Hadi, Hadi; Rautiainen, Miina

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A study on the drivers of canopy reflectance variability in a boreal forest

Hadi and Miina Rautiainen

Department of Built Environment, Aalto University, School of Engineering, Aalto, Finland; Department of Electronics and Nanoengineering, Aalto University, School of Electrical Engineering, Aalto, Finland

ABSTRACT

The degree of which the observable canopy bidirectional reflectance factors (BRF) express plant trait variation at leaf and canopy scales is the fundamental physical basis underlying the use of optical remote sensing data for discriminating tree species and estimating forest biophysical variables. In this study, we quantified the relative contribution of variations in leaf optical properties (LOP), canopy structural properties, and understory reflectance, to canopy BRF variability in a boreal forest, at the spatial and spectral resolutions of Sentinel-2 (S2) Multi-Spectral Instrument. Our approach was based on physically-based forest reflectance model and global sensitivity analysis (SA) parameterized entirely with field measurements. Results showed LOP had dominant contribution to canopy BRF in shortwave infrared (SWIR) in multi-species forest areas, while canopy gap fraction in sensor’s view direction (i.e. nadir) was consistently found as the main driver of canopy BRF in red. This implies the satellite-measured BRF in red is the most robust predictor of effective canopy cover (ECC), while BRF in SWIR are optimal for tree species classification based on interspecific differences in mean leaf traits.

1. Introduction

Recent studies have called for attention on the critical importance of distinguishing physically-based causality, from indirect, possibly spurious empirical correlation, in attributing the observable canopy reflectance to traits at the scale of, individual foliage element versus whole canopy (Knyazikhin et al. 2013; Townsend et al. 2013). Indeed, systematically quantifying the contribution of canopy structural properties, versus leaf optical properties (LOP), to satellite-measured variability in forest canopy reflectance (bidirectional reflectance factors, BRF) is the most logical way of assessing the potential improvements and limitations in using optical remote sensing data for two common practical tasks: estimating forest biophysical variables and discriminating tree species. Whereas BRF variability between plots (i.e. pixels) that can be attributed to canopy structural variations contains diagnostic information of forest biophysical variables, the variability attributable to LOP variations is indicative of tree species differences. The
latter is because species differences in mean leaf traits, and thus LOP, is potentially a more stable discriminatory feature, than canopy architecture, which depends on, in addition to species, site quality and forest management practices (Fassnacht et al. 2016).

A feasible and theoretically sound way of assessing the contribution of LOP versus canopy structural properties to canopy BRF is by using the well-established physically-based principles of photon radiative transfer. Among the available canopy reflectance models, recently the PARAS model, which is especially developed for heterogeneous forest canopies, and is based on spectral invariant theory (Stenberg, Mõttus, and Rautiainen 2016; Knyazikhin et al. 2011), has emerged as a simple parameterization of canopy radiation budget (Hovi, Lukeš, and Rautiainen 2017). With demonstrably accurate performance of the model, the relative contribution of variation in LOP, versus variation in canopy structural properties, to canopy BRF, can be assessed through sensitivity analysis (SA) of the model. In particular, global SA which simultaneously varies the inputs of the investigated model, is advantageous over local SA because global SA can more fully explore the model input space and handle complex, non-linear model (Saltelli et al. 2010). Global SA of a canopy radiative transfer (RT) model has been demonstrated in previous studies (e.g. Hadi et al. 2017; Verrelst et al. 2015; Mousivand et al. 2014).

To derive proper, ecologically meaningful interpretation from global SA experiments, the degree of perturbation applied to the model inputs should be well constrained within the ecologically realistic range at any given place (ecosystem type) and time (seasonality) (Asner et al. 2000). Therefore, applying variations based on field data, whenever possible, is more justified over basing them on values reported in literature, or simply on an arbitrary decision. The increasing availability of publicly accessible spectral libraries of LOP (e.g. Hovi, Raitio, and Rautiainen 2017) helps make possible such a more realistic evaluation.

In this study, we quantified the relative contribution to boreal forest canopy BRF from variations in (i) LOP, (ii) canopy structural properties, and (iii) understory reflectance, using the PARAS forest BRF model and variance-based global SA procedure. We utilized an exceptional dataset comprising measurements of the three BRF driving factors specified above, from a boreal forest in southern Finland. We carried out the analysis at the spatial and spectral resolutions of the MSI sensor on board the recently operational Sentinel-2 (S2) satellites. Data from an S2 image was used to validate the simulations. Results from global SA experiments were interpreted primarily within the context of tree species classification and the estimation of effective canopy cover (ECC), which is closely related to the ‘fraction of vegetation cover’ in the planned S2 Level 2B product (Drusch et al. 2012).

2. Materials and methods

2.1. Field data

All measurements of LOP, canopy structure, and understory reflectance were carried out in the vicinity of Hyytiälä Forestry Field Station which is located in southern Finland (61° 50’ N, 24°17’). The area is under forest management and is dominated by Norway spruce (Picea abies (L.) Karst), Scots pine (Pinus sylvestris L.), and birches (Betula pendula Roth,
*Betula pubescens* Ehrh). The understory is covered by mosses, and depending on site fertility, also grasses, herbs, dwarf shrubs or lichens.

LOP i.e. leaf/needle reflectance and transmittance spectra (directional-hemispherical reflectance and transmittance factors i.e., DHRF and DHTF) of tree species in the 350 nm to 2500 nm were measured with ASD FieldSpec 3 PRO spectroradiometer and ASD RTS-3ZC integrating sphere in June 2012. For each species, leaves/needles were collected from 10 mature trees, located in three stands of different age classes and stand densities. From each tree, leaves/needles were collected from one branch in sun-exposed, and one branch in shaded canopy position. In total, 20–30 leaf/needle samples per species were measured. Both adaxial and abaxial sides of the leaves/needles were measured for birch and pine. For details of the measurements see Lukeš et al. (2013).

Canopy structural properties were measured in 21 plots with LAI-2000 Plant Canopy Analyzer, between 29 June and 1 July 2015. The plots were purposefully located to encompass the spatial variation of forest stands in the area in terms of species composition, age class (25–100 years), and site fertility (Table 1). In each plot, a total of 12 measurement points were located i.e. 3 points in each cardinal direction at 4m intervals so that the distances between the southernmost and northernmost, and the westernmost and easternmost measurement points were 20m (Majasalmi et al. 2012). LAI-2000 measures canopy gap fractions in five view zenith angles from 0° to 75°, and effective leaf area index (LAI_{eff}). ECC, defined as percentage of land area covered by the vertical projection of tree crowns, excluding within-crown gaps (Korhonen et al. 2017), is approximated as one minus canopy gap fraction in first ring (0°-15°).

Understory reflectance spectra (hemispherical-directional reflectance factors i.e., HDRF) in 350 nm to 2500 nm were measured with ASD FieldSpec 3 PRO spectroradiometer in 5 sites in June 2009. The sites represent the three most common site fertility types in the study area i.e., with decreasing fertility, herb-rich, mesic, and xeric site types. In each site, a total of 80–120 measurements of understory HDRF were acquired along transects. For more details on measurement set-up, see Rautiainen et al. (2011).

**Table 1.** A summary of study stands. Except for the number of plots, values shown are ranges.

<table>
<thead>
<tr>
<th>Stand variables</th>
<th>Pine-dominated*</th>
<th>Spruce-dominated</th>
<th>Birch-dominated</th>
<th>Mixed species</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of plots</td>
<td>5</td>
<td>7</td>
<td>6</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Mean diameter at breast height i.e., 1.3 m (cm)</td>
<td>15.6–27.8</td>
<td>13.7–25.3</td>
<td>11.9–20.4</td>
<td>7.0–26.5</td>
<td>7.0–27.8</td>
</tr>
<tr>
<td>Mean tree height (m)</td>
<td>12.3–23.2</td>
<td>12.8–22.1</td>
<td>14.5–21.3</td>
<td>9.3–23.1</td>
<td>9.3–23.2</td>
</tr>
<tr>
<td>Basal area (m² ha⁻¹)</td>
<td>15–30</td>
<td>20–37</td>
<td>11–27</td>
<td>9–42</td>
<td>9–42</td>
</tr>
<tr>
<td>Effective canopy cover, ECC (%)</td>
<td>49.2–74.8</td>
<td>51.4–83.9</td>
<td>36.7–95.1</td>
<td>69.7–90.2</td>
<td>36.7–95.1</td>
</tr>
<tr>
<td>Effective leaf area index, LAI_{eff} (m² m⁻²)</td>
<td>1.49–2.75</td>
<td>2.08–3.86</td>
<td>1.02–4.60</td>
<td>1.34–3.79</td>
<td>1.02–4.6</td>
</tr>
<tr>
<td>True leaf area index, LAI_{true} (m² m⁻²)</td>
<td>3.74–5.17</td>
<td>3.73–7.14</td>
<td>1.70–6.04</td>
<td>1.68–7.59</td>
<td>1.68–7.59</td>
</tr>
<tr>
<td>Clumping index (CI) ¤</td>
<td>0.34–0.57</td>
<td>0.39–0.60</td>
<td>0.60–0.89</td>
<td>0.50–0.80</td>
<td>0.34–0.89</td>
</tr>
<tr>
<td>Species basal area fraction (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pine</td>
<td>75–100</td>
<td>0–22</td>
<td>0</td>
<td>0–57</td>
<td>0–100</td>
</tr>
<tr>
<td>Spruce</td>
<td>0–8</td>
<td>70–100</td>
<td>0–30</td>
<td>33–46</td>
<td>0–100</td>
</tr>
<tr>
<td>Birch</td>
<td>0–17</td>
<td>0–23</td>
<td>70–100</td>
<td>10–67</td>
<td>0–100</td>
</tr>
<tr>
<td>Number of plots by site fertility type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herb-rich</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Mesic</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>Xeric</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

* >70% species basal area fraction. ¤_corrected for shoot- and crown- level foliage clumping. °Total clumping index at both shoot and crown levels i.e., CI = LAI_{eff}/LAI_{true}.
2.2. Satellite data

We downloaded an S2A image scene acquired on 17 August 2015 (tile number 34VFP, sun zenith angle 41.33°) from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). Atmospheric correction was performed using Sen2Cor version 2.4.0 (http://step.esa.int/main/third-party-plugins-2/sen2cor/). The satellite-measured BRF (i.e. surface reflectance) were extracted at the coordinates of the forest plots’ centre with a buffer of 12.5 m.

2.3. Forest BRF simulations

Conceptually, the PARAS BRF model (Rautiainen and Stenberg 2005) simulates forest canopy BRF as a sum of BRF contributions from forest understory (BRF_U), and forest canopy (BRF_C). BRF_U represents photons that are directly transmitted to understory, then reflected by understory and escapes the canopy towards the sensor. That is, BRF_U depends on the canopy bidirectional gap probability (i.e., portion of the understory that receives direct illumination from the sun and viewed by sensor) and reflectance of understory (\( \rho_g \)):

\[
BRF_U = cgf(\theta_{\text{sun}}) \times cgf(\theta_{\text{view}}) \times \rho_g,
\]

where \( cgf(\theta_{\text{sun}}) \) is canopy gap fraction in sun illumination direction, \( cgf(\theta_{\text{view}}) \) in sensor view direction. BRF_C represents incoming photons that are directly intercepted by the canopy, then scattered towards the sensor (nadir direction in this case):

\[
BRF_C = i_0 \times \omega_C \times Q,
\]

where \( i_0 \) is canopy direct interceptance (\( i_0 = 1 - cgf(\theta_{\text{sun}}) \)), \( \omega_C \) canopy scattering coefficient, and \( Q \) fraction of upwards scattered photons. The \( \omega_C \) upscales the leaf/needle-level signal i.e. leaf/needle single-scattering albedo (\( \omega_L = \text{DHRF} + \text{DHTF} \)) to canopy level using a spectrally-invariant parameter called photon recollision probability (\( p \)). The \( p \) in turn is analytically derived using the formula proposed by Stenberg (2007), of which \( p \) depends primarily on the degree of foliage clumping. The complete formulas of the PARAS BRF model and their references can be found e.g. in our previous publication (Hadi et al. 2017). For information on the PARAS model parameterization in this study, see Table 2.

We resampled the PARAS-simulated BRF according to the S2A sensor spectral response function. The simulated S2A BRF were then compared against measured S2A BRF based on Pearson’s correlation coefficient (\( r \)), mean difference (MD), root mean square difference (RMSD), and root mean square difference corrected for bias (RMSDC), similarly as in Hadi et al. (2017).

2.4. Global SA experiments

We applied a variance-based global SA i.e. the modified Sobol’ method proposed by Saltelli et al. (2010), to the PARAS BRF model. Relative contribution of input \( i \) to forest canopy BRF was assessed based on the total-effect sensitivity index (\( S_{Ti} \)), which is the share of variance of output (BRF) that is due to input \( i \) (i.e. first-order effect) and the interaction between input \( i \) and the other inputs (i.e. higher-order effects).

The global SA was performed by varying PARAS first-order inputs (i.e. LAI_{eff}, \( i_0 \), \( cgf(\theta_{\text{view}}) \), CI, \( \omega_L \), and \( \rho_g \); see Section 2.3) within their measured ranges according to field data. Note that here \( cgf(\theta_{\text{view}}) = 1-\text{ECC} \) as BRF were modelled for a nadir-viewing sensor. The input space (multivariate uniform distribution) was sampled using the Sobol scheme (\( n = 20,000 \)).
We performed the global SA with variations based on all plots (i.e. the case of large area mapping with large gradient in broadleaf-conifer mixture), as well as separately by species (i.e. the case of monospecific stands). In our experiment, range of $\omega_L$ was based on plot-level $\omega_L$ (i.e., species-specific mean $\omega_L$ weighted by species basal area fraction), and thus represents variability due to varying species composition. Variability in $\rho_g$ was given as range among mean $\rho_g$ per site fertility type, based on site fertility types observed in the field. Sun zenith angle was set to typical time of satellite overpass in the area during midsummer, i.e. $\text{cgf}(\theta_{\text{sun}})$ is canopy gap fraction in LAI-2000 $3^{rd}$ ring (32°-43°).

### Table 2. Parameterization of inputs to bidirectional reflectance factors (BRF) simulations for the forest plots ($n = 21$) in this study.

<table>
<thead>
<tr>
<th>Input</th>
<th>Description and formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>True leaf area index ($\text{LAI}_{\text{true}}$)</td>
<td>$\text{LAI}<em>{\text{true}} = \text{LAI}</em>{\text{eff}}/\text{CI}$, where $\text{LAI}_{\text{eff}}$ is effective leaf area index, and CI is clumping index estimated at shoot level (coniferous species) and crown level. Shoot-level CI was calculated as weighted average of species-specific shoot-level CI i.e. 0.59 for pine (Smolander, Stenberg, and Linder 1994), 0.64 for spruce (Stenberg, Linder, and Smolander 1995), and 1.00 for birch. The weights used were species basal area fraction. Crown-level clumping correction was done similarly as in Hovi et al. (2017) based on inversion of the gap fraction formula by Nilson (1999).</td>
</tr>
<tr>
<td>Canopy scattering coefficient ($\omega_C$)</td>
<td>$\omega_C = \frac{\omega_L}{1-p}$, where $p$ is photon recollision probability, and plot-level $\omega_L$ was calculated as weighted average of species-specific mean $\omega_L$. The weights used were species basal area fraction. In calculating species-specific mean $\omega_L$, we gave equal weights for all measurements i.e. of adaxial and abaxial foliage sides, and sun-exposed and shaded canopy positions.</td>
</tr>
<tr>
<td>Canopy gap fraction in sun's direction ($\text{cgf}(\theta_{\text{sun}})$)</td>
<td>Canopy gap fraction at 41.33° (i.e. sun zenith angle during image acquisition), estimated by fitting a $2^{nd}$ order polynomial to the measured canopy gap fractions (five zenithal rings).</td>
</tr>
<tr>
<td>Understory reflectance ($\rho_g$)</td>
<td>Mean understory HDRF (hemispherical-directional reflectance factors) for the corresponding site fertility type (either herb-rich, mesic, or xeric).</td>
</tr>
</tbody>
</table>

We performed the global SA with variations based on all plots (i.e. the case of large area mapping with large gradient in broadleaf-conifer mixture), as well as separately by species (i.e. the case of monospecific stands). In our experiment, range of $\omega_L$ was based on plot-level $\omega_L$ (i.e., species-specific mean $\omega_L$ weighted by species basal area fraction), and thus represents variability due to varying species composition. Variability in $\rho_g$ was given as range among mean $\rho_g$ per site fertility type, based on site fertility types observed in the field. Sun zenith angle was set to typical time of satellite overpass in the area during midsummer, i.e. $\text{cgf}(\theta_{\text{sun}})$ is canopy gap fraction in LAI-2000 $3^{rd}$ ring (32°-43°).

### 3. Results and discussion

Firstly, we assessed PARAS simulation (PARAS BRF) with satellite measurements (S2 BRF). Generally PARAS BRF are systematically higher than S2 BRF (Table 3). However, PARAS simulation taking into account crown-level (in addition to shoot-level) clumping correction reduces the differences in all spectral bands. We note however, S2 BRF has been shown in previous studies to be systematically lower than e.g. Landsat BRF (Korhonen et al. 2017; Vuolo et al. 2016). As Landsat BRF has been more rigorously validated, we suspect S2 BRF to be likely underestimated. More importantly, the linear correlation between PARAS BRF and S2 BRF is relatively high, indicating PARAS BRF well represent the variability (dynamic) in S2 BRF. Therefore, we can reliably analyze BRF variability based on global SA of PARAS BRF model.

Next, global SA was applied for all plots, and separately for birch-dominated, pine-dominated, and spruce-dominated plots (Figure 1). In the ‘all plots’ case (Figure 1(a)) representing full gradient in species composition, variations in canopy structural properties provide the highest contribution (i.e. highest $S_T$) to BRF variability from visible to RE1, while from RE2 to SWIR2, LOP i.e. $\omega_L$ provide the highest contribution. BRF contribution from $\omega_L$ is dominant in SWIR. Among the canopy structural properties, the degree of foliage clumping (CI) is most influential. This is because CI determines $p$ within the canopy (Stenberg 2007).
In the monospecific case (Figure 1(b-d)), $\omega_L$ contribution ceases to dominate, and canopy structure primarily drives BRF across the optical domain from blue to SWIR2. We performed global SA with pine and spruce data pooled together and saw minor
contribution (maximum 18%) of $\omega_L$ across all S2 bands (Table 4). Therefore, the strong expression of $\omega_L$ in the ‘all plots’ case is due to $\omega_L$ difference between broadleaved (birch) and coniferous group (pine and spruce). CI is less influential in birch plots than coniferous plots because coniferous needles are additionally clumped in shoot structure.

Together, the above results suggest, when using S2-like data in southern boreal forests similar to our study site: (1) discrimination between pine and spruce is not physically possible, especially if BRF is not corrected for canopy structure effect; (2) BRF from RE2 to SWIR2, and especially in SWIR, are optimal to discriminate broadleaved vs. coniferous group; and (3) in NIR, the commonly observed higher BRF in birch plots (as compared to pine and spruce) is primarily due to higher albedo of birch leaves (as compared to pine and spruce needles), rather than only due to differences in canopy structure.

The strong expression of LOP from RE2 to SWIR2 for the ‘all plots’ case is surprising. Recall that here contribution is measured with $S_{T,i}$, which includes contribution from interaction between inputs. We compared $S_{T,i}$ and first-order effect, and found the difference between the two was generally negligible (<10% absolute contribution), except in red spectral band for input $i_0$ and $cgf(\theta_{\text{view}})$, where interaction effects added 12%-13% contribution for ‘all plots’ and monospecific birch cases. The conclusions on the most important drivers of BRF are therefore nevertheless the same.

In all cases, BRF in red is consistently most sensitive to variation in $cgf(\theta_{\text{view}})$, and thus ECC. This suggests the relationship between red BRF and ECC is robust (i.e. it is a direct causal link) against variation in species composition, forest structure (e.g. density), and site fertility type. This provides a direct physical explanation to previous empirical studies using medium resolution satellite data that found red BRF as best predictor of ECC (Korhonen et al. 2017) and canopy cover (Hadi et al. 2016) in boreal forests. BRF variability in red was also identified as mostly contributed by ECC variation in dense tropical forests with much higher species diversity (Hadi et al. 2017), suggesting the robustness of ECC estimation with red BRF extends across forest structural and species diversity. Further, ECC contribution to red BRF in the monospecific cases (Figure 1(b-d)) is not higher, or even lower, than the ‘all plots’ case, suggesting stratification by species would unlikely improve ECC estimation accuracy.

In the weakly absorbing wavelengths (from RE2 to NIRn), canopy zero-order interceptance ($i_0$) strongly influences BRF and especially dominates BRF in birch-dominated

Table 4. Relative contribution of (a) variation in effective canopy cover, and (b) interspecific variation in leaf albedo to boreal forest bidirectional reflectance factors (BRF) at plot scale (i.e. observation scale of medium spatial resolution satellite) in different bands. B: blue; G: green; R: red; RE: red edge; NIRn: near-infrared narrow; SWIR: shortwave-infrared.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>G</th>
<th>R</th>
<th>RE1</th>
<th>RE2</th>
<th>RE3</th>
<th>NIRn</th>
<th>SWIR1</th>
<th>SWIR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>All plots (pine, spruce, birch)</td>
<td>31</td>
<td>17</td>
<td>55</td>
<td>24</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>Effective canopy cover</td>
<td>3</td>
<td>13</td>
<td>2</td>
<td>12</td>
<td>35</td>
<td>45</td>
<td>46</td>
<td>54</td>
<td>51</td>
</tr>
<tr>
<td>Interspecific variation in leaf albedo</td>
<td>26</td>
<td>18</td>
<td>45</td>
<td>22</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>33</td>
<td>42</td>
</tr>
<tr>
<td>Coniferous plots (pine, spruce)</td>
<td>11</td>
<td>8</td>
<td>1</td>
<td>11</td>
<td>8</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Effective canopy cover</td>
<td>6</td>
<td>8</td>
<td>1</td>
<td>11</td>
<td>8</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>13</td>
</tr>
</tbody>
</table>
plots (Figure 1). There were no extreme outlier values of $i_0$ in our data. Note that in the PARAS BRF model, $i_0$ (equals $1 - cgf(\theta_{sun})$) influences both canopy and understory spectral contributions, through determining the amount of incoming photons directly intercepted by canopy, and the amount transmitted to the understory. We ran global SA with very dark background ($\rho_g=0.0001$), and saw $i_0$ was still influential, suggesting its importance is largely due to determining the fraction of canopy foliar area that are directly illuminated by the sun.

Variation in $\rho_g$ due to different site fertility type has negligible influence on BRF in all global SA cases (Figure 1). Understory spectral contribution ($BRF_U = cgf(\theta_{sun}) \times cgf(\theta_{view}) \times \rho_g$) is more determined by canopy structure, which in turn determines the bidirectional gap probabilities (i.e. $cgf(\theta_{sun}) \times cgf(\theta_{view})$). This provides the physical explanation to the finding of Hadi et al. (2016) in which site fertility types have minor influence on the errors of predicting boreal forest canopy cover. Another implication of non-influential $\rho_g$ is that in the retrieval of canopy structural variables, such as ECC, using physically-based RT model inversion, the impact of uncertainty in $\rho_g$ parameterization is likely minimal.

4. Conclusions

Our physically-based analysis of BRF drivers provide two most important practical suggestions in the applications using multispectral satellite data with medium spatial resolution e.g. S2 in boreal forests. Firstly, BRF in red is the most robust (universal) predictor of ECC. Further, stratification of the area of interest by tree species is not necessary to improve ECC estimation accuracy. Secondly, BRF in SWIR are optimal for plot/pixel-level tree species classification between birch and conifer (pine and spruce); discrimination between pine and spruce is however physically not feasible.

Acknowledgments

We thank Petr Lukeš for providing leaf optical data, Titta Majasalmi for LAI measurements, and Aarne Hovi and Sara Alibakhshi for fruitful discussion. The Sentinel-2 image is provided at no-cost by the European Space Agency.

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