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Networked web-cameras monitor congruent seasonal development of birches with phenological field observations

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ABSTRACT

Ecosystems' potential to provide services, e.g. to sequester carbon, is largely driven by the phenological cycle of vegetation. Timing of phenological events is required for understanding and predicting the influence of climate change on ecosystems and to support analyses of ecosystem functioning. Analyses of conventional camera time series mounted near vegetation has been suggested as a means of monitoring phenological events and supporting wider monitoring of phenological cycle of biomes that is frequently done with satellite earth observation (EO). Especially in the boreal biome, sparsely scattered deciduous trees amongst conifer-dominant forests pose a problem for EO techniques as species phenological signal mix, and render EO data difficult to interpret. Therefore, deriving phenological information from on the ground measurements would provide valuable reference data for earth observed phenology products in a larger scale. Keeping this in mind, we established a network of digital cameras for automated monitoring of phenological activity of vegetation in the boreal ecosystems of Finland. Cameras were mounted at 14 sites, each site having 1–3 cameras. In this study, we used data from 12 sites to investigate how well networked cameras can detect the phenological development of birches (*Betula* spp.) along a latitudinal gradient. Birches typically appear in small quantities within the dominant species. We tested whether the small, scattered birch image elements allow a reliable extraction of colour indices and the temporal changes therein. We compared automatically derived phenological dates from these birch image elements both to visually determined dates from the same image time series and to independent observations recorded in the phenological monitoring network covering the same region. Automatically extracted season start dates, which were based on the change of green colour fraction in spring, corresponded well with the visually interpreted start of the season, and also to the budburst dates observed in the field. Red colour fraction turned out to be superior to the green colour-based indices in predicting leaf yellowing and fall. The latitudinal gradients derived using automated phenological date extraction corresponded well with the gradients estimated from the phenological field observations. We conclude that small and scattered birch image elements allow reliable extraction of key phenological dates for the season start and end of deciduous species studied here, thus providing important species-specific data for model validation and for explaining the temporal variation in EO phenology products.

1. Introduction

Timing of spring onset has advanced significantly during the last century (Menzel and Fabian, 1999; Menzel et al., 2006; Delbart et al., 2008; Jeong et al., 2011; Zhao et al., 2015). Seasonal variation of vegetation activity directly affects photosynthesis, growth of trees and plant reproductive investment, so it is an important driver of the global carbon balance and thus is strongly linked to climate change (Hogg et al., 2000; Richardson et al., 2013). A recent study that compared phenological data to predictions of 36 tree phenology models showed

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that both inter-annual and spatial variations of phenology is poorly predicted by the models (Basler, 2016). This is critical as the year-to-year variation in the timing of budburst of birches (*Betula* spp.) in the boreal zone varies in a wide range of 40 days (Häkkinen, 1999). Poor reproduction of the phenological cycle in biosphere models has also been shown to cause a consistent overestimation of carbon balance in comparison to measured data (Richardson et al., 2012, 2013). The predictive power of models can be expected to further degrade under climate change, due to decoupling of light and temperature cycles. Decoupling of these cycles will be pronounced in northern latitude forests, which are expected to face increases of mean temperatures by 2–7 °C (Ruosteenoja et al., 2016). Therefore, continuous, long-term monitoring of vegetation activity is needed.

Phenological monitoring has a long tradition, and phenological observation networks exist in many countries across the world (Siljamo et al., 2008). At the same time, many spectro- and radiometric instruments suitable for phenological monitoring are operating from space, complementing the dating of phenological events over wider regions (Zhang et al., 2006; Böttcher et al., 2014; Gonsamo and Chen, 2016). In recent years, also near-surface remote sensing with time lapse imaging (Richardson et al., 2007) has provided a cost-effective methodology to monitor and ground-truth phenological phenomena (Hufkens et al., 2012; Klosterman et al., 2014). Time lapse imaging solves some of the problems associated with traditional field observations, as more quantitative methods can be used to define the start of the growing season, for example, while still maintaining the link to the visual appearance of plants. Time-lapse image based phenological development could also provide a closer analogy to remote sensing than field observations of phenology, which are not fully comparable with remote sensing observations as they detect different traits (Badeck et al., 2004). Methodologically, automated curve fitting and transition date extraction methods used for camera image time series have similarities with EO data processing (Elmore et al., 2012; Klosterman et al., 2014).

Cameras have most often been used to analyse the phenological development of deciduous species (Richardson et al., 2007), although also other types of ecosystems, such as grasslands (e.g. Migliavacca et al., 2011), peatlands (Westergaard-Nielsen et al., 2013; Peichl et al., 2015; Linkosalmi et al., 2016) and coniferous forests (Nagai et al., 2012; Linkosalmi et al., 2016), have been monitored. Analyses are robust to the scene illumination angle, cloud cover and camera type, if suitable analysis methods are used (Sonnentag et al., 2012; Linkosalmi et al., 2016; Peltoniemi et al., 2017). Colour changes in plant tissue are unlikely to occur without a biochemical or biophysical mechanism, and digital photography has provided insight into these mechanisms (Keenan et al., 2014; Yang et al., 2014). For deciduous species, budburst and leaf senescence events and also their relationship with CO_2 exchange have been in a focus in a number of studies, and these phenomena have been analysed with various colour indices (Richardson et al., 2007; Ahrends et al., 2009; Sonnentag et al., 2012; Mizunuma et al., 2013; Wingate et al., 2015).

There are still open questions regarding how the camera-derived phenological data should be used in an optimal way. It would be interesting to know how the image-extracted dates compare with those based on the field definitions used in phenological observation networks, and which transition dates can be extracted with sufficient accuracy. This would provide more solid basis for using cameras to supplement existing field observation networks. Secondly, a single image may provide a wealth of information on several species, some only appearing in the margins of the image or amidst the dominant vegetation in smaller proportions and the understory, but the use of such information has been rare. Still, the non-dominant elements potentially provide important information for interpreting earth observations. In the boreal zone, deciduous trees often occur in relatively small and fragmented areal proportions in the satellite footprint. While their areal proportion may be small, their phenology causes distinctive changes in the reflective properties of canopies (Böttcher et al., 2014; Jönsson et al., 2010), which complicates phenological EO analyses of conifers in the area, and may even render results unreliable. Species-specific phenological information drawn from image time series combined with high-resolution earth observation data on species distributions could markedly improve the quality of satellite-based phenology estimation (Liang et al., 2011; Liu et al. 2015). If part of the monitoring would be based on scattered and smaller species-specific image elements, the cost of representative monitoring of wide area phenology would naturally be reduced.

We established a network of cameras at 14 boreal sites in Finland (Peltoniemi et al., 2017), each including 1–3 cameras in different positions. Most of the sites in the network are dominated by Scots pine (*Pinus sylvestris)* and Norway spruce (*Picea abies*), and some are peatlands. Twelve of the sites have a varying mixture of *Betula spp.,* allowing a cross-site study of their phenology, and making it possible to study how these sometimes small and marginal image elements of widely distributed species could benefit phenological monitoring using web-cameras.

The objectives of this study were to test the use of the recently established camera network for birch phenology analysis and supplementing existing phenological field observations. We were interested in how selected color indices compare to the conventional phenological observations, and whether the scattered and often small birch elements within the images provide a useful source of information for the phenology analysis. The tests were performed by comparing the phenological transition dates extracted from the image time series to the corresponding visual estimates, and to those observed in the field in the frame of phenological observation network of Finland, which covers a long latitudinal transect ranging from 60°N to nearly 70°N (Poikolainen et al., 1996; Pudas et al., 2008).

2. Materials and methods

2.1. Sites and camera installations

Camera sites cover nearly the full range of climatic variations observed in Finland, their location ranging from the hemiboreal Tvärminne to the sub-arctic Kaamanen (Fig. 1, Table 1). Three of the northern sites are wetlands [Sodankylä wetland, Kaamanen, Lompolojänkkä are Integrated Carbon Observation System (ICOS) sites] and two are dominated by *P. sylvestris* (Scots Pine)(Sodankylä and Värriö ICOS sites), and one by *Picea abies* L. Karst (Norway spruce) (Kenttärova, ICOS site). The Paljakka site in central Finland is dominated by spruce and it belongs to the long-term phenology monitoring network of Luke, as does the mixed species site Parkano in southern Finland. The other southern sites are dominated by *P. sylvestris* (Hyytiälä ICOS site), *Picea abies* L. Karst (Punkaharju, Tammela Level II monitoring sites of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests, ICP), or have mixed or deciduous coverage (Tvärminne, Lammi Long Term Ecosystem Research (LTER) sites). The sites vary in their ancillary measurements, the most intensively measured sites being the ICOS sites in Hyytiälä and Sodankylä while the Suonenjoki *P. sylvestris* site only hosts a meteorological station.

All cameras are set to a fixed white balance, quarter of the maximum resolution (5 MPix), targeted northwards where feasible and triggered for half-hourly submission of snapshots to an ftp server, excluding the night hours. All of the sites and analyses of this study used image time series acquired with StarDot NetCam SC5 cameras.

2.2. Phenological analyses

2.2.1. Material for phenological analyses

In this study, we used 12 networked cameras for the analyses of spring and autumn phenology of *Betula* spp from 2014 to 2016. Installation and operation dates of the cameras varied, and not every

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