in the studies addressed in this SotA review. In this regard, Pinheiro et al. (2019) discovered that within wetter and drier future projections spanning from 2040 to 2069, the water productivity of maize and soybean decreased in both projections, and their land productivity was negatively impacted by the drier scenario. Based on simulations from CMIP5 under the high forcing RCP8.5 scenario (Moss et al. 2010), the yield behavior is expected to be influenced by conditions related to soil water availability (Pinheiro et al. 2019). The high greenhouse gas emission scenario, RCP8.5, was also utilized by Moreira et al. (2023) to assess the impacts of climate change on soil water availability for soybean growth in southern Brazil. The study found that a 20% reduction in P generates a more pronounced reduction in SM than a scenario with a 2°C increase in $T_{\text{air}}$ (Moreira et al. 2023). Based on the objectives outlined by Pinheiro et al. (2019) and Moreira et al. (2023), it became evident that recent research is particularly concerned with investigating crop behavior in the future, given Brazil's heavy reliance on agriculture.

Therefore, such dependence may render the country vulnerable in the face of potential climate change impacts on this sector. Specifically concerning the global dependency of the European Union (EU) on agri-food imports, Ercin et al. (2021) evaluated the EU's susceptibility to drought severity using a cross-border climate vulnerability score. The key finding of the study was that over 44% of the EU's agricultural imports would become highly vulnerable in the future due to increased drought severity, including imports from tropical countries like Brazil. This vulnerability was assessed using a methodology where drought occurrence is interpreted as an extended period of low SM anomaly and as a consecutive sequence of months with SM quantile values below a predetermined threshold (Ercin et al. 2021). Ercin et al. (2021) also emphasized the importance of analyzing each crop and exporting location individually, as the results for the year 2050 indicated that the vulnerability level of Brazilian exports would be moderate for soybeans, high for coffee, and very high for sugarcane. In this scenario, a different approach was undertaken by Muthuvel et al. (2023), who investigated the effects of future concurrent droughts on maize yield globally. Standardized indices of P, $R_{\text{off}}$, and SM were incorporated into a multivariate standardized drought index. The high emission SSP5-8.5 (O'Neill et al. 2016) was utilized along with statistical and soft-computing techniques, and the study indicated that concurrent drought is expected to have an impact on maize yield in the far future (2061–2100), with occurrence probabilities reaching 37% in Brazil.

Regarding anthropogenic-induced drought, Duden et al. (2021) analyzed the expected impacts of increased crop production on both agricultural and hydrological drought. They compared drought indicators across Brazilian catchments from 2012 to 2030 under two scenarios: one with increasing demand for ethanol driven by sugarcane expansion, and another as a reference scenario with static ethanol demand. While differences between both scenarios were small when averaged over large areas, considerable changes are anticipated locally in regions such as the Centre West Cerrado. Almost one-third of this region, characterized by SM seasonality, is projected to experience agricultural drought due to sugarcane expansion (Duden et al. 2021). This emphasized the importance of promoting a trade-off between agricultural land use and the conservation of natural resources, as well as addressing the impacts of land use changes on water availability, particularly concerning SM deficits. An alternative frequently discussed in the studies of this section is the use of drought-resistant agriculture cultivars. For example, Santos et al. (2019) found that certain Brazilian sugarcane varieties increased their WUE when cultivated with 75% of the usual water demand, resulting in savings in irrigation costs and water availability, while still maintaining sugar yield. Montero Bulacio et al. (2023) also observed an increase in soybean yield for a variety approved for use in Brazil, which is tolerant to high temperatures and dry growing conditions, following a projected increase in P for the period from 2022 to 2044. Similarly, Hakamada et al. (2020) examined highly productive Eucalyptus in southeastern Brazil. They investigated the stocking effects on the ecosystem water balance of both a drought-sensitive and a drought-tolerant hybrid at the plot scale during 2013 and 2015. The results indicated that ET increased with stocking for both Eucalyptus hybrids, and only stockings below 1,000 trees $\text{ha}^{-1}$ exhibited greater P than ET. Although SM was not directly measured, in highly productive Eucalyptus planted in tighter spacings, a negative water balance is linked to long-term SWS, as the trees used soil water during dry periods (Hakamada et al. 2020).

Noticeably, several studies in this SotA review have highlighted the benefits of combined fertilization and irrigation approaches in enhancing the yield of various agricultural products. Furthermore, an understanding of subsurface behavior can also be considered when planning coupled fertilization-irrigation approaches for certain agricultural plantations. In this context, Asensio et al. (2020) also studied *Eucalyptus grandis* and observed hydraulic redistribution (HR), where vegetation extracted water from deep (wetter) soil layers and redistributed it to upper (drier) layers. This phenomenon was observed across experimental plots with contrasting combinations of fertilization (with or without potassium) and water supply (with or without throughfall exclusion). Despite HR occurring in all treatments, fertilizing *E. grandis* with potassium benefited wood biomass production and WUE, further facilitating tree growth during drought (Asensio et al. 2020). Another strategy identified by Fernandes et al. (2020) to enhance coffee yield involved the combined application of organic fertilization with half of the crop's water requirement. This approach resulted in a higher yield compared to exclusively mineral nutrition combined with irrigation set to meet the entirety of the coffee water demand.

Furthermore, not only the amount of irrigated water but also the type of irrigated system can impact the yield productivity. For example, Brum et al. (2021) investigated how different water supply regimes affected water fluxes within an Amazonian oil palm plantation during an ENSO-induced drought in 2015–2016. The palm trees were cultivated under three conditions: a control treatment (without irrigation) and two treatments with irrigation (drip and sprinkler systems). Although both irrigation systems were effective in mitigating drought stress, the sprinkler system was preferable for increasing yield productivity (Brum et al. 2021). Moreover, computational approaches can enhance water management and optimize agricultural yield, ultimately aiding farmers and stakeholders in strategic planning. In this regard, de Oliveira Aparecido et al. (2022b) employed soil and meteorological data, such as $T_{air}$, P, SWS, and water deficit, along with machine learning to predict *Coffea arabica* yield in southern Brazil. The models were able to successfully predict coffee yield up to 3 months before harvest (de Oliveira Aparecido et al. 2022b). Moreover, learning from the natural environment allowed Prudêncio de Araújo et al. (2020) to recognize that soils from a temporary pond in the Brazilian semiarid harbor several bacteria with high water stress tolerance and characteristics that promote plant growth under scarcity. Their findings were based on bacteria obtained from the bulk soil of *Mimosa bimucronata*, a species widely distributed in temporary ponds, which contributed to increasing the drought resistance of maize. Similarly, Lacerda-Júnior et al. (2019) concluded that the microbial communities of a preserved Caatinga forest were primarily influenced by SM, shedding further light on a better comprehension of dryland ecosystems. Finally, systematic mappings can aid researchers, farmers, and stakeholders in identifying knowledge clusters, trends, and gaps, as demonstrated by Hood et al. (2023). They developed a global systematic map of scientific studies addressing cassava farming practices. This approach facilitated the identification that Brazil not only accounts for a high number of publications on the subject but is also a major cassava producer. Moreover, this systematic mapping provided evidence-based insights into cassava production, offering a structured foundation to inspire the application of similar approaches in other systems (Hood et al. 2023).

## Summary and Conclusion

In this study, we conducted a SotA review to investigate the nexus between soil moisture and drought across Brazil. The aim was also to identify current and future feedback mechanisms between drought events and SM levels. Based on this, we observed that SM in each Brazilian biome and region may respond differently to water scarcity conditions. Overall, the strong seasonality of SM in both current and future scenarios suggests an intensification of extreme events. Although adaptive mechanisms were observed in several native vegetation species, due to the complexity of the coupled human-nature system, it became evident that the scientific community is concerned with finding ways to optimize water use in agriculture while maintaining crop productivity. The significance of these investigations is further underscored by the potential vulnerability of several typical Brazilian crops to future drier climates. Overall, it was observed that optimizing water use without compromising crop yield can be achieved through various measures, including the use of more drought-resistant cultivars, the adoption of combined fertilization and irrigation techniques, and the selection of appropriate irrigation systems. We highlight that these findings contribute to enhancing water resources management within the vadose zone, not only in Brazil but also in other agriculture-dependent countries.

Observations of the natural environment across Brazilian landscapes have been a focal point in numerous articles within this SotA review. Given the intertwining of native and managed lands, we suggest that managers and planners contemplate the adoption of strategies and policies conducive to a balanced approach between agricultural land use and the conservation of natural resources, particularly in light of water scarcity. Moreover, in addition to anthropogenic-induced land alterations, due attention should be directed toward addressing the impacts of natural climatic phenomena on SM availability. Given that soil water storage can be influenced by large-scale circulation mechanisms, a comprehensive examination of this interaction facilitates a deeper understanding of the soil moisture–drought nexus within both present and future scenarios.

Given Brazil's continental-scale dimensions, we have identified several procedures to investigate the relationship between SM and drought across various spatiotemporal scales. These methodologies encompass extensive field surveys and measurements, a wide array of modeling techniques, and the utilization of remotely sensed data. We recognized the pivotal role of drought and vegetation indices in discerning trends and patterns, alongside the significant support provided by climate projections in offering insights for the future. In this context, we have concluded that analyses conducted at the national scale are potent tools to contribute to decision-making processes and resource allocation. Simultaneously, local assessments remain indispensable for the conservation of ecosystems with distinct characteristics and specific native vegetation species.

Additionally, we emphasize that local-scale approaches are crucial for a better understanding of the physical mechanisms that govern the behavior of the land-atmosphere continuum under water deficit conditions, further aiding in drought mitigation. This is due to SM's continuous recognition as an essential variable for comprehending land-atmosphere interactions, particularly in drier climates. Moreover, the conventional practice of using other variables (such as $R_{off}$ and the number of antecedent days without P) as proxies for SM, and vice versa, must be approached cautiously in the future. This occurs because soil water storage can play a unique role that diverges from the behavior of the aforementioned variables within climatological and hydrological systems.

The overall findings of the conducted review complement the SR15, offering valuable insights to mitigate climate-related risks to food security, biodiversity conservation, and water resources management. Finally, we were able to draw conclusive remarks not only for Brazil but also to provide valuable insights beyond the Brazilian territory, especially to other tropical countries, regarding the comprehension of soil water storage under drought conditions, in both current and future scenarios.

## Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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## Author Contributions

Luis Eduardo Bertotto: Conceptualization; Formal analysis; Investigation; Project administration; Visualization; Writing – original draft; Writing – review and editing. Hirdan Katarina de Medeiros Costa: Conceptualization; Funding acquisition; Resources; Supervision; Writing – review and editing. Priscila Elise Alves Vasconcelos: Conceptualization; Resources; Writing – review and editing. Israel Lacerda de Araújo: Conceptualization; Funding acquisition; Resources; Writing – review and editing. Edson Cezar Wendland: Funding acquisition; Resources; Supervision.

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