Effect of the 2022 summer drought across forest types in Europe

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Abstract

Forests in Europe experienced record-breaking dry conditions during the 2022 summer. The direction in which various forest types respond to climate extremes during their growing season is contingent upon an array of internal and external factors. These factors include the extent and severity of the extreme conditions and the tree ecophysiological characteristics adapted to environmental cues, which exhibit significant regional variations. In this study we aimed to: 1) quantify the extent and severity of the extreme soil and atmospheric dryness in 2022 in comparison to two most extreme years in the past (2003 and 2018), 2) quantify response of different forest types to atmospheric and soil dryness in terms of canopy browning and photosynthesis, and 3) relate the functional characteristics of the forests to the emerging responses observed remotely at the canopy level. For this purpose, we used spatial meteorological datasets between 2000 to 2022 to identify conditions with extreme soil and atmospheric dryness. We used the near-infrared reflectance of vegetation (NIRv) derived from the MOderate Resolution Imaging Spectroradiometer (MODIS), and the Global OCO-2 Solar Induced Fluorescence (GOSIF) as an observational proxy for ecosystem gross productivity, to quantify the response of forests at the canopy level.

In summer 2022, southern regions of Europe experienced exceptionally pronounced atmospheric and soil dryness. These extreme conditions resulted in a 30% more widespread decline in GOSIF across forests compared to the drought of 2018, and 60% more widespread decline compared to the drought of 2003. Although the atmospheric and soil drought were more extensive and severe (indicated by a larger observed maximum z-score) in 2018 compared to 2022, the negative impact on forests, as indicated by declined GOSIF, was significantly larger in 2022. Different forest types were affected in varying degrees by the extreme conditions in 2022. Deciduous broad-leaved forests were the most negatively impacted due to the extent and severity of the drought within their distribution range. In contrast, areas dominated by Evergreen Needle-Leaf Forests (ENF) in northern Europe experienced a positive soil moisture (SM) anomaly and minimal negative vapor pressure deficit (VPD) in 2022. These conditions led to enhanced canopy greening and stronger solar-induced fluorescence (SIF) signals, benefiting from the warming. The higher degree of canopy damage in 2022, despite less extreme conditions, highlights the evident vulnerability of European forests to future droughts.

Keywords: *photosynthesis, soil drought, atmospheric drought, canopy browning, gross primary production*

Introduction

The frequency and intensity of drought events have been rising globally, and future global warming is expected to further increase their occurrence (Seneviratne et al. 2021; Röthlisberger and Papritz 2023). Particularly over the past two decades, many regions in Europe have experienced widespread drought conditions, notably during the summers of 2003, 2010, and 2018 (Bastos et al. 2020; Zhou et al. 2023). The extreme conditions caused widespread ecological disturbances (Müller and Bahn 2022) and reduced the capacity of forests for carbon uptake, thereby diminishing their potential for mitigating climate change (van der Woude et al. 2023). Additionally, heatwaves and prolonged droughts stress vegetation, making it more susceptible to other biotic and abiotic stress factors. This increased vulnerability leads to higher tree mortality, elevated wildfire risks, and a loss of biodiversity among plants and animals living at the edge of their temperature tolerance. These conditions also alter phenology and plant development, causing cascading effects on ecosystem functioning (Seidl et al. 2017).

The spatial extent and severity of drought events vary, and their impacts depend on local ecological characteristics of the forests, species-specific temperature and moisture thresholds that limit tree functioning, as well as adaptation strategies and acclimation of trees to more frequent and intense extreme conditions (Gessler et al. 2020). For example, comparing the 2003 and 2018 extreme years, the year 2018 was characterized by a climatic dipole, featuring extremely hot and dry weather conditions north of the Alps but comparably cool and moist conditions across large parts of the Mediterranean. Negative drought impacts appeared to affect an area 1.5 times larger and to be significantly stronger in summer 2018 compared to summer 2003 (Buras et al. 2020).

In 2022, Europe faced its second hottest and driest year on record, with the summer of that year being the warmest summer ever recorded. Conditions in summer 2022 led to record-breaking heatwave and drought events across many regions (Copernicus Climate Change Service, 2023). Compound drought and heatwave conditions in 2022 caused widespread crop damage, water shortages, and wildfires across Europe. The hardest-hit areas were the Iberian Peninsula, France, and Italy, where temperatures exceeded 2.5°C above normal, and severe droughts persisted from May to August (Tripathy and Mishra 2023). The reduced soil moisture due to precipitation deficits and high temperatures, contributed to the persistence and severity of drought, creating a positive feedback loop where dry soils led to even drier conditions (Tripathy and Mishra 2023).

Drought and heatwaves have a range of detrimental effects on trees and forests. The most immediate impact is that elevated air temperatures and increased dryness, whether in the soil or in the atmosphere, disrupt mesophyll and stomatal conductance, thereby impairing carbon uptake (Marchin et al. 2022). Plants reduce stomatal conductance under severe drought to reduce water stress at the expense of reduced rates of photosynthesis (Oren et al., 1999). Drought also increases the chance of hydraulic failure, which can lead to tree mortality (Choat et al. 2018). Additionally, rising temperatures reduce the enzymatic activity in trees, which in turn diminishes the forest´s gross primary productivity (Gourlez de la Motte et al. 2020). Elevated temperatures can also increase respiration rates in both soil and trees, which reduces the forest´s net carbon uptake and their ability to mitigate anthropogenic CO_2 emissions (van der Molen et al. 2011; Anjileli et al. 2021). Drought also restricts the movement of nutrients in soil water, reducing their availability to trees and consequently impacting their growth and productivity (Bauke et al. 2022). Changes in plant water-use and nutrient cycling can trigger feedback loops that magnify the effects of drought and heat stress. For instance, reduced plant cover can increase soil temperatures and further accelerate water loss and increase plant water demand (Haesen et al. 2023). On the other hand, increased atmospheric dryness or reduced soil moisture levels increase stomatal closure which limits transpiration and leads to higher leaf temperature that intensifies heat stress on plants (Drake et al. 2018). Reduced transpiration and photosynthesis elevate surface temperatures and atmospheric CO_2 concentrations, altering local and regional climate patterns and intensifying the frequency and severity of extreme events (Humphrey et al. 2018). These effects vary significantly depending on forest type and species composition. Together with the characteristics of the extreme events themselves – such as their extent and severity- this variability complicates our understanding of how drought affects the functionality of different forest ecosystems (Gharun et al. 2020; Shekhar et al. 2023). These feedback loops highlight the urgent need to assess how climate extremes impact different forest types, which are crucial for sequestering significant portions of anthropogenic emissions. Our study aims to 1) quantify the extent and severity of the extreme conditions in 2022 – focusing on soil and atmospheric dryness- and compare them to those of two previous extreme years (2003, 2018), 2) quantify the responses of different forest types to drought in terms of canopy browning and photosynthesis, and 3) connect the functional characteristics of the forests with the canopy-level responses observed.

Methods

Meteorological dataset

We used Europe-wide gridded datasets covering daily mean air temperature (Tair; °C), daily mean relative humidity (RH; %) and daily mean soil moisture (SM; m^3m^{-3}) for the topsoil layer (0-7 cm depth), spanning from 2000-2022. The study area encompasses longitudes from 11°W to 32°E, and latitudes from 35.8°N to 72°N, approximately 4.45 million km^2. We sourced the Tair and RH datasets from the E-OBS v27.0e dataset which provides daily data at 0.1°×0.1° spatial resolution (Cornes et al., 2018; Klein et al., 2002). We calculated daily mean vapor pressure deficit (VPD; kPa) from Tair and RH using Equation 1 (Dee et al. 2011).

$$VPD = (1 - \frac{RH}{100}) \times 0.6107 \times 10^{\frac{7.5 \times Tair}{237.3 + Tair}} \quad (1)$$

The topsoil SM dataset was extracted from the most recent reanalysis data from ECMWF's (European Centre for Medium-range Weather Forecasts) new land component of the fifth generation of European Reanalysis (ERA5-Land) dataset (daily at 0.1°×0.1° resolution; Munoz-Sabater et al., 2021). ERA5-Land provides soil moisture (SM) data at an hourly interval with a spatial resolution of 0.1° × 0.1°. For our analysis, we aggregated the hourly SM data into daily averages. Recent validation studies using in-situ measurements and satellite data have confirmed the high accuracy of surface SM simulations from ERA5-Land (Albergel et al., 2012; Lal et al., 2022; Muñoz-Sabater et al., 2021). Additionally, SM data from ERA5-Land have been utilized to investigate drought and global SM patterns (see Lal et al., 2023; Shekhar et al., 2024b). We re-sampled the Tair, VPD, and SM data from daily (0.1° × 0.1°) to 8-day (0.05° × 0.05°) intervals to align with the temporal and spatial resolution of the vegetation response dataset (see below).

Forest canopy response dataset

In order to assess the forest canopy response to drought stress, we used two satellite-based proxies:

1) The structure-based NIRv (Near-Infrared Reflectance of Vegetation) index derived from MODIS (Moderate Resolution Imaging Spectroradiometer; 8-day 500m x 500m MOD09Q1 v6.1 product) which is calculated using surface spectral reflectance at near-infrared band (R_{NIR}) and red band (R_{Red}) as shown in Equation 2 (Badgley et al. 2017). The calculated NIRv at 500m resolution was aggregated to a 0.05°×0.05° resolution (daily) by averaging.

$$NIR_V = R_{NIR} \times \frac{R_{NIR} - R_{Red}}{R_{NIR} + R_{Red}} \qquad (2)$$

2) The physiological-based reconstructed global OCO-2 (Observation Carbon Observatory - 2) solar induced fluorescence (GOSIF) dataset. Solar-induced fluorescence (SIF) is an energy flux (unit: $Wm^{-2}\mu m.sr^{-1}$) re-emitted as fluorescence by the chlorophyll *a* molecules in the plants during photosynthesis (Baker, 2008). Recent extensive research has established a strong link between Solar-Induced Fluorescence (SIF) and vegetation photosynthesis, validating SIF as an effective proxy for ecosystem gross primary productivity (GPP) (Li et al. 2018; Magney et al. 2019; Shekhar et al., 2022). The GOSIF dataset was created by training a Cubist Regression Tree model to gap-fill SIF retrievals from OCO-2 satellite. This was done using MODIS Enhanced Vegetation Index (EVI) and meteorological reanalysis data from MERRA-2 (Modern-Era Retrospective analysis for Research and Applications), which includes photosynthetically active radiation (PAR), VPD, and air temperature (see Li and Xiao, 2019). We downloaded GOSIF data set (v2) from the Global Ecology Data Repository (http://data.globalecology.unh.edu/data/GOSIF_v2/, last accessed on 25 July 2024). The GOSIF was available from 2000-2022 at 8-day temporal scale with a spatial resolution of 0.05°$\times$0.05° (Li and Xiao, 2019).

GOSIF signals provide information about physiological response of forest photosynthesis while NIRv (a recently developed vegetation index) signals provide information about the health status of the canopy. NIRv is preferred over NDVI and EVI as it can isolate the vegetation signal, mitigate mixed-pixel issue, and partly address the influences of background brightness and soil contamination (Zhang et al. 2022). The two vegetation proxies used in this study are anticipated to offer complementary insights into vegetation response to drought.

Land cover dataset

In this study, we focused on five different types of forests (and woodlands) across Europe, namely, evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous broadleaf forest (DBF), mixed forest (MF), and woody savannas (WSA). The spatial distribution of the five different forest types across Europe is shown in Figure 1. We used the yearly MODIS land cover product (MCD12C1 version 6.1 at 0.05°$\times$0.05° resolution) for the years of 2001, 2006, 2011, 2016 and 2021, to extract total areas covered by each forest type. Area of each grid cell was calculated using trigonometric equations considering the latitudinal and longitudinal variations arising due to Earth's spherical shape (Ellipsoid). Only areas that were consistently identified as each forest type over the five-year period were included in the analysis. This means that only pixels common across these five years were selected, and with more than 50% of the 0.05°$\times$0.05° pixel area identified as forests. The forested areas selected for this study encompassed 907,875 km^2, which represents approximately 24% of Europe's total land area. Out of the total area about 23% (206´212 km^2) was dominated by ENFs distributed largely across Northern Europe (NEU). Approximately 1% (7´000 km^2) of the area was dominated by EBFs, located entirely in Mediterranean Europe (MED), and about 10% (92´209 km^2) was dominated by DBF which was largely distributed across MED. Approximately 20% (174´934 km^2) of the total forested area was dominated by MFs largely dominating Central Europe (CEU), and about 47% (427´529 km^2) was dominated by WSA mostly found in NEU (Figure 1).

Drought detection and statistical data analysis

The focus of our analysis was on the summer months during three extreme years of 2003, 2018, and 2022. For this purpose, we subset VPD, soil moisture (SM), and both vegetation proxies (NIRv and GOSIF) for the months of June, July, August (JJA) which consisted of fourteen 8-day periods, for each forested pixel between 2000 and 2022. We restricted our analysis to the months of June-July-August so our study is 1) comparable with existing studies focused on the summer drought 2) to capture the peak of the warm and dry conditions across Europe, that would be most stressful for the vegetation functioning, from the perspective of heat and water supply.

To account for the impact of the observed greening trend across Europe on vegetation proxy anomalies during the extreme years (2003, 2018, 2022), we applied a detrending process to the summer mean NIRv and GOSIF data. This detrending was performed pixel-wise from 2000 to 2022 using a simple linear regression model (Buras et al., 2020). We then calculated pixel-wise standardized summer anomalies, expressed as z-scores (Var_z), for all variables—VPD, SM, and the detrended NIRv and GOSIF (hereafter referred to as NIRv and GOSIF)—for each year, including the extreme years, using Equation 3.

$$Var_z\ (unitless) = \frac{Var - Var_{mean}}{Var_{sd}} \qquad (3)$$

where, Var_{mean} and Var_{sd} are mean and standard deviation of any variable over the 2000-2022 period.

In drought identification studies, classification of 'normal' (not to be confused with normal distribution), 'drought' (used synonymously with 'dry'), or 'wet', is largely done using a standardized index, such as SPI (Standardized Precipitation Index), SPEI (Standardized Precipitation Evapotranspiration Index), and z-score among others (see Mishra and Singh, 2011). All studies that use a standardized index for classification, classify "normal" conditions when the index is between -1 and 1, and "below normal" conditions when the index is < -1, and "above normal" conditions when the index > 1 (Jain et al., 2015, Wable et al., 2019, Dogan et al., 2012, Tsakiris and Vangelis, 2005). In this study, we classified drought conditions as occurring when soil moisture is below normal (SMz < -1) and VPD is above normal (VPDz > 1), indicating both soil AND atmospheric dryness. This threshold-based approach using standardized anomalies aligns with established methods for drought identification and is pertinent for studying drought impacts on forests. Both soil moisture and VPD directly affect vegetation functioning, making them effective proxies for identifying environmental constraints on plant physiological performance. Furthermore, such classification of 'normal' (and thus, 'above normal' and 'below normal' used in this study) based on z-scores (also called standardized anomalies) can be done for any meteorological and/or response variables, such as NIRv and GOSIF done in this study, making the narration of results coherent across different variables.

We used the Pearson correlation coefficient (*r*) and partial correlation coefficients (Pr) to understand the spatial (across space for each year) and temporal (during each year) correlation of GOSIF and NIR_v anomalies with SM and VPD anomalies (Dang et al., 2022). We calculated the partial correlation coefficient using equations 4-7:

$$Pr(GOSIF, SM) = \frac{r(GOSIF,SM) - r(GOSIF,VPD) \times r(SM,VPD)}{\sqrt{1-r(GOSIF,VPD)^2} - \sqrt{1-r(SM,VPD)^2}} \quad (4)$$

$$Pr(GOSIF, VPD) = \frac{r(GOSIF,VPD) - r(GOSIF,SM) \times r(SM,VPD)}{\sqrt{1-r(GOSIF,SM)^2} - \sqrt{1-r(SM,VPD)^2}} \quad (5)$$

$$Pr(NIRv, SM) = \frac{r(NIRv,SM) - r(NIRv,VPD) \times r(SM,VPD)}{\sqrt{1-r(NIRv,VPD)^2} - \sqrt{1-r(SM,VPD)^2}} \quad (6)$$

$$Pr(NIRv, VPD) = \frac{r(NIRv,VPD) - r(NIRv,SM) \times r(SM,VPD)}{\sqrt{1-r(NIRv,SM)^2} - \sqrt{1-r(SM,VPD)^2}} \quad (7)$$

Results

Severity of the 2022 summer drought compared to 2018 and 2003

Figure 2 shows the extent and magnitude of anomalies (z-score) of VPD and top layer (0-7 cm) soil moisture content during the summer months in 2003, 2018, and 2022 across Europe. In summer 2022, particularly southern regions of Europe experienced the most pronounced increase in atmospheric (z-score > 1) and soil dryness (z-score < -1) (Figure 2) while in 2018 we observed the most widespread VPD and SM anomalies in northern Europe (Figure 2).

Figure 3 shows the intensity of atmospheric and soil drought via z-score values of VPD and SM anomalies over the summer months (JJA) in 2003, 2018, and 2022. The total affected area displayed in Figure 3 is the sum of all pixels within the given z-score bin during the summer period where z-scores are averaged for each bin for the summer period. Restricted to forested areas, atmospheric and soil drought was 55% and 58% more extensive in 2018 compared to 2022, and in both years more extensive than in 2003 (Figure 3). In 2022, 28 Mha of forested areas in Europe experienced an extremely high VPD (z-score > 1), while in 2018, 63 Mha experienced such extreme conditions. In 2022, 21 Mha of forested areas experienced an extremely low soil moisture content (z-score <

-1) while in 2018, 50 Mha of forests in Europe were affected by such extreme conditions. In 2003 an area of 25 Mha was affected by extremely dry air and a similar area was affected by extremely dry soil (Figure 3). A comparison of soil drought detected from SM at 0-100 cm showed a similar result in terms of drought severity and spatial coverage and thus we used SM at 0-7 cm soil layer for our analysis (see Supplementary Figure 1).

Forest canopy response to the 2022 drought

The intensity of GOSIF and NIRv anomalies over the summer months (JJA) in 2003, 2018, and 2022 are displayed in Figure 4. The extent shown in Figure 4 is the sum of all pixels within the given z-score bin during the summer period (z-scores are averaged for each bin). Compared to 2018, the extremely dry conditions in 2022 led to 30% increase in forested areas that exhibited declined photosynthesis (17 Mha in 2022 compared to 12 Mha in 2018) (Figure 4). The extent of the canopy browning observed in 2022 was similar to 2018, which in both years was 120% of the extent of observed canopy browning in 2003 (11 Mha compared to 5 Mha observed in 2003) (Figure 4).

Figure 5a shows the GOSIF anomalies (z-score) across all forested areas in Europe. The intensity and extent of the GOSIF anomalies during the summer months (JJA) in each year are shown for different forest types in Figure 5b. Across specific forest types, DBFs showed the largest negative GOSIF anomaly in 2022 but the ENFs showed a positive GOSIF anomaly in 2022, both in terms of magnitude and in terms of the spatial extent of negative GOSIF anomalies (Figure 5).

Figure 6a shows the anomalies of NIRv (average z-score over the summer months) across all forested areas in Europe. The intensity and extent of the NIRv anomalies during the summer months (JJA) in each year are shown for different forest types in Figure 6b. In terms of canopy browning response (NIRv anomalies), the largest negative NIRv anomalies in 2022 were observed in southern Europe (Figure 6). Largest negative NIRv anomalies (indicated by the maximum anomaly) were observed in the DBFs in 2022, fitting the declined GOSIF signals. The ENFs showed positive NIRv anomalies in 2022, in terms of magnitude, spatial coverage, and % of total area affected (Figure 6).

Relationship between GOSIF and NIRv

In general, the values of NIRv and GOSIF were highly correlated (Supplementary Figure 2). The anomalies of NIRv and GOSIF were most correlated across WSAs (r^2 = 0.73 in 2018) and least correlated across the ENFs (Supplementary Figure 2). Figure 7 shows the spatial regression between standardized GOSIF anomalies with (a) VPD and (b) SM and Figure 8 shows the spatial regression between standardized NIRv anomalies with (a) VPD and (b) SM over the drought areas in summers 2003, 2018 and 2022. With the increase in VPD (i.e., increased atmospheric dryness), GOSIF values declined across all forest types, across all years, except in 2022 in the WSA, and in 2018 and 2022 in EBFs (Figure 7). With decrease in soil moisture (i.e., increased soil dryness), GOSIF values also declined overall (r^2 = 0.34), but not as strongly as with the increase in air dryness (r^2 = 0.39) (Figure 7). Across different forest types, GOSIF responded most strongly to VPD anomalies in the MFs (mean r^2 = 0.48), and responded most directly to changes in the soil moisture in the WSA (Figure 7).

Between VPD and SM, in general GOSIF anomalies were more correlated with VPD than with SM anomalies, and the decline in VPD correlated well with the larger GOSIF decline that we observed in DBFs in 2022 and in ENFs in 2003 (Figure 7). Under typical conditions (regardless of drought), GOSIF's response to both air dryness and soil moisture anomalies was more pronounced than the response of NIRv (r^2 = 0.39 with GOSIF, compared to r^2 = 0.29 for NIRv) (Figure 7, 8).

Figure 9 shows the partial correlation coefficient between GOSIF with SM and VPD during summer months (JJA) for areas identified as affected (Figure 9a) and not affected (Figure 9b) by drought. The SM and VPD values across all forest types correlated well, but across DBFs the dryness in the atmosphere and the dryness in the soil were most correlated (Figure 9). Regarding canopy response to VPD, European Needleleaf Forests (ENF) exhibited the strongest reaction to changes in atmospheric dryness (Figure 9)

Discussion

Severity of the 2022 summer drought

Although the years 2003, 2018, and 2022 are all categorized as "extreme," the specific characteristics of the extreme conditions varied significantly among these years. For example, in 2003, widespread negative anomalies in soil moisture signaled a significant soil drought, whereas in 2022, widespread positive VPD anomalies indicated a notably drier atmosphere (Figure 3). It is important to note that ERA-5 Land datasets have been shown to underestimate the extent of European heatwaves in 2003, 2010, and 2018 (Duveiller et al., 2023), partly due to the use of a static leaf area index in their modeling framework. Consequently, the SM droughts in the years 2003, 2018, and 2022 may be more severe than indicated by our study, suggesting that our results might be somewhat conservative. The extensive summer drought in 2022 primarily impacted southern Europe, in contrast to the 2003 summer drought, which affected central Europe, and the 2018 drought, which extended to central and northern Europe (Figure 2) (Bastos et al., 2020). Consequently, the severe dry conditions in 2022 resulted in an average decline in GOSIF across forests that was 30% more widespread compared to 2018, and 60% more widespread compared to 2003 (Figure 4). These above-normal dry conditions during the summer reduced the photosynthetic capacity of plants and, consequently, the ecosystem's ability to absorb carbon from the atmosphere (Peters et al., 2018; van der Woude et al., 2023). Although the atmospheric and soil droughts in 2018 were more extensive and severe compared to 2022 (as indicated by the maximum observed z-scores), the adverse impact on forests, as reflected by the decline in GOSIF, was greater in 2022.

Canopy response to soil versus atmospheric dryness

The GOSIF dataset used in this study has been shown to be a reliable proxy for vegetation gross productivity, as demonstrated by comparisons with ground-based flux measurements (Shekhar et al. 2022; Pickering et al. 2022). It is important to note that GOSIF estimates are derived from a machine learning model trained with OCO-2 SIF observations, MODIS EVI data, and meteorological reanalysis data. As a result, the meteorological data used in our analyses are not entirely independent of the SIF data. However, this overlap is unlikely to impact our findings. A recent study that compared GOSIF with original OCO-2 data to assess the impacts of the 2018 U.S. drought found similar responses to drought between the two datasets (Li et al., 2020).

NIRv and SIF signals are well-correlated and effectively capture seasonal patterns in GPP (Getachew Mengistu et al. 2021). Although the strength of their relationship can vary with time, location, and forest type (see Supplementary Figure 2), reductions in SIF signals are directly associated with decreased photosynthesis. While both SIF and NIRv are reliable indicators of canopy responses to extreme climate events, SIF is more responsive to short-term climatic changes (Figure 7).

Our analysis showed that across different regions, GOSIF anomalies corresponded more strongly to increased atmospheric dryness than to increased soil dryness (Figure 7). This supports the understanding that vapor pressure deficit plays a larger role in controlling SIF signals for trees over shorter time scales than soil moisture (Pickering et al. 2022). Over shorter time frames, trees can often mitigate soil moisture deficits through mechanisms within the rooting zone and by accessing deeper water sources, whereas there is no such buffer for the impact of atmospheric dryness on tree canopies.

Ground-based observations in forest ecosystems, including both ecosystem and tree-level measurements, have shown that atmospheric dryness can constraint canopy gas exchange, even when soil moisture is not limiting (Gharun et al. 2014, Fu et al. 2022, Shekhar et al. 2024a). These findings highlight the importance of considering atmospheric dryness as a limiting factor for tree photosynthesis during extremely dry conditions and demonstrate the rapid response of various canopy types to increased levels of environmental dryness.

Canopy response to drought across different forest types

The spread of drought, measured as the total area across z-scores, exhibited distinct patterns in different years, leading to varied responses of different forest types to the climatic anomalies. Impact of drought on forests can significantly differ depending on the forest type, tree species, species composition, and past exposure to extreme conditions (Arthur and Dech 2016; Chen et al. 2022). Our analysis showed that conditions in summer 2022 reduced vegetation functioning across DBFs the most, as it was indicated by declined GOSIF signals (Figure 5). While deciduous broad-leaved forests were most negatively affected by the extreme conditions in 2022, Evergreen Needle-Leaf Forests (ENF) distributed in northern regions of Europe were not exposed to extremely dry conditions in 2022 and even showed enhanced canopy greening and GOSIF signals, through benefiting from the episodic warming (Forzieri et al. 2022). Under similar drought conditions, the mechanisms to cope with the level of drought stress vary largely among forest types, and depend on a combination of characteristics that control water loss through the coordination of stomatal regulation, hydraulic architecture, and root characteristics (e.g., rooting depth, root distribution, root morphology) (Gharun et al. 2020; Peters et al. 2023). Stomata of trees exhibit a high sensitivity to VPD fluctuations, causing a reduction in stomatal conductance as VPD increases, which, in turn, limits the exchange of CO_2 with the atmosphere during photosynthesis (Bonal and Guehl in 2011; Li et al. 2023). Different tree species show varying degrees of sensitivity in their stomatal responses to atmospheric dryness (Oren et al., 1999). For example, ring-porous species tend to maintain robust gas exchange under dry conditions, while diffuse-porous species, like those in ENFs, exhibit stronger stomatal regulation, reducing stomatal conductance as water availability decreases (Klein, 2014). This variability places plants on a spectrum of drought tolerance, reflecting their specific water relations strategies and leading to different responses among forests in similar climatic regions.

Vulnerability of forests to more frequent drought

The increased canopy damage observed in 2022, despite less severe conditions compared to the previous extreme year, suggests a lasting impact on forest canopies that could lead to a decline in forest resilience in the face of more frequent drought events (Forzieri et al., 2022). A potential decline in the resilience of forests has significant implications for vital ecosystem services, including the forest's capacity to mitigate climate change. Consequently, there is an urgent need to consider these trends when formulating robust forest-based mitigation strategies. This need is especially critical given future projections indicating that the frequency and intensity of extreme dryness across Europe will more than triple by the end of the 21st century (Shekhar et al., 2024b). In this context, it is increasingly important to investigate the vulnerability of forests to external perturbations and to develop mitigation strategies tailored to site-specific ecophysiological and environmental factors that influence forest resilience to drought. Effective management strategies should be based on an understanding of these factors to mitigate the legacy effects of drought (McDowell et al., 2020; Wang et al., 2023; Shekhar et al., 2024a).

Conclusion

The severity of the 2022 summer drought, marked by increased atmospheric dryness, significantly compromised the photosynthetic capacity of trees, leading to widespread declines in vegetation functioning, especially in deciduous broad-leaved forests. Our findings underscore the importance of considering atmospheric dryness as a critical factor influencing canopy responses during extreme climatic events, alongside soil moisture deficits. Despite less severe overall conditions compared to previous extreme years, the greater canopy damage observed in 2022 suggests a growing vulnerability of forests to drought. This raises concerns about the future climate mitigation capacity of forest ecosystems, particularly as projections indicate a continued increase in the frequency and intensity of extreme dryness across Europe.

Competing interests

The authors have no competing interests to declare.

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Data availability The R scripts used for the data analyses and plots are available upon request from the corresponding author.

Author contributions MG, AS, NB conceptualized the study. AS, JX, XL: data processing. MG and AS: data analyses. MG, AS, JX, XL: paper writing, revision and editing of the paper.

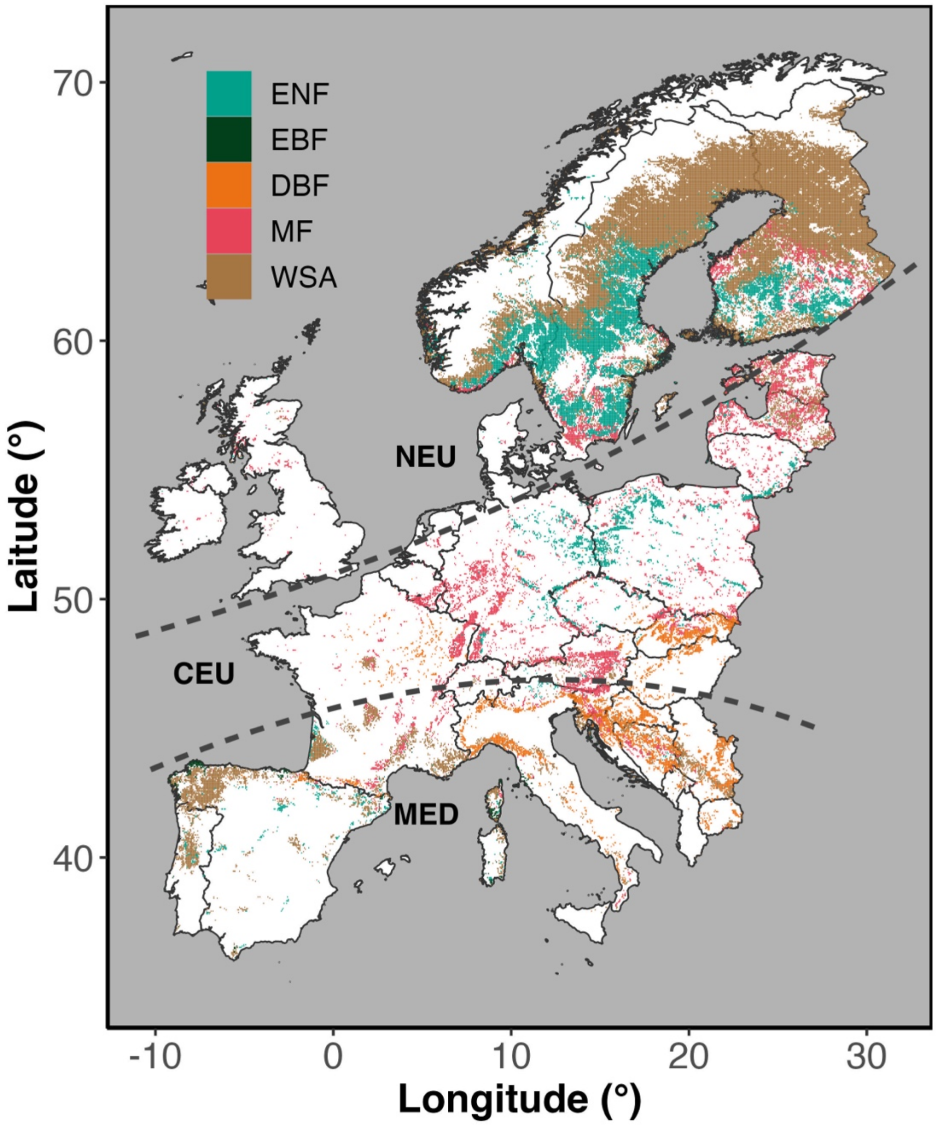

Figure 1 Spatial coverage of forests (ENF - evergreen needleleaf forest; EBF - evergreen broadleaf forest; DBF - deciduous broadleaf forest; MF - mixed forest), and woodlands (WSA - woody savannas) across Europe. Areas are differentiated into Northern Europe (NEU), Central Europe (CEU), and Mediterranean Europe (MED) following Markonis et al. (2021). The map is based on MODIS land cover product MCD12C1 (version 6.1).

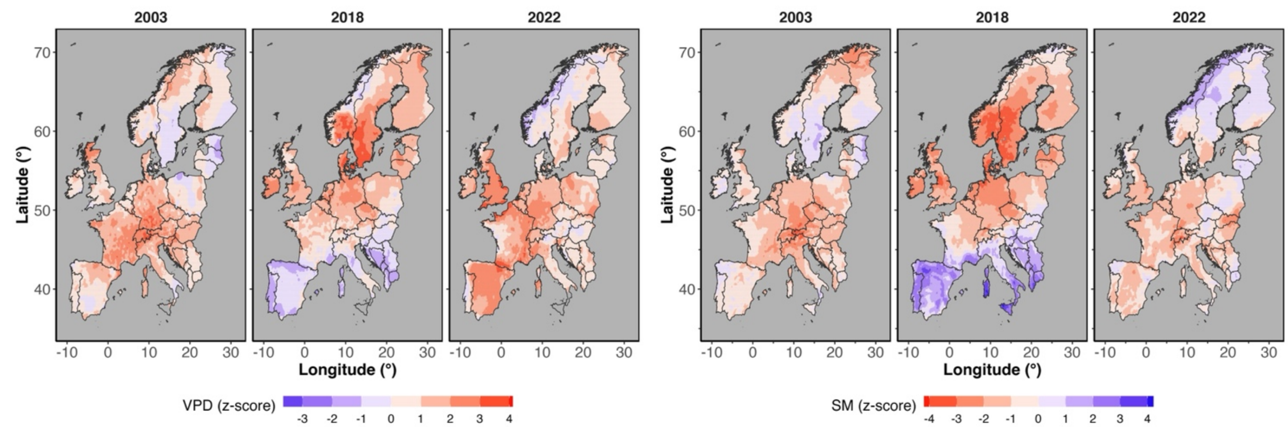

Figure 2 Standardized summer (JJA) anomalies (z-score) of mean vapor pressure deficit (VPD), and top layer (0-7 cm depth) soil moisture (SM) in 2003, 2018 and 2022, across the region of Europe.

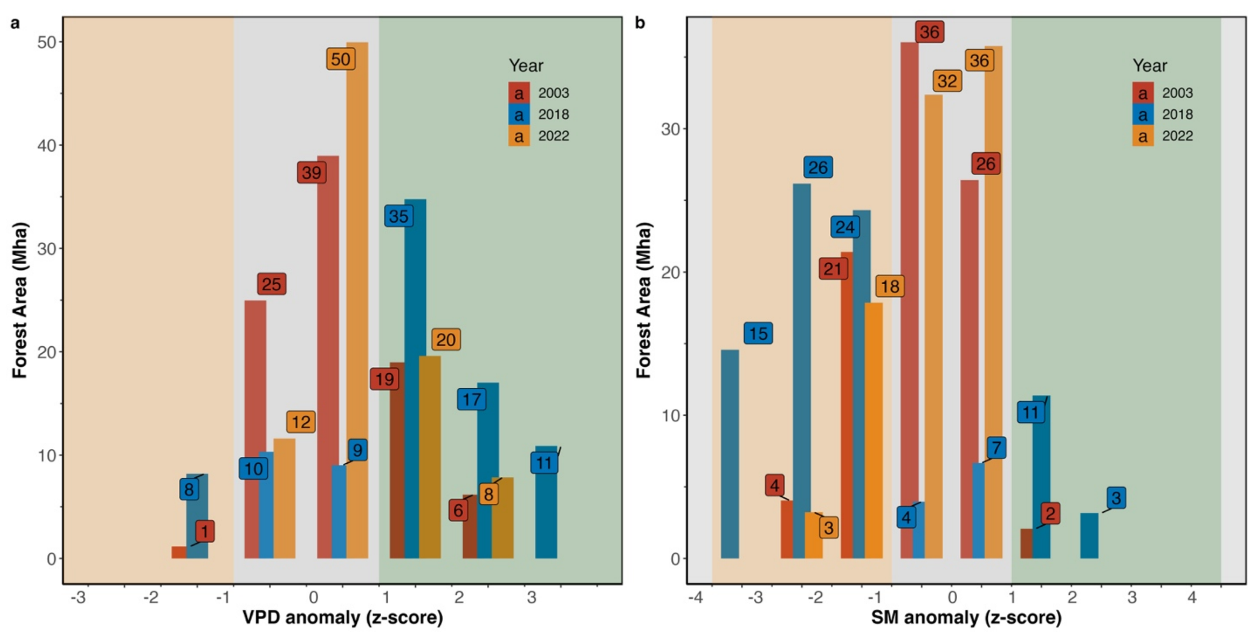

Figure 3 Intensity (z-score) and extent (area affected, Mha) of (a) VPD, and (b) SM anomalies across forested areas during the summer months (JJA). Z-score, values from -1 and 1 are considered normal (within 1 standard deviation of the mean). Orange-shaded area marks below normal and green-shaded area marks above normal conditions.

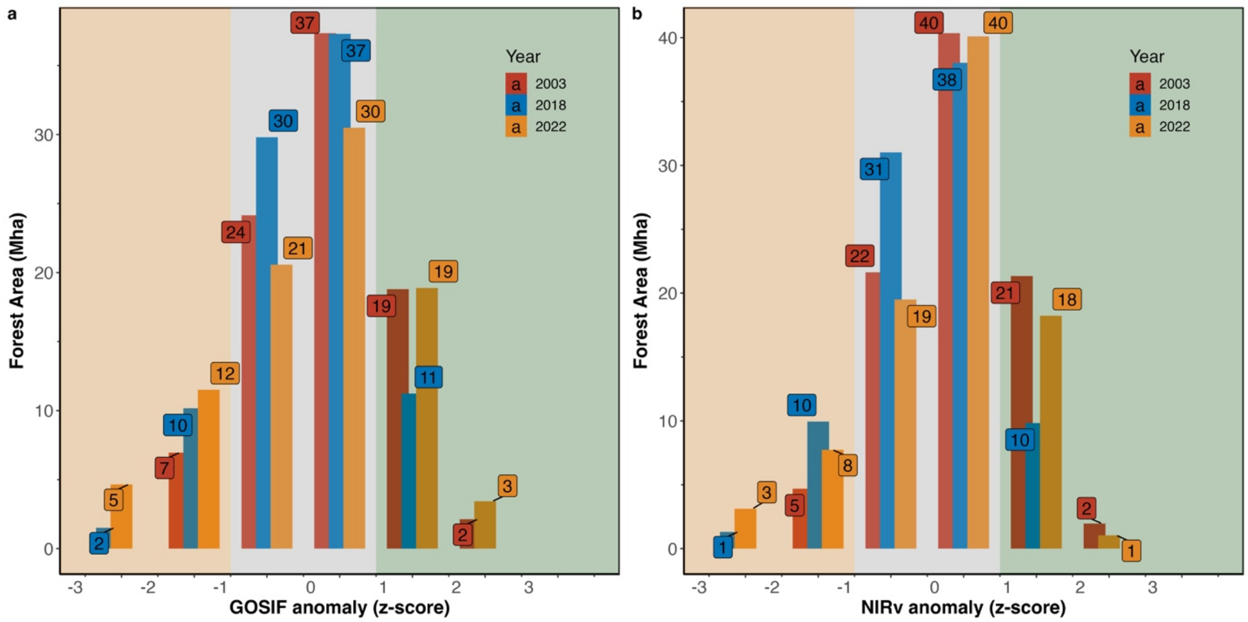

Figure 4 Intensity (z-score) and extent (area affected, Mha) for (a) GOSIF, and (b) NIRv anomalies across forested areas during the summer months (JJA). Z-score, values from -1 and 1 are considered normal (within 1 standard deviation of the mean). Orange-shaded area marks below normal and green-shaded area marks above normal conditions.

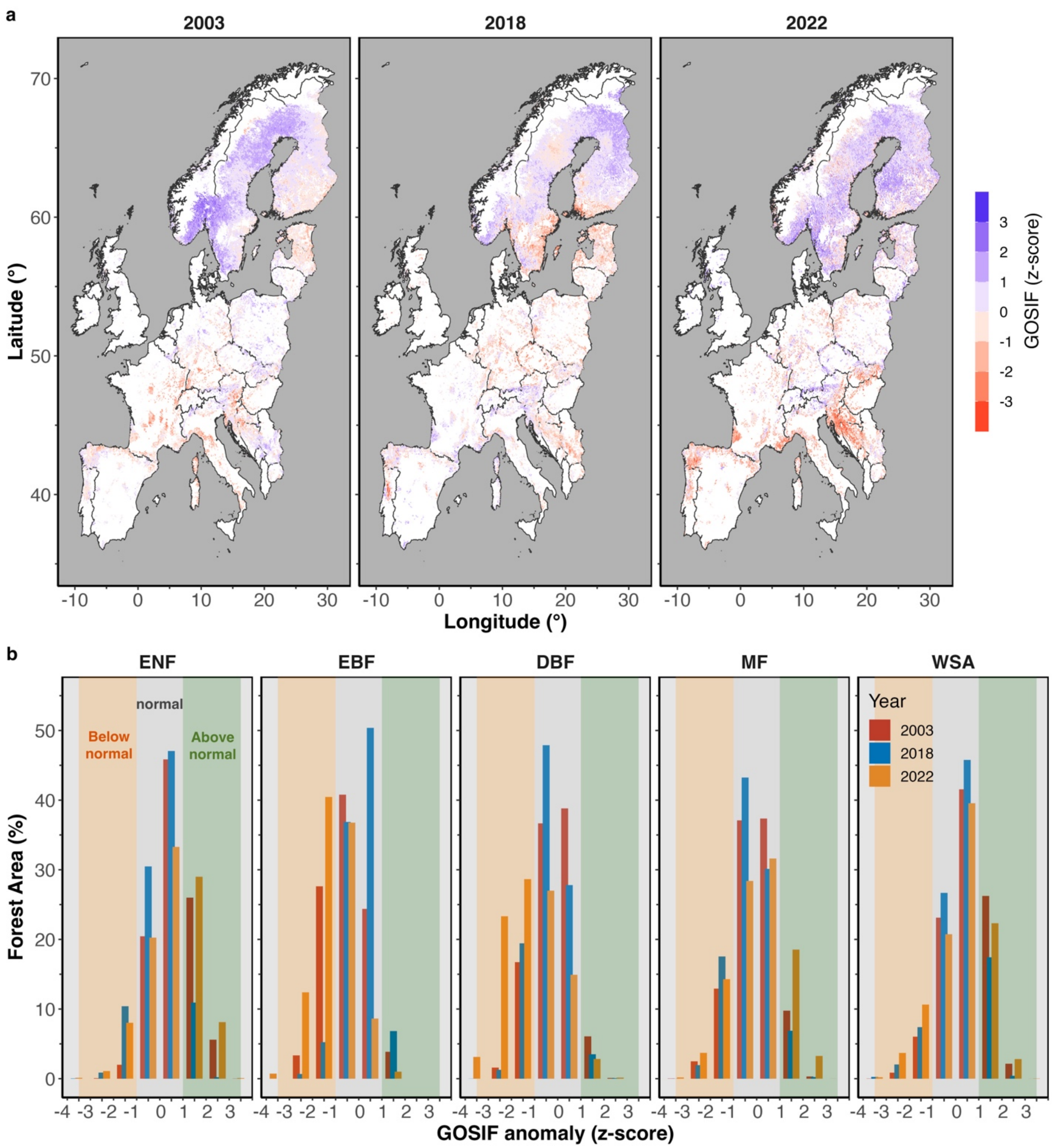

Figure 5 (a) GOSIF anomaly (in terms of z-score) across Europe, and (b) area coverage (in terms of percentage of total area for each forest type) during the summer months (JJA) in 2003, 2018 and 2022. Orange-shaded area marks below normal and green-shaded area marks above normal conditions. White areas on the map mark non-forested regions.

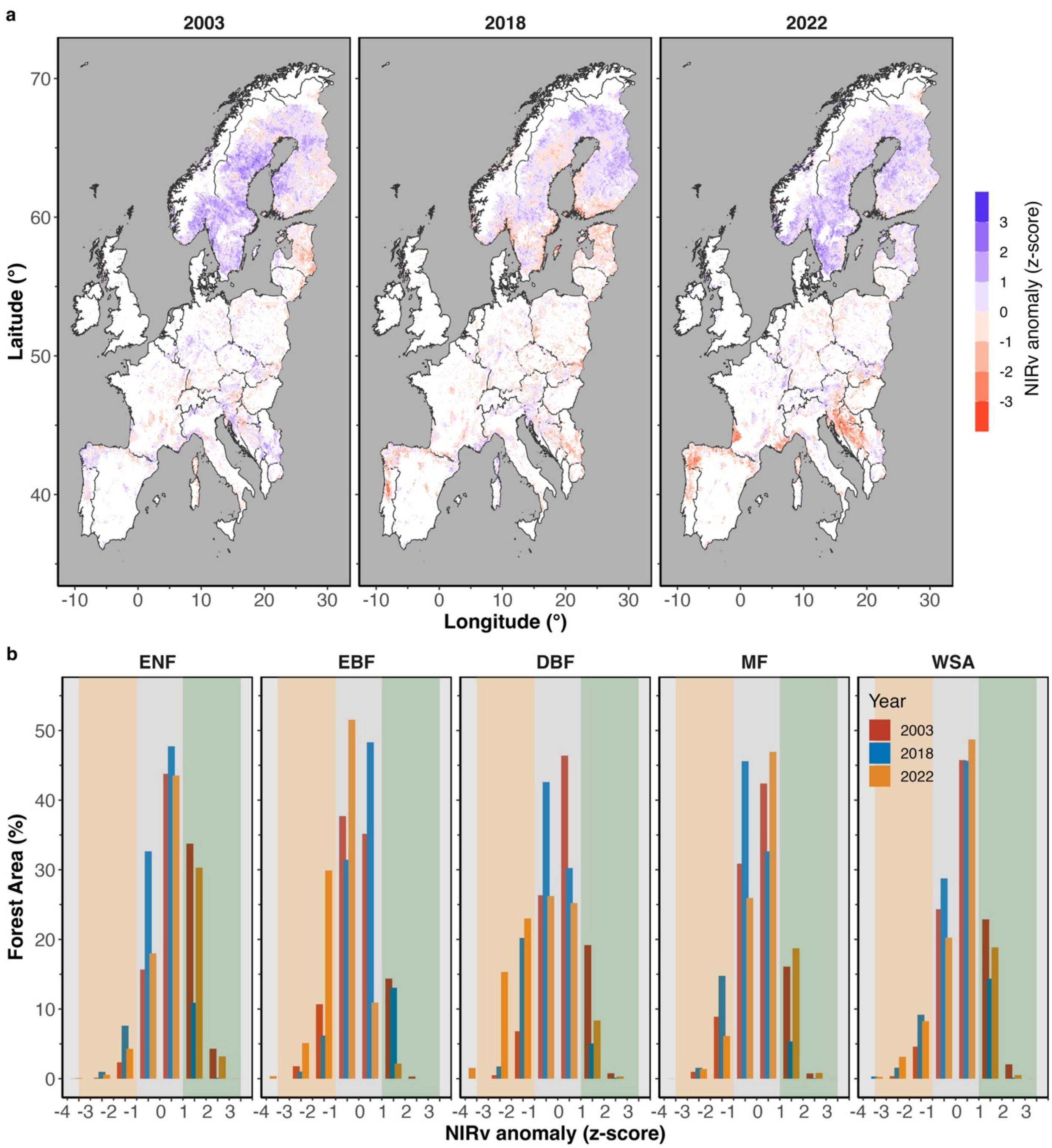

Figure 6 (a) NIRv anomaly (in terms of z-score) across Europe, and (b) area coverage (in terms of percentage of total area for each forest type) during the summer months (JJA) in 2003, 2018 and 2022. In panel (b) Orange-shaded area marks below normal and green-shaded area marks above normal conditions. White areas on the map mark non-forested regions.

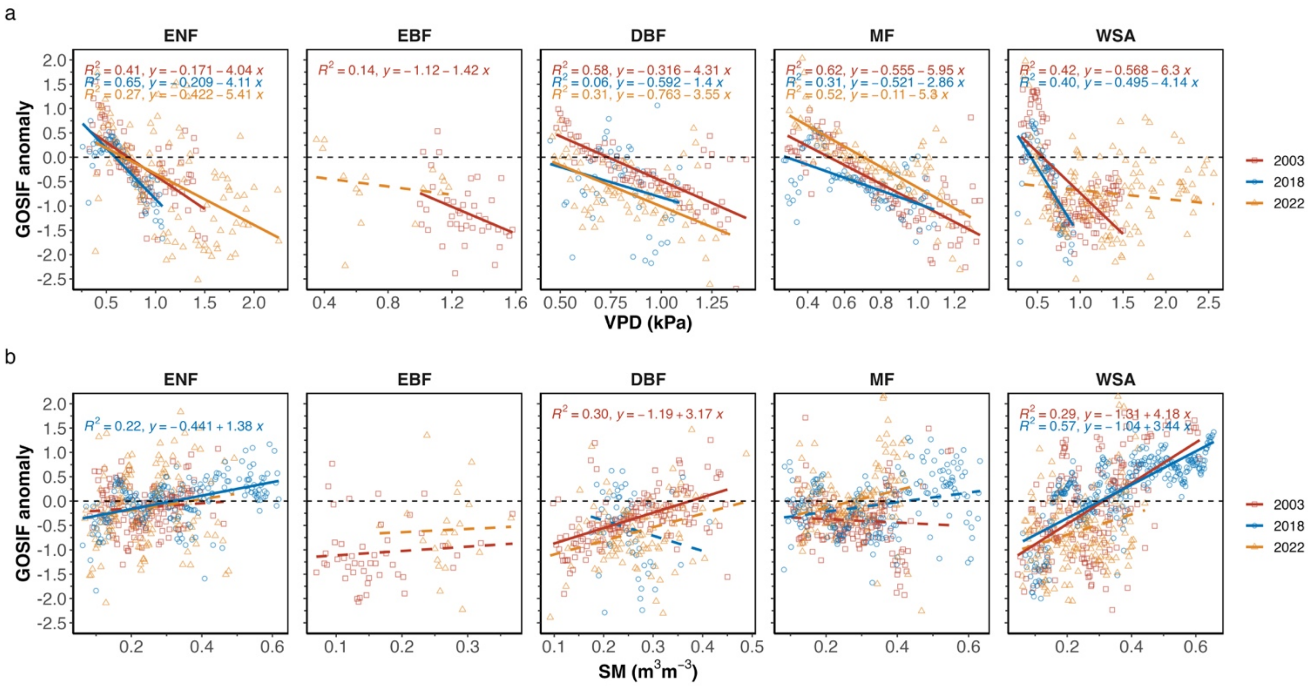

Figure 7 Spatial regression between standardized GOSIF anomalies with (a) VPD and (b) SM over the drought areas during the summer months (JJA) 2003, 2018 and 2022. Dashed lines mark a non-significant relationship (p > 0.05).

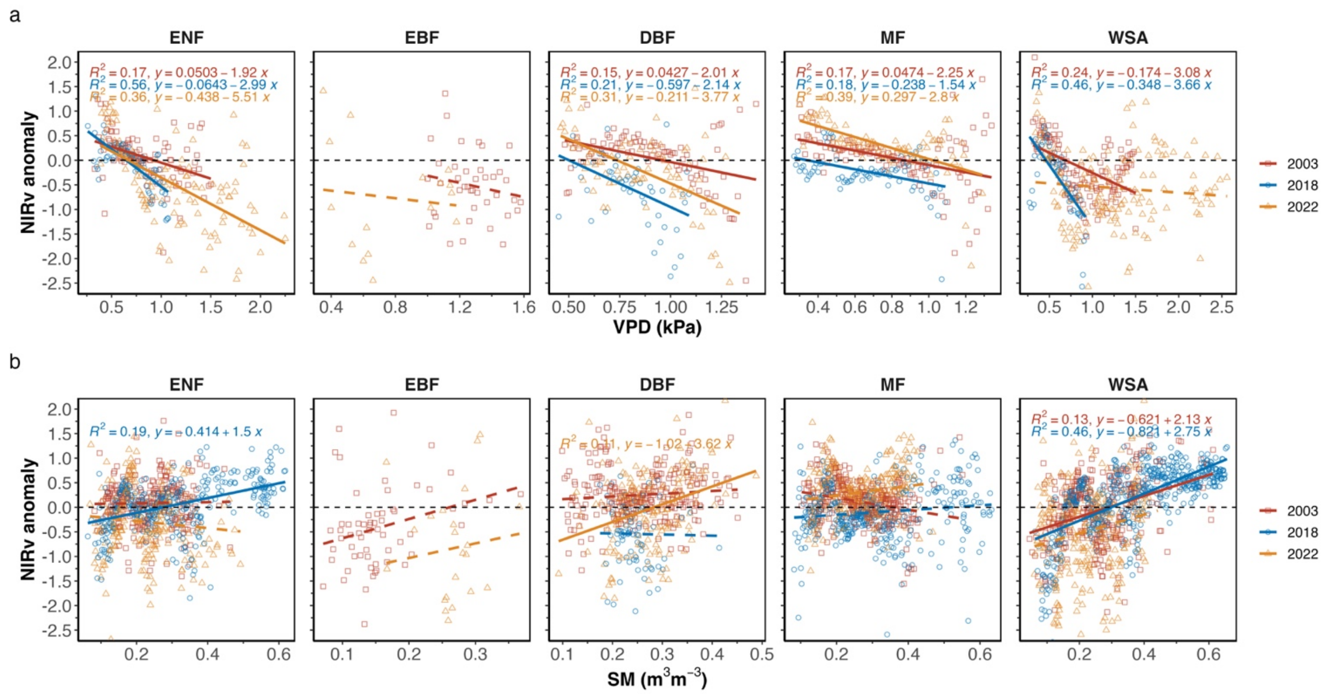

Figure 8. Spatial (over all pixels) regression between standardized NIRv anomalies with (a) VPD and (b) SM over the drought areas and normal areas in 2003, 2018, and 2022 during the summer months (JJA).

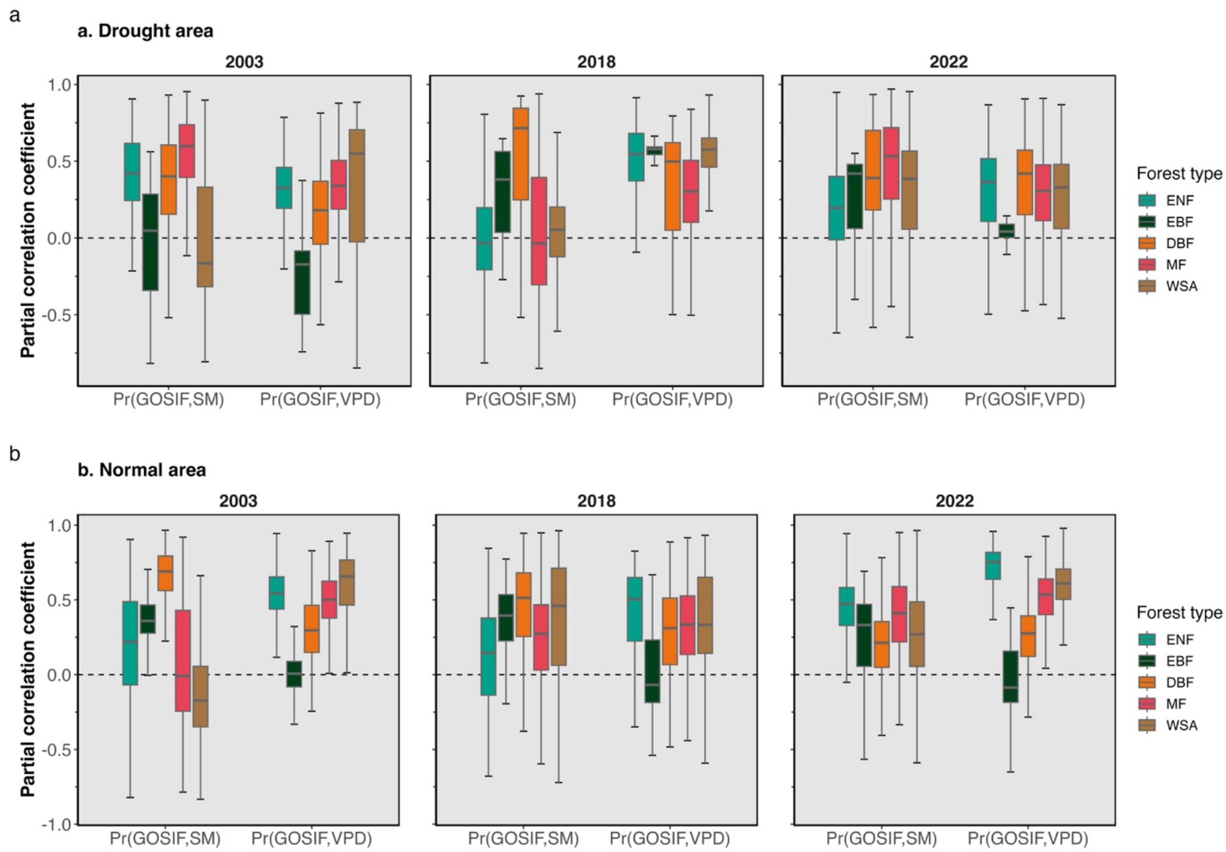

Figure 9. Temporal partial correlation coefficient of GOSIF with the absolute values of SM and VPD during the summer months (JJA) in 2003, 2018 and 2022, for detected (a) drought areas and (b) normal areas. A comparable figure for NIRv can be found in Supplementary Figure 3.

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