Soil coarsening alleviates precipitation constraint on vegetation growth in global drylands

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Abstract
Drought is an important and complicated topic, and the specific variables that are considered to represent climate drought stress and plant water stress often generate highly contradictory conclusions. As the junction of the atmosphere and the biosphere, soil may play an important role in separating climatic drought stress from vegetation water constraint. Here, we conduct a comprehensive evaluation of water constraint on vegetation growth in global drylands by separating precipitation constraint and soil moisture constraint. Although global drylands are characterized by low precipitation supply capacity, there are indeed a large number of grids showing decoupled water availability for plants from variability of precipitation, with ratios of 47%, 64%, and 61% for arid, semiarid, and subhumid regions, respectively. Soil properties, instead of climate and root length regimes, can explain the water constraint divergence between precipitation and soil moisture. Sand content emerges as the most significant soil property to weaken the precipitation constraint on vegetation growth, with a 1% increase in sand content of global arid, semiarid, and dry subhumid regions increasing an average of 0.31, 0.45, and 0.04 gC m⁻² yr⁻¹ gross primary productivity (GPP) deviation from the theoretical GPP determined by precipitation, respectively. This study provides new insight into how soil texture interacts with precipitation constraints to influence plant-available water in global drylands, which contributes to assessing ecological drought in global drylands.

1. Introduction
The fact that extreme events, such as drought, significantly suppress vegetation growth and limit vegetation productivity has come into focus (Babst et al 2019). Global drylands, comprised of arid, semiarid, and dry subhumid areas, cover ~41% of the Earth’s land surface and are among the most vulnerable to drought events (Lian et al 2021). However, drought events are so complicated that there is still no uniform definition (Slette et al 2019). Numerous drought indices representing various aspects of drought have been developed in recent decades (Williams et al 2013, Begueria et al 2014). Many previous studies have employed these drought indices, including meteorological and surface water-based indices, to assess the impact of drought on ecosystems (Dai 2013, Li et al 2019). Compared to earlier Intergovernmental Panel on Climate Change (IPCC) assessments the Special Report for Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Murray and Ebi 2012) and the Fifth Assessment Report (AR5; 2013) with limited observational evidence of drought change, the recently released IPCC Sixth Assessment Report (AR6; 2021) started to subdivide drought into three types: meteorological droughts (low precipitation), hydrological drought (a reduction in water supply), and agricultural and ecological drought (plant water stress).

Meteorological drought indices, indicating that atmospheric water requirements exceed water supply, have been widely used in previous studies to assess changes in dryness in global drylands.
and have reportedly significantly increased in drought-impacted areas under global climate change (Huang et al 2016, Zang et al 2020). However, having a climatic water supply deficit is not exactly the same as a soil water content deficit for vegetation growth; thus, meteorological drought does not necessarily increase plant-water pressure and lead to ecological drought (Jiao et al 2021). At a regional scale, vegetation growth is usually more sensitive to soil water-supply capacity than climate water-supply capacity, which is driven primarily by precipitation, demonstrating the strong role of soil moisture in indicating drought stress for vegetation growth (Wang et al 2012, Liu et al 2020).

Based on the framework of the soil–plant–atmosphere continuum, precipitation is the primary source of soil-available water (McColl et al 2017). When a precipitation event occurs, the surface soil layer retains a certain fraction of incoming precipitation, and parts of the precipitation drain to deeper groundwater storages (Evaristo et al 2015). Soil, as the interface where atmospheric and hydrologic processes are linked with the biosphere, plays a leading role in determining whether precipitation variation can turn into a variation in water supply to plants (Fatichi et al 2016). This process is influenced by water storage-related soil properties, such as soil texture and depth (Entin et al 2000). A recent study based on the relevant ecohydrological index of ecological drought, including soil moisture constraint and vegetation growth, reported an opposite result to many other studies based on climate drought press for vegetation growth and claimed no projected global dryland expansion and no significantly increased drought-impacted areas under global climate change (Berg and McColl 2021). Soil features are therefore hypothesized to change the water constraint between precipitation and soil moisture for vegetation growth. However, to the best of our knowledge, the effects of soil by separating climatic drought stress from vegetation water constraint have not yet been summarized systematically, either at a site or regional scale.

However, the relationship between water constraints and soil property is extremely heterogeneous. Previous studies have reported that most dryland soils with high sand content are relatively infertile, vegetation cover is sparse, and dryland ecosystems with sandy soils are substantially more fragile (Huang et al 2020). This phenomenon is explained by soil pores decreasing as clay content increases; capillary action strengthens, and thus soil water-retention capacity increases in finer-textured soils (Hussain et al 2020). Sandy land tends to reduce water availability by loss of water to develop drainage. Meanwhile, spatial heterogeneity in the vulnerability of woody plants to drought in Australia verifies that clayey soils constrain vegetation growth in drylands by exacerbating water stress, and the increase in subsoil clay content was associated with high tree mortality (Ding et al 2021). This abnormal phenomenon, whereby coarser-textured soils have higher vegetation productivity than fine-textured soils in extreme arid zones, was described as early as the 1970s (Noy-Meir et al 1973, 1974). And the occurrence of ‘taller and denser perennial vegetation’ on coarse-textured soils in regions with low annual precipitation was named ‘the inverse-texture effect’, as coarse-textured soils facilitate infiltration and percolation into deeper soil layers and reduce bare-soil evaporation, resulting in greater water availability and plant growth relative to fine-textured soils. We can find plenty of evidence to support the fact that desertification characterized by coarsened soil in many regions has already reduced productivity by reducing water availability (Liu et al 2016). We can also find plenty of evidence supporting the fact that coarser-textured soil in some drylands has already reduced water stress for vegetation growth by increasing water availability. The opposite conclusions above show that there is an important but unknown interaction among soil texture, mean annual precipitation, and water availability for plant growth. And whether vegetation growth is hampered by a lack of water as a consequence of coarser-textured soils remains a matter of debate.

Although the ‘inverse texture hypothesis’ is not the consensus among scientists and is still controversial (Renne et al 2019), nevertheless, the ability of coarser-textured soils to buffer water constraints for vegetation growth at lower mean annual precipitation than fine-textured soils provides new insight into whether a coarsened soil environment makes plants more vulnerable to drought stress. To the best of our knowledge, elements of this mechanism have rarely emerged in previous studies assessing the impact of desertification-induced soil coarsening on vegetation growth in global drylands. Therefore, questions about what the regulating effect of soil is in global drylands and whether coarser soil makes vegetation less vulnerable to drought stress are worth further exploration. Here, we hypothesize that soil texture can lead to a difference in the soil effect, turning climatic drought stress into vegetation water constraint, thus linking soil texture, water availability, and vegetation growth at the regional scale of global drylands.

In this study, we address this critical gap by considering the soil effect that drives the water constraint divergence between precipitation and soil moisture on global drylands. Furthermore, we analyze the causes of differential soil effects, focusing in particular on the existence of inverse texture with higher water availability under higher sand content, to determine which soil is more likely to turn climatic drought stress into vegetation water constraint. We aim to obtain a more comprehensive understanding of whether soil can buffer vegetation growth from rainfall supply limitation by effective precipitation
redistribution; this may motivate decision-makers to respond early and effectively to mitigate the pending increased plant water stress as a consequence of global desertification.

2. Data and methods

First, we used correlation and partial correlation analyses to test the vegetation water constraint, including the precipitation constraint and soil moisture constraint. Based on this, we compared unseparated precipitation and soil moisture constraints and separated precipitation and soil moisture constraints. Then, we explored whether water storage-related soil properties, rather than climate and root length regimes, induced the water constraint divergence between precipitation and soil moisture. Finally, we defined the soil effect of drylands as a linear function of soil water supply capacity and gross primary productivity (GPP) variance relative to annual rainfall and answered the question of which soil feature was favorable to reducing precipitation supply limitation for vegetation growth in global drylands.

2.1. Quantification of water constraint

Partial correlation measures the degree of association between two random variables with the effect of a set of controlling random variables removed (Xia et al 2018). The precipitation constraint is calculated by Spearman rank correlations (Cor) between a yearly normalized difference vegetation index (NDVI) anomaly and a yearly precipitation (PRE) anomaly (Cor (NDVI, PRE)) and is also assessed by removing the soil moisture effect, using partial correlations between the NDVI anomaly and precipitation anomaly (Partial cor (NDVI, PRE)). Third-generation biweekly Advanced Very High-Resolution Radiometer (AVHRR) NDVI data (GIMMS-NDVI) is used in this study as a proxy for vegetation growth between 1982 and 2015 (Zhang et al 2021, available at https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0). The precipitation datasets with a spatial resolution of 0.5° used in this study are the Climate Research Unit (CRU) datasets (available at www.uea.ac.uk/web/groups-and-centres/climatic-research-unit/data; Wu et al 2015), covering NDVI and the soil moisture time series period. The climate datasets are interpolated from meteorological stations based on spatial autocorrelation functions. We use linear detrending methods for each grid cell by removing the slope of yearly NDVI and precipitation between 1982 and 2015. The Global Land Evaporation Amsterdam Model is a set of algorithms dedicated to estimating terrestrial soil moisture from satellite data (available at www.gleam.eu; Martens et al 2017). All datasets are provided on a 0.25° × 0.25° regular grid with a daily temporal resolution. Consistent with the method used to assess the precipitation constraint, the soil moisture (SM) constraint is calculated using the yearly NDVI anomaly and yearly soil moisture anomaly (Cor (NDVI, SM)) and is also assessed by removing the precipitation effect using partial correlations between the NDVI anomaly and soil moisture anomaly (Partial cor (NDVI, PRE)).

2.2. Establishing the relationship between the soil effect and water availability

As the existence of soil drives the water constraint divergence between precipitation and soil moisture, we define the soil effect from a weakening precipitation constraint perspective and thus quantify the ability of separating vegetation water constraint (represented by soil moisture constraint) from climatic drought stress (represented by precipitation constraint). A grid with a strong soil effect to buffer vegetation water constraints from climatic drought stress will show significant soil moisture limitations and will not be affected by precipitation variations, corresponding to the grid where the soil moisture constraint value is large, and the precipitation constraint value is small. Thus, we can quantify the soil effect by the difference between the separated precipitation constraint and the soil moisture constraint. If the value is larger, the grid is more inclined to the precipitation constraint pattern, and the soil has less buffer ability; if the value is smaller, it is opposite, favoring a stronger soil effect to reduce the effect of the precipitation constraint. The linear trend test is applied to global arid, semiarid, and dry subhumid regions to examine the impact of the soil effect on water availability and vegetation productivity.

Water availability is characterized by subsurface water supply capacity in local precipitation redistribution to vegetation growth. The precipitation vegetation drought index (PVDI) is an effective index generated from optical remote sensing imagery to monitor regional subsurface stored precipitation available to vegetation growth (Zhu et al 2021, Liu et al 2022). Similar vegetation is supported by different precipitation supply levels, indicating a difference in the available water that can be redistributed to vegetation. It is a simple parameterized calculation method to quantify the soil capacity in local precipitation redistribution to vegetation growth and characterize the stored precipitation fraction for vegetation growth at landscape or regional scales. The value of the index is defined between 0 and 1, and the larger the value is, the more plant-underutilized water loss there will be. Therefore, a lower value represents a more favorable subsurface water supply capacity relative to annual rainfall.

A long-term series of terrestrial gross primary productivity data is derived from Version 6 of GPP (MOD17A2H), which is aggregated to 0.5° × 0.5° to match the resolution of meteorological data (available at http://eft101.cr.usgs.gov/MOLT/MOD17A2H.006; Sun et al 2019). The deviation between actual GPP and precipitation-determined GPP was
calculated. The precipitation-determined theoretical GPP is determined by the regression line at all points of actual GPP and precipitation. In addition, we also used a univariate analysis of variance (ANOVA) to detect whether there was a significant difference in water storage-related soil properties in the soil-effect performance, mainly including soil texture and soil depth.

The soil texture data were extracted from version 1.2 of the Harmonized World Soil Database (HWSD) (available at www.fao.org/soils-portal/soil-survey/s oil-maps-and-databases/harmo-nized-world-soil-da database-v12/en/; Todd-Brown et al 2013). It combines existing regional and national updates of soil information worldwide and represents the most comprehensive soil database to date. The dataset reports global soil texture at a resolution of 30 arc-seconds based on the U.S. classification standard for sand, silt, and clay percentages. A global map of soil depth to bedrock at a spatial resolution of 100 m was developed by Yan et al (2020). This product was developed under an automated soil-mapping framework (Shangguan et al 2014). All data in this study are resampled to a spatial resolution of 0.5° in ARCGIS 10.3.

3. Results

3.1. Patterns of precipitation and soil moisture constraint on vegetation growth

We characterize two defining water-constraint types: the precipitation constraint and the soil moisture constraint. Positive values indicate a water-limited vegetation growth regime and negative values reflect an energy-limited regime (figures 1(a) and (b)). The high precipitation constraint occurs in parts of North America, South America, central and south Asia, and northern China. These constraints also occur in the savannah of Africa and Australia. After removing the soil moisture effect, the area of significant precipitation constraint decreases considerably and covers a total of 14% of global drylands. The dryland subtypes of dry subhumid, semiarid, and arid areas comprise 2%, 5%, and 7%, respectively, mainly in central Asia, northern Africa, northern China, and parts of Australia (figure 1(a)). The soil moisture constraint is also quantified in figure 1(b). It is consistently high in parts of North and South America, Australia, and southern Africa (figure 1(b)). If the precipitation supply effect is removed, the soil moisture constraint decreases markedly in northern North America and northern China and increases slightly in western Asia (figure 1(b)). With the precipitation effect removed, significant soil moisture constraint covers a total of 21% of global drylands. The dryland subtypes of dry subhumid, semiarid, and arid areas comprise 7%, 10%, and 7%, respectively. The correlations of soil moisture and precipitation with vegetation growth are very similar in global drylands, constituting a confounding factor that is often overlooked when assessing the impact of dryness stress on vegetation growth (figure 1(c)). It is therefore necessary to separate the precipitation and soil moisture constraint. The relationship between the separated precipitation constraint and the soil moisture constraint shows that there are indeed a large number of grids limited only by precipitation or soil moisture (figure 1(d)).

3.2. The soil drivers of precipitation and soil moisture constraint divergence

In any subtype of global drylands, over 90% of the water-limited grids follow either a significant water-constraint pattern of precipitation or soil moisture constraint (figure 2(a)). Forty-five percent and 47% of the grids from global arid regions show a significant precipitation and soil moisture constraint, respectively. The majority of grids from semiarid and subhumid areas have a significant soil moisture constraint, with a percentage of 64% and 61%, respectively, which is more than two times that of the precipitation constrained areas (figure 2(a)). There are no significant differences in climatic conditions (including temperature and precipitation) and root systems in areas with precipitation and soil water constraint grid areas (supplementary figure S1). The difference in the water-storage-related soil properties thus explains some of the divergence between the precipitation and soil moisture constraint pattern. Differences in soil depth do not fully explain the water constraint divergence over drylands (supplementary figure S1). A major forcing separating climatic drought stress from vegetation water constraint is the high soil sand content (figure 2(b)). Higher soil sand content in either subtype of global dryland tends to have a soil moisture constraint pattern to separate vegetation water constraints from climatic drought stress.

3.3. The relationships between the soil effect and water availability

We further examine whether the value of the soil effect to buffer precipitation constraint on vegetation growth decreases monotonically with increasing mean soil sand content, albeit with higher sand content being more likely to reduce the impact of precipitation constraint on vegetation growth (as shown in figure 2(d)). As the soil sand content increases, the soil effect is enhanced overall for the three subtypes of global drylands (figure 3(a)). Variation in the soil effect caused by the soil sand content was the most obvious in arid regions. The soil texture-impacted soil-buffering effect in dry subhumid regions was the least varied, and that of the semiarid regions was in-between. The stronger soil effect, weakening the precipitation constraint (lower value), corresponds to a more favorable subsurface water supply capacity and higher GPP relative to the precipitation supply capacity (figure 3(b)). The spatial distribution of the soil effect (supplementary figure S2) is highly consistent with the water-constraint pattern.
Figure 1. (a) Spatial distribution of the precipitation constraint (Cor (NDVI, PRE)) and removing the soil moisture-influenced precipitation constraint (Partial cor (NDVI, PRE)) for the entire study period. (b) Spatial distribution of the soil moisture constraint (Cor (NDVI, SM)) and removing the precipitation-influenced soil moisture constraint (Partial cor (NDVI, SM)). (c) The relation between the precipitation constraint (Cor (NDVI, PRE)) and the soil moisture constraint (Cor (NDVI, SM)). The red line shows the modeled effect. (d) The relation between the separated precipitation constraint (Partial cor (NDVI, PRE)) and the soil moisture constraint (Partial cor (NDVI, SM)).

shown in figure 2(a). For example, the significant soil moisture-limited grids and the not affected by precipitation variation grids in figure 2(a) tend to show stronger soil effects to weaken the precipitation constraint. If vegetation growth is more dependent on soil moisture than precipitation, this means less plant-underutilized water loss and higher productivity. On average, a 1% increase in the sand content of global arid, semiarid, and dry subhumid regions can release 0.31 gC m$^{-2}$ yr$^{-1}$, 0.45 gC m$^{-2}$ yr$^{-1}$, and 0.04 gC m$^{-2}$ yr$^{-1}$ GPP deviations from the theoretical GPP determined by precipitation, respectively, by enhancing the soil-buffering effect to weaken the precipitation constraint on vegetation growth. The soil effects we developed reveal that soil can buffer plant water supply stress and, consequently, plant productivity from rainfall supply potential, especially in arid and semiarid regions of the world (figure 4).

4. Discussion

Our results show that soil features drive the water-constraint divergence between precipitation and soil moisture and consequently increase or decrease the amount of local precipitation used by vegetation growth. Although precipitation is the main source of soil water, more than 90% of the water-limit grids follow either precipitation or soil water constraints. The area with precipitation and soil moisture constraint patterns is roughly equal in global arid areas, while the area with a soil moisture constraint pattern in semiarid and dry subhumid areas is approximately twice
Figure 2. (a) Spatial distribution of the separated water constraint on vegetation growth. The blue grids represent significant precipitation but not soil moisture constraint on vegetation growth; the red grids represent significant soil moisture constraint but not precipitation constraint; and the gray grids represent both significant precipitation and soil moisture constraint on vegetation growth. The frequency distribution of the water-limited grids in each subtype is shown at the bottom left. (b) An ANOVA of the soil texture for different water constraint patterns (Prec corresponds to the precipitation constraint but not the soil moisture constraint pattern and SM corresponds to the soil moisture constraint but not the precipitation-constraint pattern). Boxplots show the median (the white plot in the box), 25th, and 75th percentiles (top and bottom of the box, respectively), and * represents the significance of the difference. * represents P values less than 0.05, and ** represents P values less than 0.01.

Figure 3. (a) Comparison of the soil effect in evenly spaced soil sand content. The points represent the mean, and the whiskers represent the entire range in the selected subclimate dryland regions worldwide. The line shows the linear modeled effect between the soil sand content and the soil effect. (b) Relationships between the soil effect and soil water supply capacity (PVDI) and GPP deviation between actual GPP and precipitation-determined GPP.
Figure 4. The impact of different soil performances on water availability and GPP. In two areas with the same precipitation constraint level but different soil textures, the area with a higher sand content is more likely to reduce the impact of precipitation constraints on vegetation growth by effective precipitation redistribution, which corresponds to a higher GPP.

We not only distinguish two water-constraint types but also assess the soil-buffering effect on reducing the precipitation constraint. The soil effect may be closely related to the complex subsurface water-redistribution process. Many previous studies have provided observational evidence to show that dryland ecosystems are particularly well adapted to using past precipitation and remote precipitation to overcome irregular drought events, thus exhibiting the soil moisture constraint pattern rather than the precipitation-constraint pattern (Miguez-Macho and Fan 2021). Meanwhile, it has also been widely observed in arid ecosystems that each rain event generates a pulse of moisture and promotes vegetation growth (Feldman et al 2018). Ecosystems with adaptations to this precipitation pulse-driven pattern may be more inclined to the precipitation-constraint pattern, and soil has very little buffering effect. Based on our results, a stronger soil-buffer effect corresponds to a more favorable subsurface water supply capacity and higher GPP relative to precipitation, and most dryland regions have an obvious soil-buffer effect, which may release vegetation growth and productivity from rainfall supply potential, especially in global arid and semiarid regions.

Soil texture is an important determinant of the soil-buffering effect. Contrary to the potential impression that coarser-textured soils or a desertified soil environment represented by a higher sand fraction cause plants to be more vulnerable to drought stress than fine-textured soils in very arid zones, our results show that a higher sand content tends to have a stronger soil-buffering effect and is more
likely to reduce the impact of precipitation constraints on vegetation growth. The range and intensity of desertification have increased in some dryland areas over recent decades (Yao et al. 2020). Land desertification is often associated with two characteristics: coarser-textured soils across a range of potential texture divisions represented by sand content, and adverse conditions for vegetation growth, particularly when coupled with droughts (Wang 2016). If clay soils can preclude vegetation growth by exacerbating aridity somewhere, it could be expected that drought-induced plant water stress and tree mortality in most previous studies would be exaggerated on coarse-textured soils. Our results also complement and support the well-known site-scale theory—the inverse-texture hypothesis—at a regional scale and explain some potential exceptions to the inverse-texture effect in previous studies (Bradford et al. 2006). In global drylands, coarse soil is more likely to separate vegetation water constraint (represented by soil moisture constraint) from climatic drought stress (represented by precipitation constraint), thus having favorable subsurface water supply capacity and higher productivity relative to annual rainfall. This phenomenon is pronounced in global arid regions and global semiarid regions. The soil texture-impacted soil-buffering effect was the least varied in global dry subhumid regions. Therefore, the potential for soil coarsening to release vegetation productivity from rainfall supply potential by alleviating precipitation constraints vary across the three subtypes of global drylands and is more pronounced in arid and semiarid regions.

Finally, we stress that the concept of the soil-buffering effect we developed is independent of absolute precipitation and soil moisture, and thus our study does not question the many documented adverse impacts of soil coarsening: for example, coarser-texture soils tend to have lower soil moisture (Jian et al. 2015). However, we argue that there is an important interaction among soil, precipitation, and water availability for vegetation growth. Numerous previous studies with a broad but incomplete description of drought often generate highly conflicting conclusions, and water availability should be viewed and evaluated under a coupled soil–plant–atmosphere continuum frame.

5. Conclusions

In this study, we have comprehensively evaluated the precipitation constraint and soil moisture constraint in global drylands and have found that, in global drylands, the existence of soil drives the water-constraint divergence between precipitation and soil moisture. Soil texture emerges as the most significant soil property along water constraint divergence gradients, and, overall, we find that increased soil sand content has a stronger buffering effect, which weakens the precipitation constraint and corresponds to more favorable subsurface water supply capacity and higher GPP, especially in arid and semiarid regions of the world.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that they have no competing interests.

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