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EDITED BY
Weili Duan,
Xinjiang Institute of Ecology and Geography (CAS), China

REVIEWED BY
Qiang Li,
Northwest A and F University, China
Dengfeng Liu,
Xi'an University of Technology, China

*CORRESPONDENCE
Fubo Zhao,
zfubo789@163.com
Yiping Wu,
rocky.ypwu@gmail.com

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Increased response of vegetation to soil moisture in the northern hemisphere drylands

Xi Wang, Fubo Zhao* and Yiping Wu*

Department of Earth and Environmental Science, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, China

Vegetation plays a significant role in terrestrial ecosystems due to its strong carbon absorption capability and multiple feedback effects on the climate system. The soil moisture availability determines vegetation growth, especially in the drylands. Although there has been increasing interest in issues such as the vegetation's response to a specific climate variable, it remains unclear how soil moisture can quantitatively influence the vegetation in the drylands. In this study, we investigated the increased response of the vegetation to soil moisture and identified its key mechanism in the northern hemisphere drylands (NHD) from 1982 to 2010. The Methods included the use of the Lindeman-Merenda-Gold method. The results showed that the sensitivity of the vegetation dynamics to soil moisture significantly increased over the past 29 years (slope = 0.008, $p < 0.0001$), and the trend during 1996–2007 (slope = 0.025 m^3/m^3/yr, $p < 0.0001$) increased more rapidly than the trend during 1984–1995 (slope = −0.005 m^3/m^3/yr, p = 0.0143), which indicates increased water restrictions in recent years. Further analysis showed that atmospheric CO_2 was the major contributor (27.2%) to the sensitivity changes, followed by climate change (27%), and nitrogen deposition (19%). The changes in the ecosystem structure (represented by the non-tree cover areas) and climate vacillation contributed similarly to the sensitivity change (14% and 12%). These findings can help with understanding the spatiotemporal impact of water restrictions on vegetation in the NHD and the related influencing mechanisms of vegetation growth and soil moisture in the greening and warming of the NHD.

KEYWORDS

climate change, north hemisphere, sensitivity, soil moisture, vegetation growth, water availability

1 Introduction

Since the industrial revolution, the ever-increasing greenhouse gases have been changing the surface radiation and energy budget processes, which has increased the surface temperature and led to climate warming, particularly in the northern hemisphere (IPCC, 2014). It is estimated that the past 30 years (1983–2012) were the warmest period in the northern hemisphere during past 1,400 years (IPCC, 2014). Vegetation plays a significant role in terrestrial ecosystems since it accounts for about 42% (~28 PgC) of terrestrial carbon storage and assimilates approximately 20% of the annual anthropogenic CO_2 emissions (Pan et al., 2011; Le Quere et al., 2016). However, not only energy and food security but also vegetation growth is vulnerable and restricted under climate warming and socio-economic changes because of water shortages (Huang et al., 2021; Qin et al., 2022), which is the most important factor in driving vegetation growth around the world. The enhanced ecohydrosphere (Yang et al., 2021), changes in precipitation patterns (Dore, 2005; Gu and Adler, 2013; Duan et al., 2022), possible soil moisture decreases (Sherwood and Fu, 2014; Huang et al., 2016), more frequent and severe floods and droughts (Turner et al., 2020), changes in land cover/land use (Huang et al., 2018), and changes in vegetation types (Hufnagel and Garamvolgyi, 2014) due to climate change are all exacerbating the impact of water availability on vegetation (Lemordant et al., 2018; Fernandez-Martinez et al., 2019). Drylands, where rainfall is scarce and soil moisture is almost the only effective source of water availability (Wang et al., 2013; Zhao et al., 2020), are a key area where vegetation growth is subject to water stress. Thus, understanding the properties of vegetation and soil moisture, the close relationship between them, and the drivers of vegetation sensitivity to soil moisture in the drylands is important for climate and ecosystem management on a global scale.

The growth dynamics of terrestrial vegetation directly or indirectly control the energy transfer process between the surface and the atmosphere and the feedback on the climate system (Richardson et al., 2013). Although the growth of terrestrial vegetation is comprehensively regulated by environmental factors, such as light, temperature, water availability, atmospheric CO_2 concentration, and nutrient availability (Cleland et al., 2007; Korner and Basler, 2010; Korner, 2018), water availability is still the main factor that controls vegetation growth in the drylands (Feng et al., 2021; Zhao et al., 2021). In recent years, with the development in remote sensing technology for hydrology analysis and water resources management (Duan et al., 2021), many studies have investigated the response of vegetation to water availability under climate warming. For example, Wu et al. (2018) and Wu et al. (2022) both assessed drought legacy effects on vegetation. Zhao et al. (2023) indicated that the ecosystem of a typical drylands was facing crucial water limitation in recent decades. Additionally, Wang et al. (2021) investigated the changes in the length of the four seasons and their impact on vegetation in the drylands. Moreover, Anderegg et al. (2018) studied vegetation resilience under and recovery from severe drought. These studies mainly focused on the interaction between vegetation and certain indicators related to drought temporally. However, the vegetation responses to water availability factors are complex and have a fierce controversy due to limited knowledge of vegetation response on a global scale (Zhao and Running, 2010). In addition, several studies have focused attention on soil moisture, a hydrological variable directly related to the water availability of vegetation in drylands, showing that soil moisture is important in controlling vegetation growth in the drylands (Vicente-Serrano et al., 2013; Knapp et al., 2015). For example, Li et al. (2022) suggested that the sensitivity of the leaf area index (LAI) to soil moisture has increased significantly in many drylands globally. Also, Dang et al. (2022) found that soil moisture had a greater impact on vegetation production in arid and semi-arid regions, while temperature changes in humid regions had a greater impact on vegetation. Nevertheless, it remains unclear what is the exact impact of soil moisture on vegetation growth within the context of climate change in the drylands. The northern hemisphere drylands (NHD) have a regulating effect on global climate change and play an important role in maintaining the balance of the ecosystem. As an arid zone spanning three continents, the NHD has research significance in terms of determining how vegetation growth is affected by drought in this region (Xu et al., 2016).

To address these, this study aimed to quantify the spatiotemporal response of the vegetation to soil water sensitivity during 1982–2010 using the growing season remote sensing normalized difference vegetation index (NDVI) and algorithm-based soil moisture (0–10 cm depth) in the NHD. The objectives of this study were to 1) investigate spatiotemporal changes in the vegetation sensitivity to soil moisture in different continents during 1982–2010, and 2) provide a northern hemisphere overview of the potential controlling factors of sensitivity changes in the drylands.

2 Materials and methods

2.1 Study area

In this study, the drylands were classified according to the criteria of the United Nations Environment Programme. In 1977, the World Atlas of Desertification was proposed by the United Nations Food and Agriculture Organization and other institutions, and it uses the aridity index (AI; the ratio of the average annual precipitation and the average potential evapotranspiration). Areas with an AI lower than 0.65 are defined as drylands (Feng and Fu, 2013), and the drylands are divided into four zones: the dry-humid ($0.5 < AI < 0.65$), semiarid ($0.2 < AI < 0.5$), arid ($0.05 < AI < 0.2$), and hyper-arid regions ($AI < 0.05$). In this study, three (Supplementary Figure S1) parts of the Northern Hemisphere were selected as the study area and termed the Northern Hemisphere Drylands (NHD). This included the dry-humid, semiarid, and arid regions, which are mainly located at mid-latitudes (30°–60°) across Asia, Europe, Africa, and North America. Specifically, the drylands are mainly distributed in mid-latitude southwestern Europe, Central Asia, North Africa, and western North America. The hyperarid region was excluded since the seasonality of the vegetation growth in the extremely arid areas is not obvious. Globally, drylands cover 41.3% of the Earth's land surface, and dryland vegetation provides 40% of the net primary productivity of vegetation globally (Wang et al., 2012).

2.2 Datasets

The NDVI has been widely used to reflect global-scale vegetation growth. In this study, the Global Inventory Modeling and Mapping Studies NDVI3g dataset (Tucker et al., 2005) with a spatial resolution of 0.0833° and a 15-day temporal resolution from 1981 to 2015 was used. The dataset has the characteristics of good correlation with the *in situ* observation data and long-term monitoring of vegetation dynamic changes. To match the meteorological and soil moisture data, the GIMMMS NDVI was spatially aggregated at a 0.5° spatial resolution.

The Global Land Evaporation Amsterdam Model soil moisture v3.5a dataset from 1980 to 2020 with a spatial resolution of 0.25° was used to obtain the soil moisture data (Miralles et al., 2011; Martens et al., 2017b). The model is a set of algorithms that separately estimate terrestrial evaporation, surface soil moisture (0–10 cm), and root-zone soil moisture (10–250 cm), and it has been widely used for estimating vegetation-climate feedback and large-scale hydrological applications (Martens et al., 2016; Martens et al., 2017a). The surface soil moisture was selected as the main focus since it largely reflects precipitation and temperature.

The CO_2 concentration and nitrogen deposition from 1700 to 2010 with a spatial resolution of 0.5° were obtained from the Multi-scale Synthesis and Terrestrial Model Intercomparison Project, which was designed to provide a consistent and unified modeling framework (Liu et al., 2014; Wei et al., 2014; Huntzinger et al., 2018; Huntzinger et al., 2021).

The ecosystem structure was represented by the tree cover (percentage of pixels that were covered by the tree canopy), which was obtained from a data layer from the Vegetation Continuous Fields Version 1 data product. This layer contains the percentage of tree cover, non-tree vegetation, and bare ground from 1982 to 2015 with a spatial resolution of 0.05° (Hansen and Song, 2018).

The air temperature (°C) and precipitation were converted from the air temperature (K) and precipitation rate of the China Meteorological Forcing Dataset (CMFD; Yang and He, 2019) from 1979 to 2018 with a spatial resolution of 0.1°. The CMFD is widely used in hydrological and climate modeling research (Yang et al., 2010; He et al., 2020).

To accurately reflect the vegetation growth in the drylands, the seasons with poor vegetation growth were discarded and a time series was chosen for the growing seasons (4–10 months). For easier computer processing, all of the above data were resampled at a 0.1° × 0.1° spatial resolution using the bilinear interpolation method by Arcgis 10.2. Because of the dataset limits, the study period was chosen from 1982 to 2010. Except for the temperature and precipitation, the other data were detrended and normalized using linear de-trending (Eq. 1) and the Min-Max normalization method Eq. 2 by Python 3.8. These methods were used to emphasize the fluctuation of the data trend and make the characteristics of the different dimensions comparable. Additionally, the temperature and precipitation data were only used after linear de-trending (TEM+PR) and Min-Max normalization (TEM_{var}+PR_{var}) to represent climate change and climate vacillation, respectively. Eq. 1 is provided below:

$$x_j^* = x_j - s_j j \quad j = 1, 2, 3 \ldots 29 \tag{1}$$

where j represents the year from 1982 to 2010, x_j is the data after the second data preprocessing, s_j is the slope of the data at one raster from 1982 to 2010, and x_j^* is the data after the detrending. Eq. 2 is provided below:

$$x_j' = \frac{x_j - x_{Min}}{x_{Max} - x_{Min}} \quad j = 1, 2, 3 \ldots 29 \tag{2}$$

where x_{Max} is the maximum of x_j from 1982 to 2010, x_{Min} is the minimum of x_j from 1982 to 2010, and x_j' is the data after the Min-Max normalization.

2.3 Defining the sensitivity of the vegetation to soil moisture

To quantify the sensitivity of the vegetation to soil moisture, a one-variable linear model was built. The model is defined as follows:

$$NDVI_j = \theta_{SM} SM_j + \varepsilon \tag{3}$$

$$\theta_{SM} = \frac{\partial NDVI}{\partial SM} \tag{4}$$

where $NDVI_j$ and SM_j represent the growing season NDVI and surface soil moisture after preprocessing, respectively, and ε is the error term. Furthermore, θ_{SM} is the focus partial derivative, which was used to quantify the sensitivity of the vegetation to soil moisture. The higher the θ_{SM}, the more sensitive the vegetation response to soil moisture.

For the temporal sensitivity trend analysis, three moving windows, namely, 5-year, 10-year, and 15-year moving windows were used. For the spatial sensitivity trend analysis, 29-year data was used to calculate the overall θ_{SM}. The Mann-Kendall trend test, or the M-K test, was used to analyze data collected over time for consistently increasing or decreasing trends in θ_{SM}.

2.4 Attribution method

In this study, a multivariate linear regression model Eq. 5 was built to quantify the relative importance of the meteorological indexes to the sensitivity of the vegetation to soil moisture for each grid cell, assessing the factors that affect the water resources and vegetation in the drylands. The equations are as follows:

$$\theta_{SM} \sim CO_2 + ND + ES + CC + CV \tag{5}$$

$$\theta_{SM} = a = \frac{\partial a}{\partial CO_2} CO_2 + \frac{\partial a}{\partial ND} ND + \frac{\partial a}{\partial ES} ES + \frac{\partial a}{\partial CC} CC + \frac{\partial a}{\partial CV} CV + \gamma \tag{6}$$

where θ_{SM} indicates the sensitivity of the vegetation to soil water; CO_2, ND, ES, CC, and CV represent the CO_2 concentration, nitrogen deposition, ecosystem structure (percentage tree cover), climate change (TEM+PR), and climate vacillation (TEM_{var}+PR_{var}), respectively. The γ is the error term.

To obtain the importance rankings, a function was used to calculate the relative importance metrics for the linear models in the "relaimpo" package in R (https://prof.bht-berlin.de/groemping/software/relaimpo/). The Lindeman-Merenda-Gold (LMG) method was used to quantify the relative importance of the meteorological indexes to the sensitivity of the vegetation to soil moisture for each grid cell. The LMG method is typically used to avoid the order effect of the regression variables (Li et al., 2021) and evaluate the robustness of the attribution analysis (Jiao et al., 2021). The Mann-Kendall trend test, was used to analyze trends of the importance rankings over years.

3 Results

3.1 Spatial patterns of the changes in the vegetation and soil moisture

The spatial patterns of the monthly mean growing season (April to October) NDVI and soil moisture were drawn at a spatial resolution of 0.1° × 0.1° during 1982–2010 (Figures 1A–D). The

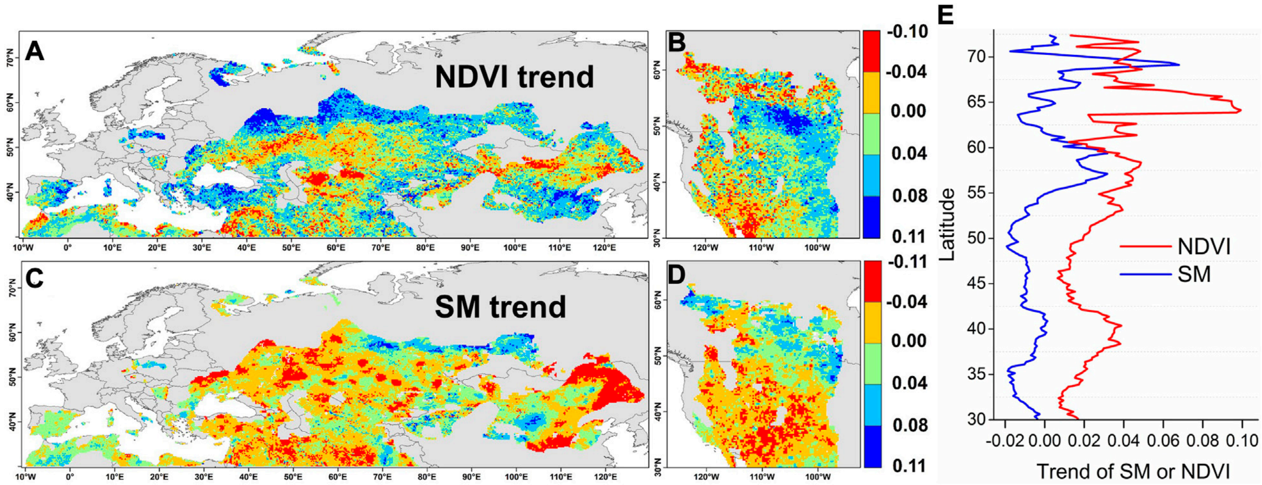

FIGURE 1
(A, B) Spatiotemporal trend of the normalized difference vegetation index (NDVI) and soil moisture (SM) in the drylands of the Northern Hemisphere from 1982 to 2010 and **(C,D)** The spatial distribution trend of the NDVI and SM, respectively. **(E)** The average trend of the NDVI and SM per pixel per continent in the different latitudes.

NDVI exhibited generally increasing trends (Figures 1A, B), and the overall growth trend of the NDVI in the NHD was 0.035 years^{-1}. Specifically, the NHD regions in the middle and high latitudes of Eurasia (55–65°N), Mideast of North America, Iberian Peninsula, and central China, and regions around the Black Sea and Caspian Sea, exhibited a vegetation greening trend and significantly increasing trends. Decreasing NDVI trends were observed in other regions of the NHD, such as Midwest North Asia and near Mongolia. In summary, NDVI in 70.74% of the area increased and only 29.14% of the area decreased during past three decades. The soil moisture had widely decreased trends (Figures 1C, D), and the overall descending trend of the soil moisture in the NHD was −0.015 $m^3/m^3/year^{-1}$. Except for the NHD regions in central Russia, west regions around the Mediterranean Sea, and a small part of central and northwest China, the other regions exhibited an obvious decrease in soil moisture. Statistically, soil moisture in 59.15% of the total area of the decreased and 40.85% of the area increased during the study period.

The average trends of the NDVI and soil moisture in terms of pixels per continent in the different latitudes are shown in Figure 1E. Overall, the NDVI in the different latitudes was generally increasing, while the soil moisture was decreasing below 55°N and fluctuated in the high latitudes. Importantly, there was an apparent positive correlation between vegetation greening and soil moisture between 30°N and 60°N (Figure 1E). This indicated the increased response of the vegetation to soil moisture in the major areas of the drylands in the northern hemisphere, which suggests a water constraint.

3.2 Increasing sensitivity of the vegetation to soil moisture

To further support the potential water constraint based on the response of the vegetation to soil moisture, the significant positive and negative trends in the vegetation-soil moisture sensitivity (θ_{SM}) were analyzed using 5-year moving windows and a Mann-Kendall trend test (p < 0.05; Figure 2).

Spatially, 70% and 20% of the NHD area were dominated by significant positive and negative trends (p < 0.05) during the study period, respectively, whereas only 10% of the NHD land fractions had a non-significant change (Figure 2A). Moreover, higher positive sensitivity of the vegetation to soil moisture was found in southern North America and central Eurasia. This indicated widespread increased sensitivity to soil moisture.

Temporally, a significantly increasing trend (p < 0.0001) was identified for θ_{SM} with a rate of 0.008 m^3/m^3/yr. Notably, the trend (Supplementary Figure S2A) during 1996–2007 (slope = 0.025 m^3/m^3/yr, p < 0.0001) increased more rapidly than the trend during 1984–1995 (slope = −0.005 m^3/m^3/yr, p = 0.0143). This result indicates that the vegetation growth of the NHD gradually become more constrained by the water deficit during the study period, which is supported by a spatially significant increase in the θ_{SM} in large areas. Moreover, to verify the increase in the θ_{SM} and evaluate the robustness of the results, 10-year and 15-year moving windows (Supplementary Figure S2B) during 1982–2010 were tested for θ_{SM}, and the similar significant results (p < 0.01) supported our findings.

In addition, the sensitivity of the vegetation to soil moisture in the different continents in the NHD is shown in Figure 2D. The continents with significantly increased sensitivity were: Europe, North America, Africa, and Asia. Europe was the most sensitive to moisture, with 31% of the drylands showing a significant increase in sensitivity and only 6% of the drylands showing a significant decrease in sensitivity, which was slightly different from the other continents. In contrast, 23% of the NHD had significantly increased vegetation sensitivity, 9% had significantly decreased vegetation sensitivity, and 68% had no significant change in vegetation sensitivity. This result was also consistent with the results in Figure 1A, where a considerable part of the drylands faced productivity constraints.

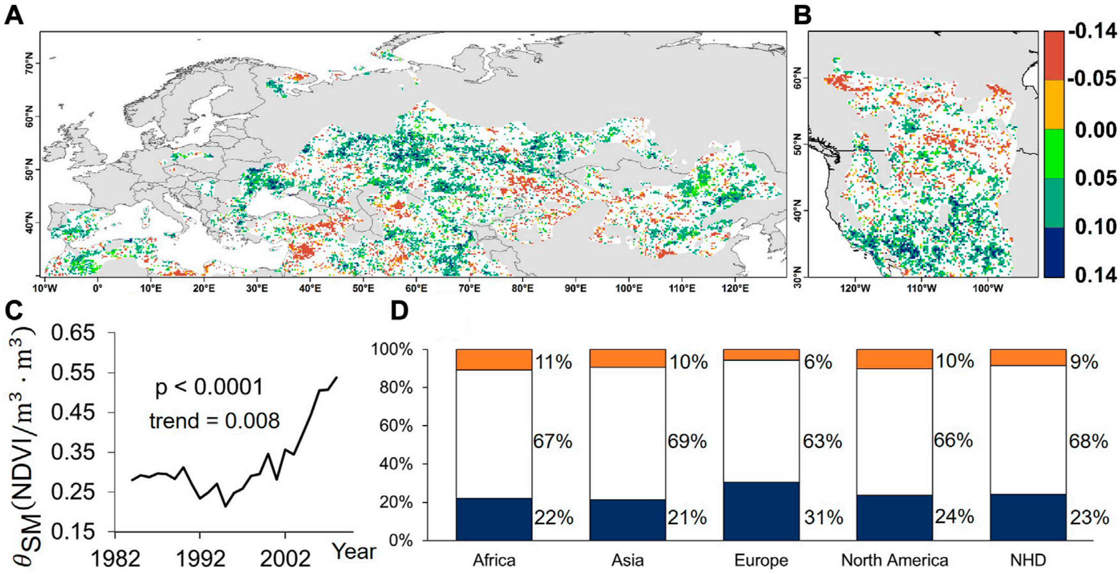

FIGURE 2
Significant positive and negative trends in vegetation-soil moisture sensitivity (Mann-Kendall test, p < 0.05) across the Northern Hemisphere drylands (NHD). The normalized difference vegetation index and soil moisture were represented by NDVI and SM. **(A, B)** The spatial distribution of the vegetation-soil moisture sensitivity trends across the NHD. **(C)** A time series of the vegetation-soil moisture sensitivity during 1982–2010. **(D)** The fractions (%) of significant positive (dark blue) and negative (orange) pixels per continent. The blanks in **(A, B, D)** are land fractions that underwent a non-significant change.

3.3 Mechanisms for sensitivity changes

Finally, we evaluated the order of importance of the CO_2 concentration, nitrogen deposition, ecosystem structure, climate change, and climate vacillation for θ_{SM} using an attribution analysis. The main drivers of the significant trends (Mann-Kendall, $p < 0.05$) in the vegetation-soil moisture sensitivity per pixel are shown in Figure 3. The spatial patterns of the relative importance, which were calculated using the LMG method, are shown in Supplementary Figure S3, and the most important controllers were spatially aggregated in one pattern in different colors (Figure 3A). The results showed that the CO_2 concentration (28%) and nitrogen deposition (19%) were the main factors that determined increasing sensitivity, which was also summarized for each continent (Figure 3B). Except for nitrogen deposition in Europe, which ranked first in importance, CO_2 deposition in the other continents was the main controlling factor of the increase in vegetation sensitivity. To verify the robustness of the attribution, the regression coefficient of every controller was also calculated, which quantified the spatial patterns (Supplementary Figure S4). The results of regression coefficients were similar to the LMG attribute analyses.

The trend and fluctuation values of the precipitation and temperature were combined to visualize the climate and vegetation contributions to the enhanced response with the LMG method (Figure 4). The results (Figure 4A) showed that the most important controlling factor in the whole NHD region was the CO_2 concentration (28%). The second most important controlling factor was climate change (27%), which was followed by nitrogen deposition (19%), ecosystem structure (14%), and climate vacillation (12%). All of the controlling factors played a positive role in the sensitivity increase (Figure 4B), which indicated strong water limitation in the future.

4 Discussion

In this study, an obvious increase in the NDVI and decrease in the soil moisture was observed regionally and latitudinally (in the mid-latitudes) during the study period. Generally, the large-scale greening of vegetation is consistent with other studies, for example, Xu et al. (2016); Lian et al. (2020) both found that the growing season in the middle latitudes of the northern hemisphere was brought forward and that the region was greening. In addition, this greening also reduced soil moisture and aggravated soil moisture limitation (Deng et al., 2020), especially in several semi-arid and arid regions of the world. These findings were also consistent with this study, that is, the soil moisture decreased significantly in the NHD.

Additionally, the NDVI showed a trend of a steady fluctuation and then a gradual increase in response to the soil moisture at the corresponding latitude, reflecting the response of the vegetation growth to water availability. However, there were unique climate conditions that should also be considered. For example, due to the westerly and polar circulation, the climate in the central and northern parts of Eurasia was wetter than that in the other arid regions during the study period, so the vegetation growth was less affected by the water constraint. Moreover, the vegetation changes in the NHD were also affected by human activities, especially land use/land cover changes (de Beurs and Henebry, 2004). For example, in 1991, after the disintegration of the former Soviet Union, a large

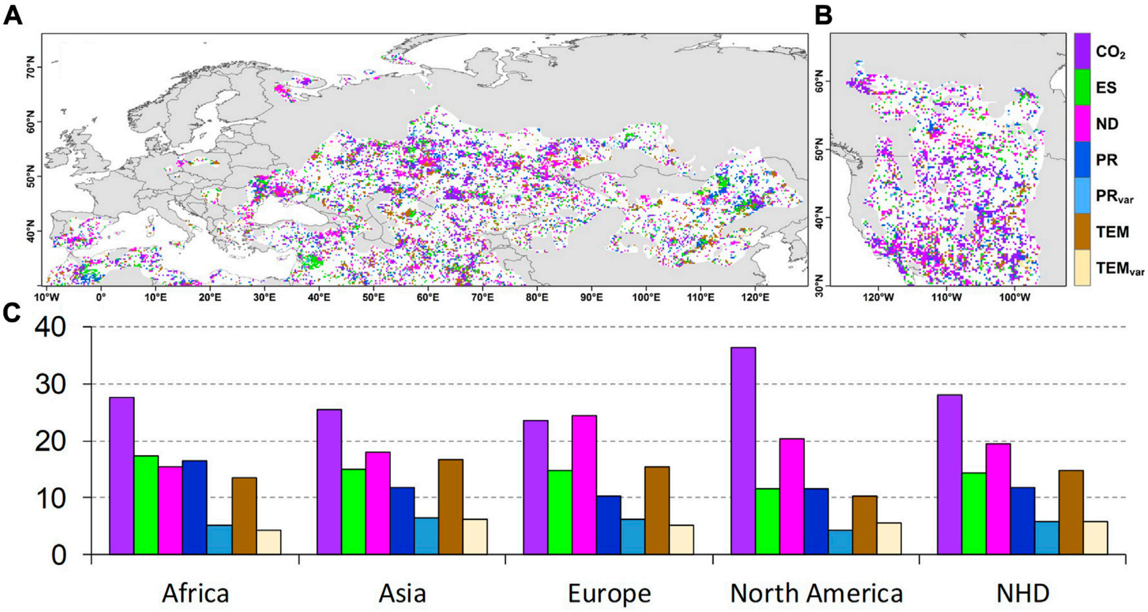

FIGURE 3
Main drivers of the significant trends (Mann-Kendall, $p < 0.05$) in the vegetation-soil moisture sensitivity per pixel. **(A, B)** The spatial distribution of the drivers of the vegetation-soil moisture sensitivity in the Northern Hemisphere drylands (NHD). **(C)** The area fractions of the lands that are dominated by each factor (%). Abbreviations: CO_2, ES, ND, PR, PR_{var}, TEM, and TEM_{var} are the CO_2 concentration, ecosystem structure, nitrogen deposition, precipitation, variation in precipitation, air temperature, and variation in air temperature, respectively.

amount of farmland was abandoned, and livestock production declined sharply (Propastin et al., 2008). Also, Kazakhstan's grassland fires were among the most serious in the world from 2001 to 2009 (Loboda et al., 2012). The Loess Plateau, the world's largest and deepest deposit region of loess located in China, has undergone significant greening since the implementation of the Grain for Green Project in 1999 (Feng et al., 2016; Fu et al., 2017). Thus plowing, fire, grazing, and urbanization have all changed the drylands' NDVI. Overall, vegetation change is the comprehensive result of various factors, except in the drylands, where the soil moisture plays a more important role.

The results of this study showed that there was a large area with a significant increase in vegetation sensitivity to soil moisture in the drylands of each continent. Similar results were also reported by other researchers. For example, Papagiannopoulou et al. (2017) suggested that water availability was the most powerful factor that drove vegetation growth globally (about 61% of the vegetated surface was primarily water-limited) during 1981–2010.

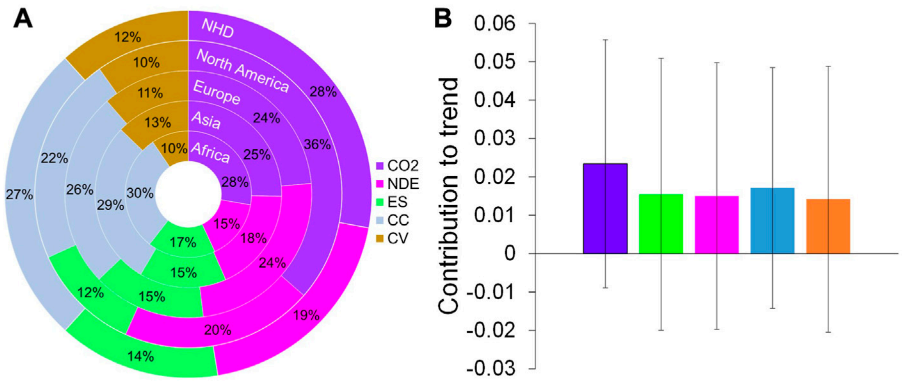

FIGURE 4
Climate and vegetation contributions to the enhanced response in the Northern Hemisphere drylands (NHD). **(A)** The proportional contribution of the control factors based on the Lindeman-Merenda-Gold method. **(B)** The contribution to the total trend for the five major control factors. Abbreviations: CO_2, NDE, ES, CC, and CV are the CO_2 concentration, nitrogen deposition, ecosystem structure, climate change, and climate vacillation, respectively.

Jiao et al. (2021) suggest that there was a strong increase in water constraints between 1982 and 2015 in the extratropical Northern Hemisphere. Furthermore; Li et al. (2022) indicated that the sensitivity of the LAI to water availability has increased significantly, especially in many arid and semi-arid regions globally in the past 40 years. These results were also supported by studies on the drylands in Australia, China, and America (Ma et al., 2015; Feng et al., 2016; Maurer et al., 2020).

Temporally, the θ_{SM} consistently increased since the 1980s in all three moving windows. During the time interval, the θ_{SM} increased but at different rates in different 5-year time periods. From 1984 to 1994, the increase rate was closer to 0 with statistical insignificance ($R^2 = 0.3094$, $p = 0.0755$). However, from 1995 to 2008, the increase was statistically significant ($R^2 = 0.9196$, $p < 10^{-7}$), which was similar to the vegetation-water sensitivity found in a different period by Gonsamo et al. (2021). This finding means that a certain amount of soil moisture gradually maintained more vegetation photosynthesis over time.

To find out what caused the increased θ_{SM}, an attribution analysis was conducted, and the results showed that it was mainly caused by CO_2 and climate change, which could explain 55% of the increase. CO_2 played the most important role in the θ_{SM} increase, which is consistent with its fertilization effect on vegetation. Several studies have indicated that elevated CO_2 causes vegetation to conserve water so that limited water supports more plant growth in water-limited regions (Zhang et al., 2022). This also explained the decrease in the soil moisture with the increase in the NDVI, which was due to the increase in the global CO_2 concentration. However, it should be noted that the increase in vegetation water constraints may in turn offset the fertilization effects of CO_2 and nitrogen on vegetation growth, leading to a decrease in the carbon sinks in drylands in the northern hemisphere. Moreover, climate change was another important factor. Recent studies suggest that vegetation types have been affected by climate changes (Hufnagel and Garamvölgyi, 2014). Shifts in the dominant vegetation types may cause them to respond differently to CO_2 fertilization, and the sensitivity of the vegetation to soil moisture could change. In addition, with climate change, widespread regime shifts from ecosystem energy to water limitation have occurred around the world (Denissen et al., 2022). Thus, the increased air temperature could enhance the sensitivity of the vegetation to soil moisture by increasing water stress and supplying sufficient energy (Adams et al., 2009). Therefore, with climate warming, the ecosystem of the NHD region will be more unstable, and more attention should be paid to these areas.

Such effects could be even more serious in drylands due to the enhanced changes in the lengths of spring, summer, and autumn. Global mean surface warming reached 1.08C above the preindustrial period (1850–1900) in 2017 (Hoegh-Guldberg et al., 2019). The trend in temperature might be amplified in the future with the rising radiative forcing. Accordingly, the changes of the four seasons would be intensified (Wang et al., 2021), resulting in a series of severer impacts and risks in physical and biological systems. The changes in the four seasons and related influences in drylands could be further enhanced because of their high sensitivity to temperature changes. Therefore, future investigations should consider the effects of seasonal variations in drylands.

Overall, our findings highlight a strong dependence of global vegetation on water availability. These results suggest that vegetation development may be more susceptible to future fluctuation of soil water availability. Also, most of these areas are projected to face more severe hydrological conditions (Satoh et al., 2022). Due to the high sensitivity of drylands vegetation to soil moisture, the related impact of water availability may be further enhanced.

5 Conclusion and perspectives

This study investigated the increased response of vegetation to soil moisture and identified its key mechanisms in the NHD from 1982 to 2010. The results identified significant greening in the NHD. The NDVI showed a trend of steady fluctuation and then a gradual increase in response to the soil moisture at the corresponding latitude, reflecting the response of the vegetation growth to water availability. The increased sensitivity of the vegetation to soil moisture (θ_{SM}) was identified after 1996 in the NHD in multiple moving windows. The θ_{SM} during the growing season shifted from a slight decreasing rate of −0.005 m^3/m^3/yr to a significant increasing rate of 0.025 m^3/m^3/yr ($p < 0.0001$) in 5-year moving windows. Despite the underlying factors affecting the vegetation growth in the different parts of the NHD being complex and diverse, the factors that led to the increased θ_{SM} were relatively clear; the atmospheric CO_2 concentration accounted for 28% of the increased θ_{SM} in the NHD. This was followed by climate change (27%), nitrogen deposition (19%), ecosystem structure (14%), and climate vacillation (12%). This study helps with understanding the interactions between vegetation growth and soil moisture in the NHD in both time and space and the related influencing factors in the different parts of the NHD, which is valuable for ecosystem management in the NHD.

This study has limitations and uncertainties that should be acknowledged. Eq. 5 was used to explain the sensitivity of vegetation change to soil moisture, and CO_2, ND, ES, CC, and CV were selected as the relevant factors. However, many other variables also play a role in this relationship and some of them may not yet be fully understood. As a result, the focus on these five factors alone may not accurately reflect the complexities of the relationship and should be kept in mind in future studies. Additionally, the study only considered surface soil moisture (0–10 cm) data, as it is more positively related to vegetation growth in typical drylands in the North Hemisphere (Yu et al., 2022). However, the relationship between deep soil moisture and vegetation growth is also important and should be considered in future research (Schenk and Jackson, 2002).

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found here: The GIMMMS NDVI is downloaded from https://data.tpdc.ac.cn/en/data/9775f2b4-7370-4e5e-a537-3482c9a83d88/. The GLEAM soil moisture data are available online at https://www.gleam.eu/. The CMFD climate data are available at https://www.tpdc.ac.cn/zh-hans/data. The atmospheric CO2 concentration and nitrogen deposition data can be obtained from https://nacp.ornl.gov/MsTMIP.shtml. The tree cover data are available at https://lpdaac.usgs.gov/products/vcf5kyrv001/.

Author contributions

Conceptualization, XW, FZ, and YW; formal analysis, XW, FZ, and YW; funding acquisition, FZ and YW; methodology, FZ and YW; validation, XW; visualization, XW; writing—original draft, XW and FZ; writing—review and editing, FZ and YW. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2023.1144410/full#supplementary-material

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