Assessing for spatio-temporal phenological changes in Western European deciduous forests

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Abstract

Plant phenology is changing because of global warming, and this change may precipitate changes in animal distribution (e.g. pests), alter the synchronization between species, and have feedback effects on the climate system through the alteration of biogeochemical and physical processes of vegetated land surface. Despite these possible alarming consequences resulting from changes in plant phenology, we do not have a certain global picture of where change in plant phenology is occurring. Satellite data are seen as possible source of wall-to-wall information on plant phenology, but the reliability of this information for monitoring changes in plant phenology is not well established. Here, we used both ground phenological observations and satellite-derived metrics covering the period of 2001 through 2011 to assess for trends in the start-of-season (SOS) for Western European deciduous forests to determine if climatic warming recorded between 2001 and 2011 has resulted into changes in SOS. First, we tested for trends in ground observations using Mann-Kendall trend test. This trend test was then applied to satellite-derived SOS metrics to determine if trends detected in ground observations match with those detected from satellite-derived SOS metrics. Second, we assessed if trends in SOS for Western European deciduous forests were only limited to photoperiodic-insensitive species. The spatial consistency of the satellite-derived SOS metrics was also evaluated. Our results showed that, in temperate region, there was statistically significant negative trend in ground observations. Though not statistically significant, this trend was correctly mirrored in satellite-derived SOS metrics. Although the analysis of trends in satellite-derived SOS at pixels corresponding to phenological stations did not show statistically significant trends, in other parts of the study area significant trends were detected. We found both negative and positive trends in satellite-derived SOS metrics. Positive trend was predominantly occurring in Mediterranean areas where rainfall is the main limiting factor to plant greening, suggesting that rainfall might have been starting later in these areas. However, there were no ground observations in these areas to validate this positive trend. Negative trend, on the other hand, was prevalent in temperate areas where temperature is a key limiting factor to SOS, thus suggesting that the reported climatic warming has precipitated changes in SOS. Though satellite-derived SOS metrics can capture changes in SOS, they may however show smaller magnitude of change than what is observed at individual plants. We observed that both photoperiodic-sensitive-and-insensitive species have experienced statistically significant changes in their SOS even in temperate areas where temperature is the main limiting factor – hence supporting the notion that phenological changes are not only limited to photoperiodic-insensitive species. Our satellite-derived SOS metrics were spatially consistent. We conclude that with carefully extracted phenological metrics, changes in plant phenology as a result of climatic warming can be captured reasonably well using satellite data.

Keywords: Plant phenology, start-of-season, satellite-derived SOS metrics, trend, photoperiodic-sensitive-and-insensitive species.
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1 Introduction

1.1 Context and background

Plant phenology, the timing of plant's seasonal developmental phases, is changing in response to global warming (Menzel & Fabian, 1999; Badeck et al., 2004; Menzel et al., 2006; Cleland et al., 2007; Peñuelas et al., 2009; Steltzer & Post, 2009; Polgar & Primack, 2011). Recent studies on plant phenology based on in-situ observations (Menzel & Fabian, 1999; Menzel et al., 2006), phenology models (Mao et al., 2012) and remote sensing data (Myneni et al., 1997, Cleland et al., 2007; White et al., 2009; De Jong et al., 2011; Jeong et al., 2011; Zeng et al., 2011) have documented cases of early spring arrival and/or lengthened growing season, especially in the Northern Hemisphere. Other studies found greening (De Jong et al., 2012; Mao et al., 2012), browning (De Jong et al., 2012) and spring arrival (White et al., 2009) trends in plant phenology. Changes in plant phenology are largely attributed to climatic warming (Badeck et al., 2004; Menzel et al., 2006; Linkosalo et al., 2006), thus they can be used as indicators of climate change (Kross et al., 2011). Of concern about changes in plant phenology are the effects it may have on seasonal availability of food for animals and interactions between the atmosphere and biosphere. Shift in the timing of food supplies controlled by seasonality may precipitate changes in animal distribution and can alter the synchronization between species (Peñuelas & Filella, 2001; Post et al., 2008), hence affecting biodiversity. On atmosphere-biosphere interaction, early spring arrival and the increase in the length of the growing season can have feedback effects on the climate system through the alteration of biogeochemical (e.g. carbon sequestration) and physical (e.g. water balance) processes of vegetated land surface (Peñuelas & Filella, 2001). Changes in plant phenology may therefore have alarming consequences on the ecosystem and socio-economic activities of the human population (Peñuelas & Filella, 2001). It is therefore important that we monitor changes in plant phenology at various scales (spatial and temporal).

One way of monitoring plant phenology is through phenological networks where people observe phenological events. Initiatives such as Pan European Phenological Network and USA-NPN phenology network have been established to contribute to the monitoring of how changes in climate are affecting the phenology of plants (Mayer, 2010; van Vliet et al., 2003). Data from these phenology networks, mainly collected by citizens who are interested in observing nature, have been used in many studies (e.g. Menzel & Fabian, 1999; Menzel et al., 2006) to assess for changes in phenology of various plant species. Although important, these networks only cover limited parts of the globe, particularly in the Northern Hemisphere, hence giving only a limited global picture of how plants are responding to global warming. In addition, data from phenological networks are point-observations and focused on individual selected species, and as a result may not give clear picture of whether or not phenological responses to global warming are occurring also at ecosystem or landscape level.
In recent years, satellite data have been used to assess and monitor plant phenology (White et al., 2009; O’Connor et al., 2012), hence addressing spatial limitation associated with phenological in-situ observations from phenology networks. Though phenological information derived from satellite data is not identical to plant phenology, it is generally considered to be closely related (De Jong et al., 2011, Liang & Schwartz, 2009, White et al, 2009, Kross et al., 2011). Phenological metrics (i.e. start-of-season (SOS) and end-of-season (EOS)) derived from time series of satellite vegetation indices (e.g. Normalised Difference Vegetation Index (NDVI)) are therefore used as proxy indicators (phenological measures) of plant phenology. Based on these metrics, researchers have studied changes in plant phenology with some studies reporting temporal trends in plant phenology (White et al., 2009). However, phenological metrics from satellite data can also be highly inaccurate and inconsistent with ground observations (White et al., 2009), thus inviting doubts on the reliability of these metrics for monitoring the impact of global warming (climate change) on plant phenology.
1.2 Problem definition

Global warming is causing phenological changes in plants (Menzel & Fabian, 1999; Cleland et al., 2007; Peñuelas et al., 2009; Steltzer & Post, 2009; Polgar & Primack, 2011). Phenological changes in plants are feared to trigger devastating changes in animals, ranging from changes in animal distribution (especially pest) to species de-synchronization (e.g. plant and their pollinators) (Peñuelas & Filella, 2001; Post et al., 2008). Though phenological networks have been established to monitor the phenology of plants, these networks are limited to few areas of the globe. So, little is known on how plant phenology is responding to global warming in most parts of the globe. We, therefore, urgently need to monitor changes in plant phenology across the globe in order to have picture of where changes in plant phenology are occurring. Reliable wall-to-wall information on plant phenology is however lacking and is therefore urgently needed for spatially elaborate prognosis of the effect of global warming on plant phenology. Satellite data are seen as an important data source that will help to understand how plant phenology is responding to global warming globally (Peñuelas and Filella, 2001), but little is known if phenological changes detected from satellite data are consistent with real changes.

Research on plant phenology has received considerable attention from the remote sensing community (e.g. Zhang et al., 2009; White et al., 2009; Verbesselt et al., 2010a,b; Kross et al., 2011). The focus generally is to extract phenological information from satellite data. Nonetheless, a large part of the efforts has been focused on developing and improving the methods for extracting phenological metrics such as the SOS, EOS and length-of-growing season (LOS) from satellite data (e.g. White et al., 1997; Roerink et al., 2000; Zhang et al., 2003). Some of the studies focused on assessing the effect the compositing period of satellite data has on accuracy of the phenological metrics (e.g. Pouliot et al., 2011; Kross et al., 2011), whereas other studies used satellite data to assess and monitor changes in plant phenology (Myneni et al, 1997; Zhang et al., 2009; White et al., 2009; Jeong et al., 2011; Zeng et al., 2011). Although satellite data provides an opportunity to study the dynamics of plant phenology in a more spatially explicit manner, validating the changes that might be detected is equally challenging, especially in areas where no ground data are available. In addition, satellite data are inundated by many factors (e.g. cloud contamination, sensor errors, low spatial resolution) which subsequently affect the accuracy of satellite-derived biophysical information (Carreiras et al., 2003; Kobayashi & Dye, 2005; Hird & McDermid, 2009), including phenological metrics. Inaccurate phenological metrics may invite doubts on how well changes in plant phenology resulting from global warming can be detected and monitored using satellite data.

In some areas in North America the SOS estimated from Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data was found to deviate as much as 60 days from observed values, depending on the method used to retrieve the phenological metrics (White et al., 2009). Using the same data source, Kross et al. (2011) found the mean absolute errors (MAE) in SOS estimates to range between 13 and 40 days in Canadian broadleaf forests. Moreover, Zhang et
al. (2009) evaluated the effect of data gaps on the accuracy of phenological metrics using simulated data and concluded that the largest error in SOS is produced when data gaps occur around the onsets of phenological transition dates. Data gaps are inherent in satellite time-series, especially in areas with prolonged cloud and snow covers. With one data gap, the error in phenological metrics can be as large as 15 days; but if missing values are limited to 1 and 2 throughout a year, the probability of errors larger than 5 days is < 3% and 15 %, respectively (Zhang et al., 2009). If a single data gap can result into an error of 15 days as reported by Zhang et al. (2009), it may be difficult to assess and monitor phenological responses to global warming in regions (e.g. tropical and semi-tropical regions) where cloud cover is more frequent. Inaccurate satellite-derived phenological metrics may also be a result of understory vegetation which greens earlier than the observed species, especially tree species (Ahl et al., 2006), hence resulting into large deviations between estimated metrics and observed phenological events. However, this problem cannot be resolved easily, to reduce the deviations between estimated metrics and observed phenological events. Another reason for large deviations between ground observations and satellite-derived metrics could be linked to the location of the individual plant whose phenological events are observed. For example, if the target tree is located in the urban centre or in the grassland, the mixed-pixel problem (White et al., 2009) may become more prominent, hence the extracted phenological metrics may not match the phenological events of the observed plant species at that particular location. These landscape complexities may degrade the accuracy of metrics derived from satellite data, thus contributing to doubts about the usefulness of satellite data to monitor changes in plant phenology.

On the backdrop of inherently low accuracy of satellite-derived phenological metrics, a number of studies have reported changes in SOS (White et al., 2009; Zeng et al., 2011) and LOS (Myneni et al, 1997; Jeong et al., 2011), especially in Northern Hemisphere, based on satellite data. Although the findings from these studies may confirm the relevance of satellite data to plant phenology monitoring, uncertainties still exist on the reliability of phenological metrics derived from satellite data to monitor spatio-temporal dynamics in plant phenology induced by global warming. For, example, it is not yet known if phenological changes detected from satellite-derived metrics are commensurate to changes detected from ground observations. This area of research is largely under-investigated. Of particular interest are findings by White et al. (2009) where no evidence of time trends in spring arrival was found in ground observations, but trends were detected in satellite-derived SOS for about 12% of North America. Typically, it is surprising for phenological changes to be detected at ecosystem/pixel level and not at individual plant level.

So far, research on satellite-based plant phenology has focused mainly on extracting accurate phenological metrics from satellite data (White et al., 2009; Zhang et al., 2009; Kross et al., 2011). Although accurate phenological metrics may be important for detailed assessment of phenological responses to global warming, here we argue that the key requirements are spatial and temporal consistencies. By temporal consistency we mean that if the ground observations show a negative temporal trend, phenological metrics from satellite data should also show a negative trend, and not
otherwise. For spatial consistency, we mean that the satellite-derived phenological metrics should be able to capture spatial differences in plant phenology (e.g. spatial effect that could be explained by, for instance, a natural spatial pattern of temperature, rainfall or elevation). So, in this case, even if phenological metrics from satellite data are less accurate but consistent with ground observations, it may be possible to detect spatio-temporal changes in plant phenology which are commensurate to real changes. Many studies (e.g. White et al., 2009; Zhang et al., 2009) only focused on assessing how well the satellite-derived metrics correlate to ground observations, but not on the consistency of trends. Lack of spatio-temporal consistency coupled with inherently limited accuracy in satellite-derived phenological metrics would make it difficult to distinguish real phenological changes from artificial ones.

Reported changes in plant phenology (Myneni et al, 1997; Menzel & Fabian, 1999; Badeck et al., 2004; White et al., 2009) are not found in all eco-zones even in the Northern Hemisphere where phenological changes are widely reported (White et al., 2009). Some researchers argue that species which are photoperiod-sensitive should not track the climatic warming (Körner and Basler, 2010). Photoperiod-sensitive species refer to species which use light-sensitive proteins (e.g. phytochrome) to sense seasonal changes in the length of day and night (Hillman, 1966). A threshold on change in day length should be met, before any other subsequent processes necessary for sprouting take place (Körner and Basler, 2010). According to Körner and Basler (2010) photoperiod-insensitive tree species (e.g. Betula pendula) which are opportunistic in nature would response to climatic warming, but long-lived and late successional species (e.g. Fagus sylvatica and Quercus robur) which are photoperiod-sensitive would not. Under a warming climate, Körner and Basler (2010) argue that photoperiod-sensitive tree species would instead become constrained by internal controls, unless new genotypes emerge – but it would take hundreds of years for new genotypes to emerge. This may explain why phenological changes are only limited to some areas. But other researchers have contested the notion that phenological changes are likely to be restricted to photoperiodic-insensitive species only - thus suggesting that climatic warming is causing phenological changes even in species which are known to be photoperiod-sensitive (Chuine et al., 2010; Morin et al., 2010). Of recent, Bauerle et al. (2012) acknowledged the importance of temperature to photosynthetic physiology of plant species, but emphasised that photoperiod-controlled species will show limited responsiveness to warming. Of interest to the studies which use satellite data is the explanation of why phenological changes detected from satellite data (e.g. White et al., 2009) are only found in some areas and not others. Some researchers attributed these differences to variations in microhabitat conditions (Myking & Skroppa, 2007). To our knowledge, little is known about what causes local differences in how plant phenology responds to climatic warming. Here, we questioned whether we can reasonably explain the generally localised phenological changes detected from satellite data by using dominant species maps. We hypothesise that these localised phenological changes might be linked to the fact these changes are only or mainly occurring in photoperiod-insensitive species (e.g. Betula pendula), hence such areas where change is detected are perhaps dominated by photoperiod-insensitive species.
Though changes in plant phenology are largely attributed to climatic warming especially in regions where temperature is a key limiting factor to plant activities (Linkosalo et al., 2006), interpreting phenological changes without looking at dynamics in air temperature regimes during the period of interest may lead to generalized conclusions. This is because an area may experience several temperature regimes during the period of interest. For example, while there is compelling evidence that global temperature has generally been increasing since 1885, some periods (e.g. 1995 to 2006) tend to be warmer than others (IPCC, 2007). Also, there might be localised differences in the temperature regimes as a result of microhabitat conditions (Myking & Skroppa, 2007). It is therefore important that studies which focus on assessing for changes in plant phenology to also explore the behaviour of temperature regimes during the period of interest.

In combination, the National Oceanic and Atmospheric Administration (NOAA) (www.noaanews.noaa.gov/stories2009/20091208_globalstats.html), World Meteorological Organization (WMO) (www.wmo.int/pages/mediacentre/press_releases/pr_869_en.html), and NASA (www.nasa.gov/topics/earth/features/temp-analysis-2009.html) and Intergovernmental Panel on Climate Change (IPCC) (2007) all reported that 1995 to 2009 was the warmest period since instrumental measurements of temperatures began in the 1880s, especially in higher northern latitudes. This warming has resulted into increased net primary production (NPP) over the Northern Hemisphere (Zhao and Running, 2010). Because climatic warming leads to changes in plant phenology (Menzel et al., 2006; Linkosalo et al., 2006), we questioned whether this warming has resulted into phenological changes in plants.

Previous studies on plant phenology which were based on satellite data mainly used data from AVHRR sensor (Delbart et al., 2006; White et al., 2009; Kross et al., 2011). These data have a coarse spatial resolution (1 km x 1 km), with some studies (e.g. Delbart et al., 2006; White et al., 2009) adopting even a much coarser resolution (8 km x 8 km). Coarser spatial resolution may conceal subtle variations in phenological response to climatic warming. The time series data from a new family of sensors such as MODIS and Medium Resolution Imaging Spectrometer (MERIS) with much higher resolutions are increasingly becoming available, hence enabling for monitoring of vegetation in more detailed manner. Though available for a much shorter time series, data from MODIS may provide an opportunity to understand how climatic warming affects plant phenology especially in short-term at a more detailed spatial level. Satellite data from Moderate Resolution Imaging Spectroradiometer (MODIS) overlap partly with the warmest period of 1995 through 2009. Ground phenological data are also available. If, based on ground data, the warming between 1995 and 2009 has caused changes in plant phenology; can we detect these changes using phenological metrics derived from MODIS NDVI time series?
1.3 Research focus, objectives and questions

Our overall goal was to assess for trends in the SOS for Western European deciduous forests, determine if the trends detected from satellite-derived SOS metrics were commensurate to trends in ground observations, and investigate if trends were only limited to photoperiod-insensitive species. We achieved our overall goal through two specific objectives. Our first objective was to determine if there were trends in ground observations (SOS) for deciduous forest in Western Europe between 2001 and 2011; evaluate if these trends are reflected in satellite-derived SOS metrics, and if the trends were only limited to photoperiod-insensitive species. We hypothesised that if climatic warming between 1995 and 2009 has caused changes in the SOS for Western European deciduous forests, such changes should be larger for individual plants than the changes detected at the pixel level. Principally, we do not expect changes to be detected in satellite data if no trends are detected in ground observations. The second objective was to investigate if satellite-derived SOS metrics for deciduous forest in Western Europe were spatially consistent. We argue here that satellite-derived SOS metrics should be spatially with spatial pattern of factors (e.g. temperature) which control SOS in order to be useful for assessment of the effects of climatic warming on plant phenology. In essence there would be no need to derive temporal trends from SOS metrics which are spatially inconsistent because the trends are likely to be misleading. This study contributes to the understanding of how climatic warming is causing changes in the phenology of plants. It is also provide insights into the reliability of satellite-derived SOS metrics to monitor the impact of climatic warming on plant phenology.

The following research questions were addressed in order to meet the objectives of this study:

1. Based on ground observations, are there trends in SOS for deciduous forest in Western Europe between 2001 and 2011?
   a. If there are trends in ground observations (q1), are these reflected in SOS metrics derived from satellite data?
   b. Are these trends in SOS limited to photoperiod-insensitive species?

2. Are satellite-derived SOS metrics for deciduous forest in Western Europe spatially consistent?

1.4 Outline of the thesis

In the next sections, we present the approach, the results, discussion and the conclusion for this study. In section 2, the approach that was followed to answer the research questions of this study is presented. The results are presented in section 3, followed by discussion of the results in section 4. The main conclusions of the study are presented in section 5. We have also suggested in section 6 areas of further research. At the end, the references cited in this study are provided.
2 Materials and methods

In this section, we outline the approach that was followed to answer the research questions of this study. The background information about the study area and the data is provided in sub-section 2.1 and 2.2. Information about the pre-processing of the data is presented in sub-section 2.3. In sub-section 2.4, we test for trends in air temperature. Steps followed to extract phenological metrics from satellite data are provided in sub-section 2.5. We test for trends in ground observations and satellite-derived SOS metrics in sub-section 2.6. In sub-section 2.7, we explored if phenological changes were limited to photoperiod-insensitive species. Finally, the spatial consistency of satellite-derived SOS is assessed in sub-section 2.8. In Fig. 1 we provide an overview of the workflow of this study. More detailed information about procedures of each analysis is provided in the subsequent sub-sections.

Fig. 1: An overview of the workflow of this study.
2.1 Study area

This study focused on various deciduous forests in Western Europe to assessing for changes in the SOS between 2001 and 2011. Fig. 2 shows the study area and the distribution of the deciduous forest in the Western Europe. The study area covers 11 Western European countries, namely: Portugal, Spain, Andorra, France, Luxembourg, Belgium, Netherlands, Italy, Germany, Switzerland and Austria; bounded between 56˚N & 9˚W and 35˚N &19˚E. The climate in the study area ranges from Mediterranean in the south to temperate northwards. In Mediterranean region (covering mainly Spain and Portugal), the growing season (greening) starts around October, whereas in temperate regions it starts around April. We only considered deciduous forest because of its well-defined seasonality in phenology which would make it ideal to date the SOS. We chose Western Europe as our study area for two reasons. First, it is in the northern hemisphere where climatic warming was reportedly the highest between 1995 and 2006 (IPCC, 2007). Second, ground observations on phenological events are available and easily accessible, hence enabling for validation of satellite derived metrics.

Fig. 2: Distribution of the deciduous forest in the study area.
2.2 Data

2.2.1 Land cover

Land cover map was important for the identification of deciduous forest in the study area. We identified deciduous forest from CORINE landcover map of 2006. This land cover map with spatial resolution of 250m x 250m was sourced from The European Topic Centre on Land Use and Spatial Information (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-1/clc-2006-v13-250m, last accessed, 20 February 2012). Information related to the classification accuracy of CORINE landcover map of 2006 was not available –thus presenting a challenge on how to evaluate the “fit-for-use” level of this dataset. Nonetheless, we used this dataset in our analysis because it was the official dataset that European Environment Agency uses, indicating that the dataset could be used for policy formulation.

2.2.2 Satellite data

NDVI is correlated with vegetation productivity (Prince & Tucker, 1986), therefore a good proxy measure of the start of vegetation photosynthetic activities. In this study, MODIS NDVI 16-day composite (MOD13Q1) dataset covering the period of 2000 – 2012 was used for extraction of phenological metrics. This dataset is distributed with a spatial resolution of about 231.65m x 231.65m. Amongst others, it contains NDVI and pixel reliability layers. Pixel reliability layer contains information about how reliable the quality of data at each pixel is.

2.2.3 Dominant tree species

As part of our analysis, we needed to identify tree species dominant at each location (pixel). The European tree species dataset (Brus et al., 2011) sourced from the European Forest Institute database (http://www.efi.int/projects/tree-species-map/register.php, last accessed, 20 February 2012) was used for this purpose. This dataset with spatial resolution of 1 km x 1km, shows the distribution of 20 tree species over Europe, indicating which tree species is dominant at each location (Brus et al., 2011). A tree species is dominant on pixel if it has the highest probability of occurrence at such pixel as per prediction results (Brus et al., 2011). The weakness about this dataset is linked to two aspects: (1) the spatial resolution which is more courser than that of our land cover map and satellite data, (2) and that the dominant species at each pixel was estimated – possibly there are still prediction errors.
2.2.4 Ground observations

In-situ point observations on phenological events of deciduous tree species were used to validate phenological metrics derived from satellite data. We sourced these data from the Pan European Phenological Database (http://www.pep725.eu/, accessed, February 2012). Phenological events of seven individual deciduous tree species (Alnus glutinosa, Betula pendula, Fagus sylvatica, Fraxinus excelsior, Larix decidua, Quercus robur, and Tilia cordata) were used for validation. Betula pendula is a photoperiodic-insensitive species. We focused on these species for two reasons. First, they were among the 20 dominant tree species in Europe (Brus et al., 2011). Second, some of their phenological events (e.g. leaf unfolding, first leaves separation) were regularly recorded during the period of interest to us (2001 – 2011). Except for Larix decidua, leave unfolding was frequently recorded for all species; for Larix decidua first leaves separation was frequently recorded instead. For our study period, frequently recorded phenological events were only available for Germany, and Switzerland, thus limiting the validation only to deciduous forests in these countries. An ideal validation dataset of phenological events in our study area should include areas such as Spain where Mediterranean climatic conditions prevail. Spatially-limited availability of in-situ observations on plant phenology is one of the reasons why there is an urgent need to evaluate how well satellite derived phenological metrics can be used to monitor the response of plant phenology to climatic warming overtime in order to fill this information gap. On the other hand, ground-based records on plant phenology are important
for validation of satellite derived metrics, so when they are spatially-limited the validation may be more difficult. Nonetheless, we assumed that the validation dataset of phenological events we acquired would be sufficient to answer our research questions.

Fig. 4 shows the location of 26 phenological stations where phenological events for deciduous tree species used in this study were recorded; and the name and coordinates of each station are provided in Table 1. Not all species were recorded at each of these stations. Out of 26 stations, phenological events for *Betula pendula* were recorded at 23 of them; *Alnus glutinosa* at 15, *Fagus sylvatica* at 20, *Larix decidua* at 25, *Quercus robur* at 17, *Tilia cordata* at 3 and *Fraxinus excelsior* at 18 stations. The maximum number of species recorded per station was six (6), suggesting that although stations are provided as point locations, the observed individual plants may not be located exactly on these sites.

2.2.5 Air temperature

Although it has been already reported that the increase in air temperature was higher in the northern latitudes between 1995 and 2006 (IPCC, 2007), in order to reasonably relate phenological changes to climatic warming we explored for trends in air temperature over Western Europe between 2001 and 2011. A gridded (pixel = 0.25° x 0.25°) daily mean temperature dataset (Haylock et al., 2008), covering our study area, was sourced from the database of European Climate Assessment & Dataset Project (http://eca.knmi.nl/, last accessed, July 2012).
Table 1: Names and coordinates of phenological stations where phenological events used in this study were recorded.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Name</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Obendorf/Wankendorf</td>
<td>10.167</td>
<td>54.117</td>
</tr>
<tr>
<td>304</td>
<td>Trittau</td>
<td>10.417</td>
<td>53.617</td>
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<td>Heinade</td>
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<td>Wiershausen</td>
<td>10.067</td>
<td>51.817</td>
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<td>Holzheim</td>
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<td>51.150</td>
</tr>
<tr>
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<td>Rhoda</td>
<td>8.500</td>
<td>50.967</td>
</tr>
<tr>
<td>2286</td>
<td>Emstal-Menshausen</td>
<td>9.267</td>
<td>51.233</td>
</tr>
<tr>
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<td>Schoenstein</td>
<td>9.067</td>
<td>51.000</td>
</tr>
<tr>
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<td>Eichenbach</td>
<td>6.817</td>
<td>50.433</td>
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<td>Weinheim</td>
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<tr>
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<td>48.767</td>
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<td>Traustadt</td>
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<td>49.950</td>
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<td>Tutow</td>
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</tr>
<tr>
<td>5543</td>
<td>Markranstaedt</td>
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<td>Questenberg</td>
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<td>8.600</td>
<td>46.233</td>
</tr>
</tbody>
</table>

2.3 Pre-processing steps

A number of data pre-processing steps were followed before implementing data analysis steps. Pre-processing is an important step preceding data analysis; done to ensure that the data are properly collated. Under this sub-section, we briefly elucidate how each dataset, were applicable, was pre-processed.

2.3.1 Land cover

The CORINE landcover map contains information about various land cover types in Europe. It is from this dataset deciduous forest had to be identified. First, we extracted the part of landcover map that covers Western Europe, using the boundaries of our study area. The MOD13Q1 product is distributed with the spatial resolution of about 231.65m x 231.65m, slightly higher than that of the CORINE land dataset (250m x 250m). We resampled the landcover map to the spatial resolution of 231.65m x 231.65m so that the MOD13Q1 product where phenological metrics were extracted is kept as it is. The resampled landcover map was re-projected from Lambert Azimuthal Equal Area (Datum: D_ETRS_1989) to sinusoidal projection using the rigorous method in ENVI software, which involves wrapping of the pixel to pixel. Ideally, the projection of Lambert Azimuthal Equal Area with a datum of D_ETRS_1989 should be preferred because this is specifically suitable for Western Europe. But, we did not want to make any transformation to the MOD13Q1 product before phenological metrics were derived.
2.3.2 NDVI

Our study area cut across nine (9) MODIS scenes (7v3 – 9v3, 7v4 – 9v4 and 7v5 – 9v5). Also, MOD13Q1 product contains other layers (e.g. Near-infrared surface reflectance) which were not of interest to this study. As such, we extracted NDVI and pixel reliability layers from MOD13Q1 products, subset all scenes to our study area and mosaicked the subsets. We used MODIS re-projection tool ([https://lpdaac.usgs.gov/tools/modis_reprojection_tool/](https://lpdaac.usgs.gov/tools/modis_reprojection_tool/), last accessed: 25 February 2012) which is designed to extract layers from MODIS products, and subset and mosaic the scenes concurrently. The coordinate system of extracted layers remained in sinusoidal projection.

The next step was to mask the pixels with unreliable quality or which were not deciduous forest as per the land cover map. First, for each year, we create two layer stacks: one for NDVI layers (23 layers per year) and the other for pixel reliability layers (23 layers per year). In a second step, using a python script, we iterated through each NDVI layer and the corresponding pixel reliability layer in addition to land cover map, and set the value of each pixel in NDVI layer to 3000 if the pixel reliability value is > 1 or if the land cover type was not deciduous forest. These steps were applied to data for each year, 2000 through 2012.

After the NDVI cleaning process, a layer stack (from year 2000 through 2012) was created using ENVI-IDL software. This step was necessary because a smoothing function had to be applied before extracting phenological metrics. It is much better to fit a smoothing function to longer time-series than a shorter one. But the resultant challenge of stacking up a much longer time-series is data size which may be unmanageable in terms of computational demand leading to memory problem especially if the study area is relatively larger. In our case, the data size was 103 GB, far too heavy for R software we used for analysis. As such, the data (the stack) was sub-divided into 36 spatial subsets, each with about 1600 rows and 1748 columns, with a disk size of about 2.8 GB; the spatial sub-setting was done using ENVI-IDL software.

2.4 Assessing for trends in air temperature

Early spring arrival and increased growing season have been linked to the increase in air temperature (Menzel & Fabian, 1999; Menzel et al., 2006). But temperature trends are usually reported at low spatial resolution. For example, NASA uses 2° x 2° as the lowest spatial unit to report trends in air temperature – which is unlikely to capture important local variations in temperature. As part of our study to assess for phenological changes in Western Europe between 2001 and 2011, we also explored if there were trends in air temperature in this area during the observation period because it is important for interpretation of the results from phenological analysis. Using a dataset with spatial resolution of 0.2° x 0.2°, we adopted the approach used by NASA (Hansen et al., 2010) to assess for trends in air temperature - focusing on mean annual temperature and mean temperatures for different seasons (December – February, March – May, June – August, and September - October). We used a simple linear model to assess for trends in air temperature regressing temperature on time (2001 –
2011). Here, we do not intend to determine if trend is significant; only to show if there was upward or down trend in areas that experienced change in SOS. An upward trend would imply warming and versa-visa. In Mediterranean region of our study area, the main limiting factor to vegetation greening is rainfall (Christensen et al., 2007; Matesanz et al., 2009), but we do not intend to analyse for trends in rainfall in this study. We only take note that the phenological changes in Mediterranean areas should be interpreted cautiously.

2.5 Extracting phenological metrics from NDVI time series

In our analysis of phenological changes in deciduous forests in Western Europe, the metric of interest was the SOS. The SOS was extracted from NDVI (MOD13Q1) time series for each year, 2001 through 2011. We used Midpoint\textsubscript{pixel} method (White et al., 1997) to extract the SOS. Midpoint\textsubscript{pixel} method is known to produce phenological metrics more consistent with in-situ observations than other methods evaluated by White et al. (2009) in North America.

It is important to make a distinction between the field-based phenological events and remote sensing-based phenological metrics. Hereon, field-based measurements are referred to as ground observations while the remote sensing-based measurements are either prefixed with “estimated” (e.g. estimated SOS) or referred to as satellite-derived SOS metric. Ideally, the SOS would mean the point in time where the vegetation starts to green, but, this is not the case especially with remote sensing-based measurements. To put it in context, the estimated SOS is defined here as the point where NDVI has increased to 50% of the maximum NDVI as proposed by White et al. (1997). The ground observations refer to field-based phenological events which were found to correlate more with estimated SOS, respectively.

For Midpoint\textsubscript{pixel} method, normalisation of NDVI data (Eq. 2) is a necessary step before extracting phenological metrics (White et. al., 1997). But before doing so, we followed a number of steps, which may differ to those of White et al. (1997; 2009). First, a pixel was masked if more than 30% of data points were missing. In this paper we argue that whereas the number of missing values matters to accuracy of estimated metrics, what would matter the most is the successiveness of the missing data points on the time series because successive gaps are more difficult to interpolate reasonably. Hence, we relaxed our threshold on missing data to 30%. Data gaps were then filled through linear interpolation. In the next step, we removed the dips, which possibly are a result of factors such as cloud contamination and atmospheric scatter, from the entire time series (2000 - 2012) by replacing each dip ($x_t$) with an average of its two immediate neighbours - the right ($x_{t+1}$) and left ($x_{t-1}$) sides using Eq. 1, such that,

$$x_t = \frac{x_{t-1} + x_{t+1}}{2} \text{ if } x_t - x_{t-1} < -0.01x_{t-1} \text{ and } x_t - x_{t+1} < -0.01x_{t+1} \text{ (Eq. 1),}$$
if the differences between $x_t$ and $x_{t-1}$, and $x_t$ and $x_{t+1}$ are less than $1\%$ of $x_{t-1}$ and $x_{t+1}$, respectively. The $1\%$ was arrived at after several optimisations to effectively remove dips, but this value is equally subjective because it is not based on any theoretical underpinning. And as such, dips which may be real changes, not data artefacts, can possibly also be removed. However, we opted to remove dips which we assumed to be “noise” because fitting a Savitzky-Golay filter to “noisy” data is known to result into poor smoothing (O’Connor et al., 2012), whereas over smoothing may result into simplistic NDVI profile. Fig. 5a shows an example of how dips were removed. In the third step, Savitzky-Golay filter (filter order = 4 and, filter window = 21) was subsequently fitted on entire time series after the dips were removed (Fig. 5b). Fourthly, the smoothed NDVI data (with 16-days interval) were then interpolated to daily values (368 days per year) using the cubic spline method. In essence, no year has 368 days, but we opted to add two and half extra days per year just to make an equal interval between 16-day composites prior to interpolation. Spline interpolation may create spikes at the beginning and/or end of the time series which are undesirable. But in our case, the spikes were not of a concern because in the time series we included data points for year 2000 and 2012 though phenological metrics were only extracted for year 2001 through 2011. Year 2000 and 2012 were not included in the analysis because complete year of satellite images was not available.

\textit{Fig. 5:} An illustration of (a) how “noise” was removed from NDVI time series and (b) the smoothing of data using Savitzky-Golay fitting. Noise removal and smoothing for NDVI time series were pre-processing steps before extracting SOS metrics from NDVI time series.
The next step after interpolation was to normalise the NDVI data points for each year separately based on Eq. 2 (White et. al., 1997; 2009).

$$\text{NDVI}_{\text{ratio}} = \frac{(\text{NDVI} - \text{NDVI}_{\text{min}})}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}} \quad (\text{Eq. 2})$$

where NDVI is the NDVI value for each day (368 days in total) in the time series of each pixel, \(\text{NDVI}_{\text{max}}\) and \(\text{NDVI}_{\text{min}}\) are maximum and minimum NDVI values for such pixel during the growing season (White et. al, 1997). The resultant values range between 0 and 1. In some cases however, we noticed that the minimum NDVI value in the time series may be found at the end of the growing season instead of the beginning – a situation not ideal for dating the SOS because the dated value may be too early; or the SOS would not be detected at all because no value is below 50% of maximum NDVI between first value in the time series and the maximum value (\(\text{NDVI}_{\text{max}}\)). To deal with this problem, here we deviated from the approach described in White et al. (1997; 2009). Instead of calculating the NDVI ratios for each year using Eq. 2, we used Eq. 3. With this approach, we first determined the position of yearly \(\text{NDVI}_{\text{max}}\) on the time series. Then, the \(\text{NDVI}_{\text{min}}\) value (referred herein as \(\text{NDVI}_{\text{minSOS}}\)) was the lowest NDVI value among the data points from first day in the time series to the position of \(\text{NDVI}_{\text{max}}\) (Fig 6a). So, for SOS, the \(\text{NDVI}_{\text{ratio}}\) (herein referred to as \(\text{NDVI}_{\text{ratioSOS}}\)) was only calculated for NDVI values (herein referred to as \(\text{NDVI}_{\text{SOS}}\)) between \(\text{NDVI}_{\text{minSOS}}\) and \(\text{NDVI}_{\text{max}}\) (Eq. 3). The SOS was then determined as a day between day 1 and the day of maximum NDVI where \(\text{NDVI}_{\text{ratioSOS}}\) value first exceeds 0.5 (e.g. Fig. 6b).

$$\text{NDVI}_{\text{ratioSOS}} = \frac{(\text{NDVI}_{\text{SOS}} - \text{NDVI}_{\text{minSOS}})}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{minSOS}}} \quad (\text{Eq. 3})$$

All steps followed here to extract SOS from NDVI time series using Midpoint\(_{\text{pixel}}\) were implemented in R software. Noteworthy, in their analysis, White et al. (2009) excluded the pixels which had missing values for one of the composite periods deemed to be critical for the detection of \(\text{NDVI}_{\text{max}}\) and \(\text{NDVI}_{\text{min}}\). Though this consideration might be very important for accuracy of the estimated SOS, in areas (e.g. Western Europe) where snow and cloud cover are prevalent it is unlikely that a pixel would not have one of the critical composite periods missing. Therefore, in our analysis the criterion of the critical composite periods was not considered.
2.6 Assessing for trends in ground observations and estimated SOS

The focus was to assess if there were trends in SOS over Western Europe between 2001 and 2011. We used Mann-Kendall trend test to assess for trends in ground observations and estimated SOS. Mann-Kendall trend test is one of the widely used methods for temporal trend analyses in plant phenology (De Beurs and Henebry, 2005, De Jong et al., 2011), hydrology (Hirsch et al., 1982) and temperature (Croitoru et al., 2012). This method is known to be robust against non-normality and missing values (Hirsch et al., 1982; De Beurs and Henebry, 2005). Though Mann-Kendall trend test is robust against missing values, the test was only done if there were at least 8 values - to avoid testing for trends based on too few data points. The trend is quantified by means of Kendall tau (τ). A trend was considered to be significant at 5% threshold. For estimated SOS, a map showing the statistical significance of Kendall’s tau was produced. In areas where there was an early SOS between 2001 and 2011, a negative Kendall’s tau statistic was expected, and vice-versa.
2.7 Determining the dominant tree species in areas with SOS trends

One of the highly contested areas in phenological studies is whether photoperiod-sensitive species are also responding to climatic warming or not (Körner and Basler, 2010; Chuine et al., 2010). From the remote sensing perspective it is difficult to arrive to such conclusions because the measurements are made at pixel level – not at individual level especially in the case of satellite data. However, if the response to climatic warming is at the community/ecosystem level, it might be possible to link the changes in the phenology to the species which is dominant in such areas. Our goal here was to identify the dominant species in areas where SOS trends were detected. The aim was to find out if trends in satellite-derived SOS were only found in areas dominated by photoperiodic insensitive species (in this case, *Betula pendula*). So to address this problem, we overlaid the map of trends in SOS produced in section 2.6 with a tree species map produced by Brus et al. (2011). The tree species map contains 20 tree species (Fig. 3), including the non-deciduous conifers ones. We only considered areas dominated by deciduous tree species. Next, we identified the dominant tree species at each pixel where the trends SOS was detected, and calculate, per species, the proportion of area with trends.

2.8 Assessing for spatial consistency of satellite-derived SOS

As a novel approach, we determined if satellite-derived SOS for deciduous forest in Western Europe were spatially consistent. We used the presence of “natural” latitudinal gradient as a simplistic measure of spatial consistency for SOS derived from satellite data. If satellite-derived SOS show a latitudinal gradient as expected in a particular area, then we conclude that they are spatially consistent. In temperate region of Western Europe, we expect SOS to show an increasing gradient northward due to latitudinal differences in insolation and temperature (Schwartz and Reiter, 2000; Schwartz et al., 2006). To assess for presence latitudinal gradient, we first created a transect (width = 18 km), transecting from southern Spain to northern Germany (Fig. 7). Second, we calculated the mean SOS per pixel for a period of 2001 through 2011. Third, a generalised additive model (GAM) (Hastie and Tibshirani, 1986) was fitted to SOS with latitudes being the explanatory variable. We used GAM because it has ability to deal with highly non-linear relationships between the response and the set of explanatory variables (Guisan et al., 2002). Of recent, GAMs are increasingly being used to study non-linear relationships between response and explanatory variables, both in time and space (Li et al., 2011; Staelens et al., 2012). Here, we do not intend to reproduce the theoretical and mathematical underpinnings of GAM, hence the reader is referred to Hastie and Tibshirani (1986) where more information about GAM is provided. We tested several model parameterisations, and used Bayesian Information Criterion (BIC) to select the most optimal model fit. Eventually, the splines were used as the fitting method with Gamma as a link function. Similar procedures were followed to fit the model to SOS in temperate region only. We identified part of the transect that covers the temperate region by determining the point on the latitudinal profile of SOS, based on model fit of entire transect, where the SOS started to increase northward. We found this point at around 43˚N. For our
analysis, we therefore defined part of the transect from 43°N northward as temperate region, and fitted GAM to SOS metrics. Data gaps in satellite data time series, as a result of snow and/or cloud covers, could potentially affect the spatial consistency of satellite-derived SOS metrics. As such we explored if areas with high number of data gaps tend to influence the latitudinal gradient of satellite-derived SOS metrics for deciduous forest in Western Europe. We then plotted the number of data gaps per year throughout the transect.

Fig. 7: A transect through the study area along which spatial consistency satellite-derived SOS metrics was assessed in this study.
3 Results

3.1 Trends in air temperature

We analysed for trends in air temperature with the aim of validating the warming of air temperature reported in Northern Hemisphere (e.g. by IPCC, 2007) to enable for reasonable interpretation of changes in SOS. Fig 8 shows the trend in annual air temperature and temperatures of different seasons. Our results show that there was a widespread positive trend in Western Europe during the periods of March – May and September-November. A negative trend was more prevalent during the periods of December – February and June – August. The annual mean temperature was confounded by both negative and positive trends proportionally. In temperate regions of Western Europe, the vegetation generally starts to green during the period of March – May, whereas in the Mediterranean (e.g. southern Spain) the greening starts during the period of September – November. We therefore observe that there was warming in Western Europe during the periods critical for vegetation greening.

![Temperature trends in Western Europe for a period of 2001–2011](image)

**Fig. 8: Air temperature trends in Western Europe for a period of 2001 – 2011.**

3.2 Trends in SOS for deciduous forest

We determined if, based on ground observations, there were trends in SOS for deciduous forest in Western Europe between 2001 and 2011 as a result of climatic warming. Table 2 shows the results of
trend analysis in ground observations for each species per phenological station. At about 73% of phenological stations, statistically significant trends were detected at least in SOS for one of the deciduous tree species we considered in this study. These trends were all negative. Fig. 9 shows the spatial distribution of phenological stations where trends were detected in SOS for each species. No station recorded statistically significant trend in all species documented on such station (Table 2 & Fig. 9). At some stations, some species experienced statistically significant early SOS while others did not (Fig. 9). By species, the proportion of phenological stations where the trend was statistically significant was less than 30%, except for *Fagus sylvatica* which showed significant negative trend at about 70% of the stations. When considering only the trend (i.e. positive or negative) and not whether the trend is statistically significant, 96% of phenological stations recorded a negative Kendall’s tau at least in SOS for one of the species we observed.

All phenological stations we considered in this study were in temperate areas. Using Mar–May temperature trends, we observe that there was warming at all phenological stations as depicted by positive slope (Table 2). There are cases, however, that at some stations (e.g. 6800, 6846) the warming was more than at other stations (e.g. 2075, 6248) but no statistically significant trends were detected in SOS (Table 2).

Similar pattern of high prevalence of a negative Kendall’s tau in the SOS observed at individual species level is mirrored at pixel level. For a trend analysis in satellite-derived SOS, more than 80% of pixels corresponding to phenological stations have recorded negative Kendall’s tau; and more than 90% of these pixels have recorded Kendall’s tau with a sign (i.e. negative or positive) matching at least that of one of the observed species. Only at one phenological station (=199) where all observed species recorded a negative Kendall’s tau in their SOS but the Kendall’s tau for satellite-derived SOS was positive. When we look at the magnitude of the Kendall’s tau for satellite-derived SOS metrics whose sign matches that of ground observations, we observe that the magnitude of Kendall’s tau for satellite-derived SOS was consistently lower than that of ground observations at about 96% of phenological stations.

Although some species that experienced statistically significant trend in SOS were dominant at pixel corresponding to the phenological station, we did not find statistically significant trends in satellite-derived SOS for pixels corresponding to these phenological stations. The proportion of the dominant species at these pixels was however <60% in all cases and only at 5 out 26 stations where the proportion a dominant species was above <30% (Fig. 10). Some of the pixels were even dominated by non-deciduous conifer tree species despite being classified as deciduous forest in CORINE landcover map.
Table 2: Trends for ground-based and estimated SOS, and March-May temperature in Western Europe between 2001 and 2011; and the species dominant at pixels corresponding to phenological stations where ground-based SOS were observed.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Species</th>
<th>Estimated SOS</th>
<th>Mar-May temperature</th>
<th>Dominant species</th>
</tr>
</thead>
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<td>Betula pendula</td>
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<td>-0.67*</td>
<td>Fagus spp</td>
</tr>
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</tr>
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<td>0.04</td>
<td>Fagus spp</td>
</tr>
<tr>
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<tr>
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<td>Fraxinus excelsior</td>
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*pd value < 0.05; **BM = Broadleaved miscellaneous (group of broadleaved tree species not specified (Brus et al., 2011))

Fig. 9: Spatial distribution of phenological stations where trend were detected in SOS for each species and estimated SOS.
Fig. 10: Proportion of dominant tree species at pixels corresponding to phenological stations considered in this study. The proportions were derived from species prediction map which was part of dominant species dataset (Brus et al., 2011). The name of species dominant at each pixel/phenological station is provided in the graph – perpendicular to corresponding bar.

Although the analysis of trends in satellite-derived SOS at pixels corresponding to phenological stations did not show statistically significant trends, in other parts of the study area significant trends were detected (Fig. 11). About 13,944.6 km$^2$ (representing 6.4%) of the 218,571.5 km$^2$ total area of deciduous forest we analysed in Western Europe recorded statistically significant trend (Fig. 11). For the total area that recorded statistically significant trend, about 45.3% of this area experienced a downward trend; the remaining 54.7% was positive. Positive trend was more prevalent in southern part of our study area (Fig. 11), especially in Spain and Portugal where Mediterranean climatic conditions prevail; and the negative trend was more common in the temperate region, especially in Germany (Fig. 11). But both positive and negative trends were not limited exclusively to a particular part of the study area. Following along the transect created in section 2.8, we observe that the negative SOS trend was mainly between latitude 45° N and 53°N, hence conforming that earlier SOS was largely occurring in the temperate region of our study area from 2001 through 2011 (Fig. 12b). Generally, it is between latitude 45° N and 53°N where warming was also the greatest (Fig. 12a).
Fig. 11: Trends in satellite-derived SOS for Western European deciduous forest between 2001 and 2011.
3.3 SOS trends and photoperiodism

As photoperiodic-sensitive species are barely expected to respond to climatic warming, we analysed if trends we detected in Western European deciduous forest are only limited to photoperiodic-insensitive species. For the species we considered, only *Betula pendula* is known to be photoperiodic-insensitive (Körner & Basler, 2010). From Table 2, we see that all species except *Tilia cordata* have recorded statistically significant trends at one or more phenological stations. The trends were not only limited to *Betula pendula*. In fact, the number of phenological stations where *Betula pendula* recorded significant trends was far less when compared to *Fagus sylvatica* – a photoperiodic-sensitive species (Table 2). When using dominant tree species map and the map for SOS trends calculated based on satellite data, trends were detected in areas dominated by any of the species we considered (Fig. 13a). *Tilia cordata* was not among the dominant tree species in Europe (Brus et al., 2011), hence it is not presented in this analysis. *Betula pendula* recorded the highest proportion (6.5%) of area with trends, followed by *Larix decidua* (6.1%), *Fagus sylvatica* (5.8%), *Quercus robur* & *Quercus petraea* (5%), *Fraxinus excelsior* (4.6%) and the lowest was *Alnus glutinosa* (2.9%). Overall, there is no evidence that trends were mainly limited to photoperiodic-insensitive species.

We calculated the total number of pixels dominated by each species, and derived the percentage of pixels with statistically significant trend. For all species, the large proportion of pixels that recorded statistically significant trend did experience a negative trend (Fig. 13b). *Larix decidua* recorded the highest proportion (89.8%) of pixels with negative trend, followed by *Fraxinus excelsior* (88.7%), *Betula pendula* (83.2%), *Fagus sylvatica* (81.3%), *Alnus glutinosa* (64.3%) and *Quercus robur* & *Quercus petraea* (60.5%) (Fig. 13b).
3.4 Spatial consistency of satellite-derived SOS

Monitoring the impact of climatic warming on plant phenology using satellite data would require that the satellite-derived metrics are able to reasonably represent the spatial variation in SOS commensurate to natural variation of factors that control SOS. As such, we analysed the latitudinal gradient of satellite-derived SOS for deciduous forest in Western Europe as a measure of spatial consistency to show that we tested for trends on spatially consistent SOS metrics. Fig. 14a displays the latitudinal profile of the mean SOS from southern Spain to northern Germany. Spatially, the profile clearly shows that the deciduous forest starts to green at end of the year (around October) in Mediterranean region (e.g. southern Spain), and around April in temperate region. However, we expected an abrupt change in the profile between the forest that greens at end of the year (in Mediterranean area) and the temperate forest which greens around April.

Fig. 14b shows the SOS profile for the temperate area. The results show a delay in the SOS as one move northwards up to latitude 50° N, thereafter the forest starts greening early again. This pattern is surprising. By looking at average number of data gaps per year along the same trajectory, this early arrival of forest greening after latitude 50°N cannot be attributed to data gaps. The residuals are also generally symmetrical around zero – no trend is remaining (Fig. 14c & d). As a follow-up, we used ground observations to validate the pattern of earlier SOS at latitude 52°N than 50°N. Three phenological stations (3173, 4415, and 4692) which were located at latitude 48°N, 50°N and 52°N respectively were chosen for this validation. The time series of ground observations for 6 species we considered in this study, which were recorded at these stations were then plotted (Fig. 15). Our validation results show that all species we considered were indeed greening earlier at latitudes 48°N
and 52˚N than at 50˚N (Fig. 15). So, early SOS after latitude 50˚N found in satellite-derived SOS was consistent with ground observations. These results highlight how spatially consistent our satellite-derived SOS metrics were - a key requirement to be fulfilled when detecting spatio-temporal trends in SOS.

Fig. 14: Latitudinal profile of mean SOS in Western European deciduous forests. (a) SOS gradient from southern Spain to Northern Germany, (b) SOS gradient from southern France to northern Germany, (c) and (d) are SOS residuals after fitting the model to SOS, (e) and (f) are latitudinal profile of average number of data gaps/year – the red lines represent the fitted values after applying an additive model. Note: in (a) we expected an abrupt change in the SOS profile between Mediterranean and temperate regions.
Fig. 15: Time series of the ground-based SOS for six deciduous tree species at latitudes 48°N (station 3173), 50°N (station 4415) and 52°N (Station 4692). All species were greening early at latitude 52°N than at 50°N, a pattern we did not expect; we expected that the SOS would be later at latitude 52°N as this latitude is further way from equator and temperature would start rising much later than at latitude 50°N. Nonetheless, this result confirms the validity the profile of satellite-derived SOS in Fig. 14.
4 Discussion

4.1 Trends in air temperature

Increased air temperature as a result of global warming is causing phenological changes in plants (Menzel & Fabian, 1999; Badeck et al., 2004; Menzel et al., 2006; Cleland et al., 2007; Peñuelas et al., 2009). Many studies (e.g. Menzel & Fabian, 1999, De Jong et al., 2011; Jeong et al., 2011; Zeng et al., 2011) which reported phenological changes based on ground observations and satellite data, and attributed such changes to climatic warming do not validate if warming has indeed occurred at the pixels/locations where phenological changes are documented. As novel approach, we validated the warming reported in Northern Hemisphere (e.g. by NASA and IPCC) but focusing only in Western Europe for the period of 2001 through 2011. Adopting NASA approach of deriving temperature trends, we found widespread warming across Western Europe especially during March-May period, except for a large part of southern Italy and eastern Spain. This period corresponds with the time when vegetation starts to green in temperate regions. Our temperature trends were derived from a temperature dataset with much higher spatial resolution than the resolution where NASA reports its global temperature trends. However, our results largely agree with those of NASA (http://data.giss.nasa.gov/gistemp/maps/), though cognisant of the differences that might be resulting from different spatial resolution of the dataset we used. Temperature anomalies from NASA (http://data.giss.nasa.gov/gistemp/maps/) also show that the Northern Hemisphere, Western Europe in particular, has indeed warmed between 2001 and 2011. We found warming at all phenological stations we considered in this study.

4.2 Trends in ground-based SOS for deciduous forests

Using ground observations from European Phenological Network, we found statistically significant trend in SOS for deciduous tree species we considered in this study –except Tilia cordata. The trend in SOS was negative at all phenological stations suggesting that the deciduous tree species were greening earlier from 2001 to 2011. All the phenological stations were located in temperate region where temperature is a key limiting factor to SOS. Our results of a negative trend in ground observation agree with the positive trend we observed in the air temperature, mainly during March-May period. The period of March-May where we found warming in the air temperature across Western Europe corresponds to the time when temperate vegetation start to green. We therefore conclude that the warming between 2001 and 2011 in Western Europe during the period of March-May triggered the vegetation to start greening early. Our results corroborate with the findings from other studies that some plants species are greening early in Europe (Menzel et al., 2006), a phenomenon attributed mainly to climatic warming (Menzel et al., 2006; Cleland et al., 2007).

Despite much higher warming recorded at some phenological stations (e.g. 6800, 6846, 4342, 569) no statistically significant trends were found in the SOS for tree species at these stations, however.
We speculate that other factors (e.g. inter-population differences in sensitivity to temperature) might have contributed to no trend in SOS for tree species at some phenological stations. For example, by using Google Earth, we found that station 6800 is located in a relatively narrow valley in Switzerland, with mountain ranges on the north and south sides. So, the air temperature recorded at a pixel of 0.25° x 0.25° resolution may not be representative of air temperature in the valley, especially when the grid temperature dataset was created through interpolation of sparse point observations. According to Haylock et al. (2008), the gridded air temperature dataset was created (1) by first interpolating the monthly precipitation totals and monthly mean temperature using three-dimensional thin-plate splines, (2) then interpolating the daily anomalies using indicator and universal kriging for precipitation and kriging with an external drift for temperature, (3) and by combining the monthly and daily estimates. Topography (e.g. elevation) was not considered. It is therefore possible that at some locations the air temperature has been underestimated or even over-estimated, especially in mountainous areas – hence affecting the magnitude of the temperature trend derived at such pixel. We found that station 6846 was located on top of mountain range. Again, the air temperature recorded on the pixel corresponding to this station could be unrepresentative of the true temperature regimes occurring at this station because the pixel for temperature dataset covers both mountain range top and a valley. For other stations (4342 and 569) where topography was not characterised by mountain ranges, spatial differences in temperature sensitivity might have played a major role in SOS. Other researchers have documented spatial differences in the degree of how plant populations (same species) respond to temperature (Linkosalo et al., 2006).

We noted that at phenological stations where statistically significant trend was detected, the trend was not significant for all species which were recorded at such stations. This pattern shows that though warming is triggering early greening in plants at a particular location, the degree of response to warming would differ greatly between different species. This difference in how each species responds to warming is likely to also vary from place to place, depending on prevailing local conditions.

4.3 Trends in estimated SOS for deciduous forests

At pixels corresponding to phenological stations we did not find statistically significant trends in satellite-derived SOS metrics. However, the results show that at more than 90% of the stations the sign of Kendall’s tau for satellite-derived SOS matches at least with Kendall’s tau for one of the species we considered. This pattern shows that the change in SOS for individual plants was reflected in the satellite-derived SOS. We observed that, except for two stations, the Kendall’s tau for satellite-derived SOS was consistently lower than the Kendall’s tau for ground observations indicating that the magnitude of change at pixel level was smaller than at individual level. SOS trends detected at pixel level should be smaller than at individual plants because pixel measurements are confounded by many factors (e.g. the presence of different plant species at a pixel, degradation of signal by atmospheric scattering and cloud contamination) which would eventually degrade the magnitude of change recorded at the pixel level. These findings are in line with what we have hypothesised – that
the change in SOS detected at individual level would be greater than the change at ecosystem/landscape level. Our results are however are in sharp contrast with findings in North America where trends in SOS were detected in satellite-derived SOS metrics and not in ground observations (White et al., 2009).

Only at the pixel corresponding to the phenological station 199 the sign of Kendall’s tau for satellite-derived SOS did not match any of the observed species. By using Google Earth, we noted that the pixel corresponding to this station cuts across two different land cover types – forest and grassland/cropland. The problem of dynamic mixed-pixel was therefore inevitable, probably resulting in less temporally consistent SOS estimated at the pixel. Estimating temporally consistent SOS for areas where anthropogenic influences are continuously occurring may be challenging, and the trends derived on such areas might amount to noise – and not real trends induced by climatic warming.

Although no significant negative trends were detected in satellite-derived SOS at pixels corresponding to phenological stations, trends were detected at other pixels, representing about 6.4% of the total area of deciduous forest we considered. This trend was positive for some pixels and negative for others - a pattern similar to SOS trends detected in North America (White et al., 2009). As our results show, the positive trend was more prevalent in southern Spain where Mediterranean conditions prevail. In this area, the main limiting factor to greening of vegetation is rainfall (soil moisture) (Christensen et al., 2007; Matesanz et al., 2009). As we did not analyse for trends in rainfall, here we only speculate that rainfall might have been starting later in this area between 2001 and 2011, thus resulting in later greening of deciduous forest. A detailed analysis of trends in the start of rainfall season will be crucial to determine if positive trends in SOS detected in southern Spain in this study can indeed be explained by changes in the start of rain season between 2001 and 2011.

Unlike the positive trend, our results show that the negative trend was more prevalent in temperate regions especially in the deciduous forest in Germany. This negative trend suggests that the greening of the deciduous forest was occurring early from 2001 to 2011, a pattern similar to what we observed in ground observations. Early greening of vegetation, particularly in temperate regions, has been documented, and is mainly attributed to climatic warming (Menzel et al., 2006; Linkosalo et al., 2006). The negative trend in satellite-derived SOS metrics is therefore a result of warming that we observed in March-May air temperature. Our results show that satellite-derived SOS metrics are able to capture statistically significant changes in SOS at pixel level - not only the general pattern of change as we have seen at pixels corresponding to phenological stations.

Apart from a negative SOS trend in temperate deciduous forests, we also found statistically significant positive trends in satellite-derived SOS metrics in some parts of the temperate region where warming occurred. But the pixels in temperate region where positive trend was observed were highly scattered and random. Possibly, this positive trend could be a result of mixed-pixel problem - where a pixel is composed of more than two land cover types (e.g. forest, grassland and/or cropland), hence resulting
in SOS trend not related to forest. As seen at the pixel corresponding to phenological station 199, a combination of forest and cropland could easily result into an upward SOS slope despite that all tree species were showing a downward slope. However, further detailed investigation is required in order to understand why there were positive SOS trends in temperate areas where climatic warming has occurred.

While significant trends detected in satellite-derived SOS were found across the entire study area, generally these trends were highly localised - a sign that there were localised differences in how the plants were responding to factors that trigger early greening. In North America, SOS trends detected from satellite data were also limited to only few areas (White et al., 2009), but this pattern was not explained. In this study we also did not investigate why the statistically significant trends in SOS were highly localised (clumped). Further research focusing on landscape characterisation of the areas where -trends are detected is needed in order to find an explanation for this localised distribution of SOS trends.

Finally, although we demonstrated here that satellite data can capture changes in plant phenology commensurate to changes observed on the ground data, monitoring the impact of global warming in areas under constant and immense anthropogenic influence (e.g. croplands) using satellite data would not make much sense. This is because it would almost be impossible to distinguish climate-induced phenological changes from human-induced changes. For proper monitoring of how global warming is causing changes in plant phenology using satellite data, there is a need to devise a landscape sampling scheme that would mask out areas where anthropogenic influence is maximal, and where there are different land types falling in one pixel of the satellite data. This may minimise the chance of deriving SOS trends at pixels which are temporally unstable; but such sampling scheme would require a more accurate land cover map, which is currently lacking at global scale (Bontemps et al., 2011).

4.4 SOS trends and photoperiodism

Other researchers argued that early greening in photoperiodic-sensitive species (e.g. *Fagus sylvatica*) as a result of climatic warming is unlikely; only photoperiodic-insensitive species (e.g. *Betula pendula*) would mainly respond to climatic warming (Bauerle et al., 2012). Based on ground observations, we found trends in SOS for both photoperiodic-sensitive and insensitive species. The number of phenological stations where *Betula pendula* recorded significant trends was surprisingly far less when compared to *Fagus sylvatica* – a photoperiodic-sensitive species. By using the European dominant tree map (spatial resolution: 1 km x 1km), we determined, per species, the proportion of the area that experienced changes in SOS; *Betula pendula* recorded marginally higher proportion area with SOS trends. But trends were equally recorded in areas dominated by other deciduous species. Our findings from both ground observations and satellite data support existing findings by Chuine et al. (2010) and Menzel et al., (2006) that phenological changes are not only limited or mainly occurring in photoperiodic-insensitive species. We have hoped that localised distribution of SOS trends can be
explained by photoperiodism, but do not find compelling evidence that such localised distribution is due to photoperiodic effect.

4.5 Spatial consistency of satellite-derived SOS metrics

Monitoring changes in plant phenology using satellite data requires that satellite-derived metrics are able to capture natural spatial variation in plant phenology. This variation should be commensurate to variation of factors (e.g. temperature and rainfall) which control plant phenology. In our quest to assess for changes in SOS for deciduous forest in Western Europe, we evaluated if satellite-derived SOS metrics were spatially consistent. The results show that our satellite-derived SOS metrics were spatially consistent, and therefore could be used to assess for temporal trends in SOS. Though, in the temperate region of our study area, we expected the SOS to continuously arrive late as one moves in a northward direction due to latitudinal differences in insolation and temperature (Schwartz and Reiter, 2000; Schwartz et al., 2006), the results show that this expected pattern only exist up to latitude 50° N – thereafter the SOS start to arrive early again. Possibly, the northern sea (warm ocean currents) might be causing the air temperature over northern Germany to warm much early in the year, hence triggering the vegetation to green earlier than in the central part. Checking for spatial consistency in satellite-derived SOS metrics is novel way to ensure that temporal trends are not derived for SOS metrics which are spatially incorrect. Many studies (e.g. De Jong et al., 2011; Jeong et al., 2011; Zeng et al., 2011) that assessed for changes in plant phenology using satellite-derived phenological metrics did not evaluate the spatial consistence of such metrics. We argue here that it would not make much sense to derive phenological trends from satellite-derived metrics if such metrics do not show spatial pattern matching the pattern of the factors (e.g. temperature and precipitation) which control the phenology of plants.

4.6 Limitations and lessons learned

Although we have shown in this study that satellite-derived SOS did capture changes detected in ground observations reasonably well, we noted that the extraction of SOS metrics from satellite data need to be enhanced. Interpolating data gaps especially linearly is problematic, and should be avoided. A seasonal-trend model proposed by Verbesselt et al (2012), where no data gap interpolation is required, may be a robust way for smoothing NDVI time series before extracting phenological metrics. However, this method should be accompanied by a criterion which defines the number of successive data gaps that should be allowed for SOS metrics to be extracted.

We further noted that some of the pixels which were classified as deciduous forest, their minimum NDVI never fell below 0.6 throughout the entire observation period. These pixels might have been misclassified as deciduous forest while they are non-deciduous-conifer or other land types. For studies focusing on phenological analysis in deciduous forest based on satellite data, using only the land cover map (e.g. CORINE Landcover map), especially whose accuracies are not known as was in
our case, to identify landcover types (e.g. deciduous forest) may not be sufficient. We propose that annual minimum NDVI value be used in conjunction with landcover map.

Our ground observations were confined to a small part of the study area. We could not therefore present extensive validation of trends detected in satellite-derived SOS. For example, we detected positive trends mainly in southern Spain, but because we did not have ground observations in this area, uncertainties still exist on whether they are indeed really trends or artefacts.

Phenological ground observations used in this study were not collected with the purpose of validating satellite–derived SOS metrics. The positional accuracy of the phenological stations is not known. As such, it is highly possible that, in some cases, a pixel we identified as corresponding to the phenological station was incorrect - resulting in comparing mismatched values especially if the forest is heterogenous.

Finally, SOS trends were assessed from data that span only over 11 years, at most. Other researchers who used data spanning over more than 20 years have cautioned that such time span might be too short to detect temporal trends in plant phenology which can be reasonably attributed to global warming (White et al., 2009). We raise the same caution here that the trends detected in our study may be just part of natural phenological variations.
5 Conclusion

We assessed for phenological changes in Western European deciduous forest using ground observations and satellite data while focusing on SOS. Our overall objective was to verify how climatic warming is influencing trends in SOS of Western European deciduous forest, and if such changes can be captured by satellite data. We also determined if these trends are only limited to photoperiodic-insensitive tree species. The spatial consistency of satellite-derived SOS metrics was assessed. Based on ground observations and satellite-derived SOS, our results showed that there were trends in SOS for Western European deciduous forest, possibly as a result of climatic warming. But we also found positive trends in southern Spain where rainfall is the main limiting factor to vegetation activities – thus suggesting that rainfall might have been arriving later. We demonstrated that satellite-derived SOS can capture change in SOS consistent with real changes. In this study, we have also shown that changes in phenology are not only occurring to photoperiodic-insensitive species. Based on a simplistic latitudinal gradient analysis of SOS derived from satellite data, we showed that our satellite-derived SOS metrics conform to expected spatial pattern of SOS commensurate to latitudinal gradient of main factors (e.g. temperature) that control SOS. In summary, results indicate that climatic warming in Northern Hemisphere is potentially driving temporal shifts in SOS for deciduous tree species, and these shifts can be captured by temporally and spatially consistent satellite-derived SOS metrics. Moreover, a novel approach is proposed and tested in this study to establish the reliability of satellite derived SOS trends by evaluating the temporal and spatial consistencies SOS metrics in relation to in-situ measurements. Because of this novel approach, we now have confidence that with carefully derived SOS metrics as was done in this study satellite data can be used reliably to monitor the impact of climatic warming on plant phenology. This study contributes to the understanding of how climatic warming is causing changes in the phenology of plants.
6 Further work

SOS trend analysis was done using data spanning over only 11 years, at most. This period is relatively short to capture SOS trends differentiable from natural variability – the variability as caused by short-term variations in climatic factors (e.g. temperature and/or precipitation). We propose that further work should make use of data from AVHRR sensor that span over 25 years to assess for SOS trends in Western European deciduous forests. However, the shortcoming of these data is embedded in the spatial resolution which is about 1km x 1 km or even 8 km x 8 km for the Global Inventory Modeling and Mapping Studies (GIMMS) dataset which is publically available. Deciduous forest in Western Europe is highly fragmented; many 1 km x 1 km pixels, or much worse 8 km x 8 km pixels, are likely be composed of different land cover types thus affecting the temporal consistency of SOS estimates at such pixels. This may result in noisy SOS trends.

In this study, the focus was only on SOS. Other phenological events i.e. EOS and LOS apparently are also changing as a result of climatic warming (Menzel & Fabian, 1999; Cleland et al., 2007; De Jong et al., 2011). Many satellite-based studies (e.g. De Jong et al., 2011; Jeong et al., 2011; Zeng et al., 2011) have also documented trends in EOS and LOS. It is not yet known if the trends detected in satellite-derived EOS and LOS are commensurate to real changes – the changes observed in the ground observations. We therefore propose that further work focus on assessing if trends detected in satellite-derived EOS and LOS are consistent with trends in ground observations.
7 References


