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Detecting plant seasonality from webcams using Bayesian multiple change point analysis

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ABSTRACT

Phenological observations have a long tradition. By contrast, digital webcam-based phenological research has only developed in recent years, prompted by the development of cheaper user-friendly digital camera systems and by higher staff costs. Webcam photography provides spectral information in red, green and blue (RGB) wavelengths which mirror the seasonal colour changes in trees during bud burst, leaf unfolding, senescence and leaf fall.

Recent publications have mainly used two types of image data analysis to define onset dates of certain phenological stages and to compare species and growing seasons. These methods work well, but require high quality of the webcam images. However, changing light and weather conditions complicate data analysis particularly at increasing camera-to-subject distances. We investigated a series of images providing colour information on different tree species, e.g. *Fagus sylvatica*, *Populus tremula*, as well as of trees at different altitudes (700–1200 m) in the Bavarian Forest National Park, Germany. Webcam images were analysed by the two previously published methods and compared with results derived from a newly developed Bayesian multiple change point analysis. In particular, transition dates of leaf development were identified in the green, as well as the red, colour channel.

The Bayesian analysis described phenological transition dates in spring and autumn and specified the uncertainties of the model fit. By contrast, previously employed methods have shortcomings associated with unrealistic asymptotic assumptions in logistic model fits or inability to cope with noise in data series.

The change point analysis at different elevations showed how the Bayesian approach coped with increasingly degraded image quality. A delay in green-up of about 2.5 days per 100 m of altitude was estimated for *Fagus sylvatica* in the study area. Autumn phenology at different altitudes did not show clear patterns.

The Bayesian model approach allows not only the calculation of phenological change points during the year but also estimates the probability of those changes occurring on a particular day. This method appears to estimate reliably phenological events in the growing season, especially when handling low quality webcam data, either from poor weather conditions or when the subject is at a considerable distance from the camera.

1. Introduction

Phenology is "probably as old as civilization itself" (Schwartz, 2003). Almost certainly, early man was aware of the relationship between plants and their environment in order to help with the cultivation of crops, or the exploitation of wild resources.

Phenological observations have a long history; starting with the first phenological calendars recorded by the Ancient Greeks, phenology has recently been developed as one of the main research fields for assessing the impact of climate change on ecosystems (Menzel, 2002). Sparks et al. (2009) showed the growing importance of phenological research from 1990 to 2009 which can be linked to increasing air temperatures and the demand for indicators of the influence of climate change on the biosphere. In recent years, various studies have focussed on the effect of global warming on phenology (Jeong et al., 2011; Menzel et al., 2006; Rosenzweig et al., 2008).

Menzel (2002) suggested that phenology is probably the easiest way to track climate change effects on species, however it is both labour- and time-intensive, therefore satellite- or webcam-based observation methods have been investigated as possible alternatives. Due to the insufficient spatial and temporal resolution of satellite recordings, inexpensive automated digital cameras have

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increasingly become popular alternatives to the current system of phenological monitoring of ecosystems (Ahrends et al., 2009; Ide and Oguma, 2010; Kurc and Benton, 2010; Nagai et al., 2011; Richardson et al., 2007, 2009). Furthermore, analyses of worldwide outdoor webcam images have proved to be useful alternatives to both ground and satellite phenological observation methods (Graham et al., 2010; Jacobs et al., 2009).

Digital cameras store spectral information in red, green and blue colour channels. Changes which occur in this colour information during the year can be directly linked to phenological changes. Estimating spring green-up from the green colour channel (Ahrends et al., 2009; Ide and Oguma, 2010; Richardson et al., 2009) as well as detecting leaf colouring in autumn from red colour channel information (Richardson et al., 2009) has been achieved. However, these analysis methods, when applied to other species and/or locations, have not shown the same suitability as in the original publications.

Dose and Menzel (2004) introduced Bayesian analysis for the detection of a change point in phenological time series. That study as well as those of Menzel et al. (2008) and Schleip et al. (2006) demonstrated the potential of Bayesian statistics for analysing functional behaviour in ecosystems.

In the current study, we applied Bayesian analysis to describe phenological events such as leaf unfolding and maturity in spring, and leaf colouring and fall in autumn. Therefore a multiple change point analysis based on the Bayesian one change point model (Dose and Menzel, 2004) was developed. In addition to a phenological analysis of deciduous tree species at an altitudinal gradient in the Bavarian Forest National Park in Germany we highlighted differences between recent image data analysis methods and our Bayesian multiple change point method.

2. Materials and methods

2.1. Study site and camera setup

The mountain “Großer Falkenstein” (49°05′N, 13°16′E; 1315 m a.s.l.) is located in the Bavarian Forest National Park in the south-east of Germany, 3 km west of the Czech border. The mountain rises some 600 m above its surroundings. The climate is humid continental, the mean annual temperature varies between 3 and 5 °C and the annual precipitation is about 1400 mm, of which a third derives from fog. At higher elevations, snow cover lasts up to 8 months (German Meteorological Service, National Park Administration).

A digital single-lens reflex camera (Canon EOS 350 D) facing slightly upwards to the south slope of the mountain was installed on an outside wall of a house. Between March 2006 and August 2007 the camera was automatically controlled by a timer and took daily JPEG images (image resolution of 7.9 MP) in the early afternoon (1–3 h p.m.). Exposure and aperture mode, as well as the white balance, were set to automatic.

The images displayed about 600 m altitudinal difference. Trees in the foreground were located within 50–350 m of the camera at the edge of a settlement (Lindberg, 680 m) (Fig. 1). These species were European Silver Fir, *Abies alba* Mill., Norway Spruce, *Picea abies* (L.) H. Karst., Common Beech, *Fagus sylvatica* L. and Common Aspen, *Populus tremula* L. Remote trees on the slope in the background were at a distance of 2.5–5 km from the camera and mainly consisted of Norway Spruce and Common Beech; sporadically European Larch, *Larix decidua* Mill. occurred in small groups at 800–1000 m.

2.2. Data processing

Contour lines were created and afterwards distorted to the camera’s perspective using ESRI ArcScene (3D visualization application

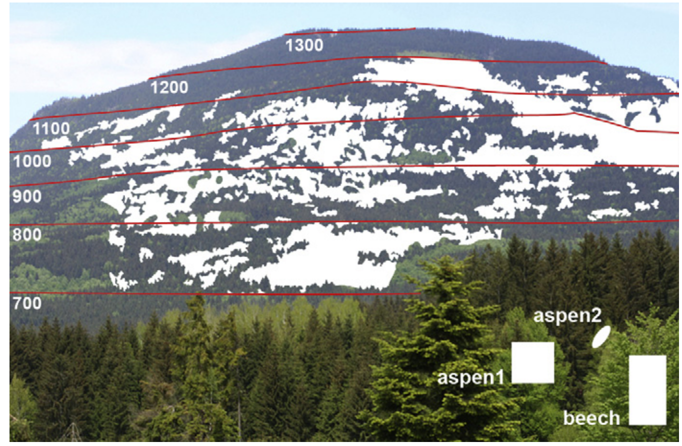

Fig. 1. Sample image of the “Großer Falkenstein” (recorded May 22, 2006, DOY 142). White sections indicate regions of interest (ROI), contours from 700 to 1300 m in 100 m steps are shown in red. ROI: aspen1 and aspen2: Common Aspen, beech: Common Beech, non-numbered sections on the slope refer to altitudinal ROI (700–1200 m). The left hand part of the image was excluded from the analysis because it was not visible during the whole time series due to interference from a foreground tree close to the camera.

for GIS data), an elevation model and the relevant geo-coordinates (camera site, mountain peak). In a second step, the contour lines were transferred onto an image by using picture processing software (Adobe Photoshop) and then indicated the altitudinal bands for further analysis.

Because the camera was initially installed for educational, and not for scientific purposes, just one image was taken per day.

Image analysis was conducted by defining different regions of interest (ROI) as described by Ahrends et al. (2009) and Richardson et al. (2007, 2009). For each ROI a mask (binary image) was created. Three ROI of foreground trees (hereafter called beech, aspen1 and aspen2) were selected manually based on various images as a compromise between maximizing the size of the ROI and avoiding disturbances in the background from tree species with different phenological behaviour (Fig. 1).

For the analysis of altitudinal bands, the use of non-rectangular and discontinuous ROI was necessary to separate Common Beech (deciduous) and Norway Spruce (evergreen) trees during the data processing. For creating masks of the altitudinal ROI which covered Common Beech trees, image sections with similar colour values were tagged using the “Magic Stick” tool (Adobe Photoshop, tolerance value 8) using an image from May 22, 2006 (day of year (DOY) 142, Fig. 1).

Similarly to the methods of Richardson et al. (2007), a custom script (Python Software Foundation) colour-split the digital image files sequentially and, taking the mask into account, extracted and averaged the colour channel information (digital numbers; red DN, green DN, blue DN). This procedure was repeated for each mask/ROI. The overall brightness of each ROI (Eq. (1), DN = digital number) and the proportional value for the green and red colour channels (Eq. (2)) were calculated to minimize the influence of sunshine differences between days.

$$\text{total RGB DN} = \text{red DN} + \text{green DN} + \text{blue DN} \tag{1}$$

$$\text{green\%} = \frac{\text{green DN}}{\text{total RGB DN}} \qquad \text{red\%} = \frac{\text{red DN}}{\text{total RGB DN}} \tag{2}$$

In Bayesian analysis the noise turns out to be as important as the data itself (Bretthorst, 1992, 1991, 1990), therefore and by contrast to the image quality control measures of Ahrends et al. (2009), we