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Extreme warm temperatures alter forest phenology and productivity in Europe

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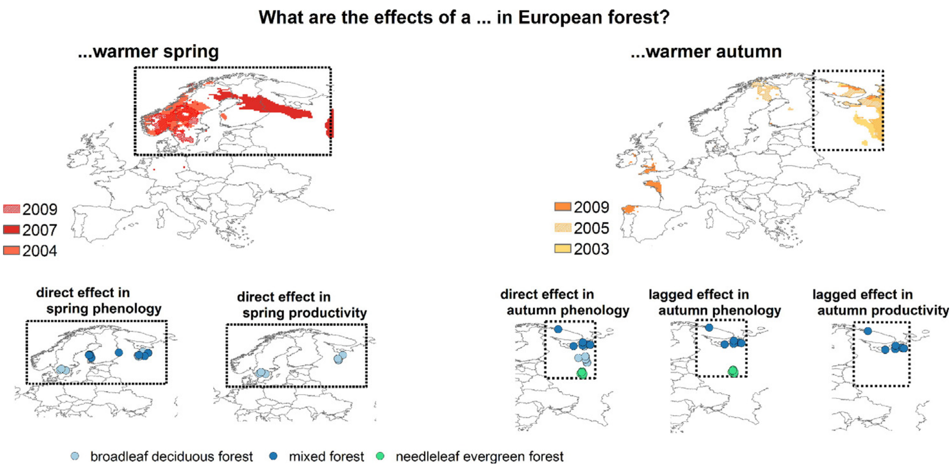
HIGHLIGHTS

- Frequency of extreme warm temperature is increasing across Europe.
- Impacts of these extremes on forest phenology and productivity were evaluated.
- Time series of satellite derived estimate of chlorophyll content was analysed.
- Direct and lagged effects occurred in both phenology and productivity.
- Forest types in Europe responded differently to warmer spring and autumn events.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent climate warming has shifted the timing of spring and autumn vegetation phenological events in the temperate and boreal forest ecosystems of Europe. In many areas spring phenological events start earlier and autumn events switch between earlier and later onset. Consequently, the length of growing season in mid and high latitudes of European forest is extended. However, the lagged effects (i.e. the impact of a warm spring or autumn on the subsequent phenological events) on vegetation phenology and productivity are less explored. In this study, we have (1) characterised extreme warm spring and extreme warm autumn events in Europe during 2003–2011, and (2) investigated if direct impact on forest phenology and productivity due to a specific warm event translated to a lagged effect in subsequent phenological events. We found that warmer events in spring occurred extensively in high latitude Europe producing a significant earlier onset of greening (OG) in broadleaf deciduous forest (BLDF) and mixed forest (MF). However, this earlier OG did not show any significant lagged effects on autumnal senescence. Needleleaf evergreen forest (NLEF), BLDF and MF showed a significantly delayed end of senescence (EOS) as a result of extreme warm autumn events; and in the following year's spring phenological

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Lagged effect
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events, OG started significantly earlier. Extreme warm spring events directly led to significant ($p = 0.0189$) increases in the productivity of BLDF. In order to have a complete understanding of ecosystems response to warm temperature during key phenological events, particularly autumn events, the lagged effect on the next growing season should be considered.

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1. Introduction

Land surface phenology can be defined as the seasonal pattern of variation in vegetation growth as observed by remote sensing data; and this has been used as a surrogate measure of global change in many studies (eg. Piao et al., 2006; White et al., 2009; Atzberger and Eilers, 2011; Tan et al., 2011). Monitoring the growth and development dynamics of temperate and boreal vegetation is essential in understanding the impacts of climate on a vast range of terrestrial life-forms (Reed et al., 1994; Menzel, 2000; Morisette et al., 2009; Morin et al., 2009). Forest phenology largely drives the competition and interactions (via the complex food chain and food web processes) among plant and animal species (Rathcke and Lacey, 1985; Memmott et al., 2007; Yang and Rudolf, 2010). Additionally, the amount and quality of vegetation cover regulates land–atmosphere interactions such as albedo and carbon, water and energy exchanges (Wilson and Baldocchi, 2000; Molod et al., 2003; Richardson et al., 2013), as well as key ecosystem services such as food, fibre, fuel, medicine and recreation (Badeck et al., 2004; Kauserud et al., 2012). Consequently, shifting in the dates at which leaves unfold and fall is of paramount importance from an ecological point of view. As a result, numerous earlier studies have tried to characterise the land surface phenology at different spatial scales (eg. Brown et al., 2010; Atzberger and Eilers, 2011; Jones et al., 2012; Rodriguez-Galiano et al., 2015).

Although photoperiod influences the phenology of certain northern high latitude forest species (Heide, 1993; Fracheboud et al., 2009; Sanz-Pérez et al., 2009; Vitasse and Basler, 2013; Way and Montgomery, 2015), air temperature was found to be the most crucial cue in determining the seasonal onset and senescence (Vitasse et al., 2009b; Shen et al., 2014). A sequence of normal temperature range ensures optimal growth of plants by indirectly supplying energy (via photosynthesis and respiration) for metabolic processes and development. Temperature directly regulates the dynamics of plant development via the processes of chilling and forcing requirements during dormancy (Luedeling et al., 2013).

The timing of vegetation phenology directly influences forest productivity by regulating the duration available for carbon fixation (Chang et al., 2013; Sakuraba et al., 2014). For example, biochemical compositions of the leaf such as foliar nitrogen enhance carbon fixation process during the growing seasons and hence, results in an increase in forest productivity (Smith et al., 2002; Charrier and Améglio, 2011). Other factors such as stand age (Ryan et al., 1997; Bond, 2000; Smith and Long, 2001; Song et al., 2014), soil quality (Pastor et al., 1984; Reich et al., 1997), latitudinal differences (Gillman et al., 2015) and species richness (Zhang et al., 2012; Gillman et al., 2015) also determine variations in forest productivity.

Regional and global changes in temperatures (Hurrell and VanLoon, 1997; Overland et al., 2008) have shifted the timing of forest phenology in mid and high latitudes of Europe (Sparks and Menzel, 2002; Vitasse et al., 2011). Many forest ecosystems in Europe have thus experienced prolongation of active growing season and consequent increase in photosynthetic activity (Myneni et al., 1997; Tucker et al., 2001) and in turn ecosystem productivity (Richardson et al., 2010; Pilegaard et al., 2011). More importantly, recent temperature anomalies in mid and high latitude Europe (Tuomenvirta et al., 2000; Xoplaki et al., 2005; Luterbacher et al., 2007; Van Oldenborgh, 2007; Cattiaux et al., 2009) have been responsible for earlier onset of greening (OG) and later end of senescence (EOS) (Roetzer et al., 2000; Walther et al., 2002; Parmesan and Yohe, 2003; Mimet et al., 2009); altering ecosystem functions and services (Hanninen et al., 1990; Kellomaki et al., 1995; Inouye, 2008; Piao et al., 2008; Hufkens et al., 2012).

Spring season sets out the start of the productive time in temperate and boreal forest ecosystem; and hence, gained the attentions of many researchers. Many studies have looked into the consequences of a warmer spring on tree phenology and productivity (eg. Richardson et al., 2010; Polgar and Primack, 2011; Way, 2011; Clark et al., 2014; Friedl et al.,2014; Guo et al., 2015). Recently, the relationship between spring and autumn leaf phenology in the conditions of warming climate in temperate forest ecosystems has been reported (Fu et al., 2014; Keenan and Richardson, 2015a, b). It has been shown that a warmer winter affects spring and autumn vegetation phenology the subsequent year (this is often termed as the ‘lagged’ effect) (Fu et al., 2014). Studies analysing the impact of warm temperature during spring and autumn phenological events mostly focus on the ‘direct’ effect of changes in spring and autumn temperatures on vegetation phenology, but studies investigating lagged effects are limited. In northern high latitude regions of Europe where temperature mostly controls vegetation phenology (Gulen and Eris, 2004; He et al., 2005); it has thus become imperative to investigate the extent to which extreme warm temperatures in spring and autumn phenology directly affect forest greenness (productivity) and also to investigate if this direct effect translates to a lagged effect in subsequent spring or autumn phenology. This would provide a better understanding of forest ecosystem response to these warm climatic events and resulting change (if any) in the forest productivity. To this end, this study aimed to: (1) characterise the extremely warm spring and autumn events in the whole of Europe between the years 2002 and 2012, and (2) investigate the effects of these warmer events on phenology and productivity of different forest types. This study was limited to extreme warm spring (EWS) and extreme warm autumn (EWA) events only and not to cold events because the former were more widespread within the study period and the spatial resolution of satellite data limited the detection of extreme cold events.

2. Materials and methods

2.1. Data

2.1.1. Temperature data

Daily mean temperatures for the periods 2003–2011 and 1961–1990, called study temperature and reference temperature respectively hereafter, were obtained from the *E*-OBS dataset (http://eca.knmi.nl/). The E-OBS temperature data are part of the Europe's ENSEMBLE project (Haylock et al., 2008). They are daily gridded data sets with $0.25° \times 0.25°$ pixel size and 25° N–75°N × 40° W–75° E areal coverage. This reference temperature was used to determine the standardised anomalies because it is the climate with the best estimate per the World Meteorological Organization (WMO) quality assessment work (WMO, 1996).

2.1.2. GlobCover Land Cover

This GlobCover Land Cover map (http://due.esrin.esa.int/globcover) of 2005–2006 was used to identify the spatial locations of key forest types such as broadleaf deciduous forest (BLDF), needleleaf evergreen forest (NLEF) and mixed forest (MF) in Europe. GlobCover is a global land cover map developed by the European Space Agency from ENVISAT Medium Resolution Imaging Spectrometer (MERIS) imagery at a 300 m spatial resolution (Bontemps et al., 2011).

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