Spectral reflectance patterns and seasonal dynamics of common understory types in three mature hemi-boreal forests

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Introduction

The understory is like a miniature forest. Similarly to forest tree layer or canopy, the understory (also called forest floor or background) goes through versatile changes during the vegetation period (Rautiainen et al., 2011). When compared to tree layer it is more compact, but structurally more complex due to large species variation (Peltoniemi et al., 2005). Similarly to forest tree layer, the scattering properties of understory are determined by leaves, their orientation, and spatial distribution. The underlying soil, litter layer, and topography also affect the scattering properties of understory (Ruusk, 2001). Due to vast variety of species the reflectance factor is formed by each individual component within a certain understory community (Nilson et al., 2012).

The properties of understory vegetation are also determined by the properties of a tree layer. For example, the solar radiation transmitted to the forest floor is one of the factors which determine the understory vegetation (Nilson and Peterson, 1994). That means changes in canopy closure or tree layer leaf area index (LAI) will lead to a change in the species composition, green LAI, roughness characteristics of ground vegetation, and consequently the reflectance (e.g., Waring et al., 1998; Rautiainen and Heiskanen, 2013). Understory vegetation is thus not entirely independent from the tree canopy (Hallik et al., 2009).

The tree layer influences the understory, but the forest floor contributes to the total stand reflectance considerably as well (Eriksson et al., 2006; Rautiainen and Stenberg, 2005). Modelling studies have shown that background optical properties become essential in predicting total stand reflectance especially at low values of upper canopy cover (Nilson and Peterson, 1994; Hanan, 2001; Rautiainen, 2005). It has been also previously highlighted that the understory effect has to be removed from the forest reflectance for more reliable estimation of biophysical properties of the tree layer (e.g., Eriksson et al., 2006; Garrigues et al., 2008; Rautiainen and Heiskanen, 2013).

Due to the fact that ground measurements are time-consuming, there have been recent attempts to retrieve boreal forest understory reflectance directly from remote sensing data (e.g., Pisek et al., 2010, 2012). However, the understory reflectance retrieval algorithms still need to be further validated with in situ measurements. Only relatively few efforts had been previously undertaken to collect various understory components and/or creating limited spectral databases (e.g., Goward et al., 1994; Miller et al., 1997; Lang et al., 2002; Rees et al., 2004; Peltoniemi et al., 2005; Rautiainen

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et al., 2007; Hallik et al., 2009). The most recent study was conducted by Rautiainen et al. (2011) who tracked a wide range of seasonal dynamics and temporal patterns of different understory types in a southern boreal forest. Their results confirmed that indeed the understory signal cannot be ignored due to its spatial and temporal variation.

The main objective of this paper was to track out temporal reflectance courses of common hemi-boreal understory types in three forest stands with different overstory species in Järvselja, Estonia, in 2013. Importantly, we highlight how similar or different might be the seasonal dynamics in understory composition and reflectance spectra for stands with similar overstory in the neighboring hemi-boreal and boreal zones.

Materials and methods

Study site

The study site is located in South-East Estonia (58°30′ N, 27°30′ E) at the Järvselja Training and Experimental Forestry District. Järvselja forests are typical for the hemi-boreal zone. Dominant tree species are Scots pine (Pinus sylvestris L.), Norway spruce (Picea abies (L.) Karst.), and birches (Betula pendula Roth, Betula pubescens) (Kuusk et al., 2009a,b). Three sites representing different forest fertility types were selected (Table 1). In this study, to maintain the comparability with Rautiainen et al. (2011), we use the Cajander (1930) forest site type classification. The RAMI (Radiation Model Inter-comparison; Widlowski et al., 2007) birch stand can be described as an herb-rich forest, dominated by the herbaceous species and graminoids; moss layer is sparse or missing. The RAMI pine stand grows on a transitional bog. The understory vegetation is composed of sparse labrador tea (Ledum palustre), cotton grass (Eriophorum vaginatum), and a continuous Sphagnum spp. moss layer. The sampling area in the additional spruce stand consists of two parts with different conditions for understory growth: a sub-xeric section where the understory vegetation is virtually missing, and a mesic part dominated by mosses and dwarf shrubs. More details about the stand parameters for the tree-layer vegetation can be found in Kuusk et al. (2010).

A 100 m long permanent transect was set up at each test site. All transects ran across the stands from northwest to southeast. In addition, four intensive study plots (1 m × 1 m) were marked next to the transects at 20 m intervals. The field campaign started on 9 May (day of year, DOY 128) and ended on 29 September 2013 (DOY 272). The fractional cover of understory and understory spectra were estimated every 2–3 weeks.

Estimates of fractional cover

Digital camera (Pentax K10D) was used to photograph the four 1 m × 1 m intensive study plots at each site to estimate fractional coverage. Plant functional types (PFT) were estimated from the photos throughout the growing season. This was the only feasible method for detecting the changes in coverage – destructive sampling (e.g., biomass or leaf area index analysis) was not possible as the plots were continuously measured and the natural phenology could not be disturbed.

A 10 × 10 cm grid was laid on top of each image and examined visually to estimate the vertically projected fractional cover for each PFT every 2–3 weeks corresponding to the dates of spectroscopy measurements. Fractional cover measurements were all made by the same person for the overall consistency. An arithmetical mean of four plots was calculated for the PFT coverage determination. Plot-specific values were used to relate the cover data to spectral data. In addition to the stand parameters, all herbaceous species in the intensive study plots were also identified to provide an extensive overview of the stands (Table 2).

Measurements of understory spectra

The vegetation growing period usually lasts 175–180 days in Estonia, from mid-April to October (Hallik et al., 2009). In 2013, the vegetation period started abruptly in April when the monthly average temperature reached 4 °C (Estonian Environment Agency, 2014). The growing period was then already under way when the first measurements were taken (9 May).

The understory spectra were measured under diffuse light conditions with fiber input supplied FieldSpec-Pro VNIR spectrometer by Analytical Spectral Devices (ASD), Inc., covering 350–1050 nm region. The sampling interval was 1.4 nm with the resolution 3 nm at full width half maximum (FWHM) at 700 nm. The instrument was controlled by a laptop carried by the instrument operator. Sufficient warm-up time (approximately 30 min) was allowed for the spectrometer, regular dark current measurements were taken and the white reference panel was kept clean to achieve the best results.

All measurements were taken when the sun was completely blocked by the clouds or direct solar radiance was totally attenuated by the long path length in tree crown layer at low solar elevation near sunset. Diffuse irradiation conditions are needed for two reasons: to eliminate the effect of incidence angle on the measured reflectance signal and to reduce spatial variation in the incident radiation field. In addition the high anisotropy of vegetation scattering was also reduced by using diffuse light conditions (Rautiainen et al., 2011).

The downward-pointed spectroradiometer was held by the outstretched hand of the operator. Due to the fact that the instrument has a 25° field of view the area sampled during each spectral measurement corresponded approximately to a circle with a diameter of 50 cm. No fore-optics was used. The understory spectra was measured every 2 m along transect, resulting in 50 measurements per transect. Three spectra above a 10-inch Spectralon SRT-99–100 white panel were recorded at the beginning and end of each transect and also along it after every four understory spectra measurement points (every 8 m). Regarding the four intensive study plots, each 1 m × 1 m square was divided into quarters (area 0.25 m²) and the spectrum of each quarter was measured separately. The white reference panel was measured three times before and after the understory measurements to obtain the incident spectra measurements.

Table 1

<table>
<thead>
<tr>
<th>Study site</th>
<th>Dominant tree species</th>
<th>Mean tree height, m</th>
<th>Mean breast height diameter, cm</th>
<th>Effective leaf area index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herb-rich</td>
<td>B. pendula Roth</td>
<td>22(5.5)</td>
<td>18(6.2)</td>
<td>2.9(0.25)/0.8*</td>
</tr>
<tr>
<td>Transitional bog</td>
<td>P. sylvestris L</td>
<td>16(1.5)</td>
<td>18(4.4)</td>
<td>1.8(0.15)</td>
</tr>
<tr>
<td>Sub-xeric/mesic</td>
<td>P. abies (L.) Karst/</td>
<td>19(5.2)</td>
<td>17(7.3)</td>
<td>3.8(0.62)</td>
</tr>
<tr>
<td></td>
<td>B. pendula Roth</td>
<td></td>
<td></td>
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</tbody>
</table>

In brackets is the standard deviation of a measure.

* LAI<sub>eff</sub>(July)/LAI<sub>eff</sub>(November).

Spectral measurements were processed to correspond to hemispherical-directional reflectance factors (HDFR). Two Spectral reflectance measurements made before and after each understory spectrum quadruplet along given transect (or, the quartet of intensive study plot spectra) were interpolated linearly in time to estimate the spectral irradiance for the moments when the understory spectra were recorded. A hemispherical–conical reflectance factor was obtained with an “uncalibrated” Spectral reflectance spectrum and the interpolated irradiance. Due to the fact that the field-of-view of the spectroradiometer is a considerably narrower cone than the whole hemisphere, some of the reflectance directionality was captured corresponding to normal remote sensing viewing geometry. In this work the reflectance factors measured by the spectroradiometer are referred similarly to the satellite-derived HDFRs.

Due to the fact that the radiation receiving element of the spectrometer has low sensitivity at the extremes of its spectral measurement interval and the peak of spectral irradiance in a forest under natural daylight conditions is located in the visible spectral region or near the red edge (around 700 nm), wavelengths below 400 nm and above 900 nm had a high signal-to-noise ratio. The analyzed wavelengths were thus limited to 400–900 nm.

The averaged spectra (HDFRs) obtained from spectral measurements made along the transects are predominantly used in this study. Spectral measurements from the intensive study plots were only used to calculate correlation coefficients for understory cover with vegetation indices (Fig. 6).

### Analysis of spectral data

The spectral data was examined and compared in its full spectral resolution to find out the spectral dynamics of the different understory types. Then the red edge inflection point (REIP) was obtained through first derivative spectroscopy to see changes due to changing chlorophyll content of leaves. In addition, two narrow-band vegetation indices were calculated. First, the photochemical reflectance index (PRI = [HDFR(570 nm) – HDFR(531 nm)]/[HDFR(570 nm) + HDFR(531 nm)]) (Gamon et al., 1992) that characterizes the photosynthetic efficiency (Garbulsky et al., 2011) and plant senescence reflectance index (PSRI = [HDFR(680 nm) – HDFR(500 nm)]/[HDFR(750 nm)]) (Merzylik et al., 1999), which is sensitive to the changing chlorophyll:carotenoids ratio and can be used as a quantitative measure of leaf senescence and fruit ripening. These indices were selected since they are typically used to characterize the changing physiolog- logical status of vegetation. Same wavelengths were used as in the work of Rautiainen et al. (2011) to make results comparable.

Finally a relative spectral response function was used for Moderate Resolution Imaging Spectroradiometer (MODIS) to compute broadband HDFRs for green (545–565 nm), red (620–670 nm), and NIR (841–876 nm) wavelengths. In addition, a normalized difference vegetation index (NDVI) (Rouse et al., 1973) was calculated from red and NIR band. MODIS wavelengths were selected because its bands represent typical wavelengths that are used in vegetation remote sensing. Error bars with standard deviation are shown only in the figures which report raw measurement data (Figs. 2–4).

### Results and discussion

#### Fractional cover

Estonian hemi-boreal forests are composed of two understory layers: the upper understory layer and the ground layer. As bare mineral soil is rarely visible in a hemi-boreal forest, the ground layer was divided into three groups: (1) litter, (2) lichens, and (3) mosses. Mosses are the most abundant in the mesic and transitional bog sites as indicated in Fig. 1A. For the upper understory the PFT groups were classified as follows: (1) dwarf shrubs, (2) pteridophytes with herbaceous species, and (3) graminoids. Different herbaceous species are the most abundant PFT in the upper understory layer (Fig. 1B) at the birch stand. Dwarf shrubs were present at all sites except the sub-xeric portion of the spruce stand, where only graminoids were found. The graminoids were entirely absent in the mesic portion of the spruce stand. Upper understory covered from 2% (sub-xeric) to 53% (herb-rich) of the ground floor. The cover percentage is clearly linked with the site fertility. Since no bare soil was visible the ground layer had always 100% coverage.

#### Mean seasonal changes in the composition of understory layers

The four sites had clearly different seasonal cycles of upper understory coverage. The most pronounced seasonal cycle of changes in understory vegetation coverage was observed in the herb-rich stand (Fig. 2B). Sub-xeric stand was almost invariant during the monitored period (May–September). Vegetation in herb-rich forest was already germinated causing the high 45% cover at the beginning of the monitored period (DOY 128). In late May (DOY 150), the upper understory layer in herb-rich forest reached its highest cover (>80%). The peak in mesic stand was

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Table 2: Species composition of the ground and upper understory layers of the study sites.

<table>
<thead>
<tr>
<th>Study site</th>
<th>Upper understory</th>
<th>Graminoids</th>
<th>Ground layer</th>
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<tbody>
<tr>
<td></td>
<td>Dwarf shrubs</td>
<td>Pteridophytes + herbaceous</td>
<td>Mosses</td>
</tr>
<tr>
<td>Herb-rich</td>
<td>Corylus avellana</td>
<td>Anemone nemorosa, Hepatica nobilis</td>
<td>Sphagnum ssp.</td>
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<tr>
<td></td>
<td></td>
<td>Mill, Oxalis acetosella, Maianthemum Bifolium, Galeobdolon luteum, Stellaria holostea, Galium odoratum, Lathyrus vernus, Aegopodium Podagaria, Equisetum Sylvaticum, Dryopteris carthusiana, rubus Saxatilis</td>
<td></td>
</tr>
<tr>
<td>Transitional bog</td>
<td>Vaccinium myrtillus</td>
<td>Eriophorum Vaginatum</td>
<td>Sphagnum ssp.</td>
</tr>
<tr>
<td></td>
<td>L. palustré</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vaccinium vitis-idaea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-xeric</td>
<td></td>
<td>Agrostis Stolonifera</td>
<td>H. splendens</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>P. schreberi</td>
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<tr>
<td>Mesic</td>
<td>V. myrtillus</td>
<td>H. splendens</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L. palustré</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>V. vitis-idaea</td>
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</table>

reached in early June (DOY 164), somewhat later than in the herb-rich stand (Fig. 2B). The transitional bog experienced the highest upper understory coverage (25%) much later, in early August (DOY 217), followed by a not very pronounced senescence phase. For the sub-xeric site the upper understory was composed of only 2% by graminoids (Fig. 1B); no obvious green-up or senescence processes were observed.

**Understory spectra**

The main aim was to study spectral dynamics of different understory types during the growing season. Transitional bog had the brightest NIR spectra throughout the monitored period. The sub-xeric stand had the lowest NIR reflectance throughout the whole season, since the understory was constantly dominated by the presence of litter (Fig. 2). The spectra of the herb-rich and mesic stands were similar in the NIR region (except in early summer DOY 164–179), but varied in visible spectrum (VIS). Despite the differences in understory coverage, in agreement with previous observations by Miller et al. (1997) and Rautiainen et al. (2011) the differences in understory spectra between sites became more pronounced as the growing period proceeded. In spring (DOY 136–150; Fig. 3A) the different sites had distinct spectra, because there was already vegetation at different stages in the study sites. A month later, in early summer (DOY 164–179) (Fig. 3B) the red edge had become steeper for all the sites except for sub-xeric which was experiencing continuing green-up. Understory of different stands could be very well separated especially in NIR region, while variation within stands was also the largest. In mid-summer (DOY 192–217; Fig. 3C) herb-rich and mesic sites were again rather similar in NIR. Lower values in the herb-rich site were caused by the decreased coverage of the upper understory layer (Fig. 2B). By late summer (DOY 234–272; Fig. 3D) senescence was notable in the VIS region for all understory types except sub-xeric. The decrease in VIS region was most likely caused by the decreasing cover of upper understory; therefore, there was more exposed ground that appeared darker in VIS region (Hallik et al., 2009). The sub-xeric site had the highest values in the late summer and this was caused by constant dominance of the fallen leaves/litter on the forest floor. It can be concluded differences in and between different understory types are greater in late summer than in spring. Only transitional bog had clearly higher values in late summer due to evergreen plants and constantly growing moss layer.

**Red edge inflection point**

The seasonal change for different understory types in the location of red edge was examined next using red edge inflection points (REIP) obtained through first order derivative spectroscopy. The first derivative is used to enhance absorption features that might be masked out. Changes in REIP were expected due to the changing chlorophyll content in leaves and green LAI and the fact that REIP...
will shift towards longer NIR wavelengths as the growing period proceeds. The shift was the strongest in the herb-rich stand (from 694 nm at the beginning towards 719 nm at the peak of the growing season) (Fig. 4). The REIP position shifted for less fertile sites as well, although with smaller variations throughout the growing season (from 685 nm to 698 nm). The REIP for the understory types differed most notably in early summer (DOY 164–179), at the peak of the growing season. The respective REIP positions throughout the season reflected the changes in the understory cover percentage very well (Fig. 2B).

### HDRFs and upper understory correlation

A correlation between upper understory layer cover and HDRFs (400–900 nm) was examined throughout the growing season (Fig. 5). This was essential for identifying possible relationships between understory cover and spectral regions that are independent of the growing period phases. The analysis is based on four 1 m × 1 m intensive study plots for each of the site. For the correlation the spectral measurements and mean changes in the understory compositions were used for each of the sites.

Overall the strongest correlations between the fraction of vegetation cover and HDRFs occurred in the NIR region for the transitional bog site ($R = 0.9$); for the herb-rich site $R = 0.77$ and for mesic $R = 0.58$. The herb-rich site differed from the rest by displaying the strongest correlation in the VIS range (590–690 nm) where the correlation coefficients between HDRF and upper understory layer cover were over 0.8. In contrast to Rautiainen et al. (2011), no improvement can be observed when the earliest measurements are removed. This is because the growing period was already under way when the first (spring) measurements were taken. At approximately 550 nm, herb-rich stand had the lowest correlation between vegetation cover and VIS HDRF; whereas, transitional bog and mesic had the highest correlation values in that region. This is caused by the faulty measurement (apparently caused by momentary dominance of direct sunlight) on DOY 234 in the herb-rich stand. If spectral and fractional cover measurements from this day are removed the correlation improves ($R = 0.56$). Sub-xeric had the lowest correlation due to the fact that the upper understory cover is missing or it is very sparse. There is also a very small variation in

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**Fig. 3.** The spectra of herb-rich, transitional bog, sub-xeric and mesic sites understory layers during the growing period. (A) Spring (DOY 136–150), (B) early summer (DOY 164–179), (C) mid-summer (DOY 192–217), (D) late summer (DOY 234–272). [The error bars show standard deviation.]

**Fig. 4.** The seasonal change in red edge inflection points for the herb-rich (diamonds), transitional bog (triangles), mesic (crosses), and sub-xeric (squares) site understory layers. [The error bars show standard deviation.]
the cover percentage and HDRFs during the summer that causes a low correlation for sub-xeric site.

**Narrowband indices PRI and PSRI**

Two narrowband vegetation indices, photochemical reflectance index (PRI) and plant senescence reflectance index (PSRI) were examined next (Fig. 6). Due to the fact that PRI is related to the photosynthetic efficiency the most fertile site (herb-rich) had the highest values and the least fertile site (sub-xeric) has the lowest PRI values. In addition, the PRI values in autumn were considerably lower than in spring, possibly since the final decay of the plant material occurred only during the winter. The herb-rich site had a drop in PRI value on DOY 179 that was partially caused by human interference (vegetation was disturbed and stomped upon by a third party). From this data it could be seen that the vegetation recovered quickly, the disturbance was not severe and did not affect further development of the vegetation. For the mesic and sub-xeric sites the drop was most likely caused by too moist soil due to heavy rain on the previous day (DOY 178) (Barton and North, 2001). The drop in PRI value on DOY 179 can indicate that the original findings by Panigada et al. (2014) and Suárez et al. (2008), showing decreased PRI values can be connected with moister conditions that can cause stress, might be valid in the hemi-boreal region as well.

Hesketh and Sánchez-Azofeifa (2012) previously observed that higher PSRI values are observed in the dry forest sites and lower values are observed in more humid sites. This is in agreement with our findings with higher PSRI values at the dry sub-xeric site and lower values at the moist transitional bog (Fig. 6B). When compared with PRI, PSRI also had slightly higher values in autumn than in spring. The higher value on the DOY 179 further confirmed the effect of interference at the herb-rich site and its quick recovery. Senescence was the most notable for herb-rich and mesic sites.

**HDRFs corresponding to MODIS channels**

Finally a seasonal course of the broadband HDRFs corresponding to the MODIS green, red, and NIR bands (Fig. 7) was examined. For all understory types the weakest seasonal dynamics were observed in the NIR band and the strongest in the red band during the study period. From NIR and green bands it could be observed the peak of the growing period fell on DOY 197 where transitional bog, herb-rich and mesic sites had the highest reflectance values. Different site types were distinguishable in NIR band, where all the site types had the highest values in mid-summer (DOY 192). This was true except for the sub-xeric site, which had higher values in late summer when the understory reflectance was influenced by the fallen leaves. In red band the least and most fertile sites were clearly distinguishable (least fertile had the highest values and most fertile had the lowest values), but classification beyond this point was not possible in that band. The higher value in late summer (DOY 259) for the herb-rich stand was caused by the senescence and decay of the plant material. For the sub-xeric site the increased values in late summer were caused by the fallen leaves.

Normalized Difference Vegetation Index (NDVI; Fig. 7D) was computed from the broadband red and NIR HDRFs. The NDVI corre-
Fig. 7. The seasonal course of HDRF’s corresponding to MODIS channels for herb-rich, transitional bog, sub-xeric, and mesic site understory layers. (A) Green (545–565 nm), (B) red (620–670 nm), (C) NIR (842–875 nm), (D) normalized difference vegetation index (NDVI).

Conclusions

In this paper, we documented the seasonal variation (April–September) and spectral changes occurring in typical European hemi-boreal forest understory layers. When compared with previous similar study carried in a boreal forest in Finland, it can be seen that it was not possible to make easy generalizations about the understory even for the stands with the same overstory tree species. The understory layers were clearly much different, and this has important implications for forest reflectance models as well, where site-specific values would be required for their accurate and successful inversion. Overall it can be also concluded that vegetation processes in hemi-boreal forests of Järvselja are at least a week ahead of southern boreal forests in Hyytiälä, 3° (~500 km) north of Järvselja.

The collected dataset presented within this study would be of much use to improve and validate algorithms or models for extracting spectral properties of understory from multi-angular remote sensing data. It can be also further used as a valuable input in radiative transfer simulations that are used to quantify the roles of forest tree layer and understory components in forming a seasonal reflectance course of a hemi-boreal forest, and the upcoming phases of the RARadiation Model Intercomparion (RAMI) experiment.

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References


Estonian Environment Agency, webpage (Former EMHI)


