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Radiative Transfer Model parametrization for simulating the reflectance of meadow vegetation

Abstract

Natural vegetation is complex and its reflectance is not easy to model. The aim of this study was to adjust the Radiative Transfer Model parameters for modelling the reflectance of heterogeneous meadows and evaluate its accuracy dependent on the vegetation characteristics. PROSAIL input parameters and reference spectra were collected during field measurements. Two different datasets were created: in the first, the input parameters were modelled using only field measurements; in the second, three input parameters were adjusted to minimize the differences between modelled and measured spectra. Reflectance was modelled using two datasets and then verified based on field reflectance using the RMSE. The average RMSE for the first dataset was equal to 0.1058, the second was 0.0362. The accuracy of the simulated spectra was analysed dependent on the value of the biophysical parameters. Better results were obtained for meadows with higher biomass value, greater LAI and lower water content.

Keywords

Meadows • spectral reflectance • Radiative Transfer Model • PROSAIL

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Introduction

Because of environmental pollution and ecosystem changes, plant monitoring is a very important issue. Remote sensing data are often used in plant monitoring (Jensen 1983). This kind of method can also be used to monitor large areas. Spectrometry analyses the interaction between radiation and an object and uses the measurement of radiation intensity as a function of wavelength (Kumar et al. 2006). Each object reflects, transmits and absorbs different quantities of radiation, so it is possible to recognize an object and estimate its characteristics by analysing the spectrum.

Two approaches are used in canopy analysis: statistical and modelling (Jacquemoud 1993; Kumar et al. 2006). In the statistical approach, biophysical parameters measured during field measurements are correlated with spectral response. Based on the regression model the biophysical parameter is retrieved from the image. In the second approach a physically based model is used to represent the photon transport occurring inside leaves and canopy. The development of the model results in a better understanding of the light interaction with canopy and leaves. Radiative Transfer Models (RTM) are physically based models which describe the interactions of radiation with the atmosphere and vegetation. Radiative Transfer Models are often applied to vegetation modelling (Kumar et al. 2006). Adjusted models can be used to swiftly and precisely analyse biophysical parameters of the canopy (Jacquemoud et al. 2009; Haboudane et al. 2004). RTM are quite rarely used to model reflectance from meadows (Jarocińska 2012; Jarocińska 2011). However, the PROSAIL model was used to retrieve biophysical parameters from grasslands, especially chlorophyll, water content and Leaf Area Index (Clevers et al. 2010; Darvishzadeh et al. 2008; Darvishzadeh et al. 2011; Zhang & Zhao 2009).

The main objective of this study was to adjust the Radiative Transfer Model input parameters to receive enough accuracy in modelling the reflectance of the heterogeneous vegetation cover of meadows in Poland to make the model inversion possible. The second aim was to evaluate the accuracy of RTM in modelling dependent on different vegetation characteristics (amount of fresh biomass, value of Leaf Area Index and water content). In this study the PROSAIL model on canopy level was applied. The study was conducted on semi-natural meadows in Poland, which are very diverse.

Methods

Study area

The areas analysed were Polish meadows. Human usage of the meadows determines their proper functioning. Grasslands, which consist of meadows and pastures, make up 10% of Poland's land area (Kucharski 2009). Meadows are often used for a variety of purposes; crops from meadows, hay and green forage, are rather low. Meadows in Poland are floristically and morphologically very diverse. Many factors influence this ecosystem – excessive cultivation and also abandonment degrade the environment, which is why monitoring of these areas is very important (Kucharski 2009).

The meadows consist mainly of plants from the *Poaceae, Cyperaceae* and sometimes *Fabaceae* families. The *Poaceae* and *Cyperaceae* are morphologically rather similar, but can also be diverse. In Poland there are about 160 different species of *Poaceae* (Nawara 2006).The plants from the *Fabaceae* family have a completely different construction.

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In the research the Srodkowopolskie Plains were analysed in three different areas: Northen Mazovia, the Valley of Central Vistula and Central Mazovia. All of the analysed meadows were extensively used and located on a flat area. All analysed meadows can be defined as diverse and have at least four different species. The most common were: from the *Poaceae* family *Agrostis capillaris*, *Dactylis glomerata*, *Phleum pretense* and *Poa trivialis*; from the *Fabaceae* family *Trifolium pretense* and herbs and weeds like *Plantago lanceolata*, *Plantago maior* and *Rumex acetosa*.

Radiative Transfer Model

Canopy can be described as a homogeneous layer or layers consisting of leaves and the spaces between them in the model (Jacquemoud & Baret 1990; Kumar et al. 2006). Radiative Transfer Models are algorithms which vary according to input and output parameters, level of the analysis, types of plants and other modifications. The models are used on two levels: single leaf and whole canopy.

In this study the PROSAIL model was used to simulate reflectance on the canopy level (Jacquemoud et al. 2009). The PROSAIL model is a combination of the PROSPECT and SAIL models. The PROSPECT model describes multidirectional reflectance and diffusion on the leaf level (Jacquemoud & Baret 1990). It is often employed with other models that describe the whole canopy. The input parameters for the PROSPECT-5 model are: chlorophyll and carotenoid content, Equivalent Water Thickness and dry matter content, as well as the leaf structure parameter which describes the leaf structure and complexity (Feret et al. 2008).

The second model is the canopy reflectance model SAIL (Scattering by Arbitrarily Inclined Leaves) (Verhoef 1984; Verhoef et al. 2007). It simulates the top of the canopy's bidirectional reflectance and describes the canopy structure in a fairly simple way. In this analysis the 4-SAIL model will be used. This version has a few input parameters that describe plants and soil: spectrometric data – reflectance and transmittance from leaves (the output parameters from the PROSPECT model), biophysical canopy parameters (Leaf Area Index, brown pigment content, mean leaf inclination angle), soil brightness parameter, reflectance geometry (Solar zenith angle, observer zenith angle, relative azimuth angle), ratio of diffusion to total incident radiation and two hot spot size parameters. The SAIL model is often combined with the model for leaf level – the PROSAIL model. The PROSPECT and SAIL models are rarely used to meadows, because this kind of ecosystem is normally rather heterogeneous and modelling is quite difficult; however, these models were used to simulate spectral reflectance in different kinds of meadows (Clevers et al. 2010; Darvishzadeh et al. 2008; Darvishzadeh et al. 2011; Zhang & Zhao 2009; Jarocińska 2012).

The Radiative Transfer Models are generally more efficient for homogeneous ecosystems with a uniform structure. When the canopy is built of plants with a different structure, like plants from the *Poaceae*, *Cyperaceae* and *Fabaceae* families, the simulation may be less accurate.

Field measurements and data analysis

The field measurements to model PROSAIL were conducted on the Srodkowopolskie Plains in 50 test polygons in July and August 2010. In each polygon biophysical parameters and information used to calculate input data for the PROSAIL model were collected: the chlorophyll content (using chlorometer CCM-200); fresh biomass in grams cut from 1 m^2; Leaf Area Index (using the LAI Plant Canopy Analyser); average plant height in meters; average leaf length in centimetres; date and time of measurement and coordinates average. The dry matter content in % and leaf angle in degrees were estimated visually. In addition, spectral reflectance was collected using FieldSpec3 FR.

Subsequently the measurements were used to calculate input parameters for each polygon separately. Chlorophyll content in μg/cm^2 was calculated using the Chlorophyll Content Index and Leaf Area Index. Carotenoid content was estimated using chlorophyll content (Car=Ca/5). Brown pigment content was recalculated using dry matter content in %. Dry matter and water content were calculated using Leaf Area Index and the fresh biomass, which was weighed, dried and weighed again. One of the hot spot size parameters was calculated using average leaf length and canopy height. Average Leaf Angle and Leaf Area Index were measured directly during the field measurements. Solar zenith angle was estimated using coordinates, time and date of measurements.

Other parameters were ascertained or estimated based on the literature. The structural parameter N was estimated empirically, using literature (Damarez & Gastellu-Etchegorry 2000; Ceccato et al. 2001; Darvishzadeh et al. 2008; Clevers et al. 2010). The soil brightness parameter was fixed as 1, ratio of diffusion to total incident radiation as 70% and second hot spot size parameter as 1 (http://teledetection.ipgp.jussieu.fr/prosail/; Verhoef & Bach 2007; Darvishzadeh et al. 2008). The observer zenith angle and Azimuth observer angle were fixed, because the spectrometer was in the same place for each measurement.

For each polygon input parameters for the PROSAIL model were calculated. Two datasets were created for each polygon. In the first one (PROSAIL-1), all input parameters were calculated using field measurements and the aforementioned methods. This dataset was analysed in previous studies (Jarocińska 2012). Because of large errors in modelling (especially in the chlorophyll and water absorption regions) a second dataset was created using the same parameters as in the first, except the pigments (carotenoid and chlorophyll) and water content, which were adjusted. Moreover, it is intended to use these data to obtain information about the biomass (LAI or dry biomass content). The maximum and minimum values for chlorophyll and water content and the range between values were fixed based on the field measurements. Carotenoid content was calculated using the same procedure as for the first dataset. For each polygon reflectance was calculated (for the whole range from 0.4 to 2.5 μm) using different combinations of pigments and water content. The best combination of input parameters was manually chosen based on the smallest error compared to the field measurements.

The spectral reflectance obtained from the model based on the two datasets was compared with field measurements. Based on the calculated Root Mean Square Error the simulation was verified. The RMSE values were calculated for the whole range 0.4-2.5 μm and for specific ranges related to the regions where the four main biophysical parameters have a big influence on reflectance: chlorophyll (0.4-0.8 μm), carotenoids (0.4-0.6 μm), dry matter (0.8-1.5 μm) and water content (1.5-2.5 μm).

Finally, the accuracy of the simulated spectra was analysed dependent on the value of three different biophysical parameters (Leaf Area Index, fresh biomass content and water content). These parameters are associated with the yield obtained from the meadows. The three values were also correlated with each other using Spearman's rank correlation test. Based on the value of the biophysical parameters the polygons were divided into three groups. In each group the average RMSE value was calculated for the whole range 0.4-2.5 μm and for the aforementioned specific ranges. The statistical significance of the RMSE difference between groups was analysed using the Kruskal-Wallis test.

A similar procedure was performed using combined information from two biophysical parameters: (1) water content

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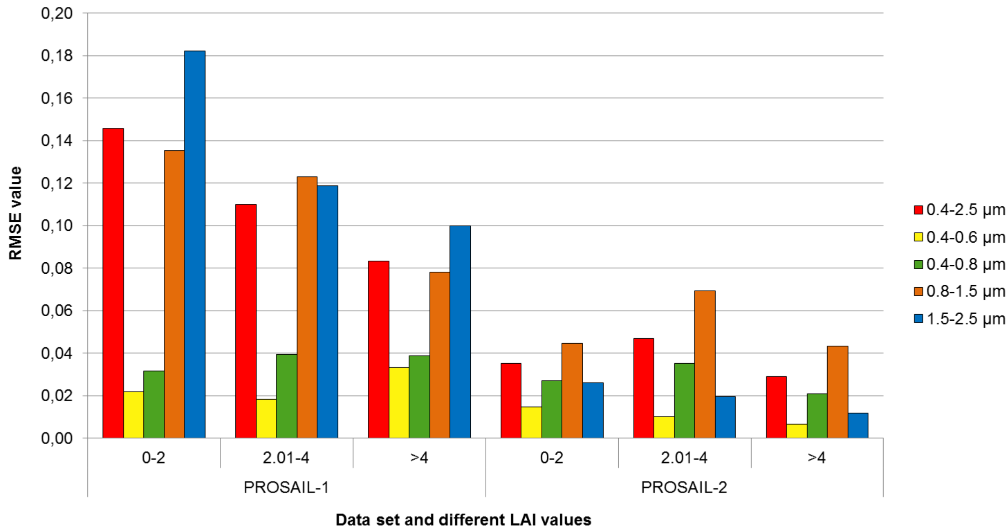

Figure 1. RMSE value for meadows with different Leaf Area Index values (LAI value between 0 and 2, from 2.01 to 4 and above 4), calculated using two datasets: PROSAIL-1 and PROSAIL-2

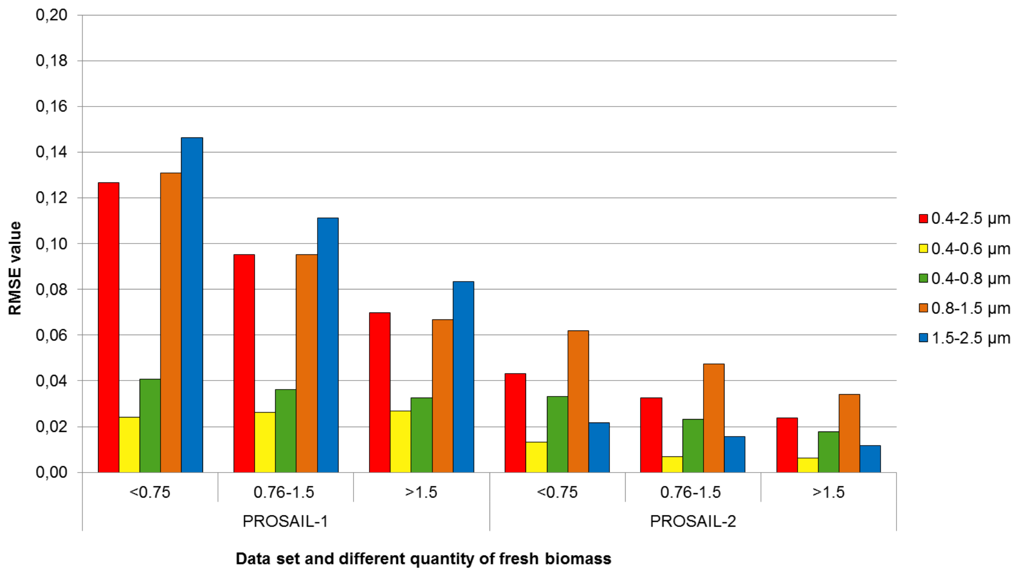

Figure 2. RMSE value for meadows with different amounts of fresh biomass (amount of fresh biomass less than 0.75 kg/1m^2, from 0.76 to 1.5 kg/1m^2 and above 1.5 kg/1m^2), calculated using two datasets: PROSAIL-1 and PROSAIL-2

and LAI, (2) water content and fresh biomass and (3) LAI and fresh biomass. The polygons for each parameter combination were divided into four groups: higher values for both parameters (one case), lower values for one parameter and higher for the other (two cases) and lower values for both parameters (one case). The LAI polygons were divided based on values below and above 3; for fresh biomass, below and above 1 kg/1m^2; for water content, below and above 70%. The significance of the differences between RMSE values for each group was tested using the Kruskal-Wallis test for the whole range 0.4-2.5 μm and for specific ranges.

Results

The results obtained from the analysis show that the PROSAIL model can be used to simulate reflectance from diverse meadows, but after the recalculation of pigment and water content the errors are smaller. The average RMSE for the first dataset was equal to 0.1058; for the second, where the data were corrected, 0.0362. The biggest errors in the first dataset for PROSAIL-1 were observed in the middle infrared (0.1230); for the second (PROSAIL-2), in near infrared (0.0519). Generally smaller errors were noticed in visible light compared to infrared. This can be related to the fact that many factors influence reflectance in infrared. Also, reflectance values for vegetation in visible light are much smaller than in infrared. The modifications to the PROSAIL-2 dataset make the spectrum more accurate, and the variations of RMSE values in the second dataset were also much smaller than in the first one.

The values of water content, LAI and fresh biomass amount were not normally distributed, so the autocorrelation of parameters was performed using Spearman's rank correlation coefficient (N=50). The strongest correlation was observed

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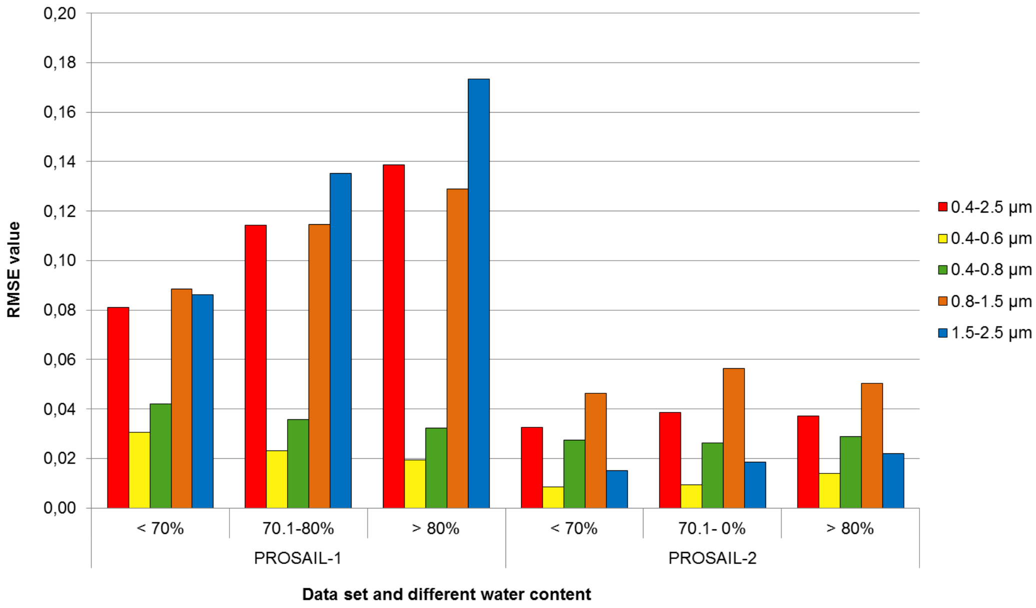

Figure 3. RMSE value for meadows with different water content (below 70% water content, from 70.1% to 80% and above 80%), calculated using two datasets: PROSAIL-1 and PROSAIL-2

between fresh biomass and LAI (R=0.75; $p \leq 0.001$). Smaller correlations were found between LAI and water content (R=-0.51; $p \leq 0.001$) and biomass and water content (R=-0.36, $p \leq 0.005$). The three biophysical variables are quite close related to each other, especially fresh biomass and LAI.

The accuracy of the simulated spectra was analysed dependent on the value of the three different biophysical parameters and the combination of the parameters.

Firstly the RMSE values dependent on the Leaf Area Index were analysed (Figure 1). The values of RMSE for the first dataset were higher for lower LAI values; the differences in errors were also quite big. The differences in RMSE values were significant for the whole range 0.4-2.5 µm and in infrared ($p \leq 0.005$). For the second dataset (PROSAIL-2), where the data had been corrected, the RMSE values were much smaller. Only in middle infrared the same statistically significant ($p \leq 0.005$) difference in RMSE as for PROSAIL-1 was noticed.

Similar results were observed for fresh biomass: for a large biomass quantity the RMSE value decreases (Figure 2). For the first dataset (PROSAIL-1) the differences were quite big and statistically significant for the whole range 0.4-2.5 µm ($p \leq 0.005$), as well as in near infrared ($p \leq 0.005$) and middle infrared ($p \leq 0.006$). For the second dataset (PROSAIL-2) the differences in error value were smaller and not significant only in one range – near infrared; for all others the differences were statistically significant (for 0.4-2.5 µm – $p \leq 0.022$; for 0.4-0.6 µm – $p \leq 0.016$; for 0.4-0.8 µm – $p \leq 0.016$ and for 1.5-2.5 µm – $p \leq 0.028$).

A different relationship was noticed for water content. For first dataset PROSAI-1, for higher water content the values of RMSE are bigger (Figure 3). The differences were statistically significant in the range 0.4-2.5 µm and middle infrared range ($p \leq 0.005$). The differences in errors for the PROSAIL-2 dataset are much smaller and statistically not significant (for 0.4-2.5 µm – $p \leq 0.546$; for 0.4-0.6 µm – $p \leq 0.99$; for 0.4-0.8 µm – $p \leq 0.958$; 0.8-1.5 µm – $p \leq 0.481$ and for 1.5-2.5 µm – $p \leq 0.731$).

Very similar results were acquired using the combination of two parameters: (1) water content and LAI, (2) water content and fresh biomass and (3) LAI and fresh biomass. For the differences in groups using the combination of parameters water content-LAI and LAI-fresh biomass, the statistical significance of the differences in different ranges was similar. The differences were statistically significant for the PROSAIL-1 dataset for the whole analysed range 0.4-2.5 µm ($p \leq 0.005$ for both combinations), as well as near ($p \leq 0.005$ for both combinations) and middle infrared ($p \leq 0.005$ for both combinations). For the PROSAIL-2 dataset the differences were statistically significant for 0.4-2.5 µm ($p \leq 0.03$ for both combinations) and middle infrared ($p \leq 0.005$ for water content and LAI and $p \leq 0.007$ for water content and fresh biomass). Quite similar results were also observed for the combination of fresh biomass and LAI. The differences were statistically significant for the PROSAIL-1 dataset for the whole analysed range 0.4-2.5 µm, and near and middle infrared ($p \leq 0.005$ for each range). For the PROSAIL-2 dataset the differences were statistically significance in the ranges: 0.4-2.5 µm ($p \leq 0.025$), 0.4-0.6 µm ($p \leq 0.036$) and 0.4-2.5 µm ($p \leq 0.005$).

Conclusions

Generally, the PROSAIL radiative transfer model can be used to simulate the spectral reflectance of vegetation on heterogeneous meadows. In the future, the model can be used to estimate biophysical parameters (dry matter content or Leaf Area Index), with the proposed adjustment. Meadows are very complex environments and some of the parameters should be recalculated. The proposed correction of the input parameters improves the modelling results.

The correctness of the spectrum is dependent on the value of biophysical variables. Better results were obtained on meadows with a higher biomass value, bigger LAI and lower water content. The proposed corrections of pigment and water content make the modelling results less sensitive to the changes of a single biophysical parameter, but not less sensitive to the combination of two biophysical parameters. For fresh biomass and LAI the differences in errors are statistically significant.

The RMSE values were slightly higher than in other studies (Darvishzadeh et al. 2011; Zhang & Zhao 2009). However, the meadows

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analysed were very diverse. The errors in the second dataset (PROSAIL-2) were admissible. The errors might be related to the field measurements (some parameters were estimated visually and errors can also be caused by the inaccuracy of the instruments). Additionally, the PROSAIL model is dedicated for average vegetation, whereas the analysed meadows were very diverse in terms of plants and structure.

In conclusion, the results of these datasets can be used in further analysis, for instance, a model inversion to estimate the value of biomass, LAI or dry matter content.

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