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Seasonal reflectance trends of hemiboreal birch forests

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ABSTRACT

MODIS, AVHRR and SPOT VEGETATION satellite images have recently been used to track coarse scale seasonal vegetation dynamics of boreal and temperate forests. However, the understanding of driving factors of reflectance seasonality at forest stand level is still in its infancy, and has only preliminarily been linked to, for example, forest structure or site fertility. We present results from a study on the seasonal reflectance trends of 145 hemiboreal birch stands in Estonia from budburst to initial senescence. A time series comprising 32 high resolution Landsat ETM+, TM and SPOT HRVIR, HRV images from April to September was assembled for analyzing empirical reflectance courses of birch stands. The most noteworthy seasonal reflectance dynamics were observed in the red and NIR channels, changes in the green and SWIR spectral channels were relatively small. The most stable period in stand reflectance in all the spectral channels occurred in midsummer i.e. when stand leaf area index (LAI) reached its highest level and changes in solar angle were the smallest. A twenty-day difference was observed between the reflectance development of birch stands growing on infertile and fertile sites. Next, to provide an explanation for the observed reflectance changes, we simulated the mean seasonal reflectance trajectories of the study stands at 10 day intervals for the same period using a radiative transfer model (FRT). Simulated seasonal reflectance courses for the different site fertility classes followed the general pattern of the measured courses. Simulation results indicated that the main driving factors for reflectance seasonality for all the site fertility classes in the red and green bands were stand LAI and leaf chlorophyll content, in the NIR band stand LAI, and in the SWIR band LAI and general water content. Finally, we discuss current limitations related to applying forest radiative transfer models in investigating the driving factors of seasonal reflectance changes in the boreal zone.

1. Introduction

Monitoring vegetation phenology with Earth Observation data is currently a widely investigated topic. A key motivation for phenological studies is the changing climate and, especially in the northern latitudes, the ecological consequences of a longer or altered growing period (e.g. Myneni et al., 1997; Zhou et al., 2001). Global-scale plant phenology observation is needed, for example, to understand the seasonality of biosphere–atmosphere interactions (Moulin et al., 1997).

Satellite remote sensing offers an efficient means for making spatially and temporally continuous observations of vegetation dynamics. MODIS, AVHRR and SPOT VEGETATION data sets have been used to monitor coarse scale seasonal vegetation dynamics of boreal and temperate forests (e.g. Ahl et al., 2006; Beck et al., 2006; Delbart et al., 2005; Karlsen et al., 2008; Kobayashi et al., 2007; Soudani et al., 2008; Wang et al., 2005; Zhang et al., 2006). Recently, a specific interest has been assessing interannual variations in leaf appearance timing at continental scale (e.g. Delbart et al., 2008). These studies have provided valuable information on general trends of the onset and offset of vegetation growth, and changes in growth patterns needed for global change studies. Even though the biological processes controlling reflectance phenology are the same for coarse, medium and high resolution satellite images, coarse scale data sets cannot necessarily differentiate all phenological contrasts present in a fragmented landscape. Seasonal reflectance patterns of vegetation communities at high latitudes become more complex when assessed at coarser resolutions mainly due to the presence of various local climatic gradients and different vegetation communities (Beck et al., 2006). So far, investigations have concentrated on general phenological trends of vegetation and developing methodologies for detecting growth phases from remote sensing data. However, the understanding of reflectance seasonality and its driving factors at forest stand level is still in its infancy: seasonal reflectance variation has only preliminarily been linked to detailed stand structure (e.g. Nilson et al., 2008a; Suviste et al., 2007) or variation in leaf spectra resulting from climatic-elevational factors and site quality (e.g. Richardson & Berlyn, 2002).

According to the IPCC (2007) synthesis report, northern ecosystems are especially likely to be affected by climate change. Therefore, understanding the seasonal dynamics of boreal ecosystems and

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linking its different phases to satellite reflectance data is crucial for efficient monitoring and modeling of northern hemisphere vegetation dynamics and productivity trends in the future. Interpreting any properties of a boreal tree canopy layer is complicated by the presence of a varying understory layer (Canisius & Chen, 2007; Eriksson et al., 2006; Rautiainen et al., 2007). Thus, also the seasonal reflectance course of a boreal forest is a sum of the temporal reflectance cycle of both the tree canopy and the understory layers. Seasonal reflectance changes of the two layers are explained by the complex combination of changes in biochemistry and geometrical structure of the different plant species (e.g. growth of leaves, stems, flowers, seeds and berries) as well as seasonal and diurnal variation in solar illumination. Analyzing the role of each of the contributing factors can only be achieved by linking stand-level radiative transfer modeling to empirical reflectance data sets.

It is commonly understood that the seasonal reflectance course in boreal deciduous forests is more pronounced than in coniferous forests (e.g. Peterson, 1992). Based on empirical reflectance data and radiative transfer modeling, forest canopy and understory leaf area index, tree density and snow melt have been identified as key factors driving the spring–summer reflectance changes in a northern forest (Nilson et al., 2008a; Kobayashi et al., 2007). However, seasonal variability of understory reflectance in boreal forests is very characteristic of stand type, and the reflectance differences between stands have been reported to become more pronounced as the growing period progresses (Miller et al., 1997). Some of the differences in understory reflectance may also not be caused by phenology, but instead merely by the varying moisture conditions. An important practical application of phenology studies would be identifying a system for classifying forests into different seasonal reflectance trajectory groups. A possible solution to this may be achieved through routine site type classification systems applied in forest management. A study by Nilson et al. (2008a) preliminarily indicated that the seasonal reflectance courses of deciduous and coniferous stands growing on infertile and fertile site types may differ considerably from each other. Their result is an important motivation for carrying out this continuation study.

A key ecological and economic genus in the European boreal zone is birch (*Betula* sp.). A specific advantage of using birch in phenological studies is that it has five distinct phenophases (budburst, first leaves open, full-sized leaves, leaf coloring and leaf fall) unlike the coniferous species in the region (Karlsen et al., 2008). In addition, seasonal growth patterns of birch in the European boreal region have been studied extensively through traditional, systematic in situ observations in phenological networks (e.g. Pudas et al., 2008) and by phenological modeling (e.g. Häkkinen et al., 1998; Linkosalo et al., 2000; Myking & Heide, 1995), and thus, basic ground reference information is available. However, from the perspective of modeling the seasonal reflectance trajectories of birch stands, a specific challenge is often the lack of information on seasonal changes in canopy and understory composition together with leaf optical properties and biochemical parameters.

In this paper, we focus on the reflectance seasonality of birch stands in southern Estonia from budburst to initial senescence using a time series of 32 Landsat TM, ETM+ and SPOT HRVIR, HRV satellite images collected between April and September. The specific aims of our study were (1) to track the seasonal reflectance changes of mature hemiboreal birch stands growing on different types of fertile and infertile soils and (2) to evaluate the main driving factors for the observed seasonal reflectance courses through radiative transfer modeling.

2. Materials and methods

2.1. Ground reference site

Ground reference data was collected from the Järvselja Training and Experimental Forestry District (27.3° E, 58.3° N) which is located in southeastern Estonia in a lowland area close to a large lake, the Peipsi lake, and covers an area of 10 618 ha. It serves as the main training base for forestry students at the Estonian University of Life Sciences and as a test site for the international VALERI (Validation of Land European Remote Sensing Instruments) project (VALERI, 2008). Approximately half of the territory is covered with forests, birch (*Betula pendula* Roth., *Betula pubescens* Ehrh.) being the most widespread species (49% of timber volume), and Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) the subdominant species.

The climate in Järvselja is damp, and characterized by warm summers and moderately mild winters. Day light hours range from approximately 6.5 h in December to 18.5 h in June, and vegetative growth typically begins in April (i.e. 15 h day light). During our study period, precipitation in Järvselja ranged from 31.4 mm (April average) to 85.3 mm (August average). Based on the meteorological data collected at Tartu Observatory located 45 km from the Järvselja test site, growing degree days (i.e. GDD, calculated by taking the average of the daily maximum and minimum temperatures compared to a base temperature of 5 °C) in southeastern Estonia typically start in the beginning of April and reach their plateau by mid-October. Unfortunately, there are no published data records in Estonia on the relationship between degree days and vegetative growth of different plant species throughout the summer. However, unpublished budburst and senescence records of the Estonian Plant Breeding Institute (pers. comm. Laine Keppart, Jõgeva station) indicate that during the past 50 years, birches have begun growing leaves between April 16 and May 20, and yellowing has occurred between August 24 and October 6. Some supporting information may also be obtained from phenological records of neighboring regions. For example, published records for the years 2001–2007 from the southern boreal zone of Finland are more detailed and indicate that growth of birch usually starts in the beginning of May (May 6–13), full leaves are reached by mid-June (June 3–10) and forests turn yellow by mid-September (September 12–26) (MetInfo, 2007).

2.2. Study stands

For our study, we selected 145 mature birch (*Betula* sp.) dominated, approximately 50 year-old stands from Järvselja which had not undergone significant management procedures recently. A stand was defined birch dominated when at least 75% of the trees (by stem count) in the stand were birches. We also limited the size of the stands; a minimum size requirement of 1.5 ha was set in order to guarantee a sufficient number of satellite image pixels per stand. Stand inventory data for Järvselja were obtained from a complete forest inventory data base collected by a local forest inventory company (Metsaekspert OÜ, year 2001). The GIS database includes standwise information on, for example, tree species composition, site index, stand age, stand density, tree height and breast height diameter.

Leaf area index (LAI) values for the study stands, on the other hand, were not available in the forest inventory database. However, since the Järvselja site serves as test site in the VALERI project, the LAI of approximately 60 stands has been intensively measured with optical devices (LAI-2000 Plant Canopy Analyzer, hemispherical photography) since 2000, and the datasets are publicly available through the VALERI network website (VALERI, 2008). However, the seasonal course of LAI has not been fully recorded: measurements have been made in April (2007), June (2001, 2002, 2005) and July (2000, 2003, 2007). Therefore, in our study, the LAI course of the study stands had to be extrapolated from the measurement and phenological observation data, and should be carefully treated as an ‘expert guess’ time series. The LAI of the moss layer was assumed to have a 20% increase from spring to midsummer (i.e. from LAI 0.4 to LAI 0.5). In this paper, we use two leaf area index concepts: tree canopy LAI (the hemisurface,