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LiDAR derived topography and forest stand characteristics largely explain the spatial variability observed in MODIS land surface phenology

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ABSTRACT

In the past, studies have successfully identified climatic controls on the temporal variability of the land surface phenology (LSP). Yet we lack a deeper understanding of the spatial variability observed in LSP within a land cover type and the factors that control it. Here we make use of a high resolution LiDAR based dataset to study the effect of subpixel forest stand characteristics on the spatial variability of LSP metrics based on MODIS NDVI. Multiple linear regression techniques (MLR) were applied on forest stand information and topography derived from LiDAR as well as land cover information (i.e. CORINE and proprietary habitat maps for the year 2012) to predict average LSP metrics of the mountainous Bavarian Forest National Park, Germany. Six different LSP metrics, i.e. start of season (SOS), end of season (EOS), length of season (LOS), NDVI integrated over the growing season (NDVIsum), maximum NDVI value (NDVImax) and day of maximum NDVI (maxDOY) were modelled in this study. It was found that irrespective of the land cover, the mean SOS, LOS and NDVIsum were largely driven by elevation. However, inclusion of detailed forest stand information improved the models considerably. The EOS however was more complex to model, and the subpixel percentage of broadleaf forests and the slope of the terrain were found to be more strongly linked to EOS. The explained variance of the NDVImax improved from 0.45 to 0.71 when additionally considering land cover information, which further improved to 0.84 when including LiDAR based subpixelforest stand characteristics. Since completely homogenous pixels are rare in nature, our results suggest that incorporation of subpixel forest stand information along with land cover type leads to an improved performance of topography based LSP models. The novelty of this study lies in the use of topography, land cover and subpixel vegetation characteristics derived from LiDAR in a stepwise manner with increasing level of complexity, which demonstrates the importance of forest stand information on LSP at the pixel level.

1. Introduction

Phenology, the science of annual recurring events in organisms, has been studied and manually recorded for centuries, e.g. the observations of Japanese cherry blossoms started in the 9th century (Nagai et al., 2016). Since the changing climate is known to affect species in various degrees, such long term records provide insights into the life cycle of organisms and their adaptation strategies (Thackeray et al., 2016). The study of temporal and spatial variations of phenology is therefore particularly important in assessing threats to key species interactions affecting the stability of whole ecosystems. Phenology has been extensively studied to elucidate the impact of climate change on biota (Cleland et al., 2007; Menzel et al., 2006; Parmesan and Yohe, 2003) based on various data types such as in situ observations of species' phenology including citizen science initiatives, remote sensing indices, as well as measurement of carbon fluxes and isotopes (Gonsamo et al., 2017; Menzel and Fabian, 1999; Walther et al., 2002; White et al., 2009).

In the last few decades, remote sensing based detection of vegetation phenology or Land Surface Phenology (LSP) has gained

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considerable attention due to its ease in data acquisition with very little time lag. Unlike traditional methods of surveying, remote sensing based platforms provide repetitive coverage of the earth at multiple spatial scales, allowing the analysis of important events in the vegetation cycles over large areas. Remote sensing based studies of vegetation dynamics have therefore been used to map land cover, to report trends in phenology, to detect disturbances (i.e. fire, wind throws and pests) as well as to assess ecosystem productivity (Di-Mauro et al., 2014; Matiu et al., 2017; Myneni et al., 1997; Simonetti et al., 2015).

Despite several advantages when compared to classical i.e. ground based phenological approaches, LSP studies face certain limitations and require specialized knowledge to process and interpret time series of remote sensing data adequately. Apart from choosing from multiple options of data selection and processing, there is no optimal method to derive LSP (Cai et al., 2017). Therefore studies have used multiple approaches/methods to process remote sensing data and to estimate LSP interchangeably (Eklundh and Jonsson, 2015; Hird and McDermid, 2009; Studer et al., 2007; White et al., 1997). The start of season (SOS), end of season (EOS), and length of season (LOS) and other phenological metrics have been computed in various ways including fixed thresholds, amplitudes and rate of change of curvature (derivatives), with each method providing a different estimate (Misra et al., 2016; Nagai et al., 2010; Soudani et al., 2008). Studies suggest a large variability among different LSP measures (Schwartz et al., 2002; Shang et al., 2017; Studer et al., 2007), which might however be explicitly used for estimating different phenological phases (Fisher and Mustard, 2007; Misra et al., 2016; Soudani et al., 2008) or to differentiate understory from tree canopy (Badeck et al., 2004; Misra et al., 2016; Rautiainen et al., 2012; Richardson and O'Keefe, 2009). The ecological meaning of many LSP estimates is therefore still not very clear and requires further investigation (Eklundh and Jonsson, 2015; Nagai et al., 2016).

Additionally, studies frequently lack clarity in validating LSP estimates with ground phenology (GP) observations (Duncan et al., 2015; Hanes et al., 2014). In this regard, pixel based LSP has been linked with species based GP and the limitations of this approach have been discussed (Han et al., 2013; Rodriguez-Galiano et al., 2015a; Studer et al., 2007). Apart from the difficulty in detecting a single date from the NDVI time series to report SOS or the even more prolonged EOS period (Gallinat et al., 2015; Stöckli et al., 2008), errors in estimation of LSP have also been reported to be affected by flowering and retention of withered leaves which are a species specific characteristic (Nakaji et al., 2011). Most importantly, mixing of land cover with in a pixel presents challenges in correlating GP data. More specifically, GP data are based on visual observation of phenological events of single plant species on the ground which are correlated with LSP estimates based on changes observed in the spectral reflectance of vegetation mixtures within the pixel. Since completely pure and homogenous pixels of forest tree species with 100% fractional cover are rare and difficult to identify in medium to coarse resolution remote sensing data, data on the mixing of land cover and vegetation types that occurs in the pixel from which the LSP is estimated seems important (Fisher and Mustard, 2007; Liang et al., 2011), especially when drivers of the observed temporal and spatial variability in LSP are to be analyzed. Variability in LSP has been linked to different climatic factors, geo-location (latitude, longitude and elevation) and general land use types (with discrete classes) so far, but has not considered the effect of subpixel composition of vegetation (Koster et al., 2014; Luo and Yu, 2017; S. Wang et al., 2016; Y. Wang et al., 2016; Wang et al., 2017; Y. Zhang et al., 2017). In this context, the lack of subpixel information has certain drawbacks such as reporting an underestimation of green-up dates and overestimation of dormancy dates in coarser resolution data as observed in studies on the effect of different pixel sizes on LSP (Klosterman et al., 2014; S. Wang et al., 2016; Y. Wang et al., 2016; Zhao et al., 2012).

Since the uncertainty in LSP estimates increases in the absence of sub pixel land cover information (Doktor et al., 2009; Liang et al., 2011), the importance of high resolution land cover cannot be ignored. It is therefore essential to understand the uncertainties associated with LSP estimated from readily available and popular medium to coarse resolution data sets since high resolution datasets are not always readily accessible. In this regard a few recent studies have reported LSP to be linearly or logarithmically varying across scales, with earlier greening pixels driving the SOS more strongly than later pixels (Peng et al., 2017; X. Zhang et al., 2017). Even though previous studies (Cho et al., 2017; Fuller, 1999) have reported the influence of the percentage of general canopy cover or fractional cover on LSP, the effect of subpixel based detailed forest stand information on LSP needs further investigation. Hwang et al. (2011) found that apart from topographical variables, the minimum Leaf Area Index (indicating the evergreen proportion of the pixel) significantly influenced the LSP, too. However, their study was restricted to broadleaf dominated pixels and mainly used topographical predictors to explain variability in LSP. The effect of mixed pixel on LSP was simulated by Chen et al. (2018) through varying fractional cover of two different end members that revealed considerable effects of the proportions of sub pixel land cover or species on the estimated LSP metrics. Subpixel information on land cover mixing is also important to attribute changes in LSP behavior to its real cause i.e. climatic or land cover changes (Chen et al., 2018; Doktor et al., 2009; Helman, 2018; Xie et al., 2015b).Though limited research exists on effects of mixed pixels on LSP and uncertainty in LSP can be better estimated using information on homogeneity of pixels, an intensive investigation is however required in this field in to understand the role of class mixing on the LSP of complex landscapes. For this purpose, high resolution LiDAR and hyperspectral data may provide valuable insights for mapping species at the subpixel level (Branson et al., 2018) and understanding the LSP estimates obtained from medium to coarse resolution remote sensing data. Apart from land cover type and homogeneity of pixels, LSP is also known to be affected by events such as snow, droughts, fire and pest infestation (Gessner et al., 2015; Kobayashi et al., 2016; Norman et al., 2017; Studer et al., 2007; Xie et al., 2015b). Therefore, besides high quality remote sensing data, research has also indicated the importance of not only detailed but also up-to-date land cover information in LSP studies (Badeck et al., 2004; Doktor et al., 2009; Misra et al., 2016; Norman et al., 2017; S. Wang et al., 2016; Y. Wang et al., 2016).

To overcome this knowledge gap, we here assess here the effects of land cover information and subpixel forest stand characteristics on the estimated pixel based mean LSP (2002–2015) of the mountainous Bavarian Forest National Park (BFNP) in Germany. High resolution LiDAR data was aggregated at Moderate Resolution Imaging Spectrometer (MODIS) pixel resolution (250 m) to various measures describing forest stand characteristics and was then compared to two other land cover products (the freely available CORINE and proprietary habitat maps for the BFNP) regarding their ability to improve topography based LSP models. A 4-day maximum value composite Normalized Difference Vegetation Index (NDVI) dataset covering the years 2002–2015 from the MODIS sensor was used in this study since a shorter compositing period is known to be more robust in estimating LSP (Brown and de Beurs, 2008; Kross et al., 2011). Since inter-annual NDVI variations are driven by climatic anomalies (Schultz and Halpert, 1993; Zeng et al., 2013), we assume that the 14-year mean values of phenological metrics represent the site or pixel specific climatic averaged signal. Therefore, temporal deviations from this mean MODIS pixel LSP would be the result of yearly weather conditions, whereas spatial variations in the pixel means may be traced back both to the spatial variability in topography reflecting site specific mean climatic conditions and in the characteristics of the forest stands. We hence hypothesize that the models predicting mean LSP increase in the explanatory power when incorporating high resolution forest stand information. In this study, we set forth to understand the spatial variability observed in the mean LSP metrics of the BFNP region. The central research questions of this study are:

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