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Phenological variation decreased carbon uptake in European forests during 1999–2013

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ABSTRACT

A number of studies have suggested that the duration of a growing season has significantly lengthened during the past decades, but the connections between phenology variability and the terrestrial carbon cycle are far from clear. In this study, we used a process-based ecosystem simulation model, BIOME-BGC, to investigate spatio-temporal variation in phenology and its impacts on carbon fluxes in European forests during 1999–2013. We found that the start of vegetation growing season advanced on average by $0.22 \pm 0.55\,d\,yr^{-1}$ and the length of growing season extended on average by $0.42 \pm 0.86\,d\,yr^{-1}$ for the period 1999–2013. Model simulations indicated that European forests acted as a weak carbon (C) sink with a mean value of $0.27\,Tg\,C\,yr^{-1}$ ($1\,Tg = 10^{12}\,g$) during 1999–2013. Phenological variation lowered the net ecosystem exchange (NEE) by 3.99 Tg C for the same period, and this could be explained by the opposing effect of enhanced heterotrophic respiration directly induced by the extension of growing season. NEE effects were negatively correlated with heterotrophic respiration ($R^2 = 0.43$), and one Tg increase in the heterotrophic respiration decreased NEE by 2.28 Tg C. The implications for the practical management is that a climate change will result in a significant change of selection pressure, and that phenology is a major aspect of tree functioning that will need adjusting for a future climate.

1. Introduction

Climate change has already affected the terrestrial ecosystems both structurally and functionally (Parmesan, 2006). An easily observable effect of climate change is the timing of vegetation phenological events, such as bud-burst, flowering, leaf unfolding, and leaf coloration (Guo et al., 2015). Most studies that have evaluated ecosystem responses to global warming have shown progressive advances in spring phenology (Chmielewski and Rötzer, 2001; Guo et al., 2015; Menzel et al., 2006; Yuan et al., 2014).

Changes in vegetation phenology can affect the carbon balance of terrestrial ecosystems. Warmer springs, for example, stimulate an early emergence from winter dormancy, leading to an extension of an ecosystem's carbon uptake period (Richardson et al., 2010). Warmer autumns, on the other hand, are thought to lead to carbon losses from ecosystems due to a greater increase in respiration than photosynthesis (Barichivich et al., 2013). Global mean temperatures have risen over the past decades (IPCC, 2013). It is therefore imperative to develop a robust understanding of both the temperature sensitivity of phenology (Wolkovich et al., 2012), and the associated changes in carbon cycling (Richardson et al., 2013).

Keenan et al. (2014) suggests that warming may increase the length of the growing season and consequently increase the carbon store of temperate forests. However, Moore et al. (2006) indicates that warmer springs will not have a strong impact on the annual carbon budget for temperate and boreal bogs, as earlier springs may not necessarily result in an increased use of solar radiation. Longer growing seasons are associated with increased gross primary production (GPP) and increased net ecosystem exchange (NEE) (Aurela et al., 2004; Richardson et al., 2010). Yet an increase in ecosystem respiration can offset the increase in GPP, resulting in insignificant changes in NEE (Moore et al., 2006), or alternatively, increases in respiration may exceed the increases in GPP resulting in a net carbon loss to the atmosphere (Piao et al., 2008; Sacks et al., 2007).

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According to IPCC (2013) the temperature rise foreseen during the 21st century is expected to be highest at high latitudes in the Northern hemisphere during the winter period, and the amount of precipitation is very likely to increase. In Europe, forests represent approximately 41% of Europe's land area (Eurostat, 2015) and are important in the development of climate change mitigation strategies for greenhouse gases emissions. Given the recent changes in temperature and precipitation, much attention has been focused on the detection of climate-induced trends in forest phenology (Garonna et al., 2014; Han et al., 2013; Ivits et al., 2013; Sparks et al., 2009). However, the long-term impacts of phenology resulting from climate change on forest carbon uptake and storage at the regional scale are still unclear.

The objectives of this study were to: (1) quantify the spatio-temporal variation of phenology across European forests in the period from 1999 through to 2013, and (2) examine the impact of vegetation phenology on net ecosystem CO_2 exchange. The intended goal of this analysis is to improve our fundamental understanding of the role of phenology in ecosystem CO_2 exchange processes in European forests.

2. Materials and methods

2.1. Derivation of phenological metrics from time series satellite data

Analysis of remotely sensed satellite indices is increasingly regarded as a key technique in understanding phenological characteristics of large areas of vegetation and related seasonal phenomena. The most commonly used remotely sensed spectral vegetation index in seasonal studies is the normalized difference vegetation index (NDVI). SPOT VEGETATION (VGT) is an NDVI product derived from the Satellite Pour l'Observation de la Terre (SPOT). SPOT VGT S10 is a ten-day Maximum Value Composite (MVC) NDVI product, with a 1 km spatial resolution. It also provides atmospheric and aerosol corrections (Rahman and Dedieu, 1994), and has been evaluated and widely used in many studies (Fontana et al., 2008; Upadhyay et al., 2008; Van Leeuwen et al., 2013). In this study, time series SPOT VGT S10 products over a 15-year period from 1999 to 2013 were obtained from www.vito-eodata.be (540 images, three images per month) to explore temporal NDVI data and to retrieve phenological characteristics in European forests.

The TIMESAT program was developed to explore time series of NDVI data and to retrieve phenology metrics (Jönsson and Eklundh, 2004). In this TIMESAT implementation, we used a local quadratic polynomial fit and the adaptive Savitzky-Golay filter applied to a moving window size of seven composites (Han and Xu, 2013). We eliminated NDVI spikes larger than two times the standard deviation of the median values of the closest neighbors in the time series and fitted the remaining upper envelope (Bradley et al., 2007). Start of season (SOS) and end of season (EOS) are defined as the interpolated composite period when the NDVI has increased or decreased 20% of the seasonal amplitude from the growing season minimum level (Pan et al., 2015; Van Leeuwen, 2008; White et al., 2009). Length of season (LOS) is defined as time from the start to the end of the season.

Seven years of ground observations provided by the International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests, http://www.icp-forests.org) were also used to analyze the phenological trends. 42 participating countries of ICP Forests monitor forest ecosystems including their phenology in Europe and North America. A subset of phenological data is measured from approximately 500 intensive plots (Lorenz and Becher, 2012) based on a harmonized methodology (Ferretti and Fischer, 2013). After screening, data from 110 plots provided complete time series, covering the following countries: France, Germany, Italy, Spain, Sweden, Hungary and Romania.

2.2. Net ecosystem exchange modelling

2.2.1. BIOME-BGC model

BIOME-BGC is a mechanistic biogeochemical model simulating the storage and flux of carbon, water, and nitrogen between the ecosystem and the atmosphere, and within the components of the terrestrial ecosystem (Cienciala and Tatarinov, 2006; Running, 1994; Running and Hunt, 1993; Tatarinov and Cienciala, 2006; Thornton, 1998). The model is a development of the FOREST-BGC model (Running and Gower, 1991). The carbon budget simulated by BIOME-BGC includes all forest production output variables such as GPP, NPP, and NEE.

Three groups of input data are required by BIOME-BGC: site characteristics, meteorological variables and ecophysiological parameters. Site characteristics include soil texture (percentage of sand, silt and clay), elevation, latitude and albedo. In this study, the soil property data was derived from the Harmonized World Soil Database (version 1.2) (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/) at a resolution of 1 km. Daily meteorological data was derived from the E-OBS dataset (version 4.0), a high resolution gridded dataset funded by the EU-FP6 (http://E-OBS-eu.metoffice.com) (Haylock et al., 2008). These climate dataset were originally provided at 0.25° spatial resolution and then downscaled to 1 km by applying a locally calibrated regression procedure for model use. The ecophysiology of vegetation types is described by constant input parameters. Some parameters control the allocation of photosynthetically accumulated carbon to leaf, stems and root pools (White et al., 2000).

The phenology model used by BIOME-BGC is described in White et al. (1997), and can also be user specified if the user has information about the onset and senescence of growing season. Therefore, in order to quantify the influence of changing phenology on carbon dynamics in European forests, phenological metrics derived from Section 2.1 were used as input data.

2.2.2. Model validation and simulations design

After parameterizing BIOME-BGC model, flux data downloaded from the FLUXNET project (http://fluxnet.fluxdata.org/data/la-thuile-dataset/) were used to validate the modelled NEE. Evergreen needleleaf forest was validated using a site in Finland (61.84°N, 24.29°E) and deciduous broadleaf forest was validated using a site in Germany (51.08°N, 10.45°E). BIOME-BGC model simulations were run for 6000 years to reach soil carbon equilibrium under natural conditions by repeating climate conditions from 1999 to 2013. Impacts of the length of season on carbon dynamics were obtained using differences between scenario “PheVar” and “PheEqu”. In scenario “PheVar”, SOS and LOS were varied from 1999 to 2013 which were derived from NDVI data and in scenario “PheEqu”, we removed phenological changes during the simulation. The effect of phenology on carbon dynamics is calculated by the difference between outputs of the two scenarios.

2.3. Biogeoclimatic zonation

Climate change sensitivity and exposure differ between biogeoclimatic zones and forest types in Europe (Han et al., 2013). Thus, we analyzed climate change impacts separately for different biogeoclimatic zones and forest types. The bioclimatic map of Europe was used as the reference classification (EEA, 2011). European forests cover five major biogeoclimatic zones: Alpine, Boreal, Atlantic, Continental, and Mediterranean. The study area encompasses four forest functional types, namely evergreen broadleaf forest, evergreen needleleaf forest, deciduous broadleaf forest, and deciduous needleleaf forest according to tree species map provided by the European Forest Institute (Brus et al., 2012; Hengeveld et al., 2012; Troeltzsch et al., 2009). The distribution of biogeoclimatic zones and forest types is presented in Fig. 1.