Controlling factors for land productivity under extreme climatic events in continental Europe and the Mediterranean Basin

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Highlights:

- Extreme heat and drought events cause large reductions in land productivity
- Soil is important for controlling land productivity under extreme climatic events
- The final impact of extreme climatic events depends on local ecosystem conditions
- Natural land cover types, especially taiga and boreal forest, were most sensitive
- Policies should aim for maintaining soil functioning in vulnerable ecosystems

Abstract

Within the context of achieving Land Degradation Neutrality by 2030, this work studied to which extent soil variability acts as controlling factor for changes in observed land productivity under extreme climatic events. This was done by analysing 30 years of Normalized Difference Vegetation Index (NDVI) data and coinciding extreme warm, dry and their compound events in continental Europe and the Mediterranean Basin. In order to better understand the response of vegetation activity to extreme climatic events in relation to soil functioning, the data was segmented into different climate zones and further studied as a function of land cover and soil type. This study demonstrated that extreme climatic events cause substantial reductions in the NDVI with the maximum median impact up to 31%, one month after the occurrence of an extreme climatic event. However, the magnitude of NDVI drop largely depended on land cover and soil type. Our analysis showed that for soil types with root depth limitations, lower water retention capacity and the absence of specific symbiotic species in the soil, vegetation activity was more impacted by climate extremes compared to soil types having favourable growing conditions. Natural land cover types, especially taiga and boreal forest, were most sensitive. Consequently, with the expected increase in extreme events, the now stable and productive ecosystems may become unstable and less capable to absorb the CO_2 in the future, thereby enhancing climate change and land degradation. Therefore, it is important to have mitigation policies tailored towards maintaining soil functioning in vulnerable ecosystems.

Keywords: Soil variability, Vegetation activity, Extreme climatic events, Land degradation, Soil functioning

1 Introduction

In 2015, the UN adopted the Sustainable Development Goals (SDGs), which were formally referred to as Agenda 2030. One of the goals is to ensure the provision of natural resources for future generations of human society, which depends on sustainable use of natural resources (UN-DESA, 2018). Furthermore, it has been agreed that countries should aim to reach Land Degradation Neutrality by 2030. Land degradation neutrality is defined as a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and to enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems. Here, it is recognized that soils contribute to basic human needs like food, clean water and clean air, and are a major carrier for biodiversity (Keesstra et al., 2016). Specifically relevant for this study is the SDG Goal 15, Target 15.3: *By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world* (UNCCD, 2017); this is quantified by indicator 15.3.1: Proportion of land that is degraded over total land area; using SDG 15.3.1 sub-indicators *Land Cover, Land Productivity* and *Carbon Stocks*. However, achieving global land degradation neutrality in a changing world remains challenging, especially considering the expected increase of extreme climatic events (Perkins *et al.*, 2012) and their surface expanse (Coumou & Robinson, 2013, Rahmstorf & Coumou, 2011). Major effects of climate extremes include large reductions in Gross (GPP) and Net Primary Production (NPP, Bastos *et al.*, 2014, Ciais *et al.*, 2005), as well as land degradation (Frank *et al.*, 2015) and loss of biodiversity (Bajocco *et al.*, 2012). It is thus important to characterize, understand and quantify the impact of extreme climatic events, such as heat and drought events, on terrestrial ecosystem functioning in order to support appropriate mitigation and adaptation measures for land degradation. Moreover, it may be necessary to reconsider the sub-indicators and propose pathways to quantify soil functions in relation to land degradation neutrality in addition to the current set of indicators.

Recently, research advanced our understanding on how extreme climatic events influence the GPP and NPP of terrestrial ecosystems at the global scale, including the impact of heat extremes on plant productivity (Bastos *et al.*, 2014), the identification of extreme events in GPP, their spatial distribution (Zscheischler *et al.*, 2013, Zscheischler *et al.*, 2014a) and their attribution to climatic drivers (Zscheischler *et al.*, 2014b). The combined effect of continuous warming and occurrence of extreme heat and drought events has been shown to lead, for example, to widespread forest loss (Anderegg *et al.*, 2013) and changes in phenology and in the phenological cycle (Buitenwerf *et al.*, 2015). Furthermore, a clear relation between higher temperature and/or water deficits and lower vegetation activity compared to the long-term average vegetation activity, i.e. negative anomalies in vegetation activity, has been established (Liu *et al.*, 2013, Reichstein *et al.*, 2013). These insights are important, since reduction in vegetation activity may imply that less anthropogenic CO_2 can be absorbed by the terrestrial biosphere, acting as a positive feedback for atmospheric CO_2 levels (Friedlingstein *et al.*, 2006). However, concomitant analysis of the frequency in extreme climatic events and extreme events in vegetation ecosystems (i.e. phenological events) have also demonstrated a complex and variable response of vegetation to extreme climatic occurrences depending on average climate conditions and land cover type (Guo *et al.*, 2013, Liu *et al.*, 2013, Seddon *et al.*, 2016). These findings highlight the need for a more detailed evaluation of the environmental factors that control the response of vegetation to climate extremes.

On a local scale, several studies have also focused on shifts in vegetation species composition and loss of biodiversity (Kreyling *et al.*, 2011) as a consequence of climate change and climate extremes. Changes in forest canopy structure were found to be mainly controlled by local variability in species composition, environmental conditions such as water regime and soil properties (Galiano *et al.*, 2010, Lines *et al.*, 2010, Lloret *et al.*, 2004). Other studies demonstrated that the relationship between climate extremes and vegetation is even more complex and depends on previous stress, disturbance history, ontogeny, vigour, climatic sensitivity and physiology of the vegetation types in relation to the prevailing climate conditions (Reyer *et al.*, 2013, Suarez *et al.*, 2004). These results suggest that in order to improve our understanding of large-scale changes in vegetation activity due to extreme climatic events, we should also take into account the environmental conditions that were found important at the local scale.

Therefore, we aim to assess to which extent soil variability is an important controlling factor for large-scale changes in observed land productivity under extreme climatic events. This can be achieved by following a top-down approach where first the effects of land cover type and climate regime are accounted for, as previously done by the many researchers cited above, and subsequently the data is further fragmented down to a scale where soil type is also included in the analysis. This will be further referred to as a soil-landscape system analysis.

This approach was implemented by using 10 km resolution NDVI data, spanning the years 1981-2008 for continental Europe and the Mediterranean Basin. The analysis includes the response of the vegetation to extreme heat, drought and compound events as a function of land cover, climate and soil types, which were reported to be important controlling factors of the vegetation response to extreme climatic events in both large-scale and local-scale studies. The metrics used for defining the impact of extreme events on land productivity is the absolute change in NDVI between surfaces being under an extreme event or not. The vegetation activity as represented by NDVI was deemed a suitable proxy for land productivity by the UNCCD (UNCCD, 2017). Focus on the absolute change in NDVI provides information where major effects occur with respect to reductions in gross and net primary production and thus modify the land carbon sink and enhance climate change. In addition, the delay (lag-time) required to reach maximum impact and the period to which point differences are detected after the occurrence of an extreme climatic event (further referred to as impact propagation) will be quantified.

Altogether, our aim is to provide a more comprehensive understanding of the large-scale environmental controls of the vegetation response to extreme climatic events and to assess to which extent soil variability can be considered a controlling factor for changes in land productivity under extreme climatic events. Therefore, this study did not account for the alternative reasons for changes in land productivity due to abrupt events such as logging, forest fires, plant diseases, and greening and browning due to less extreme climatic events.

2 Materials

Our study comprises continental Europe and the Mediterranean basin, a scale that covers a wide variety of land cover, climate and soil types (Fig. 1), thus accounting for the combinatory effect of several key climate and ecosystem properties on land productivity. For the soil-landscape system analysis, the selected datasets comprise temperature, precipitation, climate regime, soil type, land cover and vegetation activity (Table1) and provide information on key biotic and abiotic controlling factors of vegetation activity, as recorded by the NDVI (Jenny, 1941, Lloret *et al.*, 2012).

< Table 1 >

Pre-processing of the data involved resampling explanatory data into the common 0.083° resolution matching that of NDVI, using bilinear interpolation for quantitative explanatory data and nearest neighbour (NB) interpolation for qualitative explanatory. In case of aggregation based on NB interpolation, the majority was assigned to the raster cell. Next, monthly mean NDVI, precipitation and temperature time series were created for the entire region at a resolution of 0.083°. Land cover and soil types were assumed to be invariant in time during the period of investigation (1981-2008).

< Figure 1 >

Analysis of the vegetation activity was performed using the monthly GIMMS3g Normalized Difference Vegetation Index (NDVI) data, at the original 0.083 degree resolution (Pinzon & Tucker, 2014), covering the selected years 1981 to 2008. Further data subsets were made by land cover type, according to the MODIS land cover classification (Channan *et al.*, 2014; Fig.

1a), by climate type, according to the Köppen-Geiger climate classification (Kottek *et al.*, 2006; Fig. 1b) and by dominant soil type (Fig. 1c), according to FAO-UNESCO Soil Map of the World from the Harmonized World Soil Database (FAO, 2012). Although soil maps with higher spatial resolution exist, e.g. SoilGrids (Hengl et al., 2017), it was decided to rely on soil information of similar scale to those of the climate and land cover data.

The monthly temperature (T) and precipitation (P) from the Princeton's Global Meteorological Forcing Dataset (PTON) (Sheffield *et al.*, 2006) were used to detect extreme heat, drought and compound events over the years 1981-2008 (see section 3.1). The 0.50° resolution of the PTON dataset was the coarsest of all employed datasets (Table 1).

All calculations were performed using the *R language and environment for statistical computing* (R Core Team, 2013) and the contributed packages *ncdf4* (Pierce, 2015) for pre-processing the climatic data and *gimms* (Detsch, 2015) for downloading and pre-processing the NDVI data; *raster* (Hijmans, 2015) and *rgdal* (Bivand *et al.*, 2014) for handling the spatially gridded data; *rts* for the time-series management (Naimi, 2016), *maps* (Brownrigg *et al.*, 2015) and *maptools* (Bivand & Lewin-Koh, 2016) for the graphics.

3 Methods

3.1 Detection of extreme climatic events

The analysis was performed using monthly time series of NDVI, temperature (T) and precipitation (P) for each 0.083° grid cell covering continental Europe and the Mediterranean Basin. For T and P, these time series were first de-trended on the grid-cell level following the method of Zscheischler et al. (2013), whereby the long-term linear trend over the full time-series was subtracted from the data and the mean annual cycle was subsequently removed. The outputs are gridded anomaly time series for T and P. The latter were used to identify extreme heat (T95), dry (P5) and compound events of extreme heat and dry events (P5T95), calculated on a grid-cell level. In this work extreme events were defined by the 95^{th} percentile of the T anomaly distribution and 5^{th} percentile of the P anomaly distribution, following the recommendations resulting from climatelogical data analysis (Donat *et al.*, 2013) and contemporary climate model simulations (Lewis et al., 2017). It must be noted that due to the temporal resolution, an event recorded as extreme event within a given month might be the result of several individual or consecutive daily events. However, given the temporal resolution of the climatic data it is not possible to discriminate between the two different events. Nevertheless, independent on the length of the event the resulting monthly average represents an extreme anomaly over the years 1981 to 2008. Figure 2 provides insights on the yearly counts of total events within the study area.

< Figure 2>

3.1.1 Restricting the analysis to the growing season

Furthermore, the analysis was restricted to the growing season of vegetation. In order to account for the variable length in growing seasons within the study area (Buitenwerf *et al.*, 2015; Chen et al., 2000), only the values falling within 90% of the observed NDVI range over a mean annual cycle (recorded at the grid-cell level) were retained. The set threshold was found suitable in previous studies done by Jeong et al. (2011) and Wang et al. (2017). This allowed to remove those months in which the vegetation was either absent or present but considered inactive. Consequently, to avoid bias due to occurrence of extreme climatic events outside the growing season, the T95 and P5 thresholds were calculated using only the months corresponding to the growing season, calculated on a grid-cell level.

3.2 Analysis of land productivity in relation to extreme climatic events

Using the 95th percentile threshold from the T anomalies time series and the 5th percentile threshold from the P anomalies time series, gridded indicator maps (Isaaks & Srivastava, 1990) reporting the presence or absence of an extreme P5, T95 or P5T95 event were constructed for 1981-2008, at the disaggregated 0.083° spatial resolution. These gridded indicator maps were then used for masking the NDVI time series for all months belonging to the growing season, allowing to distinguish NDVI values corresponding to grid cells *with* or *without* recorded extreme climatic event. Next, summary statistics (i.e. boxplot metrics, being the 1st, 25th, 50th, 75th and 99th percentile of the NDVI subset's probability distribution) for both data sets were calculated; first at the scale of the entire region and subsequently at increasingly finer scales by partitioning the original dataset by land cover, climate and soil types (Fig. 3). The disaggregation was performed using the 5 major land cover types as the coarsest layer, each land cover type was then partitioned among the 3 dominant climate regimes and, finally, each combination of land cover-climate regime was further subdivided according to the 3 dominant soil types (i.e. the soil-landscape system analysis). In order to ensure reliable statistical analysis, partitioned datasets covering a surface area of less than

5000 km^2 and/or gathering less than 500 recorded extreme events over the entire period of investigation were discarded from the analysis.

The impact of extreme climatic events on NDVI was assessed by evaluating the difference between those grid cells which are under an extreme event or not, per data partition. This was achieved by analysing the difference between the median NDVI (p50 from the summary statistics) between surfaces under an extreme heat event or not (ΔNDVI), per data partition, using all observations between 1981 – 2008.

3.2.1 Extending the analysis by including lag-times

The above analysis was performed by associating ΔNDVI values to absence or presence of an extreme climatic event (P5, T95 and P5T95) in the concurrent month (lag 0) and repeated up to a lag time of 4 months between given extreme events and recorded ΔNDVIs. Using this information, summary statistics (i.e. boxplot metrics, being the 1st, 25th, 50th, 75th and 99th percentile of the NDVI subset's probability distribution) were calculated for each lag-time after a given extreme event. This allows comparing differences in ΔNDVI due to extreme warm (T95), dry (P5) or extreme warm and dry compound (P5T95) events as function of time lag, for the various levels of data partitioning. Including lag times in the analysis provides valuable information on vegetation dynamics following extreme climatic events, including delays, the moment of maximum impact (i.e. the largest ΔNDVI) and the month to which the reduction of vegetation activity due to extreme events was detectable. The latter is further referred to as impact propagation.

< Figure 3 >

4 Results

4.1 Broad spatial patterns in land productivity losses following climate extremes

Within the study area, the largest impact of climate extremes on NDVI results from a compound event of extreme low precipitation and extreme high temperature (P5T95). Values reached a maximum median ΔNDVI of -0.21, recorded for a time-lag of 1 month (Fig. 4), corresponding to a 31% reduction in vegetation activity. The impact of T95 extremes is causing a negative change in NDVI in the concurrent month (ΔNDVI = -0.07). Yet, the P5 and P5T95 events lead first to higher vegetation activity (ΔNDVI P5T95 = 0.10, ΔNDVI P5 = 0.08) and then to negative differences in NDVI (ΔNDVI P5T95 = -0.21, ΔNDVI P5 = -0.16). The higher vegetation activity for P5 and P5T95 events without lag-time might be partly explained by an increase in radiation due to reduced cloudiness in dryer months. Independent on the type of extreme event, the impact was detectable up to about 4 months (i.e. ΔNDVI >= 0).

< Figure 4 >

Figure 4 shows that the continental-scale impact of extreme climatic events on vegetation can reach a ΔNDVI as large as -0.21. However, this is a very general summary measure, especially given the size of the study area and the large variability in soil, climate and land cover types. This is demonstrated by the change in median ΔNDVI one month after an extreme compound event (i.e. *P5T95*) partitioned by land cover, climate and soil type. Results reveal that there is a large spread in the median change in ΔNDVI (-0.36 < ΔNDVI > 0.01), depending on a specific combination of control factors (Fig. 5). The stratification by climate type shows that the ecosystems in the Northern continental zones of Europe are more sensitive to extremes, in terms of an absolute reduction in NDVI, compared to the southern and western parts (Fig. 5a). The stratification by climate type and land cover type leads to a refined spatial delineation of ΔNDVI (Fig. 5b). The large effect of extreme climatic events on vegetation activity in Northern Europe leads to an overestimated ΔNDVI in Eastern Europe when grouped together under one land cover type. Moreover, distinguishing the vegetation activity of land cover types by soil type suggests that specific land cover types within a similar climatic regime are less sensitive to extreme climatic events than other soil types, especially in Northern and Eastern Europe. This is further supported by the summary statistics reported in the supplementary materials S1 and S2.

< Figure 5 >

4.2 Land productivity losses as function of land cover type and climate regime

Figures 6 analyses further these broad patterns by considering, for the 3 types of extremes, the maximum reduction, delay, and impact propagation in vegetation activity as a function of specific local conditions in climate and land cover type. Moving from the most to the least affected land cover classes, woody savannas are the most affected by extreme climatic events; with ΔNDVI = -0.12 for T95 in the concurrent month and ΔNDVI = -0.22 in the subsequent month and ΔNDVI = -0.27 for P5T95 in the subsequent month (Fig. 6). The second broad class of ecosystems to be most affected by extreme climatic events were the natural forests (mixed forest and evergreen needleleaf forest); T95 had an immediate and similar impact on the different forest types (evergreen needle forest ΔNDVI = -0.07, mixed forest ΔNDVI = -0.07). P5T95 events had a stronger impact on mixed forest than on evergreen needleleaf forest (max ΔNDVI = -0.23 vs max ΔNDVI = -0.19, respectively). The least impacted land cover class is open shrubland, which also recovered faster than other land cover types (within 3 months). Yet, the P5T95 events still caused difference in ΔNDVIs in the concurrent month and subsequent month of about – 0.07 (Fig. 6).

Independent on land cover class, the land cover under a continental climate with humid and cold summers (classes *Dfb, Dfc*) is most impacted by extreme climatic events, as observed by the largest decline in vegetation activity for the different land cover types: evergreen needleleaf forest, mixed forest, woody savannas, open shrubland, grasslands and croplands (Fig. 6). The impact is particularly large for open shrublands (max ΔNDVI = -0.30) and woody savannas (max ΔNDVI = -0.35) for P5T95 events with a time lag of 1 month. Note that the woody savannas recoverless quickly than the open shrublands. In warm and dry climates (classes *Bsk, Csa, Csb*), open shrublands and woody savannas are hardly impacted by extreme T95, P5 and P5T95 events (e.g. max ΔNDVI = -0.06 in the subsequent month for P5T95 event).

The natural forests (evergreen needleleaf forest and mixed forest) are characterized by an increasing impact when moving from a climate regime with a temperate warm summer to a continental cool summer (climate classes *Cfb*, *Dfb*, *Dfc*). For T95 events, the largest reductions in NDVI are recorded in the concurrent months for both evergreen needleleaf forests and mixed forests (evergreen needle forest, max ΔNDVI = -0.04, -0.07, -0.16; mixed forest, max ΔNDVI = -0.05, -0.11, -0.12). In contrast, P5T95 events have the highest overall impact on natural forests when a time lag of 1 month between recorded extreme and NDVI values is considered (evergreen needleleaf forest, max ΔNDVI = -0.14, -0.17, -0.23; mixed forest, max ΔNDVI = -0.16, -0.29, -0.28).

Grasslands were moderately impacted (max ΔNDVI = -0.15 for P5T95) by extreme events occurring in a temperate climate regime (classes *Cfb* and *Csb)*, yet there was an immediate drop in NDVI (max ΔNDVI = -0.11 for P5T95) in the water scarce climate regime (class *Csb*). In the fully humid continental climate regime with cool summers (class *Dfc*), the response of grasslands was similar for the different type of extreme events and comparable to that of the open shrublands (max ΔNDVI = -0.27 for P5T95 event in the subsequent month) (Fig. 6).

For croplands, the impact is the least in the temperate climate regime with hot and dry summers (*Csa*, max ΔNDVI = -0.11 in the subsequent month) and the impact of the different types of events does not substantially differ from each other. The croplands are mostly affected in the fully humid continental climate with warm summers (*Dfb*, max ΔNDVI = -0.29). The interpretation and implications of these results need to be performed carefully, since croplands are under intensive land managed activities (crop type and irrigation activities) while the other land cover classes are not.

< Figure 6 >

4.3 Land productivity losses as function of soil type

In section 4.1, it was suggested that a partitioning up to the level of soil type allowed to identify distinct responses of NDVI to extreme compound events as a function of soil characteristics (Fig. 5). This is investigated further here by focusing on the lag time and impact propagation period of vegetation growing on different soil types (Fig. 7). In what follows, only the results for the compound event are outlined; See Supplementary materials

S3 and S4 for the results for extreme warm events (T95) and S5 and S6 for the results for extreme dry events (P5).

For grasslands within a humid continental climate with cool summers (*Dfc*), those growing on shallow soils were less severely impacted (Leptosol, max ΔNDVI = -0.22) compared to grasslands growing on acidic and nutrient poor soils (Podzol, max ΔNDVI = -0.32) or organic soils (Histosol, max ΔNDVI = -0.29). Alternatively, for grasslands experiencing a more favourable climate (e.g. temperate climate with warm and dry summers) and growing on productive fertile soils (Cambisols) the impact was far less substantial (max ΔNDVI = -0.03). In fact, within a temperate climate regime (*Csb* and *Cfb*) the water availability and water regulating properties in the soil appear to be the most important control factor of the response to compound events. In water limiting conditions (*Csb*) shallow soils with a typical low water availability (Leptosol, max ΔNDVI = -0.16) or unfavourable chemical or rooting conditions (Calcisol, max ΔNDVI = -0.12) were more impacted and recovered less quickly than Cambisols (max ΔNDVI = -0.06). That is, Calcisols under this climate are rather shallow soils or soils for which the rooting depth is limited by the accumulation of secondary carbonates and/or the presence of calcareous rocks. Similarly, anoxia and limiting rooting depth, were found to be an important soil property controlling the impact of extreme compound events (Gleysol, max ΔNDVI = -0.14).

For open shrublands in an arid (*BSk*) or temperate climate (*Csa*), soils did not substantially influence the response to climate extremes, except for the Cambisol (max ΔNDVI = -0.10 at the concurrent month), which sustains the highest NDVI and is known to be a favourable soil for vegetation growth. For this vegetation type, results suggest that soils are a more important control factor of the overall productivity rather than of the sensitivity of the vegetation to extreme climatic events. In particular, unfavourable chemical and structural conditions appear to reduce the vegetation activity. This is illustrated, for instance, by the low NDVIs recorded within a hot and dry temperate climate (*Bsk*), when limited rooting depth (Calcisol, Leptosol) limits vegetation growth (Cambisol, median NDVI = 0.36 vs. Calcisol, median NDVI = 0.26 and Leptosol, median NDVI = 0.22, see supplementary materials S2),

Woody savannas in a temperate climate (*Csa*, *Csb*) generally did not appear sensitive to soil type, neither in terms of overall productivity nor in terms of response to extreme climatic events. An exception is the woody savanna growing on Luvisols, which shows a distinct drop in NDVI under a climate extreme (max ΔNDVI = -0.14 at the concurrent month). This vegetation is located in southern Scandinavia, where Luvisols are generally sandy, causing a low available water capacity (e.g., Møller et al., 2019; Piikki and Söderström, 2016). Woody savannas in the continental climate regime were severely impacted by extreme climatic events, but the response of vegetation activity did not substantially deviate per soil type.

The majority of the forest is located in central and northern Europe, where climate is either humid temperate or humid continental with cold or warm summers. Within a temperate climate (*Cfb*), needleleaf forests growing on very shallow soils (Leptosol) were most sensitive to extreme compound events (ΔNDVI = 0.12 and ΔNDVI = -0.18, at the concurrent and subsequent month, respectively). Mixed and needleleaf forest growing on either Podzols or Cambisols showed a similar response (ΔNDVI = 0.05 and ΔNDVI = -0.16, at the concurrent and subsequent month, respectively). Within a continental climate (*Dfb* and *Dfc*), the dominant soil types with forest cover are Histosols, Podzols and Podzoluvisols (the latter being quite similar to Albeluvisols (WRB, 2014) and Retisols (WRB, 2015). It was found that both mixed and needleleaf forests were overall slightly less impacted by extremes when growing on Podzols compared to Histosols. The most sensitive forest ecosystems were the mixed forest growing on Podzoluvisol (max ΔNDVI = -0.32 at the subsequent month) under continental climates (*Dfb* and *Dfc*) and the needleleaf forest growing on Podzoluvisols under the *Dfc* climate (max ΔNDVI = -0.33 at the subsequent month). In Northern Europe, Podzoluvisols and Histosols are typically wet during humid periods due to the poor drainage conditions and vegetation is adapted to prolonged periods of wetness. On the contrary, the rooting depth of these forest ecosystems being limited either by the wetness (Histosols) or by the presence of an albic horizon and an abrupt textural change causing both temporary water logging and limitations to rooting (Podzoluvisol, named Albeluvisol in WRB 2014 and Retisol in WRB 2015), the vegetation is highly sensitivity to droughts. Thus, the vegetation growing here is suffering when there are large changes in the hydrological balance due to extreme heat and drought events.

For croplands, the soil properties do not alter the impact of extreme climatic events and the observed change in NDVI are in line with the changes presented in Fig. 6. That is, the impact is the least in the temperate climate regime with hot and dry summers (*Csa*, max ΔNDVI = -0.11 in the subsequent month) and largest in the colder continental climate regime (*Dfb*). Again, the interpretation and implications of these results need to be done carefully, since croplands are under intensive land managed activities that allows altering unfavourable growing conditions related to soil properties (e.g. fertilizer application, irrigation and tillage). Moreover, typically the crops have been established preferentially on the best soils (i.e. those having the best rooting and water availability properties) (Folberth *et al.*, 2016).

< Figure 7 >

5 Discussion

5.1 General Discussion

Our findings are overall in line with the work of Bastos *et al.* (2014), which suggested that European forests are more sensitive to climate extremes than croplands. They also found that forests growing in a continental climate regime were more sensitive to extreme heat events, compared to a temperate climate regime. De Keersmaecker *et al.* (2015) mapped vegetation resilience (sensitivity) based on the ability of vegetation to recover from a climate anomaly detected one month before. They concluded that the sensitivity of vegetation to these anomalies was higher in the Mediterranean compared to Central Europe while it was concluded that vegetation was not proven significantly sensitive to extreme climatic events in Northern Europe. Our work agrees with the short period of impact propagation for the Mediterranean, however, the impact of extreme climate events, in terms of absolute NDVI, was found far less severe compared to Northern Europe. Moreover, in Central and Northern Europe, impact propagation period was typically much longer than the lag time of 1 month selected by De Keersmaecker *et al.* (2015). The difficulty to develop an explanatory model representing vegetation resilience against extreme climatic events in the colder climates by De Keersmaecker *et al.* (2015) was likely caused by 1) the lack of representative explanatory variables (temperature anomalies and a drought index) for modelling the spatial and temporal variability in vegetation activity, 2) a too short lag time and 3) the use of a global model instead of a regional model. That is, our findings suggest that the resilience of vegetation against extreme climatic events can be better explained using a regional model relying on differences in precipitation, land cover, climate regime and soil type. Moreover, although the maximum impact is detected one month after an extreme event, depending on the type of event, especially for extreme heat events, the impact in the concurrent month should not be discarded, nor the total impact propagation period that may last up to 4 months. Seddon *et al.* (2016) developed a vegetation sensitivity index to climate variability, which appeared to be low in the Mediterranean, and the reported spatial trends agree with our findings.

The global-scale tendencies described by Liu *et al.* (2013) and Seddon *et al.* (2016) are confirmed by our regional analysis. The work of Liu *et al.* (2013) focused on vegetation extreme frequency patterns and modelling global vegetation vulnerability, using the major biomes of the world. Their main variables used to explain patterns in vegetation extreme frequency in relation to vegetation vulnerability and climate regime included rainfall, agricultural development, deforestation and fire. Results emphasized the high vulnerability of the Mediterranean but did not report vulnerabilities in Northern Europe, in contrast to Seddon *et al.* (2016). This might be related to the limited set of explanatory variables and modelling scale, i.e. models were calibrated by biome; they pointed out that, although the models capture the overall global relationships, they dampen the variation in characteristics within each of the biomes. Likely, the effects of climate extremes in the taiga biome are more pronounced in North America than in Northern Europe, yet the changes in Northern Europe are substantial, as demonstrated by our results and the work of e.g. Seddon *et al.* (2016). This stresses the importance of choosing an appropriate scale of analysis and using explanatory variables capturing the biotic and abiotic environmental conditions. Our work demonstrates the added value of using refined land cover datasets and distinct climate regimes and soil types in the study of vegetation response to climate extremes. By segmenting the response of the vegetation to extreme heat, drought and compound events according to this refined nomenclature (Fig. 6 and 7), regional differences in the sensitivity of terrestrial ecosystems to extreme warm and dry events are diagnosed, which were not described before.

Our results show that the impact of extreme heat and drought on land productivity increases when moving to colder climatic regimes (Fig. 7) where the ecophysiological adaptations towards extreme heat and droughts are limited (Finlay, 2008; Lehto & Zwiazek, 2011; Reyer *et al.*, 2013). Extensive areas in the Mediterranean, especially areas under climatic regimes *Bsk* and *Csa*, have an overall low productivity and appear to sustain an ecosystem prone to more extreme hot and dry events' than the rest of Europe. Here, the impact in terms of absolute ΔNDVI of an extreme heat and/or dry event is far less substantial compared to the regions further North (Figure 5), implying that the vegetation is already well adapted to warm and dry conditions (Reyer *et al.*, 2013). This is especially true for the croplands and grasslands, likely because agricultural activities are adapted to the local arid conditions (Aguilera *et al.*, 2013, Kassam *et al.*, 2012). Within the climatic regimes *Bsk* and *Csa* typical of the south of Europe, soils alter overall productivity due to unfavourable rooting conditions rather than provide resilience against extreme heat and drought events, as was demonstrated in section 4.1. For forests adapted to a colder and wetter climate, the impact of extreme climatic events is more severe since they lack the eco-physiological adaptions prevalent in arid and dry natural areas.

With respect to the soil controls on the vegetation response to climate extremes, it was found that the differential response of vegetation growing on different soil types was mainly attributed to the soil types' properties root depth limitations and water retention capacity. Interestingly, our findings in the cold climate of NE Europe show that Podzols favor higher resilience compared to soils less tolerant to the prevailing wet water regime (Podzoluvisol and Histosol). Podzols are known for their poor nutrient (phosphorous deficiency) status and high acidity, which gives suboptimal growing conditions for forests. The relatively good resistance of vegetation growing on Podzols may be explained by its capacity to modify their microecosystem in the root zone in order to optimize growing conditions. Following the work of Finlay (2008), typically, vegetation can improve their growing conditions by having a dense mycorrhiza network, where fungi compensate for the nutrient poor and acidic environment. Moreover, this symbiotic association with fungi also improves the water availability during dryer periods and provides a protected environment during stressful periods. Generally, mycorrizha do not tolerate wet conditions, and thus the symbiosis will be absent in soils such as Podzoluvisol and Histosol, thereby explaining why these soils might be less resilient to extreme climate events in addition to their low rooting depth capacity. Also, the type of mycorrhiza depends on climate conditions and land cover: less profitable myccorhiza occur in warmer climates and less productive land cover types (arbuscular vs. ectomycorrhizal (Finlay, 2008; Lehto & Zwiazek, 2011). In a temperate climate, Cambisols provide naturally more favourable growing conditions and thus the mycorrhiza network is less well developed. Thus, the unexpected small differences in ΔNDVI for forests growing on Cambisols and Podzols under temperate climate could be explained by different mycorrhizae densities.

5.2 Potentials and limitations

In this study, we aimed to provide a more comprehensive understanding of the large-scale environmental controls of the vegetation response to extreme climatic events. Moreover, we assessed to which extent soil variability can be considered a controlling factor for changes in land productivity under extreme climatic events. The results demonstrated that there are important large-scale environmental controls and that soil variability can be considered as one of the main controlling factors. However, the interactions that exist within an ecosystem (local scale) are complex, with various feedback mechanisms between the earth surface, the biosphere and atmosphere (Reyer *et al.*, 2013, Suarez *et al.*, 2004). This study was not able to address these refined local interactions, mainly due to the lack of accurate spatial and temporal information. For example, if daily or weekly time series for climate and vegetation activity were available, than we would be able to obtain better insights on the existing interactions within specific ecosystems. This would allow to distinguish between shorter (single-event) and longer (consecutive events or waves) extreme climatic events and the response it has on vegetation activity. Moreover, we need global spatial data of the climate variables that match the spatial resolution of the land productivity data which, at present, are not available.

Another limitation of this work is the use of the dominant soil type from the HWSD, as it is a large simplification of the actual soil variability. We attributed soil functioning based on the mapped dominant soil types and their known characteristics. Alternatively, future studies should rely on mapped soil properties. Using soil properties would allow to better quantify the found relationships and refine the study of soil functioning for land productivity under extreme climatic events. For example, some soil properties can easily be derived from a dominant soil type, such as Leptosols obviously having limited rooting depth. However, some other properties can only be derived using more detailed information, such as soil carbon stock or plant available water. Therefore, future research should also aim to refine the support of the soil data and delivering derived soil information, such as the plant available water. This may be achieved through global digital soil mapping projects such as *GlobalSoilMap* (Arrouays et al., 2014) and SoilGrids (Hengl et al., 2017).

Finally, soil scientists may need to address the proposed pathways of quantifying land degradation and reaching land degradation neutrality by 2030. This work demonstrated that various soil properties are important for understanding and potentially mitigating the effect of extreme climatic events on declines in land productivity. Moreover, it was concluded that there are specific soil characteristics providing resilience for land productivity against extreme climatic events. Consequently, this poses the question whether the recommended SDG 15.3.1 sub-indicator 'Carbon Stocks' (UNCCD, 2017) is sufficient as indicator for monitoring the soil for reaching global Land Degradation Neutrality by 2030. The results suggest that in order to maintain land productivity, mitigation policies may need to be tailored towards maintaining the soil condition, soil functioning and improving soil ecophysiological adaptations in ecosystems.

6 Conclusions

This work aimed to assess which extent soil variability can be considered a controlling factor for changes in observed land productivity under extreme climatic events for large-scale studies. The results suggest that extreme heat and drought events cause immediate reductions in vegetation activity, with maximum impact occurring 1 month after the climate extreme. Moreover, the soil-landscape system analysis showed that total impact on land productivity did depend on specific abiotic and biotic conditions. Vegetation was found less sensitive towards extreme climatic events when it has specific ecophysiological adaptations from which they can benefit during extreme climatic events. On soil types with root depth limitations, lower water retention capacity and the absence of specific symbiotic species in the soil, losses in vegetation activity were larger compared to soil types having favourable growing conditions. Although our study shows that soil type is an important factor for interpreting vegetation stress, more detailed information (both semantic and geographic) about soil attributes and properties is necessary to refine the assessment of the importance of soil on vegetation sensitivity to extreme climatic events. With the expected increase of extreme climatic events, the current stable and productive systems located in Northern and Eastern Europe are likely to be most affected by climate extremes and a large reduction in vegetation activity can thus be expected, partly due to the lack of ecophysiological adaptation of the system towards the changing climate. With the increasing frequency in climate extremes, these ecosystems may become instable, and various ecosystem services may be compromised in the future. Current stable forest ecosystems such as those found in Northern and Eastern Europe, absorbing large amounts of CO_2 may also become less efficient and thus modify the land carbon sink and enhance climate change. Our results also suggest that in order to mitigate these changes and successfully achieving land degradation neutrality by 2030, mitigation policies should be tailored towards maintaining soil functioning and improving soil ecophysiological adaptations in ecosystems.

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Table 2: Employed data sets and their spatial and temporal resolution

Variable	Dataset	Abbreviation	Temporal resolution	Original resolution	Reference
Vegetation activity (-)	GIMMS3g NDVI	NDVI	July 1981 – December 2013	0.083°	Pinzon & Tucker, 2014
Monthly mean Surface Temperature (K) Monthly mean Precipitation (mm/day)	Princeton climate data	T P	July 1981 – December 2008	0.50°	Sheffield et al. (2006)
Climate type (-)	Köppen-Geiger climate classification	Climate type	NA	NA	Kottek et al. (2006)
Land cover type (-)	Modis Land cover Type (MCD12Q1)	Land cover type	2001	0.083°	Channan *et al.*, 2014
Soil type (-)	Harmonized World Soil Database	Soil type	NA	1 km	FAO (2012)

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Figure 7: Change in NDVI (ΔNDVI (-)) due to extreme warm and dry compound events as function of lag time, stratified by land cover, climate and soil types.

List of Supplementary materials

S1 Summary statistics for compound events (P5T95), at lag-time 1 month, partitioned by land cover and climate types

S2 Summary statistics for compound events (P5T95), at lag-time 1 month, partitioned by land cover, climate and soil types

S3 Change in NDVI due to extreme warm events (T95) as function of lag time, partitioned by land cover, climate and soil types

S4 Summary statistics for extreme warm events (T95), at lag-time 1 month, partitioned by land cover, climate and soil types

S5 Change in NDVI due to extreme dry events (P5) as function of lag time, partitioned by land cover, climate and soil types

S6 Summary statistics for extreme dry events (P5), at lag-time 1 month, partitioned by land cover, climate and soil types

*Highlights (for review)

Highlights:

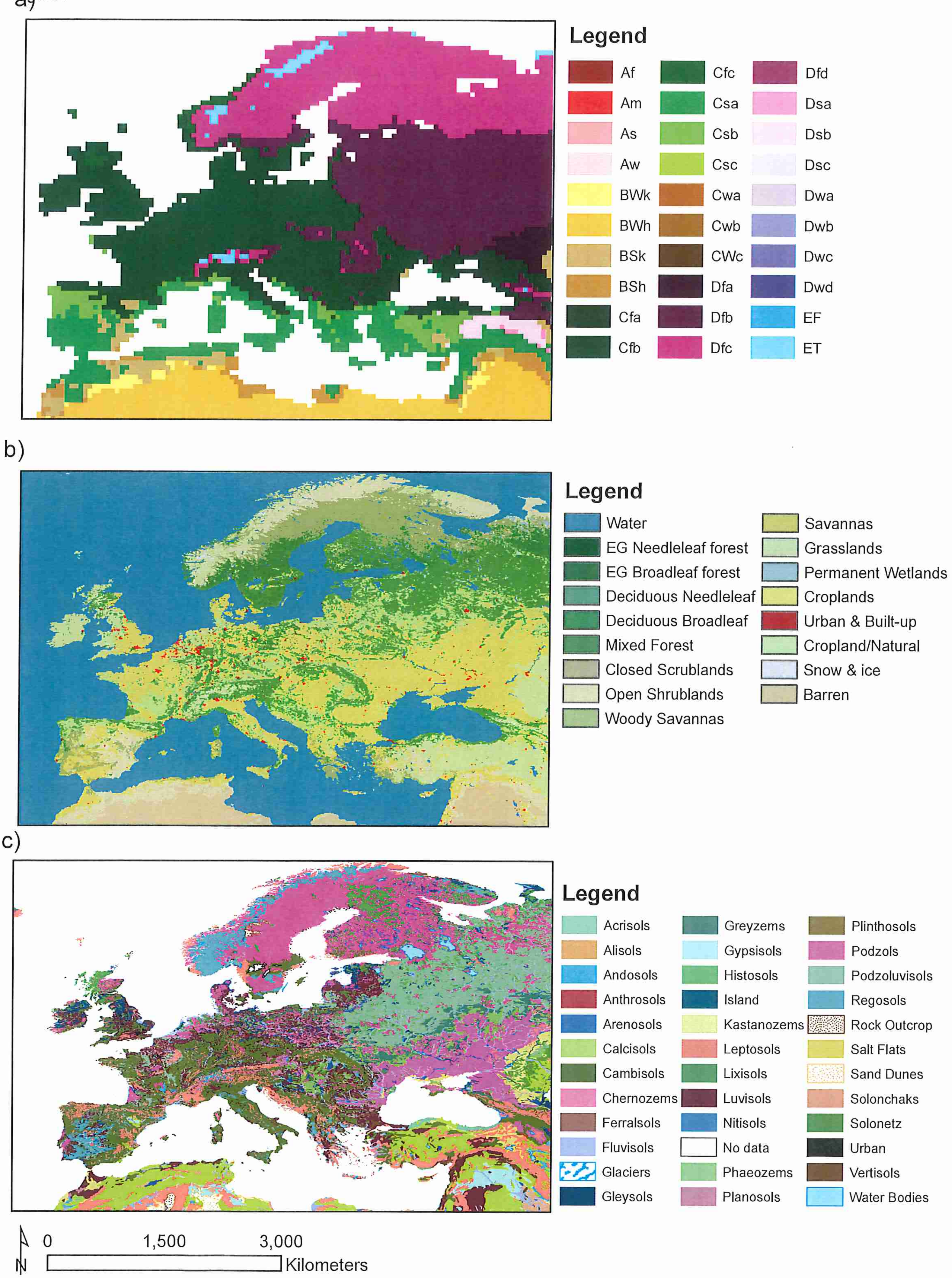
- Extreme heat and drought events cause large reductions in land productivity
- Soil is important for controlling land productivity under extreme climatic events
- The final impact of extreme climatic events depends on local ecosystem conditions
- Natural land cover types, especially taiga and boreal forest, were most sensitive
- Policies should aim for maintaining soil functioning in vulnerable ecosystems

Table 1
Click here to download Table: Table 1.docx

Table 1: Employed data sets and their spatial and temporal resolution

Variable	Dataset	Abbreviation	Temporal resolution	Original resolution	Reference
Vegetation activity (-)	GIMMS3g NDVI	NDVI	July 1981 – December 2013	0.083°	Pinzon & Tucker, 2014
Monthly mean Surface Temperature (K) Monthly mean Precipitation (mm/day)	Princeton climate data	T P	July 1981 – December 2008	0.50°	Sheffield et al. (2006)
Climate type (-)	Köppen-Geiger climate classification	Climate type	NA	Vector data converted to 0.083° grid data	Kottek et al. (2006)
Land cover type (-)	Modis Land cover Type (MCD12Q1)	Land cover type	2001	0.083°	Channan *et al.*, 2014
Soil type (-)	Harmonized World Soil Database	Soil type	NA	1 km	FAO (2012)

Figure1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EG Broadleaf forest
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Mixed Forest
Closed Scrublands
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Woody Savannas
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Grasslands
Permanent Wetlands
Croplands
Urban & Built-up
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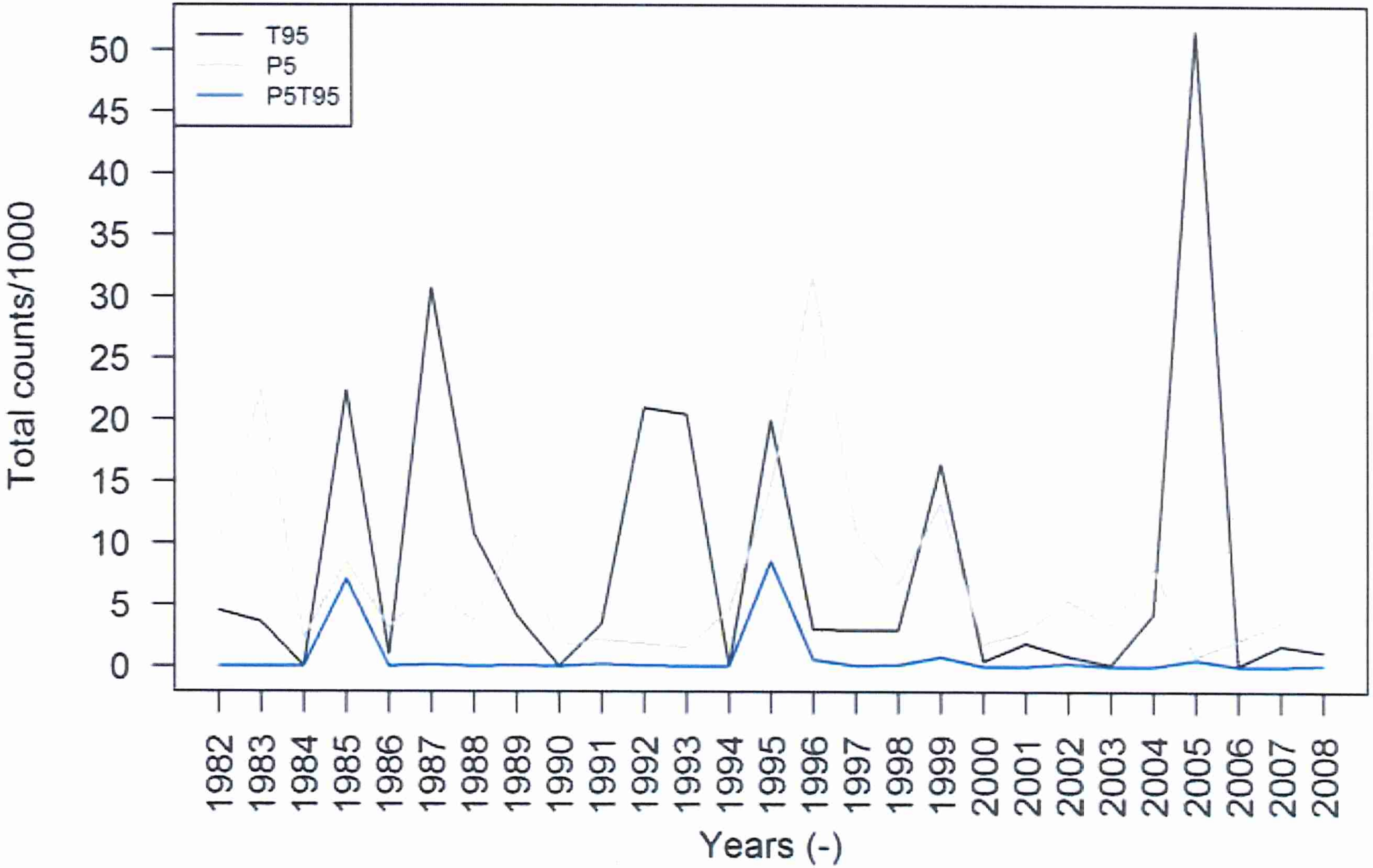
Figure2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Years (-)

Figure3

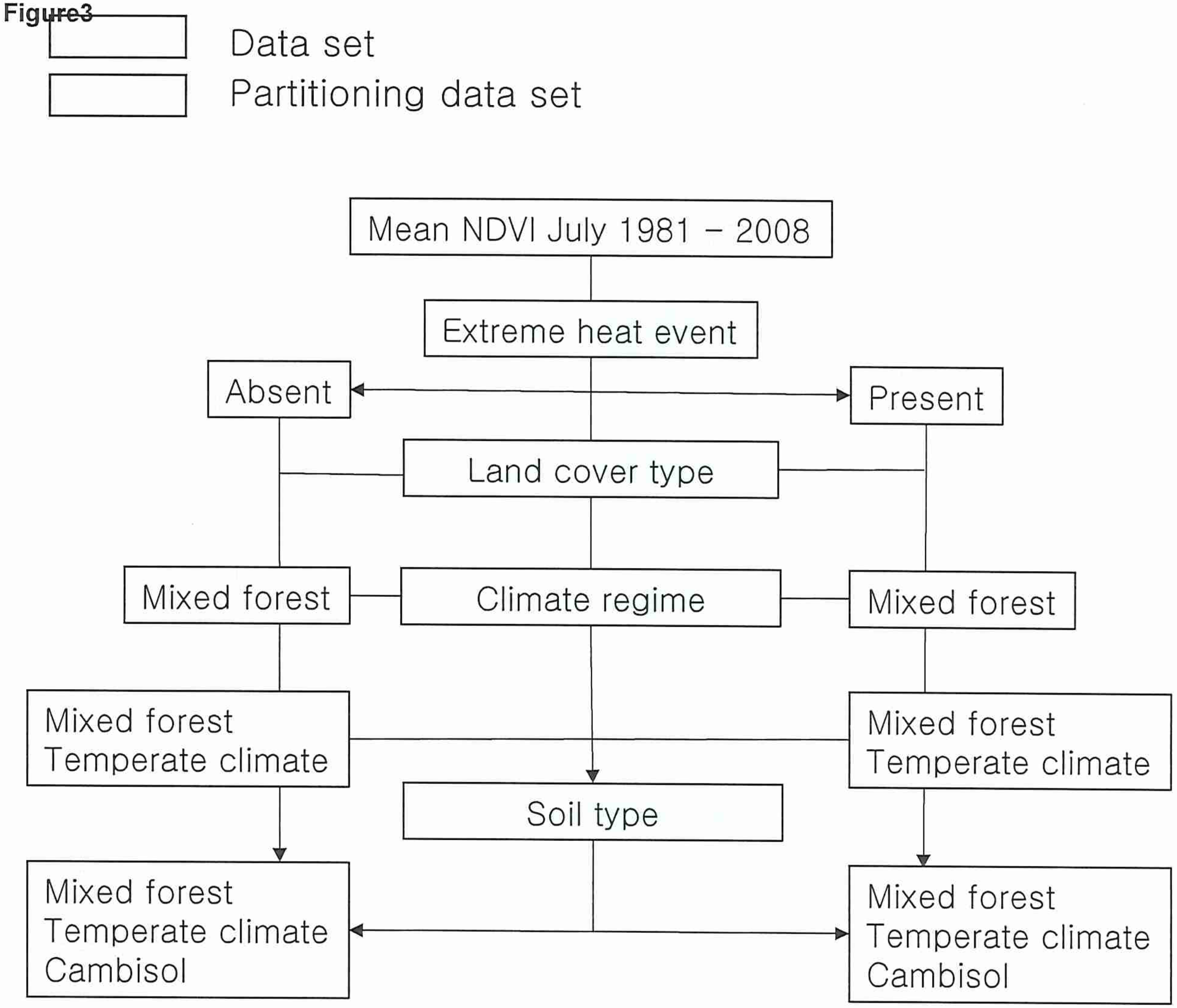

Data set
Partitioning data set
Mean NDVI July 1981 – 2008
Extreme heat event
Absent
Present
Land cover type
Mixed forest
Climate regime
Mixed forest
Mixed forest
Temperate climate
Mixed forest
Temperate climate
Soil type
Mixed forest
Temperate climate
Cambisol
Mixed forest
Temperate climate
Cambisol

Figure4

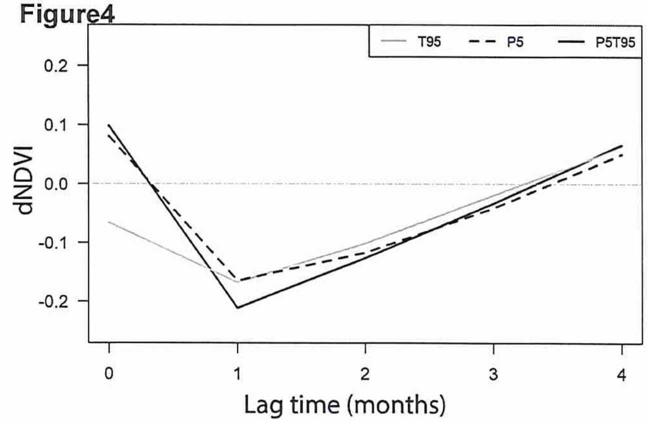


Figure5

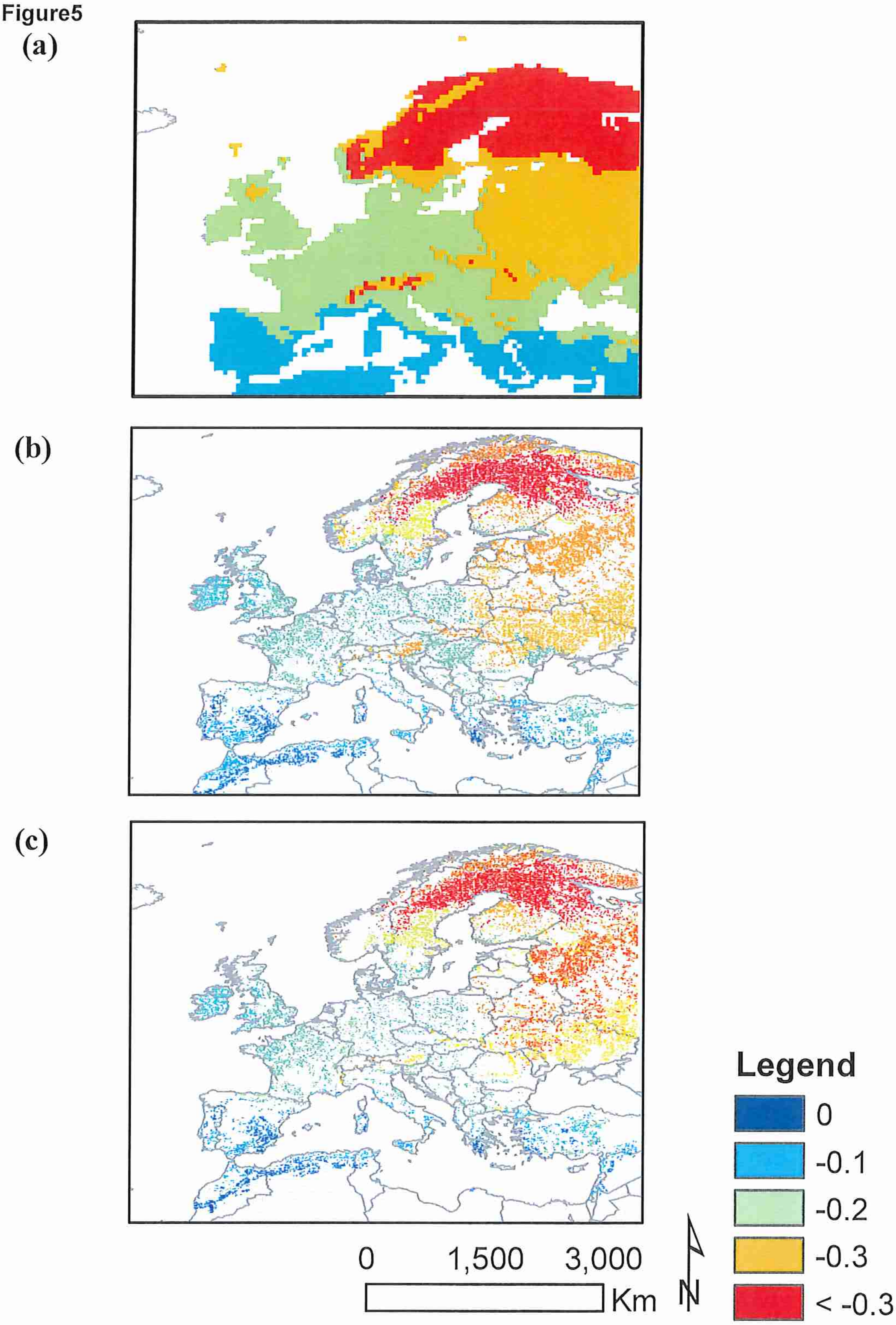


Figure6

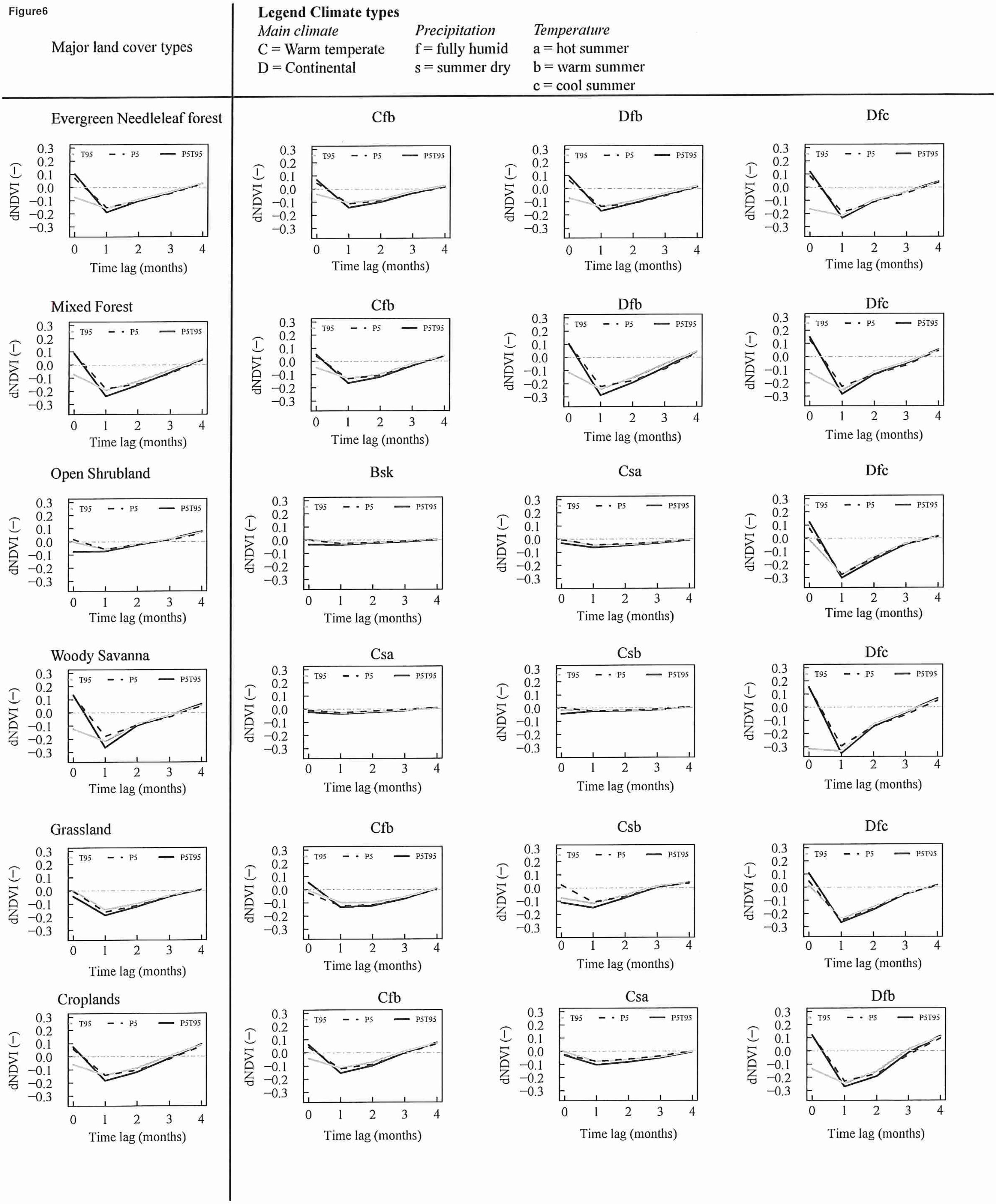
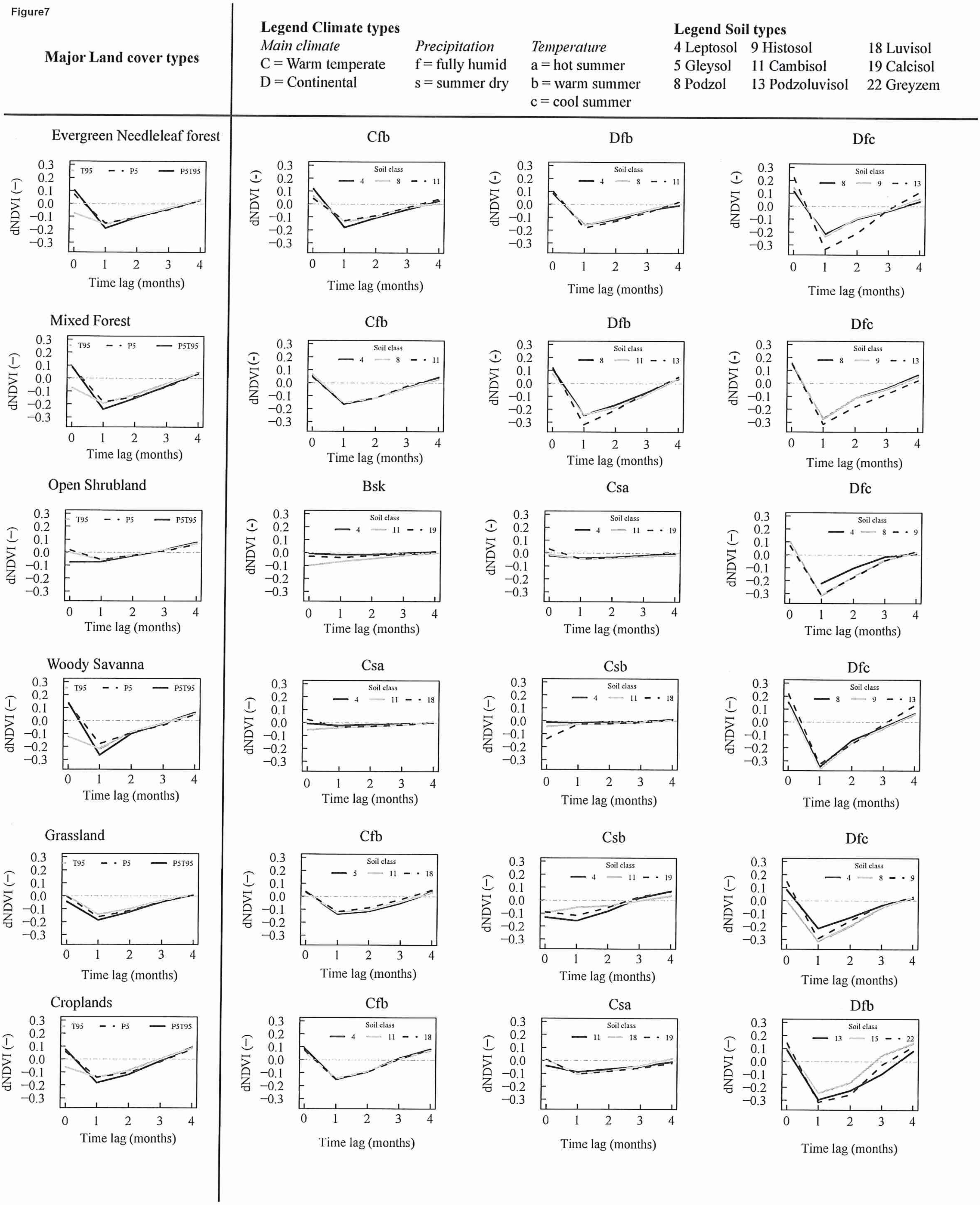

Major land cover types
Legend Climate types
Main climate
C = Warm temperate
D = Continental
Precipitation
f = fully humid
s = summer dry
Temperature
a = hot summer
b = warm summer
c = cool summer
Evergreen Needleleaf forest
Cfb
Dfb
Dfc
Mixed Forest
Cfb
Dfb
Dfc
Open Shrubland
Bsk
Csa
Dfc
Woody Savanna
Csa
Csb
Dfc
Grassland
Cfb
Csb
Dfc
Croplands
Cfb
Csa
Dfb
T95
P5
P5T95
dNDVI (−)
Time lag (months)

Figure7


Major Land cover types
Legend Climate types
Main climate
C = Warm temperate
D = Continental
Precipitation
f = fully humid
s = summer dry
Temperature
a = hot summer
b = warm summer
c = cool summer
Legend Soil types
4 Leptosol
5 Gleysol
8 Podzol
9 Histosol
11 Cambisol
13 Podzoluvisol
18 Luvisol
19 Calcisol
22 Greyzem
Evergreen Needleleaf forest
Mixed Forest
Open Shrubland
Woody Savanna
Grassland
Croplands
Cfb
Dfb
Dfc
Bsk
Csa
Csb
T95
P5
P5T95
Soil class
dNDVI (−)
Time lag (months)