

**A global analysis of  
the impact of drought  
on NPP**

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# A global analysis of the impact of drought on net primary productivity

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## Abstract

We investigated the impact of drought on interannual variability of NPP from 1997 to 2009 using the standardized precipitation evapotranspiration index (SPEI) drought index and satellite-derived vegetation greenness converted net primary productivity (NPP). We found that SPEI and NPP were coupled and in phase on a global scale. We then used the Köppen climate classification to study the SPEI-NPP relations regionally and found that while NPP and SPEI were positively related in arid and in seasonal dry regions, the opposite occurs in most boreal regions. However, high intensity drought events, such as the 2003 drought in Europe, will lead to a reduction of NPP despite NPP being usually limited by temperature and radiation here. Our findings suggest that the strong positive relation between global average moisture availability and NPP is a composite of the positive relation across dry regions and the coherent NPP decline during and after intensive drought event in humid regions. The spatial patterns of drought impact on NPP could thus be categorized by climate classification, which implies that the predication of climate zone evaluation will contribute to the quantification of the future terrestrial carbon cycle.

## 1 Introduction

Terrestrial ecosystems constitute a substantial CO<sub>2</sub> sink in the order of a quarter of emissions from fossil fuels and deforestation (Le Quéré et al., 2009). They exhibit considerable interannual variability which is to a large extent reflected in the variability of the mean global atmospheric CO<sub>2</sub> growth rate (Knorr et al., 2007; Le Quéré et al., 2009; Zhao and Running, 2010). Zhao and Running (2010) used a Moderate Resolution Imaging Spectroradiometer (MODIS) NPP algorithm and the Palmer Drought Severity Index (PDSI) as a proxy for soil moisture, and suggested a strong correlation between the global drought and NPP.

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Extreme droughts may impact terrestrial productivity in a significant way and reduce the sink strength at (sub) continental scale (Ciais et al., 2005; Reichstein et al., 2007a; van der Molen et al., 2011). Several recent droughts, such as those in Australia (2002–2009), Europe (2003), and Amazonia (2005, 2010) had a clear detectable impact on plant productivity (Gobron et al., 2010; Zhao and Running, 2010). Since the occurrence and severity of droughts is likely to increase in the future as a result of global warming (Dai, 2012, but see also Sheffield et al., 2012), there is a clear need to understand whether the global average results found by Zhao and Running (2010) also apply at smaller spatial scales, or that at the scale of biomes and climate zones potentially different relationships appear.

Droughts have traditionally been described based on their intensity, duration and spatial extent, or a mixture of this. Precipitation anomalies are often used as a proxy because precipitation is the main water source to the soils. However, the local water balance also depends on evaporation, soil moisture storage, and runoff. Compared with precipitation, drought indices have the advantage that they quantitatively describe both the character of drought events and long term variations in the mean dry and wet conditions. Furthermore, drought indices have significant advantages over precipitation in analytical applications, as they address the potential impacts much more explicitly, for instance by taking into account the duration and cumulative severity. However Sheffield et al. (2012) also point out that care has to be exercised when extrapolating drought indices that are not based on a full physical description of the relevant processes. While recently soil moisture data have become available for 30 yr (Dorigo et al., 2012; Liu et al., 2012), these data unfortunately suffer sometimes from gaps in the time series and refer in principle only to the first few, variable centimeters of the soil, making their global application in drought studies not yet straightforward.

The standardized precipitation index (SPI, McKee et al., 1993) has been recommended as a standard drought index by the World Meteorological Organization (WMO), and is widely applied to investigate vegetation response to drought (Ji and Peters, 2003; Lotsch et al., 2003; Rhee et al., 2010). Recently, the standardized precipitation

evapotranspiration index (SPEI, Vicente-Serrano et al., 2010) was generated, which relies on a similar algorithm as SPI and is a powerful tool to estimate the response of vegetation to drought (Vicente-Serrano et al., 2013). The main difference is that SPEI includes temperature to calculate evapotranspiration, therefore providing a more meaningful parameter to detect the impact of drought on vegetation. We used SPEI in this study as a proxy for moisture availability for plants.

The objective of this study was to investigate how anomalous moisture conditions, as estimated by the SPEI, are related to annual changes in NPP on multiple time scales across the globe. We use the Carnegie-Ames-Stanford-Approach (CASA) biogeochemical model (Potter et al., 1993; van der Werf et al., 2010) to estimate NPP. We specifically aimed to provide more spatial detail than Zhao and Running (2010), as it is to be expected that soil moisture–NPP relations are strongest in arid areas and those with a pronounced dry season. In contrast, in cold and humid regions we do not expect a clear relation. We suspect that the global relations as found by Zhao and Running (2010) may hide regional detail that could be important for the future behavior of the carbon cycle.

## 2 Methods

We used the Carnegie-Ames-Stanford-Approach (CASA) biogeochemical model (Potter et al., 1993; van der Werf et al., 2010) on a  $0.5^\circ$  grid with a monthly time step. NPP was calculated by the light use efficiency approach multiplying absorbed photosynthetically active radiation (PAR) and a light use efficiency coefficient,  $\varepsilon$  (Monteith, 1972, 1977):

$$\text{NPP} = \text{PAR} \times \text{fPAR} \times \varepsilon^*(\text{NPP}) \times f(\varepsilon) \quad (1)$$

where fPAR is the fraction of PAR absorbed by vegetation,  $f(\varepsilon)$  accounts for environmental stress governed by temperature and moisture.  $\varepsilon^*(\text{NPP})$  was set to  $0.5 \text{ gCMJ}^{-1}$

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PAR globally to match global NPP values of  $60 \text{ PgCyr}^{-1}$  (Beer et al., 2010). International Satellite Cloud Climatology Project (ISCCP) solar radiation data (Zhang et al., 2004) were used here to generate PAR. fPAR data were calculated based on Normalized Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR, Tucker et al., 2005) and Moderate Resolution Imaging Spectroradiometer (MODIS) products (Myneni et al., 2002). Precipitation from the Global Precipitation Climatology Project (GPCP) version 1.1 (Huffman et al., 2001) and temperature of the Goddard Institute for Space Sciences (GISS) surface temperature analysis (Hansen et al., 1999) were employed to drive environmental stress. Further details have been provided by van der Werf et al. (2010).

Global CRU TS3.1 monthly gridded temperature and precipitation (available from [http://badc.nerc.ac.uk/view/badc.nerc.ac.uk\\_\\_ATOM\\_\\_dataent\\_1256223773328276](http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276)) were used to calculate SPEI. Both temperature and precipitation have a spatial resolution of  $0.5^\circ$  and cover the period 1901–2009. Monthly potential evapotranspiration (PET) was calculated first based on Thornthwaite (1948). The difference between precipitation (PPT) and PET was calculated as

$$D = \text{PPT} - \text{PET}. \quad (2)$$

$D$  was calculated for each grid cell and month following:

$$D_j^k = \sum_{i=0}^{k-1} (\text{PPT}_{j-i} - \text{PET}_{j-i}), \quad j \geq k \quad (3)$$

where  $k$  is time, ranging from 1 to 48 months. A three-parameter log-logistic distribution was used to model these  $D$  series, with the function given by

$$F(x) = \left[ 1 + \left( \frac{\alpha}{x - \gamma} \right)^\beta \right]^{-1} \quad (4)$$

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where  $\alpha$ ,  $\beta$ , and  $\gamma$  indicate scale, shape and origin parameters, respectively. This function was chosen as the best distribution function by L-moment ratio diagrams to fit  $D$  series (Vicente-Serrano et al., 2010). Finally, SPEI data were calculated by standardizing  $F(x)$ . More details are provided in Vicente-Serrano et al. (2010).

5 The response of hydrological systems to moisture deficits varies over time scales. On short time scales surface runoff and soil moisture are of concern while at longer timescales stream flow and ground water levels are important (Changnon and Easterling, 1989). Mathematically, SPEI can be calculated on any time scale, but typical scales used are 1-, 3-, 6-, 12-, and 24-months. 3-, 5- and 6-month SPI have been used  
10 to indicate soil moisture conditions (Hirschi et al., 2011; Ji and Peters, 2003; Lotsch et al., 2003) and 2–3 months SPI may indicate agricultural drought best (Mishra and Desai, 2005). We focused our analysis on 1-, 3-, and 6-month SPEI values to capture variability in soil moisture conditions from surface to deeper rooting depths.

Pearson correlation coefficients were calculated for the annual NPP vs. 1-, 3-, and  
15 6-month SPEI values. To aid the interpretation of our analyses, we divided the global land surface into 24 climate regions across continents based on both geographical location and the Köppen climate classification (Kottek et al., 2006, Fig. 1, Table 1). We did not combine all regions with an identical climate type across continents to maintain variability due to region-specific meteorological conditions. Within the Köppen climate  
20 classifications, we mainly separated arid, humid and seasonal (summer or winter) dry types. Only those classes that occupy at least 1% of the global land surface were included in our study with the exception of temperate humid Oceania (CFOC), which is the second largest climate type there.

### 3 Results

25 Global CASA calculated NPP showed a decreasing trend for the period of 1997–2009, similar to that found by Zhao and Running (2010), but also displayed substantial interannual variation (Fig. 2). The global SPEI series exhibited almost the same trend,

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and showed a similar pattern that appeared well in phase with NPP. On a global scale, for example, dry conditions happened in 2002–2003, 2005 and 2009 with lower NPP and SPEI values. 2004 was a wet year and NPP and SPEI were above average compared to other years. SPEI values changed somewhat when calculated over different time scales, with the maximum range between 1 and 6 month SPEI occurring in 1997 and 2006. The annual variance of SPEI was increasing from 1 month to 6 months time scales as shown in Fig. 2. However, the interannual pattern was robust and the calculated correlation coefficients between NPP and SPEI range between 0.50 and 0.54 ( $\rho < 0.1$ ) for all SPEI times scales (Table 2). There was a slight declining trend in both SPEI and CASA derived NPP, similar to Zhao and Running (2010), despite adding the years 1997–1999 to the analysis.

We now proceed to investigate the spatial distribution of the correlation coefficients for grid cells to obtain a better understanding of the spatial variability. Since the spatial patterns corresponding to 1-, 3-, 6-month SPEI were similar, we only show the 3-month SPEI-CASA NPP relation (Fig. 3). Figure 3 illustrates that at 0.5-degree spatial resolution significant positive relations between SPEI and NPP are present. These occurred largely in the mid latitudes of both hemispheres. Significant negative relations were mainly observed in the boreal region. NPP in the Southern Hemisphere appeared to be more sensitive to variability in droughts.

The global scale analysis as shown in Fig. 2 hides specific regional details and the contrasting behavior as shown in Fig. 3. We therefore proceed now to analyze the relationship between SPEI and NPP in more regional detail. The Köppen climate classification was used to define climate zones across continents. Compared with the global results of NPP and SPEI, the correlation coefficients in some regions exhibited much more change with different SPEI time scales, such as the range of 0.49 in cold humid Eurasia (DFEA) (Table 2). This implies that the impact of drought on the ecosystems in this area changes a lot with different SPEI time scales, and that NPP is only sensitive to droughts for a narrow range of time scales. In contrast, other regions such as temperate with winter dry Eurasian (CWEA) show little change in response when applying

different time scales (Table 2) suggesting vegetation is not sensitive to the time scale of droughts.

Complementing Table 2, Fig. 4 shows time series of annual 3-month SPEI and NPP anomalies between 1997 and 2009 for these 24 regions. As expected, NPP and SPEI had similar temporal patterns in arid regions (Fig. 4g–k), showing significant positive correlation coefficients for arid regions of North America (BBNA), Eurasian (BBEA), Africa (BBAF) and Australia (BBOC). An exception was arid South and Central America (BBSA, Table 2), for which the correlations were not significant but still positive. In contrast, NPP and SPEI exhibited anti-phase correlations during the whole period in boreal Northern Hemisphere with cold-humid climate, i.e. North America and North Eurasian (DFNA, DFEA), as shown in Fig. 4t, u. Correlation coefficients all are negative and significant with one exception of 6-month SPEI in DFEA (Table 2).

Unlike arid and cold regions, generally, other climate zones did not show globally uniform positive or negative patterns. Weak relations were found in temperate humid regions. North America (CFNA), South and Central America (CFSA), Asia (CFAS) and Europe (CFEU) had both positive and negative correlation coefficients. An exception was Oceania of East Australia and New Zealand (CFOC) where NPP and SPEI had a significant positive relation (Table 2). However, an abnormal case was detected in temperate humid Europe. SPEI data were here in anti-phase to NPP during 1997–2002 (Fig. 4m). This can be explained because, in these temperate ecosystems without very strong water limitations, higher temperature or radiation levels lead in general to more carbon uptake. However, NPP exhibited a sharp decline with SPEI in 2003. In 2003 a severe drought hit Europe during summer and autumn, leading to considerable carbon loss across mid and southern Europe at many ecosystems (Ciais et al., 2005; Reichstein et al., 2007a). We calculated all the 1–6 months SPEI for this region, obtaining values of  $-0.46$ ,  $-0.61$ ,  $-0.68$ ,  $-0.73$ ,  $-0.77$ ,  $-0.75$ . SPEI scales thus indicate that in this region, droughts may have to last at least two months to impact plant productivity significantly. Equatorial humid regions are similar to temperate humid regions in that they generally have no obvious relation with SPEI (Fig. 4a–c, Table 2).

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The regions that have seasonally occurring dry periods including summer or winter dry periods are those in middle latitude and equatorial zones. SPEI and NPP in cold winter dry area in Eurasian (DWEA) exhibited anti-phase changes but without significance in the correlation coefficients (Table 2). However, as expected, all the winter dry equatorial regions have significant correlations between NPP and SPEI (Table 2). Further, temperate with summer dry regions around the Mediterranean (CSEA) also showed a significant value between 6-month SPEI and NPP (Table 2). This suggests that once dry seasons are occurring well within the growing season, annual NPP is also positively correlated to SPEI.

#### 4 Discussions and conclusions

The response of NPP to drought is one of the key dynamic processes of the global carbon cycle. We found a statistically significant relation between global NPP and the drought index SPEI, just like Zhao and Running (2010) who studied this for a shorter time frame. Although a substantial part of the land surface exhibited opposing patterns, this global relation was for a large part driven by the dominance of areas where more soil moisture leads to increased NPP. This was especially obvious in the response that was dominated by the landmasses in the Southern Hemisphere similar to the soil moisture driven decline in evaporation (Jung et al., 2010). Although NPP decreased slightly during this period, we prefer to emphasize here its variation rather than the trend because the variations are generally more reliable.

The El Niño/La Niña-Southern Oscillation (ENSO) is known to be correlated to the interannual variability of atmospheric CO<sub>2</sub> concentration growth rate. The mechanism for this is attributed to the variation of tropical terrestrial ecosystem NPP driven by variability in precipitation (Zeng et al., 2005) and/or increased fire and deforestation activity during drought years (van der Werf et al., 2004). We have shown how the tropical land-mass SPEI shows a clear relation with NPP (Fig. 4d–f), suggesting the mechanism is indeed related to droughts. However, negative NPP anomalies at northern mid latitudes

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caused by drought events, however, may also contribute significantly to a lower NPP and the atmospheric CO<sub>2</sub> growth during a moderate El Niño, for example the one occurring during 2002–2003 (Knorr et al., 2007).

Both regional averages and our grid scale correlation analysis showed spatial variations in the relation between NPP and SPEI. The contrast in response occurred largely between arid regions in the mid latitudes and the cold humid regions boreal in northern latitudes where NPP and SPEI were correlated positively or negatively, respectively.

Global terrestrial ecosystem growth is mainly controlled by radiation, temperature and water availability (Nemani et al., 2003). The arid regions suffer more strongly from water deficits while in those areas radiation and temperature are generally not important limiting factors. For instance, in the western US, where long-term aridity changes significantly with a warmer climate (Cook et al., 2004), SPEI and NPP exhibited significant correlations (Fig. 4i). In contrast, in boreal regions, temperature plays a more important role in explaining NPP variability (Reichstein et al., 2007b). It is important to note that apart from the arid regions, most of seasonally dry regions also show positive relations between NPP and SPEI, particularly if the dry season occurs within the growing season.

Two regional droughts are important to test the robustness of our results and serve as case studies: the 2003 European heat wave and the 2005 Amazon drought. Vegetation growth over most areas of Europe is generally presumed to be limited primarily by temperature and radiation (Nemani et al., 2003). However, we did find strong NPP and SPEI negative anomalies during 2003 (Fig. 3m) that presents a drastic change from previous years. This suggests that the net effect of temperature, radiation, and water limitation on NPP depends primarily on the intensity of drought. This highlights the sensitivity of the ecosystem carbon cycle in these areas to climate variability, in particular extreme drought events. It is however difficult from our analysis to detect a clear threshold that separates the positive from the negative effects of drought on NPP. It is clear that severe droughts, such as those in 2003 in Europe reduce NPP significantly.

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In contrast, we are not able to detect an intense NPP decline in Amazon rainforest during 2005 although Phillips et al. (2009) reported substantial tree mortality. Zhao and Running (2010) also found a clear relation between a negative anomaly in soil moisture and a decline in NPP in tropical forests. In our case, negative NPP anomalies occur at some regions where a strong decline in biomass is reported in the Phillips et al. (2009), but do not overlap fully. We note that whether there was a significant decline in NPP in 2005 in the Amazon is still subject to controversy (Samanta et al., 2011). However, if the CASA model underestimated the Amazon NPP decline in 2005, global SPEI and NPP would show an even stronger in-phase coupled behavior. Besides these two cases, for the Australian continental drought (2002–2009) we find a very strong relationship between SPEI and NPP.

In this study we aimed to provide more detail to the global relations found in Zhao and Running (2010) by analyzing the relation between moisture conditions and NPP at regional to global scales. At a global scale, 1-, 3-, 6-month SPEI and NPP are positively and significantly related, confirming the results of Zhao and Running (2010). We divided the global land surface into different regions based on the Köppen climate classification. SPEI and NPP show significant and positive relations in the arid and seasonally dry in temperate and equatorial zones regions. In contrast, SPEI and NPP in cold humid regions in the boreal Northern Hemisphere exhibit a negative relation. At grid level, grids with a significant positive relation occurred more often than those with a negative relation. At a global level, however, NPP and SPEI are mostly coupled and in phase.

Our study demonstrates that at annual time scale NPP variance is led by the change in drought. Using the drought index is an effective way to estimate drought impacts compared to using precipitation only. The spatial non-uniform pattern of drought impact on NPP should be taken into account in further analysis and may serve as benchmark for global vegetation models (Sitch et al., 2008). Our results demonstrate that the strong correlation between global NPP and drought found by Zhao and Running (2010) is a composite of the native positive relations in global extend dry regions (arid and

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seasonal dry) and some extreme drought events in humid areas, the region details of which could be categorized by climate classification. Therefore, our results imply that climate zone change prediction will help us to quantify the changes of terrestrial carbon cycle in the future. From our analysis we cannot unequivocally set a threshold to define the drought impact on ecosystems. However, with global climate change expected to lead to more frequent droughts (Dai, 2012; Sheffield et al., 2012), we can expect further large regional declines in NPP to occur. How these are counterbalanced by areas with increases in NPP, or whether they lead to an overall negative trend in NPP, can only be studied by increased monitoring of droughts and NPP, preferably through satellite remote sensing (Dolman and de Jeu, 2010).

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**Table 1.** List of regions referred to this paper. Abbreviations consist of the first two letters of Köppen climate classification (indicating climate) and two letters to identify the continent or region.

Abbreviation	Köppen climate classification	continent or region
AFAF	equatorial climates, humid and monsoon (Af, Am)	Africa
AFEA	equatorial climates, humid and monsoon (Af, Am)	Eurasia and north Oceania
AFSA	equatorial climates, humid and monsoon (Af, Am)	Central and South America
AWAF	equatorial climates with winter dry (Aw)	Africa
AWEA	equatorial climates with winter dry (Aw)	Eurasia and north Oceania
AWSA	equatorial climates with winter dry (Aw)	Central and South America
BBAF	arid climates (BWk, BWk, BSk, BSh)	Africa
BBEA	arid climates (BWk, BWk, BSk, BSh)	Eurasia
BBNA	arid climates (BWk, BWk, BSk, BSh)	North America
BBOC	arid climates (BWk, BWk, BSk, BSh)	Oceania Mexico
BBSA	arid climates (BWk, BWk, BSk, BSh)	Central and South America
CFAS	temperate climates, humid (Cfa, Cfb, Cfc)	Asian
CFEU	temperate climates, humid (Cfa, Cfb, Cfc)	Europe
CFNA	temperate climates, humid (Cfa, Cfb, Cfc)	North America
CFOC	temperate climates, humid (Cfa, Cfb, Cfc)	Oceania
CFSA	temperate climates, humid (Cfa, Cfb, Cfc)	Central and South America
CSEA	temperate climates with summer dry (Csa, Csb, Csc)	Mediterranean Sea
CWAF	temperate climates with winter dry (Cwa, Cwb, Cwc)	Africa
CWEA	temperate climates with winter dry (Cwa, Cwb, Cwc)	Eurasia
DFEA	cold climates, humid (Dfa, Dfb, Dfc, Dfd)	Eurasia
DFNA	cold climates, humid (Dfa, Dfb, Dfc, Dfd)	North America
DWEA	cold climates with winter dry (Dwa, Dwb, Dwc, Dwd)	Eurasia
ETAT	polar tundra (ET)	Arctic
ETQT	polar tundra (ET)	Eurasia

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**Table 2.** Correlation coefficients ( $R$ ) between annual anomalies of NPP and SPEI for the global and for the 24 regions explained in Table 1. Significant values ( $p < 0.1$ ) are indicated by \*.

SPEI	global	AFAF	AFEA	AFSA	AWAF	AWEA	AWSA	BBAF	BBEA
1	0.50*	0.23	-0.27	0.31	0.60*	0.41	0.57*	0.69*	0.21
3	0.54*	0.34	-0.15	0.29	0.56*	0.44	0.59*	0.65*	0.42
6	0.53*	0.41	0.12	0.33	0.48*	0.53*	0.55*	0.63*	0.48*
	BBNA	BBOC	BBSA	CFAS	CFEU	CFNA	CFOC	CFSA	CSEA
1	0.60*	0.83*	0.14	0.00	0.45	-0.06	0.64*	0.07	0.36
3	0.64*	0.83*	0.27	-0.14	0.29	0.07	0.64*	0.20	0.40
6	0.82*	0.75*	0.36	-0.21	0.45	0.19	0.54*	0.34	0.48*
	CWAF	CWEA	DFEA	DFNA	DWEA	ETAR	ETQT		
1	0.36	-0.15	-0.58*	-0.72*	-0.46	-0.44	-0.33		
3	0.39	-0.18	-0.53*	-0.81*	-0.44	-0.43	-0.16		
6	0.32	-0.15	-0.09	-0.83*	-0.28	-0.54*	-0.08		

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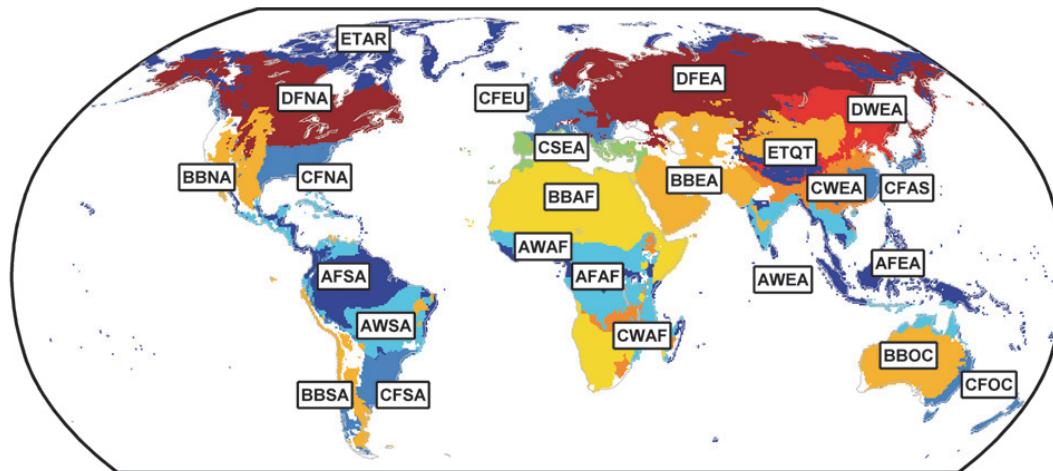


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**Fig. 1.** Map of 24 regions used in our study. Abbreviations are explained in Table 1.

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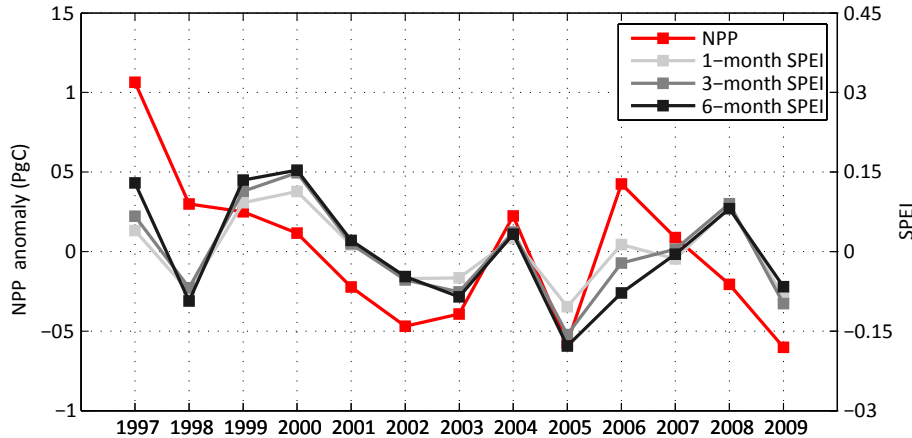


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**Fig. 2.** Interannual variation in global NPP and SPEI anomalies during 1997–2009. Both NPP and SPEI are area-weighted.

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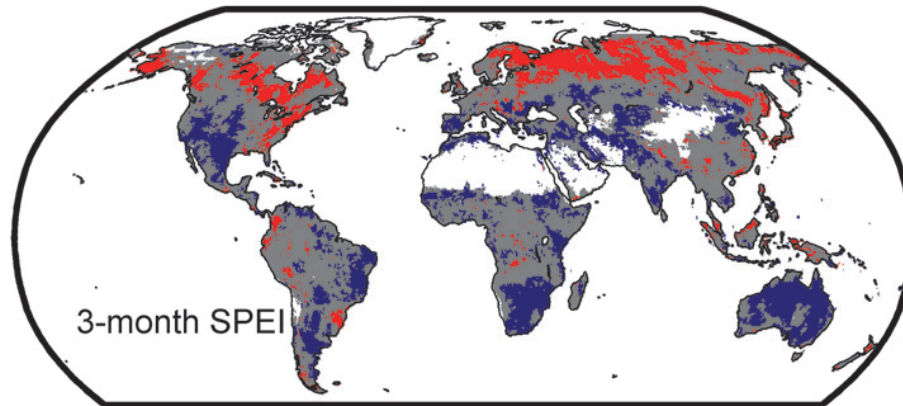


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**Fig. 3.** Spatial distribution of Pearson's correlation coefficients between annual anomalies of NPP and SPEI (3-months). Correlations that are significant ( $p < 0.1$ ) are displayed in blue (positive) and red (negative). Grey areas indicate correlations that are not significant and white areas are not available due to data structure.

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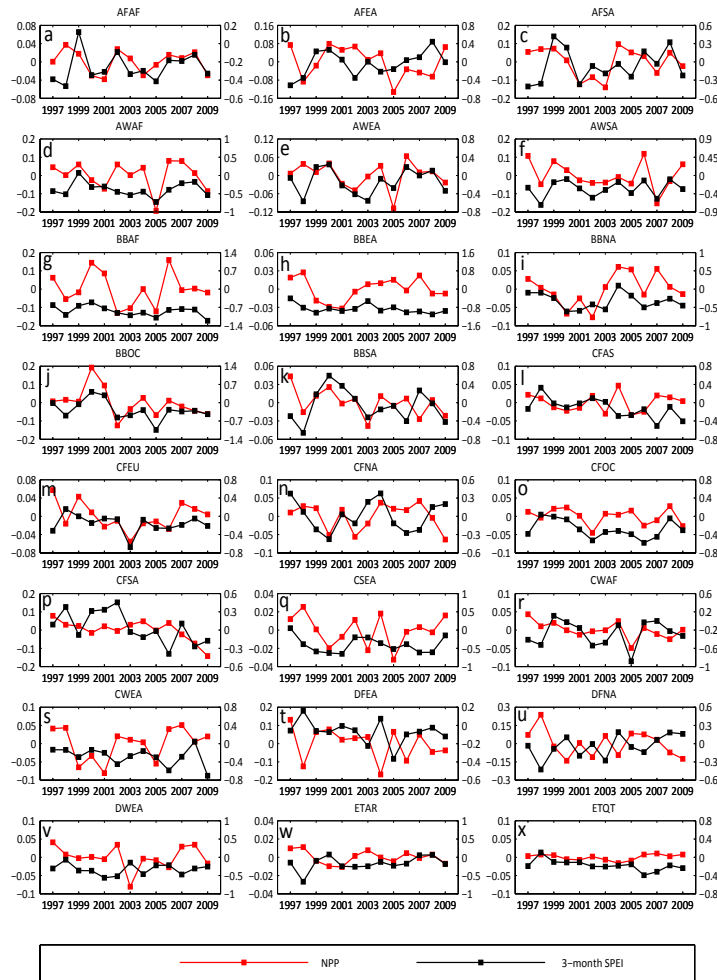
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**Fig. 4.** Regional average of SPEI and NPP anomalies for the 24 regions listed in Table 1.

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