PERFORMANCE OF THE PROSPECT LEAF RADIATIVE TRANSFER MODEL VERSION 4 FOR NORWAY SPRUCE NEEDLES

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ABSTRACT

Leaf optical properties (LOPs) are a key input parameter for vegetation canopy radiative transfer models. The uncertainty introduced in the measurement and/or the simulation of this spectral information determines a final reliability of the modelled canopy reflectance. The broad-leaf radiative transfer model PROSPECT version 3.01 has been previously applied for some needle-leaf type species (e.g. pine trees) to estimate biochemical parameters through its inversion. Nevertheless, in a particular case of Norway spruce (Picea abies (L.) Karst.) PROSPECT 3.01 showed a poor performance in near infrared wavelengths and had to be recalibrated. Therefore, the applicability of PROSPECT version 4, which has been recently released, is verified for this type of leaves in this experiment. Forward simulations of an optimized version of the original PROSPECT 4 suggest that it is possible to reduce the average RMSE of reflectance and transmittance from 8% to 3.5-4% in the near infrared domain. For this achievement, the absorption coefficients for chlorophyll and dry matter together with the refractive index had to be simultaneously optimized via model inversion using measured LOPs of Norway spruce needles.

1. INTRODUCTION

Estimation of forests quantitative parameters from spectroscopy images through a physical model based up-scaling approach requires: (1) an accurate measurement and (2) and accurate simulation of leaf optical properties (LOPs), i.e. a leaf incident light reflectance, transmittance, and absorption. The spectral information at leaf level is scaled up to the forest canopy level through radiative transfer modeling and thus, errors introduced at the leaf level increase uncertainty of modeled reflectance at the canopy level. Driving factors of the leaf radiative transfer are the biochemical composition (e.g. foliar pigments, lignin, cellulose, water, etc.) and the leaf physical characteristics related not only to the external surface structure, but also to its inner cellular configuration. In case of coniferous species, such as Norway spruce, the small size and non-bifacial structure of the leaves makes the proper measurement and simulation of optical properties a challenging issue. First, measuring needle LOPs in an integrating sphere connected to a spectroradiometer has a technical constrain when compared to broad bifacial leaves, because the size of measured sample is smaller than the illumination area of the incident light beam. Thus a set of several sample leaves has to be measured simultaneously to ensure a sufficient signal-to-noise performance of the device. Sufficient signal level cannot be achieved by illuminating only one needle-shape leaf or by reducing the illuminated area to the dimensions of a needle width. That means that the needles need to be mounted next to each other, while leaving a gap of appropriate size in-between them. Consequently, such a set-up requires correction for photons passing through the gaps. At the same time the scattering processes occurring in between the needles as a consequence of their non-flat shape nature affect the recorded signal. Mesarch et al. (1999) presented a methodology for narrow needle LOPs measurement, including the in-between leaves gap correction, which was later adopted by Malenovsky et al. (2006) for Norway spruce needles (Figure 1).

Figure 1. Measurement of needle optical properties from Norway spruce (Malenovsky et al. 2006).

Secondly, the scaling-up retrieval approaches require an appropriate simulation of needle optical properties. Here, similar issues related to narrow shape and specific inner cellular structure of needle leaves should be taken into the account when simulating the photons radiative
transfer (RT). A number of leaf RT models of different complexity has been designed, starting from the plate models, passing through N-flux models, radiative transfer equation-based, or stochastic models up to the highly accurate, but computationally demanding ray tracing models (Ustin et al., 2001). The decision towards using one or the other is related to user needs and resources. Most important factors are: the complexity of the model parameterization, the computational demands, and the inversion capabilities. PROSPECT model (Jacquemoud and Baret, 1990) is a semi-empirical leaf RT model that is extensively used due to the low number of inputs and consequent high inversion ability, while keeping a good robustness in simulation accuracy. As a plate model, PROSPECT assumes that the leaf is composed by air separated parallel plates of cells, which are infinite in the horizontal directions. This assumption is not completely fulfilled in case of the needle leaves, which are narrow and have cell layers surrounding in circles the central vascular bundle. In spite of this, the PROSPECT version 3.01 has been directly applied to simulate LOPs of some coniferous species (Zarco-Tejada et al., 2004a). However, a significant disagreement between the measured and simulated spectra, particularly within the near infrared part of the electromagnetic spectrum, was identified in case of the Norway spruce needles (Malenovsky et al., 2006). To correct this discrepancy, the authors applied a model recalibration scheme based on the simultaneous optimization of the chlorophyll and dry matter specific absorption coefficients (k_{ab} and k_{m}) together with a retrieval of the inner structural parameter N, resulting in spruce specific version called PROSPECT 3.01S. A new version 4 of the PROSPECT model was recently released (Feret et al., 2008), offering a higher spectral sampling of 1 nm (previous version had 5 nm) and the updated values of specific absorption coefficients (k_{ab}, k_{ap}, and water absorption coefficient k_{w}), of refractive index of leaf material (n), and of leaf surface roughness parameter (\sigma). Therefore, the objective of this paper is to evaluate the performance of new PROSPECT version 4 for Norway spruce needles, and to compare it with the previous model versions 3.01 and 3.01S.

2. MATERIALS AND METHODS

2.1. PROSPECT input datasets

The datasets of measured LOPs and the complementary biochemical information required as PROSPECT input (Jacquemoud and Baret, 1990) were collected within the Norway spruce forest stands located at Moravian-Silesian Beskydy Mts. (Czech Republic), during the ground campaigns conducted in 2004 and 2006. The sampling setup and laboratory protocols for foliar pigment extraction and measurements of leaf optical properties were adopted from (Malenovsky et al., 2006). The datasets are divided in age-specific subsets (1-year, 2- or 3-years old needles) based on results of a one-way ANOVA test. ANOVA was performed on the measured biochemical information (chlorophyll, dry matter and water content) and revealed the highest statistically significant difference occurred between the needle age generations. Each needle-age group contains a balanced distribution of needle samples collected from the three main functional parts of the tree crown, i.e. from the upper part or sun exposed, from the middle part called transitional, and from the lower shaded part (Malenovsky et al., 2006). Subsequently the dataset is divided in two randomly selected subsets, called ‘training’ (173 samples) and ‘testing’ subsets (103 samples). The first one was used for the model recalibration and the last one for model verification and validation purpose (Figure 2).

2.2. PROSPECT verification, inversion and validation

The analysis was focused on the accuracy assessment of three PROSPECT versions by performing the forward simulation of spruce needle optical properties between 450-1600 nm. The accuracy assessment of the biochemical inputs estimated by the model inversion is currently being in progress and thus not included in this
paper. The spectral range 350 to 450 and 1600 to 2500 nm was excluded due to the high noise contamination. Direct comparison of the measured and simulated needle optical properties between 450–1600 nm was done to evaluate the performance of the model versions. Within the first objective, forward simulations of original PROSPECT versions 3.01 and 4 were carried out using the ‘testing’ subset. Evaluation of the resulting simulations was done via direct comparison with the corresponding optical properties measured in laboratory (Figure 2). The results of this first part, did not approve direct applicability of both model versions for Norway spruce needles, therefore, a recalibration procedure following the optimization scheme proposed by Malenovsky et al. (2006) was carried out in both cases. The recalibration optimized PROSPECT $k_{ab}$ and $k_{m}$ absorption coefficients together with the $N$ structural parameter using the ‘training’ dataset. The result is an updated 3.01S version at 1 nm spectral resolution (originally 5 nm resolution) and what we call 4.01 version, a Norway-spruce-needles adapted version of the original PROSPECT version 4 (see Figure 2). Since new PROSPECT version 4 contains not only an update of the specific absorption coefficients, but also an update of the refractive index of leaf material ($n$), an inversion scheme fitting these four parameters simultaneously ($k_{ab}$, $k_{m}$, $N$ and $n$) was performed in next step. The result of this second model recalibration is called PROSPECT version 4.02. Finally, new PROSPECT versions 3.01S, 4.01 and 4.02 were validated in forward simulations of the ‘testing’ subset LOPs, and subsequent comparison with corresponding measurements.

3. RESULTS

The LOPs simulated by PROSPECT version 3.01 and 4 for ‘testing’ dataset were directly compared with the measured spectra between 450–1600 nm. This verification test approved an unacceptable performance of PROSPECT 3.01, as previously reported by Malenovsky et al. (2006), and also of new PROSPECT version 4 for case of Norway spruce needles (Table 1).

<table>
<thead>
<tr>
<th>Prospect version</th>
<th>aRMSE reflectance (%) 450-1600 nm</th>
<th>aRMSE transmittance (%) 450-1600 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3.01</td>
<td>6.35</td>
<td>6.41</td>
</tr>
<tr>
<td>P4</td>
<td>7.01</td>
<td>7.04</td>
</tr>
<tr>
<td>P3.01S</td>
<td>2.33</td>
<td>2.56</td>
</tr>
<tr>
<td>P4.01</td>
<td>3.83</td>
<td>3.85</td>
</tr>
<tr>
<td>P4.02</td>
<td>2.98</td>
<td>3.19</td>
</tr>
</tbody>
</table>

The average RMSE (aRMSE) computed for needle reflectance and transmittance from 450 to 1600 nm was 6% in case of PROSPECT 3.01, and 7% in case of PROSPECT 4. For the different needle-age groups the aRMSE varies from 5% for 1-year old, to 6% for 2-years old, and 7% for 3-years old needles in both reflectance and transmittance. For PROSPECT version 4, the 1-year old needle subset gained the aRMSE of 6% for reflectance and also transmittance, 7% for 2-years and 8% for 3-years old needles.
4.01, resulted in an aRMSe of 3.8 \% for reflectance (4\%, 3.9\% and 3.8\% for 1-, 2- and 3-years old needles, respectively). For transmittance the same error occurred, being aRMSe of 3.9\% for the 3-years old needle subset and 3.8\% for the two remaining age groups. PROSPECT version 4.02 (with n refractive index of leaf material recalibrated simultaneously with kab, km and N) resulted in aRMSe of 3\% for reflectance and transmittance (3.3\%, 2.8\% and 2.9\% for the 1-, 2- and 3-years old needles, respectively, in reflectance and 3.5\%, 3.2\% and 2.9\% for the same age groups in transmittance). It is important to note that for the wavelength range from 450 to 720 nm the accuracy of the three spruce-adapted versions is very similar (Figure 3). In case of the NIR part of the spectrum, extension of the optimization scheme by the refractive index n (PROSPECT version 4.02) improved the performance of the model in simulating both reflectance and transmittance spectral signatures (Table 2).

<table>
<thead>
<tr>
<th>Prospect version</th>
<th>aRMSe reflectance (%) 750-1600 nm</th>
<th>aRMSe transmittance (%) 750-1600 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3.01</td>
<td>7.10</td>
<td>7.32</td>
</tr>
<tr>
<td>P4</td>
<td>7.98</td>
<td>7.85</td>
</tr>
<tr>
<td>P3.01S</td>
<td>3.93</td>
<td>4.06</td>
</tr>
<tr>
<td>P4.01</td>
<td>4.64</td>
<td>4.57</td>
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<tr>
<td>P4.02</td>
<td>3.52</td>
<td>3.70</td>
</tr>
</tbody>
</table>

To summarize the results, the PROSPECT version 3.01S performs better when considering the whole tested spectral range (450-1600 nm), however, the PROSPECT version 4.02 gives better simulated results for the NIR region (750-1600 nm).

4. CONCLUSIONS

A comparison of the Norway spruce LOPs simulated by the PROSPECT version 4.02 showed that this new version is able to reproduce LOPs of Norway spruce needles more accurately than former PROSPECT versions. The recalibration scheme optimizing simultaneously four calibration coefficients (kab, km, N and refractive index n) has the lowest RMSE in both reflectance and transmittance signatures, especially in the near infrared region of the spectrum. Nevertheless, independent datasets collected at geographically and environmentally different Norway spruce forest sites are being analyzed to approve or reject these findings on performance of PROSPECT version 4, as well as on the robustness and validation of the optimized versions 4.01 and 4.02 (work in progress).

5. ACKNOWLEDGEMENTS

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6. REFERENCES


