UNIVERSITÉ DE GENÈVE
INSTITUT DES SCIENCES DE L'ENVIRONNEMENT

MAX PLANCK INSTITUTE FOR BIOGEOCHEMISTRY

Certificate of Geomatics

The impact of different types of droughts on vegetation dynamics

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2023

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Statement of authorship

I hereby declare that I have prepared this thesis independently and only using the aids and sources indicated. Direct and indirect quotations are acknowledged as references.

Jena, June14, 2023

Myriam Terristi

Acknowledgments

I consider myself incredibly fortunate to have had the opportunity to work alongside and be mentored by Dr. René Orth and Anne Hoek Van Dijke. I am deeply grateful for their acceptance, unwavering support, and guidance throughout this project. Their willingness “to take me under their wing” has not only provided me with invaluable knowledge and skills in scientific research but has also shaped my personal and professional growth. Their belief in me has been a constant source of inspiration, and I am truly privileged to have been part of their team.

I would also like to express my gratitude to Dr. Gregory Giuliani, my supervisor at the University of Geneva, for his continuous support and encouragement from the beginning.

I am deeply grateful to Dr. Ana Bastos for her invaluable guidance, profound insights, and unwavering belief in my abilities.

It has been inspiring to have the guidance of such esteemed scientists who are willing to dedicate their time to students and help them navigate through the research journey.

I would also like to extend my gratitude to the members of the Hydrosphere-Biosphere-Climate-Interactions (HBCI) Group at MPI-BGC for their valuable comments and contributions to my study. Their input has greatly enriched my work.

Lastly, this accomplishment would not have been possible without Him.

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First part

1. Introduction of the host organization

The Max Planck Institute for Biogeochemistry is a research institute located in Jena, Germany. It is part of the Max Planck Society, a renowned scientific organization dedicated to fundamental research in various disciplines. The institute focuses on the study of biogeochemical processes and their interactions in the Earth system, with a particular emphasis on understanding the role of terrestrial ecosystems in global environmental change.

At the Max Planck Institute for Biogeochemistry, scientists from different backgrounds, including atmospheric and climate sciences, biology, ecology, chemistry, physics, mathematics and statistics, collaborate to investigate the complex processes that occur in the biosphere, atmosphere, and hydrosphere. They aim to gain insights into the functioning of ecosystems, the cycling of essential elements like carbon, nitrogen, and water, and the impacts of human activities on the environment. The institute conducts cutting-edge research using a combination of field observations, laboratory experiments, and modeling approaches. It operates long-term monitoring networks, such as the FLUXNET network, which collects continuous measurements of greenhouse gas fluxes from ecosystems around the world. These extensive datasets contribute to our understanding of global carbon and energy cycles and help improve climate models.

In February 2023, I have joined the research group led by Dr. René Orth which] focuses on improving the understanding of the Hydrology-Biosphere-Climate system and its impacts on various aspects of human life. They combine land surface modeling with the analysis of Earth observations at a continental-to-global scale to enhance the physical understanding of the exchange of water, energy, and carbon between the land surface and the atmosphere. The group's research specifically investigates the interface of soil, vegetation, and atmosphere, aiming to uncover the exchange and feedback processes that can influence weather and climate patterns, food production, water availability, and ultimately, the economy and society. Their research has three main objectives: better understanding land-atmosphere coupling, improving the management of extreme events like droughts and heat waves, and enhancing the accuracy of weather forecasts and climate projections.

2. Traineeship insights

The Max Planck Institute for Biogeochemistry provides an excellent research environment for scientists, including postdoctoral researchers and doctoral students, fostering collaboration and knowledge exchange. A weekly department meeting is held, during which a selected scientist presents a 15-minute non-scientific talk followed by a scientific presentation on their current research. This format encourages interdisciplinary discussions and allows researchers to stay informed about the latest developments in various fields. Within our research group led by Dr. René Orth, there is a weekly meeting where each member of the group has the opportunity to present their ongoing research. These meetings provide a valuable platform for knowledge sharing, receiving feedback, and engaging in fruitful discussions. Furthermore, I, also have the privilege of having a personal weekly meeting with my two supervisors, which offers dedicated time for guidance, mentoring, and addressing any questions or concerns related to my research. Furthermore, the presence of abundant resources, combined with the diverse backgrounds of researchers at the institute, facilitate the application and advancement of my skills in geospatial data analysis and remote sensing. Engaging with my own work and collaborating with colleagues exposed me to a wide range of projects that expanded my knowledge of geomatics' practical applications, particularly in fields such as land surface modeling, climate change, and ecosystem dynamics.

One aspect that I found lacking at the Institute is a clear understanding of how the internal systems operate and how researchers can effectively connect and work with the research cluster. This lack of guidance and documentation can make it challenging for researchers to navigate and utilize the cluster resources efficiently. Indeed, working on a cluster is essential for my research on land-atmosphere-vegetation interactions due to the large-scale data analysis and computational tasks involved. It provides me the necessary computational power to process vast amounts of data and run sophisticated tasks. This can sometimes lead to challenges (e.g., working on evenings or during the weekends) in executing research tasks effectively. Additionally, there seems to be a miscommunication between the scientific department and the IT/administrative department, particularly regarding paperwork and administrative processes. Improving communication and coordination in these areas would greatly benefit newcomers and enhance their overall research experience.

Finally, I highly recommend this type of traineeship to anyone interested in the field of land-atmosphere dynamics. It provides an excellent opportunity to deepen one's skills in geospatial analysis, including the latest developments in geostatistics. The researchers at the institute are well-informed about the cutting-edge advancements in science, ensuring a stimulating and dynamic environment for learning and growth. Moreover, being part of an international organization offers unique opportunities to broaden one's horizons and gain valuable cross-cultural experiences. As an example of the rewarding nature of this internship, I had the privilege of having a group leader expressing interest in my work, leading to a meeting and an exciting proposal to pursue a PhD together.

Second part

Abstract

This study aims to deepen our understanding of droughts and their impact on vegetation productivity using Solar-Induced Fluorescence (SIF) data, recognized as a reliable proxy of gross primary production. It offers an in-depth analysis of the spatial and temporal response of vegetation to different types of droughts, including near-surface Soil Moisture (SM), Total Water Storage (TWS) anomaly, Vapor Pressure Deficit (VPD), and short and long-term precipitation deficits (PREC-3 and PREC-12). Our findings reveal that long-term precipitation deficit (PREC-12) is the main driver of negative vegetation anomalies. However, other variables may also significantly affect vegetation potentially depending on contextual factors such as biome types, soil attributes, and initial climate conditions. Additionally, the study indicates a plausible propagation effect in the influence of various drought types on plants, with the timing and sequence of impacts varying between high and low latitudinal regions. This suggests a potential role of regional characteristics in mediating drought impacts. These findings, although preliminary, provide valuable insights into the complex dynamics of vegetation-drought interactions and pave the way for more detailed future research. This understanding is crucial for effective management strategies to mitigate drought impacts on vegetation productivity, especially in the context of increasing climate variability and change.

1. Introduction

As a result of the intricate interaction between natural climate variations and anthropogenic climate change (Padrón et al., 2020), droughts are becoming more frequent and severe (IPCC, 2018, 2019). Consequently, their potential to significantly impact ecosystems, especially vegetation dynamics, has been drawing increasing attention over recent years from researchers across a broad range of fields, including ecology and economics ((Masih et al., 2014; Seleiman et al., 2021; Stige et al., 2006).

Drought is a complex climatic phenomenon commonly characterized by a substantial deviation from the normal water conditions (Heim, 2002). Its complexity means that understanding its impacts requires an in-depth exploration into the definition and concept of this occurrence. However, no scientific consensus has been reached to determine a homogeneous drought definition as it can vary in intensity, duration, and spatial extent, and can be classified into several types including meteorological (lack of precipitation or increase in atmospheric dryness), soil water content (lack of soil moisture), agricultural (adverse effect on vegetation health), hydrological (reduced runoff and water in streams and reservoirs), and socioeconomic (reduced water supply for human uses) droughts (Sheffield & Wood, 2011; Wilhite & Glantz, 1985). Notably, despite various established conceptualizations of drought, our understanding of the frequency and severity of vegetation responses to water scarcity remains incomplete. Although, a shortage of water availability can disrupt the normal functioning of the water, energy and biogeochemical cycling and consequently a decline in vegetation productivity (Chapin et al., 2011) which can, in turn, influence climate regulation (Heimann & Reichstein, 2008). Meanwhile, the impacts can be felt in agriculture, with droughts hampering crop productivity, affecting food security (Almer et al., 2017; Harari & Ferrara, 2018), and impacting economies that heavily rely on agriculture ((Iizumi & Ramankutty, 2016; Lesk et al., 2016).

Vegetation exhibits a myriad of physiological and structural responses to mitigate the effects of water stress either through lack of soil water availability and/or high atmospheric water demand. One of the first notable mechanisms occurs when plants close their stomata – microscopic pores on the plant leaf surface involved in the exchange of gases and water vapor between the plant and the atmosphere ((Kozlowski & Pallardy, 2002) – to reduce water loss by transpiration and prevent vegetation mortality due to hydraulic failure. However, it comes with a trade-off as it limits photosynthesis due to reduced carbon dioxide uptake (Flach et al., 2021) and can potentially lead to carbon starvation (Kozlowski & Pallardy, 2002) .In addition to stomatal closure and photosynthesis reduction, plants also optimize their water use efficiency (WUE) during drought conditions which is defined as the ratio of carbon gain in photosynthesis and water loss through transpiration. It typically increases under drought as a plant's adaptive response to maintain photosynthetic output while minimizing water loss (Farooq et al., 2009). This balance between water conservation and carbon gain underpins much of the vegetation response to drought, with implications on plant growth, productivity, and ultimately survival (McDowell et al., 2008). Therefore, a comprehensive understanding of the response of vegetation to drought conditions is not only essential for terrestrial ecosystems management but also for predicting potential impacts of climate change on society as a whole (IPCC, 2018).

The functioning of vegetation dynamics depends on land-climate interactions, which serve as the basis for several biophysical processes. Nevertheless, these very same interactions have the potential to directly affect and potentially endanger their efficiency (Bonan, 2008; Chapin et al., 2011; Seneviratne et al., 2010). This explains the reason why the relationship between drought and ecosystems dynamics has been a vigorous field of study in the past few years.

Numerous studies have delved into this relationship, focusing on different drought variables that represent key facets of land-vegetation-atmosphere feedback loops (Miralles et al., 2019; Vicente-Serrano et al., 2012; Zscheischler et al., 2014). These include scenarios where soil moisture deviates from normal conditions, causing the soil to dry out and leading to a general decline in plant activity. Such reductions in plant activity translate to a decrease in evapotranspiration, consequently amplifying atmospheric dryness due to the accumulation of sensible heat. This dynamic results in a pronounced reduction in relative humidity and, therefore, rainfall, thereby intensifying the overall dry conditions (Miralles et al., 2019; Seneviratne et al., 2010).

In terms of more conventional proxy for estimating drought induced vegetation stress such as precipitation and soil moisture (SM) anomalies impacts on vegetation dynamics, several studies have reached a consensus (e.g., Méndez-Barroso et al., 2009; Ponce-Campos et al., 2013; Wang et al., 2023; Zhu et al., 2018) showing a strong negative correlation between their respective anomalies and terrestrial ecosystems. They demonstrated how drought-induced reductions in precipitation or SM can severely hamper photosynthetic activities in vegetation. However, the complexity of this relationship extends beyond these hydrological-drought indicators (Vicente-Serrano et al., 2012). To truly grasp how vegetation responds to drought, one must consider other variables that come into play, which impact the overall vegetation dynamics as well as the specific time-scale of drought that impacts vegetation most significantly (Vicente-Serrano et al., 2012). Indeed, soil moisture (near-surface soil moisture and groundwater), precipitation or Vapor Pressure Deficit (VPD) are just a few examples of these variables. Researchers have started to disentangle the influence of the different variables implied in the land-climate interactions as each can contribute in a unique way to the process, and their specific roles can be decisive in shaping the magnitude of vegetation's response to drought conditions. However, it is critical to acknowledge that these relationships, shaped by numerous variables, exhibit intricate dynamics that vary both spatially and temporally and can trigger complex, non-linear effects on ecosystems (Li et al., 2021).

In this context, Novick et al. (2016) offers valuable insights into the disentanglement between SM and VPD impacts on ecosystem functioning and highlights VPD as a pivotal variable in understanding the response of vegetation to drought conditions. The authors combined ground-based data from flux towers and climate models and assessed the independent constraining effect of SM and VPD's changes on ecosystems' growing season transpiration across a range of biomes during periods experiencing hydrological stress, both for present-day and projected future climatic conditions. Their findings confirmed that the role of VPD in inducing water stress in vegetation cannot be underestimated. They noticed a strong inverse relationship between VPD and leaf stomatal conductance, indicating that elevated VPD levels can cause even more significant changes in plant water dynamics than SM. Importantly, they found that this effect was not confined to a specific biome type, indicating that VPD sensitivity could be a ubiquitous phenomenon among various ecosystems. Their findings also highlighted that the role of VPD in vegetation dynamics could become even more significant as the role of SM in determining ecosystem transpiration tends to differ across diverse sites and models while he tendency for VPD to limit the ecosystem functioning appears to be a consistent trend for the majority of ecosystems in the future.

This aligns with the recent study conducted by (Fu et al., 2022) which examines the effects of SM and VPD on Gross Primary Productivity (GPP), a measure of photosynthesis. The authors used observations from 15 European flux towers sites to study the exceptionally severe drought in the summer of 2018.Their paper is adding weight to the argument that atmospheric dryness has a substantial effect on photosynthesis across a broad range of soil moisture levels, highlighting the importance of considering both soil and atmospheric drought in understanding and modeling ecosystem responses to future climate change.

Terrestrial Water Storage (TWS) has also emerged as a crucial variable in the evaluation of drought-induced vegetation stress (Rodell et al., 2018). TWS refers to the total water column stored on the land surface and subsurface, including soil moisture, groundwater, snow and ice, surface water, and wet biomass. For instance, it can help vegetation withstand periods of drought as deep-rooted plants and trees can access groundwater when soil moisture is low (Fan et al., 2017). TWS Anomaly (TWSA) is emerging as a valuable indicator for predicting changes in vegetation activity. In line with this, using data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission, (Khanal et al., 2023) found that in high tree-cover and arid regions, Near-Infrared Reflectance of Vegetation (NIRv) correlated more strongly with TWS than near-surface soil moisture. These findings are similar to the ones from (A et al., 2017) who investigated vegetation-moisture relationships in Texas and surrounding semi-arid regions. Their research suggests that TWS time series are a valuable resource for assessing alterations in the temporal patterns of water shifts and have a stronger impact on vegetation growth than surface SM especially under severe drought conditions. It is particularly true for natural grassland and forest areas which display a higher sensitivity to TWS changes. Yang et al. (2014), conducted extensive studies that spanned various biomes and climatic areas across the globe. Their results highlight the significant role of TWS variations in driving both greening and browning trends (measured by the Normalized Difference Vegetation Index - NDVI) both seasonally and year by year. Furthermore, (A et al., 2015) suggest that alterations in TWS due to a warming climate change might result in the loss of certain ecosystems like forests in regions presenting drying trends.

While the existing body of research has shed light on drought-vegetation dynamics, there still exist significant gaps that warrant further research. Yet, a notable shortcoming is the lack of a consensus on an accepted drought definition, making it challenging to comprehensively study the varying impact of different types of droughts on vegetation productivity. In addition, most of the existing studies often restrict their focus to one or two variables at most. However, this approach may not capture the full complexity of the drought-vegetation dynamics. As mentioned above, a comprehensive understanding of the impacts of different drought variables embedded in the land-climate continuum is of paramount importance given the distinct and significant impacts of each of them on ecosystems. Furthermore, conventional drought monitoring methods have been largely dependent on ground-based observations, while they have their merits, they offer limited spatial coverage and potential inconsistencies which can hamper the full understanding of variability in drought monitoring. Today, the emergence and widespread availability of satellite data present a significant advancement. Remote sensing data allow for a comprehensive spatial and temporal coverage, providing a more complete picture of drought conditions over a variety of scales and resolutions. Therefore, this study focuses on harnessing the advantages of satellite-derived data, aiming to overcome the limitations of traditional approaches. Addressing these identified research gaps will help in clarifying the intricate relationship between these variables, enabling better prediction and management of the effects of drought on ecosystems.

Our work is inspired by several trends in the aforementioned literature but partly differs in several ways. First, a primary objective of this research is to contribute to the ongoing debate on drought definition and broaden the scope of the investigation by incorporating a rich set of hydrometeorological drought variables. Additionally, unlike traditional vegetation indices, that predominantly concentrate on capturing light reflection from vegetation, we use Solar-Induced Fluorescence (SIF) data which provides a more nuanced picture of the photosynthetic activity, measuring directly the light emitted by plant’s chlorophyll molecules (Li et al., 2021). It has been acknowledged as a reliable proxy of gross primary production proxy (Guanter et al., 2014) for assessing the link between vegetation productivity response to hydrometeorological stressors (Li et al., 2021).

We aim to analyze how different drought types affect vegetation productivity. This will offer a more comprehensive understanding of the complex interplay between different drought types and vegetation productivity. Our research questions are:

i. How does the impact of different drought types on vegetation productivity vary spatially?
ii. Which drought type holds the most significant influence on vegetation productivity?
iii. What are the temporal patterns in the impacts of different drought types on vegetation productivity?

We argue that by elucidating how these variables influence spatio-temporally vegetation's response to drought, we can improve our understanding of how vegetation may respond to future droughts, particularly under the scenario of intensifying climate change.

2. Methods

2.1 Data

Table 1 | Overview of the datasets

Dataset	Variables	Sources	References	Resolution
Meteorological	Vapor Pressure Deficit (VPD)	ERA5-Land	(Muñoz-Sabater et al., 2021)	Monthly temporal coverage from 2007 to 2018 Spatial resolution of 0.5°×0.5°
	Precipitation-3 (PREC-3)	MSWEP v2.8	(Beck et al., 2019)	
	Precipitation-12 (PREC-12)			
Soil water storage	Near surface Soil Moisture (SM)	ESA-CCI	(Dorigo et al., 2017)	
	Total Water Storage (TWS) Anomaly	GRACE	(Landerer & Swenson, 2012)	
Vegetation functioning	Solar-induced Fluorescence (SIF)	GOME-2	(Köhler et al., 2015)	

2.1.1 Vegetation data

SIF stands for Solar-Induced Fluorescence, which is a process where "*the chlorophyll-a of photosynthetically active vegetation emits a small fraction of its absorbed energy as an electromagnetic signa*l" (Köhler et al., 2015). Therefore, the amount of fluorescence emitted is directly related to the amount of photosynthesis, making SIF a key indicator of plant productivity. We employ satellite-observed SIF data retrieved from GOME-2 (Global Ozone Monitoring Experiment, Munro et al. (2016)) instrument which is a satellite-based sensor that is capable of measuring the SIF wavelength region (650-800nm) from space. The GOME-2 SIF data provides a high spatial and temporal resolution record of photosynthetic activity over large areas of land. In addition, multiple corrections for varying solar zenith angles, differences in overpass times and cloud fraction have been applied to yield reliable SIF estimates as described by (Köhler et al., 2015; Kroll et al., 2022; Li et al., 2021).

2.1.2 Meteorological variables

VPD

As for the meteorological variable, we consider vapor Pressure Deficit (VPD) which is defined as the difference between the saturation vapor pressure (the maximum amount of moisture that the air can hold) and the actual vapor pressure (the amount of moisture that is actually in the air) from the ERA5-Land reanalysis data – the fifth generation of ECMWF (European Centre for Medium-Range Weather Forecasts) atmospheric reanalyses of the global climate– (Hersbach et al., 2020), which provides a comprehensive view of past weather and climate conditions. ERA5-Land (Muñoz-Sabater et al., 2021) provides estimates of VPD at different levels in the atmosphere, ranging from the surface up to a height of 80 km. However, for most applications, VPD at the surface level is the most relevant variable, as a high VPD can cause plants to close their stomata to conserve water, which can decrease photosynthesis and thereby decrease SIF.

Precipitation

The data used is from MSWEP which stands for the Multi-Source Weighted-Ensemble Precipitation dataset from GloH20 (Beck et al., 2019). It is a global precipitation dataset that was created to optimally merge multiple quality precipitation data sources based on timescale and location. For each location, MSWEP adjusts weighting of gauge-based, satellite-remote-sensing, and atmospheric model reanalysis estimates, resulting in a global precipitation dataset from 1979-2015 with 3-hourly and 0.25° resolution. This approach helps to reduce errors and biases in the data and provides a more accurate representation of precipitation patterns. In our study, we computed PREC-3, which represents the total rainfall accumulated over a span of three months. This three-month time-scale allows to evaluate the effects of short-term drought on the moisture content of surface soil and, consequently, on vegetation stress levels. We also computed PREC-12 to acknowledge long-term drought conditions.

2.1.3 Soil water storage

Near-surface soil moisture

In our analysis, we included two different type of soil water availability. We consider the near-surface soil moisture from the European Space Agency (ESA) Climate Change Initiative Program (CCI). Near-surface soil moisture refers to the amount of water stored in the upper few centimeters of the soil. It is an important variable in the water cycle as it directly affects the availability of water for plants and influences the rate of evaporation from the land surface.

The dataset used integrates active and passive microwave sensors to provide a cohesive, continuous record that minimizes the gaps that may occur when relying on a single satellite system (Dorigo et al., 2017).

TWS Anomaly

The TWS Anomaly data is derived from the GRACE mission (Landerer & Swenson, 2012). GRACE is a satellite-based mission that provides information about the change in total water storage, including groundwater, soil moisture, snow, and surface water. It does this by observing changes in Earth's gravity field over time, which can be attributed to changes in the distribution of water mass across the Earth's surface (Tapley et al., 2004).

2.2 Methodology

2.2.1 Preprocessing

Initially, all data sets were harmonized to correspond to a monthly temporal range from 2007 to 2018, as the concurrent availability of all data sets matched this time period. The spatial resolution was set to 0.5°, with some datasets resampled accordingly. Following these initial standardization steps, we subtracted the long-term mean monthly cycle from the absolute values to compute the monthly anomalies, thereby eliminating the seasonal cycle from the vegetation data.

Additional filtering steps were applied to focus on relevant grid cells.

Following the approach of (Li et al., 2021) only active vegetation (growing season) was considered in the analysis by discarding months with an absolute SIF value below the threshold of 0.5 mW m^{-2} sr^{-1} nm^{-1} (Fig. 1). Furthermore, an additional temperature threshold mask ($T > 5^{\circ}C$) was applied on the SM data, excluding months with frozen soil that are not relevant to plant water availability. Then, to further refine the data, each grid cell's data was scrutinized by excluding grid cells with fewer than 40 monthly anomalies over the study period.

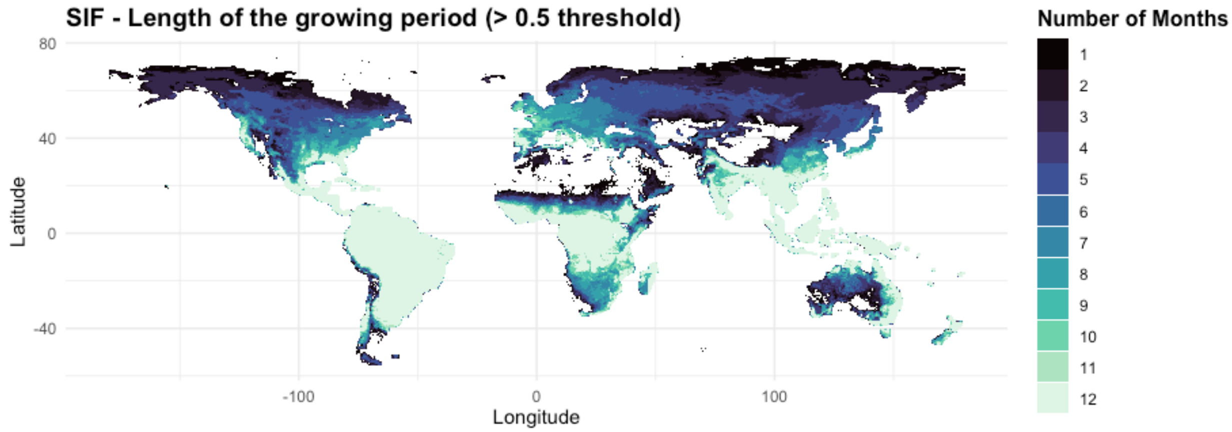

Figure 1 | Length of the growing season correspond to a SIF monthly mean seasonal cycle > 0.5 mW m−2 sr−1 nm−1.

2.2.2. Drought identification

After these filtering steps, we carried out an identification process to recognize the driest month for each hydrometeorological variable across the entire time span from 2007 to 2018. This step was crucial in isolating the periods most susceptible to show abnormal dry conditions. Upon determining these driest months, we subsequently identified the corresponding SIF anomalies for each grid cell. This allowed us to evaluate the vegetation response to these extreme drought conditions, revealing the impact of such dry spells on plant physiological processes.

2.2.3 Geospatial analysis

In this study, we employed a comprehensive array of sophisticated Geographic Information System (GIS) tools mainly within the R environment to implement our methodology and undertake complex spatiotemporal analyses of different drought types and their effects on vegetation productivity.

Prior to the utilization of R, we made use of the Climate Data Operator (CDO) program from the Max Planck Institute for Meteorology. This was instrumental in processing the large-scale datasets during the preliminary stages of our analysis. CDO facilitated the extraction of the specific time periods of interest and executed in a very effective way, the resampling operations when needed to match the 0.5° spatial resolution.

At the forefront of the geospatial approach was the 'raster', ‘rgdal’ and ‘sp’ packages in R, which offered an extensive set of functions for handling and processing the datasets, frequently formatted as netCDF files. We used these packages extensively to manage our diverse datasets, including the conversion of the data into spatial data frames, facilitating the overlay of different spatial layers to a uniform grid of 0.5, to scrutinize grid cell data by aggregating and extracting data at the cell level through function like `cellStats` and `getValues` functions, enabling us to exclude cells with insufficient monthly anomalies over our study period. Also, the 'dplyr' and 'tidyverse' packages proved to be invaluable in our data wrangling operations. They provided us with an efficient framework to clean, transform, and filter the data. The use of functions like `filter()`, `mutate()`, `summarize()`, from these packages facilitated for instance, the implementation of temperature constraints on our soil moisture data, subsequently enabling the elimination of frozen soil regions. Furthermore, leveraging the `case_when()` function allowed us to set thresholds for SIF values, assisting us in identifying areas of active vegetation growth. For the drought identification process, the function `which.min` from the base R package facilitated the temporal identification of the driest periods. By using the `merge` function from the `data.table` package, we were able to associate these periods with corresponding SIF anomalies for each grid cell.

Moreover, the study employed GIS tools for spatial mapping through packages such as ‘ggplot’ and ‘tmap’. The use of spatial data representation through maps enabled us to discern geographical patterns and variations, assess regional disparities and fine-scale patterns across the study area, and more importantly, comprehend the spatio-temporal influence of the hydrometeorological drought variables on vegetation productivity which will be further described in the results section. This form of visual analysis allowed for a more nuanced interpretation of the findings, enriching the depth of the study. It also offered a powerful tool for communicating complex spatial relationships in an accessible and visually compelling manner.

In conclusion, the use of these GIS tools in R offered a versatile and robust approach to data manipulation, spatio-temporal computation, and detailed mapping analysis.

3. Results and discussion

In the following section, all the results of this study are being presented following the initial research questions stated in the introduction.

3.1 Spatial patterns

We define how different drought types affect vegetation productivity and identify which specific form of drought holds the most significant influence on it. As described in 2.2.2, each map (Fig.2) pertaining VPD, SM, TWSA, PREC-3 and PREC-12 provides an in-depth understanding of the vegetation response to the driest month's conditions between 2007 and 2018. They illustrate the spatial variation of SIF anomalies in response to the extreme dry conditions of each variable, thereby presenting a clear picture of vegetation productivity under such conditions.

It is essential to recognize that the impacts of drought, as defined by its associated water deficit, are primarily felt in water-controlled regions, where the availability of water directly influences vegetation. However, in energy-controlled regions where sufficient water is available (e.g., in deeper soil layers or groundwater), water deficits associated with drought exert minimal or no impact on vegetation. Instead, warmer conditions typically associated with drought often affect vegetation's functioning in these areas (Denissen et al., 2020; Orth, 2021)

Across all four maps, we observe the emergence of clusters, indicative of spatial patterns in vegetation's response to drought. Areas such as central US, eastern and southern South America, Southern Africa, Western and Southern Russia, and Indonesia predominantly exhibit negative SIF anomalies. This could be indicative of a reduction in vegetation productivity during the driest periods. For instance, numerous significant drought events in the Central US have been linked in part to warmer sea surface anomalies in the North Atlantic and considerable precipitation deficits (Cook et al., 2015). Similarly, cascading effect of multi-years of reduced average rainfall combined with increased evapotranspiration due to a regional drying trend in the Western Cape region and a decrease in groundwater storage during El Niño events, have contributed to the observed conditions (Kolusu et al., 2019; Otto et al., 2018). Moreover, in Northeast Brazil, recurrent drought events have been associated with a northward shift of the Inter-Tropical Convergence Zone (ITCZ) resulting in below-normal rainfall (Marengo et al., 2018). Increased atmospheric blockings causing extended periods of higher-than-normal temperatures and soil moisture anomalies have been identified in the Siberian region (Hauser et al., 2016), while persistent drought-induced agricultural disasters during Indonesia's dry season have been influenced by El Niño events (Sabuna et al., 2022; Surmaini et al., 2019). Land-use changes also play a significant role, with long-term deforestation in the Amazon rainforest altering moisture recycling and transport mechanisms (including tree respiration, river streamflow, and atmospheric rivers), thereby affecting precipitation in the southern part of the country (Getirana et al., 2021; Marengo et al., 2018), among other factors.

Conversely, we notice clusters of positive SIF anomalies - potential signs of increased or resilient vegetation productivity during dry conditions - in high latitudes and equatorial ecosystems e.g., the Amazon rainforest, the Congo forest, Eastern Russia, and parts of Canada. These findings suggest that vegetation in these regions considered for some as energy-limited regions (Li et al., 2021; Orth, 2021; Seneviratne et al., 2010) may benefit from warmer temperatures.

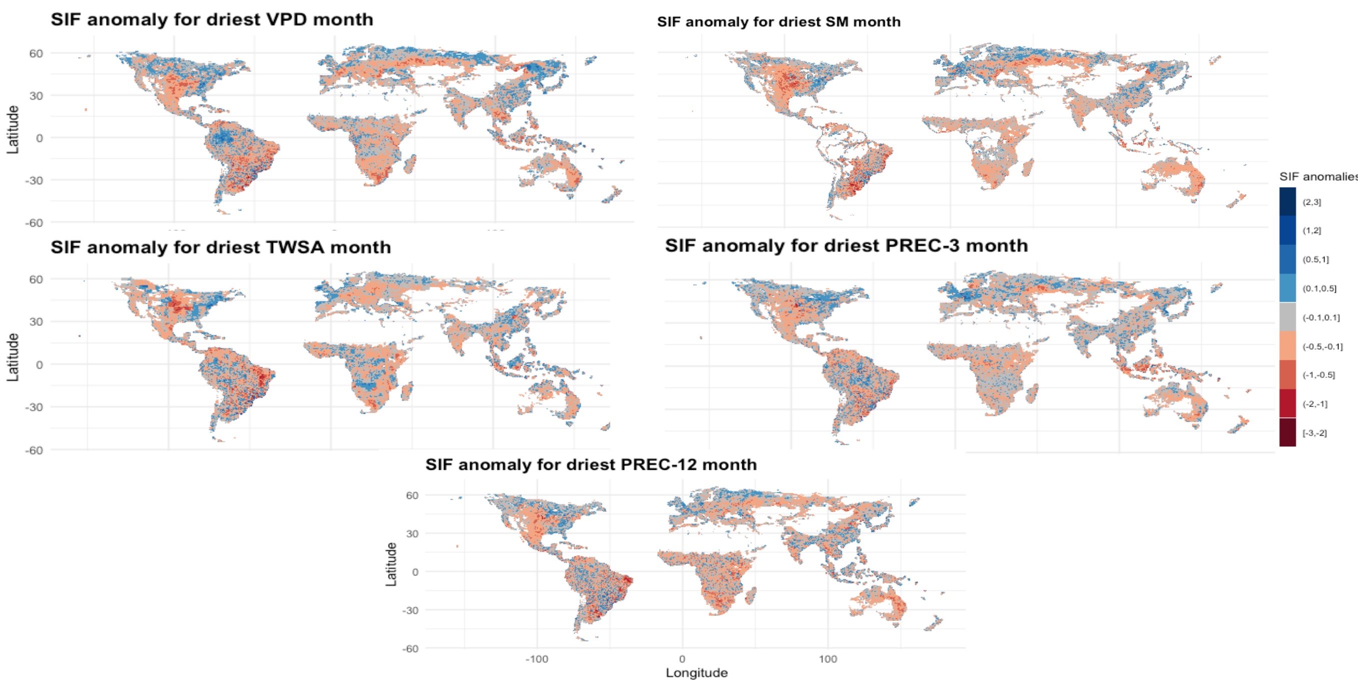

Figure 2 | Spatial Variation of Vegetation Productivity in Response to Different Types of Drought Conditions (2007-2018).

These maps offer a crucial first step towards understanding the complex spatio-temporal dynamics of vegetation response to different drought types. However, these are initial visual observations and will require further quantitative analysis to discern the nature and drivers of these patterns.

3.2 Hydrometeorological driver of negative vegetation anomalies

We aspire to develop a more nuanced understanding of the role of these drought variables in vegetation dynamics, particularly in determining the kind of drought that most profoundly affects vegetation productivity. As such, we pinpoint the hydrometeorological variable that is associated with the most negative SIF anomalies during the respective detected drought. In Fig. 3, every grid cell is delineated by a unique color representing its dominant hydrometeorological variable. We consider only the grid cells comprising clearly negative anomalies (<-0.1).

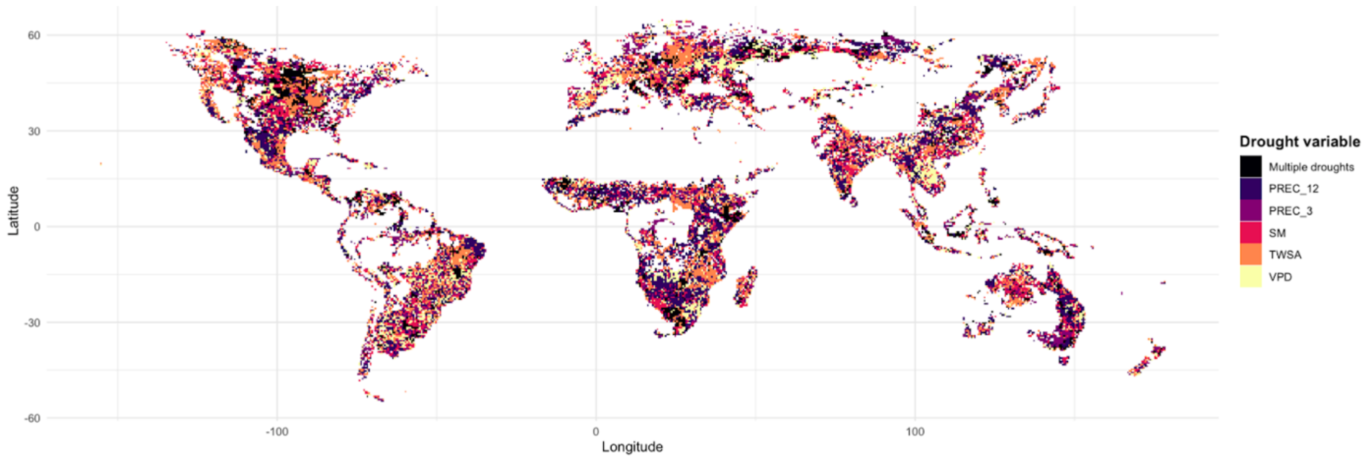

Fig. 3 | Global distribution of hydrometeorological droughts controls of negative SIF anomalies. Each grid cell identifies the most relevant variable co-occurring with negative SIF anomaly <-0.1.

Building upon the insights from Figure 3, it becomes evident that the map's interpretation is not as straightforward as it might initially seem, due to the lack of distinct spatial patterns. This result suggests that all types of droughts hold relevance across different regions globally, be they arid or mesic, and on all continents. However, despite the absence of clear spatial delineations, some clusters do emerge. Recalling our observations from Figure 2, we notice that the grid cells with negative SIF anomalies, which are observed across all variables, indicate areas affected by compound drought effects. Also, a closer look at Figure 3 reveals distinct clusters of TWSA, predominantly observed in the Baltic countries, over the Great Lake region in Africa, in Canada, and some parts of eastern Brazil. Finally, we observe clear clusters of VPD, primarily in France, Mozambique, and Southern Asia. These findings highlight that the effects of different drought types can be region-specific and influenced by other factors. Moreover, to assess the representativeness of our findings, we assume that the variable most frequently associated with negative SIF anomalies is the one that has the greatest effect on vegetation productivity. Accordingly, Table 2 presents the percentage contribution of each variable. Taking all grid cells into account, PREC-12 appears as the prevailing factor driving negative SIF anomalies.

Table 2 | Percentage Contribution of Each Hydrometeorological Variable to Negative SIF Anomalies and Vegetation Productivity.

Variable	**Frequency percentage (%)**
PREC-12	21.81%
TWSA	18.67%
Multiple droughts	17.89%
VPD	16.65%
SM	13.76%
PREC-3	11.20%

The significance of PREC-12 as the dominant variable in influencing negative SIF anomalies can be due to its ability to capture long-term water availability and long-term drought, a key resource for plant growth and survival. This measure also plays a significant role in shaping the overall dynamics of SM (Q. Liu et al., 2017), a major factor in plant health. SM, PREC-3, and VPD typically vary on the shorter-term. SM as well as short-term precipitation (PREC-3) mainly affect the upper soil layers. They can fluctuate quite rapidly due to various factors such as evapotranspiration and plant water uptake particularly under dry conditions (Seneviratne et al., 2010). It is also the case for VPD representing the atmosphere's demand for moisture. The latter affects evaporation from soil and plant surfaces as well as transpiration rather than directly altering SM. On the other hand, PREC-12 offers a long-term representation of water availability. If there has been adequate long-term precipitation, water can reach deeper soil layers that can conserve sufficient moisture to sustain plant life especially in semiarid and subhumid biomes (Vicente-Serrano et al., 2013). It can also be an indication about the overall capacity of the vegetation to withstand disturbances. While short-term precipitation might alleviate immediate drought impacts, the recovery of vegetation post-drought often relies on long-term precipitation, which influences the deeper soil moisture reservoirs that plants rely on during the recovery period (Fensholt et al., 2013).

Furthermore, the concept of 'memory effect' has gained attention in scientific research, as evidence suggests that plants can have a 'memory' of past conditions which can influence their current and future states(Kusch et al., 2022; Padisak, 1992). This memory arises from physiological adaptations that enable them to endure environmental constraints. Therefore, the accumulated rainfall deficit over a prolonged period can influence the SIF anomalies more significantly than recent precipitation deficit events alone (Ogle et al., 2015), because it impacts the historical condition of the soil and plants (McDowell et al., 2008).

Nonetheless, it's important to note that while PREC-12 can be a key variable, the impact of other hydrometeorological variables such as VPD, SM, TWSA and PREC-3 are also significant and might dominate in other specific regional or temporal contexts depending on biome types, soil characteristics, or initial climate conditions.

In this context, it is worth mentioning that two or more types of droughts occur at mostly 18%. Multiple droughts, often named "Compound" droughts, refer to two or more types of droughts occurring simultaneously. Numerous studies (e.g., Bastos et al., 2021; Zscheischler et al., 2018) have emphasized the significance of understanding compound drought events due to their amplified implications on ecosystems as they could significantly increase vegetation stress and potentially lead to large-scale mortality.

3.3 Temporal patterns

In an effort to better comprehend the spatio-temporal complexity of the relationship between long-term drought and negative SIF anomalies, this part zooms in on the temporal dynamics between the most relevant drought variable, PREC-12 and the other variables involved in the water balance of the land-atmosphere continuum, namely: PREC-12 and VPD; PREC-12 and SM; PREC-12 and TWSA; and PREC-12 and PREC-3. We aim to identify any synchronicity between them and the vegetation response. To this end, we present, for each grid cell (Fig.4), the monthly deviation between the long-term drought indicator, PREC-12, coinciding with the SIF anomalies and the monthly driest values from the other hydrometeorological variables within a 12-month time window.

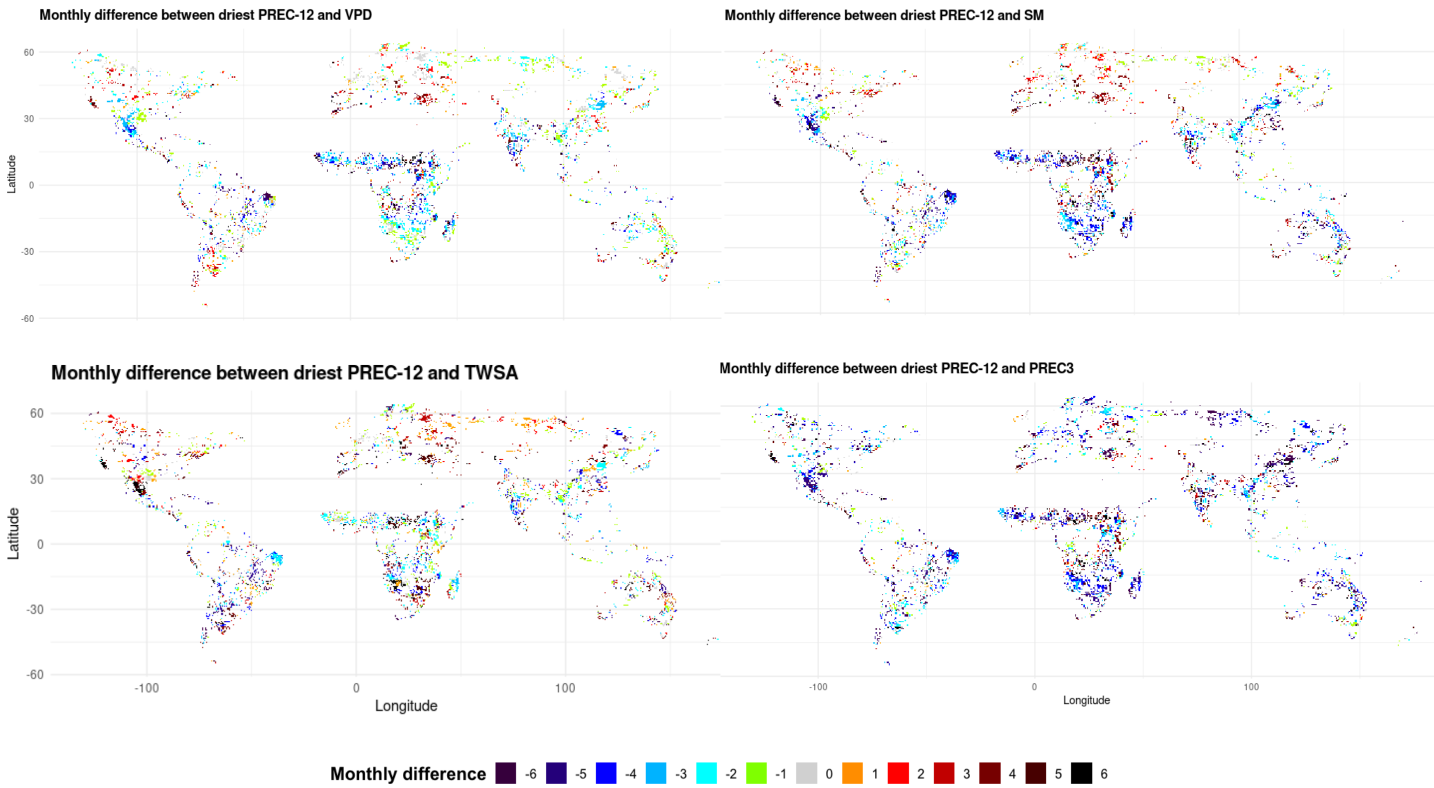

Fig. 4 | Monthly deviation distribution of PREC-12 controlling negative SIF anomalies and the other hydrometeorological droughts. Each grid cell identifies the driest monthly PREC-12 value and the corresponding driest monthly value from (top left to bottom right) VPD, SM, TWSA and PREC-3 within a 12-month window. Note: Monthly differences are in comparison to PREC-12. For instance, -6 indicates VPD peaked 6 months prior to PREC-12.

The temporal distribution mapping of the most severe effects of the different drought types on vegetation reveals an intriguing spatial and temporal complexity. A notable observation is that the timing of the strongest drought is typically not concurrent across different drought variables. Instead, these peaks happen at different times, showing that different kinds of drought don't affect plants all at once, which might be indicative of a propagation effect potentially influenced by the initial land-atmosphere interactions. In fact, the magnitude of the impacts are typically not immediate and plant's resistance and resilience mechanisms to droughts might differ between vegetation types and biomes (Vicente-Serrano et al., 2013).

The patterns, however, diverge when we compare high and low latitudinal regions. For regions closer to the equator, VPD and soil moisture (SM) droughts precede the long-term precipitation (PREC-12) droughts, whereas, at higher latitudes (above 30 degrees), the sequence is reversed:

VPD and SM droughts follow the onset of PREC-12 droughts. This latitudinal difference is particularly evident in the case of soil moisture droughts. Moreover, short-term precipitation (PREC-3) droughts seem to exert their strongest impact on vegetation ahead of the effects of PREC-12 droughts. This observation hints at the possibility of an immediate drought-induced vegetation stress response to short-term precipitation variations as explained in 3.2. The observation that short-term precipitation droughts (PREC-3) are strongest before long-term precipitation droughts (PREC-12) could be due to the immediate impact of reduced precipitation on the availability of soil water in the upper layers. Again, the effect on vegetation will be different depending on the vegetation types where forests for example are more affected by long-term precipitation deficit affecting deeper soil layers than short-term drought.

Overall, the differences between high and low latitudes could be influenced by various factors such as the type of vegetation, the climatic conditions, and the soil properties. In fact, climatic events can exhibit different spatio-temporal dynamics across latitudinal gradients. In lower latitudes, the hydrological cycle is more constant than other latitudes as those latitudes experience little seasonal variation. Moreover, they receive the highest amount of solar radiation which lead to high temperatures, evapotranspiration rates which can explain that VPD and SM impacts tend to happen earlier than a reduction in long-term precipitation. In contrast, at higher latitudes, lower temperatures and evapotranspiration rates could delay the impact of VPD and SM droughts until after a long-term reduction in precipitation has occurred.

While the current analysis doesn't permit a more granular quantification of the temporal lead and lag relationships between these variables, these initial observations provide crucial insights for future, more detailed investigations. The possibility of pinpointing, for instance, the average lag in months between different variables at specific latitudes could enhance our understanding of these complex interactions in the future.

4. Conclusion

The study provides a comprehensive overview of vegetation's spatial and temporal response to various drought types, namely near-surface SM, TWS anomaly, VPD, PREC-3 and PREC-12. The spatial patterns of vegetation response to drought, as illustrated through our maps, show that drought, as defined by water deficits, impacts vegetation primarily in water-controlled regions. However, we also see clusters of positive vegetation productivity responses in energy-limited regions such as high latitudes and equatorial ecosystems, indicating the complex nature of vegetation responses to drought conditions.

Furthermore, our examination of the most relevant drought variable driving negative vegetation anomalies reveals that long-term precipitation deficit (PREC-12) appears to be the predominant driver, with approximately 22% of all grid cells showing this factor. This observation underscores the importance of long-term water availability in vegetation productivity. However, the complexity of the interactions between different variables, and the context-dependent nature of their impacts, indicates that other variables can also be significant drivers depending on biome types, soil characteristics, or initial climate conditions. Moreover, our results suggest that different kinds of drought do not affect plants all at once, indicative of a propagation effect. Interestingly, we found that the timing and sequence of these effects differed between high and low latitudinal regions, with VPD and SM droughts preceding long-term precipitation droughts near the equator, while the sequence is reversed at higher latitudes.

This difference between latitudes points to a possible role of regional factors such as vegetation type, climatic conditions, and soil properties in mediating the impacts of drought. Understanding these nuances is crucial for developing more effective strategies for managing and mitigating the impacts of drought on vegetation productivity.

Though there are some limitations in our study, our findings, while insightful, represent a preliminary exploration into the complex dynamics of vegetation response to different drought types. Further, more detailed investigations will be needed to quantify the relationships between different variables and discern their specific roles under different contexts. This will be critical for enhancing our understanding of these complex interactions and their implications for vegetation productivity, particularly in the face of increasing climate variability and change.

5. Limitations

It’s worth mentioning that our study possesses notable strengths that enhance our understanding of the subject matter. Firstly, remote sensing data provides an expansive reach and accuracy, surpassing the limitations of traditional drought monitoring reliant on meteorological station observations in time and space. This technology enables global continuous coverage of various hydrometeorological variables crucial for drought analysis. For instance, in the case of Soil Moisture (SM), remote sensing allows us to obtain data over larger areas, a significant improvement over land surface models that often exhibit high uncertainty (McCabe, 2005; Wanders et al., 2014). Also, remote sensing data offers reliability by avoiding the underestimation of sensitivities present in Current Earth System Models (ESMs). This ensures more accurate predictions of ecosystem responses to future droughts (Liu et al., 2023).

However, the results of our study warrant a thoughtful examination in relation to two primary aspects: firstly, the implications of using a monthly scale; secondly, the complex interplay between these drought indices and vegetation growth monitoring. It's noteworthy that the typical monthly scale used for drought assessments, may not adequately capture the progression and ecological impact of a drought. Indeed, our findings are derived from relatively large spatial (0.5◦) and temporal (monthly) scales. Some studies (e.g., Liu et al., 2020) have shown differences in the vegetation–climate coupling across scales, suggesting it would be worthwhile to repeat our analysis for smaller spatiotemporal scales in the future.

As a second source of uncertainty, SIF data comes with some caveats. The GOME-2 sensor may underestimate photosynthetic activity due to saturation under high light conditions and errors introduced by atmospheric conditions such as clouds and aerosols. Separating the weak SIF signal from the stronger reflected sunlight can also lead to substantial retrieval noise. This calls for caution when interpreting SIF data under high light intensity conditions. Additionally, while photosynthetically active radiation primarily drives SIF at sub-daily timescales, the relative influence of other factors at seasonal timescales remains unclear. Finally, using SIF measurements by GOME-2 retrieved in the morning – when VPD is relatively low – may lead to an underestimation of its effects. This suggests the need for careful consideration of timing when collecting and interpreting SIF data (Fu et al., 2022; Liu et al., 2020).

6. Outlook

In the following section, we outline the outlook for our study, highlighting key considerations that can enhance our analysis. By addressing these aspects, we aim to overcome the limitations aforementioned and gain a more comprehensive understanding of vegetation response to drought.

Adding a broader spectrum of vegetation and land-over types

Understanding the nuanced responses of specific vegetation types to water deficits is crucial for enhancing our analysis of drought impacts on vegetation. Different vegetation types have unique physiological and ecological characteristics, which influence their sensitivity and adaptive responses to water deficits. Some vegetation types may exhibit greater resilience or tolerance to drought e.g., forests, while others may be more susceptible to water stress. By considering these nuanced responses, we can better identify the vulnerabilities and adaptive strategies of different vegetation types in the face of water deficits. Similarly, land-cover types play a significant role in shaping vegetation responses to drought. Land cover includes various categories such as forests, grasslands, wetlands, and agricultural areas, each with distinct characteristics and ecosystem dynamics. These land-cover types can have varying abilities to retain soil moisture, access groundwater, or regulate evapotranspiration rates. Consequently, the responses of vegetation to water deficits can differ based on the land-cover types present in a particular area. By considering the interplay between specific vegetation types and land-cover types, we can gain deeper insights into the mechanisms driving vegetation responses to water deficits.

Use of alternative vegetation Indices

Given the aforementioned challenges, our research aims to investigate alternative vegetation indices like the Near-Infrared Reflectance of Vegetation (NIRv). This metric, calculated from satellite data, quantifies the near-infrared light reflected by vegetation. Its formulation involves the multiplication of the Normalized Difference Vegetation Index (NDVI) – an indicator of green vegetation presence and density – with near-infrared reflectance. NIRv has been shown to correlate strongly with rates of photosynthesis, thereby proving its utility in estimating Gross Primary Productivity (GPP) - the process of sunlight being transformed into biomass by plants. Its efficiency in this regard surpasses other existing vegetation indices, making it a robust choice for this purpose.

Considering climate zoning

Considering different climates or aridity zoning in the study of vegetation response to drought is crucial for several reasons. Firstly, different regions experience diverse climatic conditions, such as temperature, precipitation patterns, and aridity levels. Examining vegetation response to drought across these different climate zones helps us understand how ecosystems adapt and respond to varying water stress conditions. Secondly, it provides valuable insights into the specific mechanisms and processes that influence vegetation resilience or vulnerability to drought in different climatic contexts. Lastly, studying vegetation response to drought across different climates contributes to our broader understanding of global ecosystem dynamics and enhances our ability to predict and mitigate the impacts of drought on vegetation and ecosystem functioning.

Expanding the definition of drought anomaly and identification

Drought is a complex phenomenon that cannot be adequately captured by a single metric. To gain a more holistic understanding of the temporal dynamics of drought and its impact on vegetation, future research will consider expanding the definition of drought anomalies. We aim to consider metrics such as the average of the three driest months, allowing for a more comprehensive assessment of the severity and duration of drought events.

Furthermore, expanding the study to include multivariate variables such as the Standardized Precipitation Evapotranspiration Index (SPEI) would offer a more comprehensive and nuanced understanding of drought by capturing the combined effects of multiple variables. Also, we aim to test the use of the Standardized Precipitation Index (SPI) that will allow for a better understanding of the persistence and severity of drought conditions over a longer timescale.

Employing Machine Learning techniques

The application of machine learning techniques, such as Random Forest (RF), can significantly advance our understanding of the factors influencing vegetation response to drought. It is valuable in handling complex, non-linear relationships and large datasets as it is in our case. By analyzing the feature importance scores generated by the model, we will be able to determine which hydrometeorological variable has the strongest impact on vegetation anomalies. However, it is important to note that while RF can highlight important relationships, it does not establish causality. In this study, the hydrometeorological anomalies and vegetation indices anomalies will be used as predictor and target variables, respectively, for each grid cell. Random Forest (RF) will be trained using data from the individual grid cell and its surrounding grid cells, forming 3 × 3 grid cell matrices, to ensure sufficient data availability. The performance of the RF model will be evaluated by the fraction of explained variance (R2) obtained from regression analysis using linear least squares and cross-validation. Grid cells with R2 values lower than or equal to 0 will be filtered out. Two experiments will be conducted using RF models, differing in the type of soil moisture

(SM) data utilized: total soil moisture anomalies – TWSA– versus near-surface SM, in combination with the other selected hydrometeorological variables.

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