INVERTING PROCOSINE-D FOR VERY HIGH SPATIAL AND TEMPORAL RESOLUTION RETRIEVAL OF FOLIAR BIOCHEMISTRY

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ABSTRACT

A combination of the leaf reflectance model PROSPECT-D and the directional model COSINE was inverted to create maps of leaf constituents in millimeter resolution from field imaging spectroscopy data. A diurnal series of 26 HySpex VNIR images of well-watered and drought-stressed young beech trees was created from a 3.8 m high platform with a hyperspectral camera on a rotation stage. Inversion results show detailed spatial distribution of the leaf constituents with meaningful time series and distinction between both groups in some parameters. While chlorophyll and carotenoid contents are higher in the well-watered trees throughout the day, anthocyanins and brown matter contents are higher in the drought-stressed trees. Leaf water and dry matter content cannot be reliably derived from the VNIR data. Field imaging spectroscopy and reflectance model inversion offer the capability to monitor plants in environments like orchards or greenhouses to get timely information on plant growth and health.

Index Terms— Reflectance modeling, Proximal sensing, Imaging spectroscopy, Inversion, Foliar chemistry

1. INTRODUCTION

Remote sensing of foliar constituents is usually performed using either empirically-based or physically-based approaches. For the former approach, linear or nonlinear relationships between foliar chemicals and spectral parameters are established. However, these empirical relationships often need to be recalibrated when applied to a new dataset, so they lack transferability and robustness. The physically-based approach uses radiative transfer models for inversely retrieving leaf chemicals from spectral data. The physically-based approach is more generic and robust because the physical models can be directly applied to new datasets [1]. However, physically-based estimations of foliar constituents are not automatically more precise than empirical models.

Two new developments in the field of physical reflectance modelling have recently been published: a new version of the well-known and widely used leaf reflectance and transmittance model PROSPECT [2, 3] called PROSPECT-D that includes anthocyanins and can thus be used to model leaf reflectance over the whole lifetime of a leaf [4]; and COSINE, a model for retrieving leaf orientation and specular reflectance in close-range imaging spectroscopy [5]. These two models have been combined to form the model PROCOSINE-D.

In this study, PROCOSINE-D was used to retrieve foliar biochemical variables from a diurnal course of 26 close-range field imaging spectroscopy datasets of European beech (*Fagus sylvatica* L.) seedlings. One pot of drought-stressed seedlings and one pot of well-watered seedlings were observed throughout the day using a HySpex VNIR-1600 hyperspectral scanner [6]. Some clear temporal trends and differences between well-watered and drought-stressed trees are visible in the retrieved PROCOSINE-D parameters. The very high spatial resolution of about 2.5 mm per pixel also make within-plant and even within-leaf variations discernible.

While the structure parameter, N, is equal for both groups, leaf chlorophyll and carotenoid concentrations are significantly higher in the well-watered trees. Anthocyanin and brown matter concentrations, on the other hand, are higher in the drought-stressed group. Solar incidence angle is reproduced closely by the inversion results.

2. MATERIAL AND METHODS

2.1. Drought-stress experiment

In order to study the effects of drought stress on beech trees, an experiment with four-year-old seedlings in pots was set up in 2011. Three seedlings (ca. 1 m in height) of European beech were planted into each pot before leaf flushing in spring. The trees were numbered and then randomly allocated to pots; subsequently, the pots were randomly allocated to dry group and control group. In total, 66 beeches were planted in 22 pots [7]. During several weeks in summer, the water supply for the dry group was cut off and the reactions were observed using field imaging spectroscopy. The experiment was repeated in 2012 and 2013 [8]. At the end of the 2013 drought phase, one pot of drought-stressed seedlings and one pot of well-watered

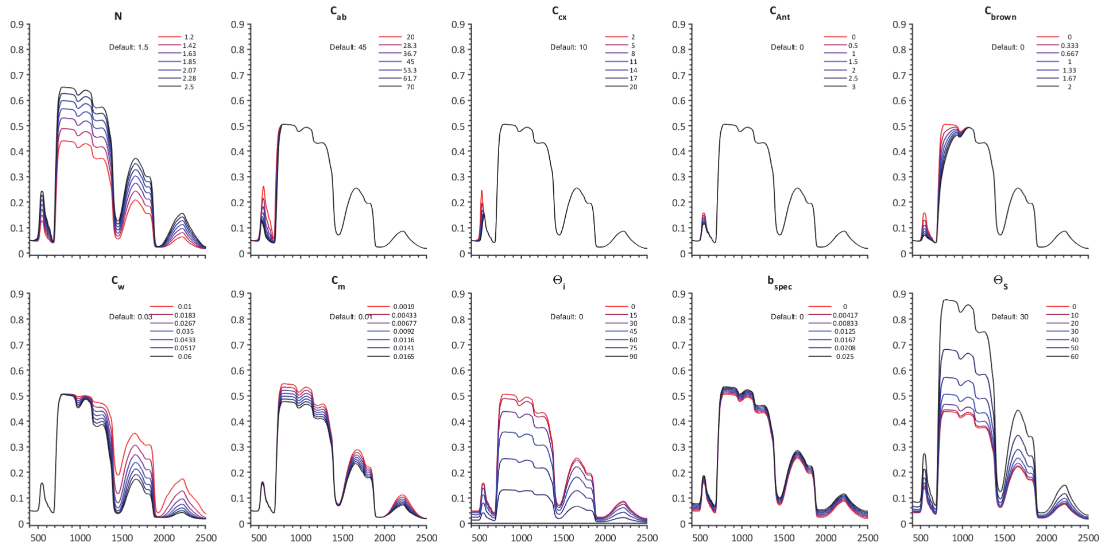

Figure 1. Sensitivity analysis of PROCOSINE-D

seedlings were selected for a diurnal experiment with photosynthesis, hyperspectral reflectance, and thermal emission measurements for the period of the day when the trees were illuminated by the sun [6]. The now six-year old seedlings were of similar height, and the leaves of the selected drought-stress trees were still green.

2.2. Reference measurements

During the course of the day, gas exchange rates and photosynthesis of the trees were measured using a LiCor LI-6400 Portable Photosynthesis System (LiCor Biosciences, Lincoln, NE, USA). The results are not discussed in this short paper.

2.3 VNIR field imaging spectroscopy

Hyperspectral images were recorded with a HySpex VNIR-1600 camera (Norsk Elektro Optikk, Skedsmokorset, Norway) mounted on a rotation stage on a 3.8 m high platform. The camera is a push-broom scanner that records lines of 1600 pixels with an across-track field of view of 17°, resulting in lines of about 1 m width. By rotating the camera images are formed. The images covered an area of about 3 m × 1 m each. The scanner was equipped with a lens for 3 m object distance with about 0.5 m depth of focus so that most of the area was imaged in focus. A white reference target (Spectralon™, Labsphere Inc, North Sutton, USA) of known reflectance was included in the scans in order to convert the recorded radiances to reflectance values. Black foam rubber mats were placed on the ground to reduce stray light from the background. The images were recorded under natural light conditions. Before each scan the integration time was adapted to current brightness.

The camera uses records 160 spectral bands in the range of 414 to 994 nm with a spectral sampling distance is 3.7 nm. Over the course of the day, 26 images were recorded, each accompanied by a measurement series with the gas exchange porometer.

Radiometric pre-processing of the images was done using software provided by the camera manufacturer. This software corrects dark current effects and responsivity differences of the sensor elements and converts the recorded digital numbers to radiance values.

In each image, the white reference was detected, its mean reflectance was calculated and all pixel values of the images were divided by their respective white reference values, resulting in relative reflectance values. Since the panel's reflectivity in the spectral range of interest is close to 99% and very uniform we did not multiply the values by panel reflectance to get absolute reflectance.

2.4 PROCOSINE-D

PROSPECT-D is the latest version of the leaf reflectance and transmittance model PROSPECT [2, 3]. Input parameters are the leaf mesophyll structure parameter N, leaf chlorophyll a and b concentration C_{ab}, carotenoid concentration C_{cx}, anthocyanin concentration C_{Ant}, brown leaf matter C_{brown}, equivalent water thickness C_w, and dry matter content C_m [4].

COSINE was developed for laboratory hyperspectral images of leaves, where different pixels are recorded under different angles and specular reflectance can play a major

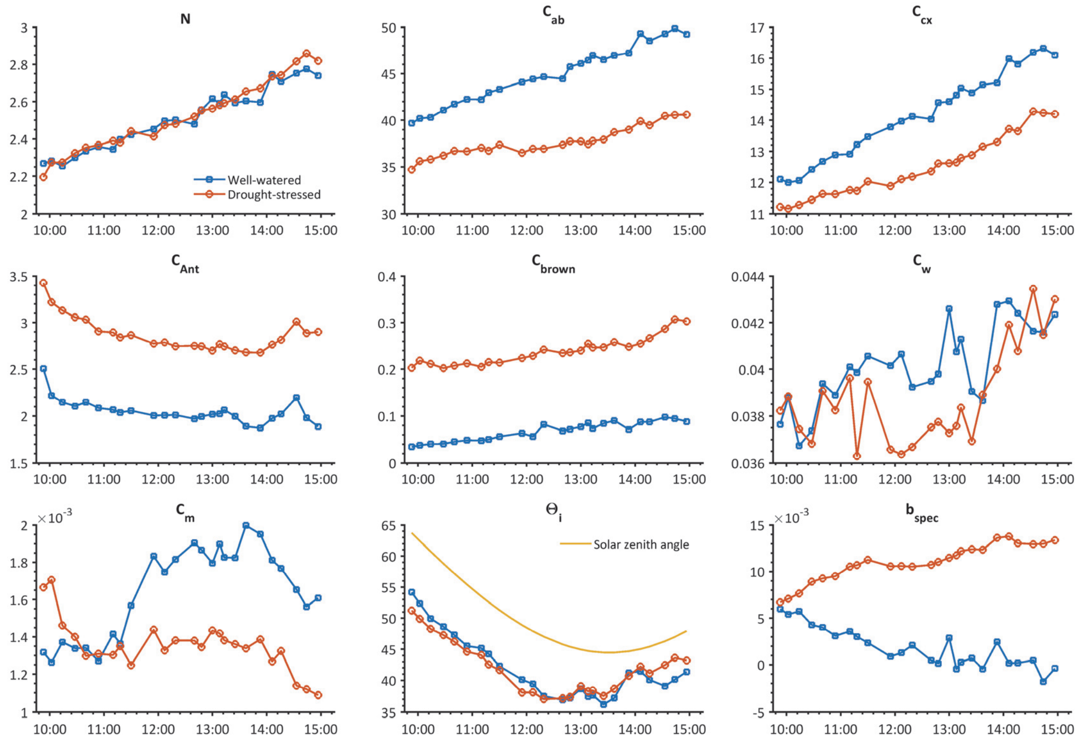

Figure 2: Diurnal course of mean retrieved PROCOSINE-D parameters

role. COSINE parameter are the incidence angle θ_i and the specular part of the reflectance spectrum b_{spec} [5].

Figure 1 shows a sensitivity analysis of PROCOSINE-D. Each parameter was varied in a realistic range around the default value while all other parameters were kept at their default value. This simple local sensitivity analysis clearly illustrates the effect of each input parameter on the resulting spectrum.

2.5 Model inversion

While lookup table-based inversion approaches are more common in the remote sensing world, we used a numerical inversion approach. Like Jay et al. in their study introducing the PROCOSINE model [5], we used a trust-region reflective algorithm, the nonlinear least squares solver `lsqcurvefit` in Matlab (Version 2017b, The Mathworks, Natick, MA, USA) for parameter retrieval.

Default values, and upper and lower bounds were set and the images were inverted on a pixel-by-pixel basis. Only pixels with a NDVI greater than 0.7 were inverted. To save processing time, the number of pixel was reduced by a factor of 16. The mean value of 4 × 4 pixels of the original images was used as input for the inversion process so that the parameter maps are 400 × 650 pixels in size which corresponds to a spatial resolution of about 2.5 mm per pixel. Processing time for each image was about one hour.

3. RESULTS AND DISCUSSION

Figure 2 shows diurnal courses of the mean values of all parameters retrieved through inversion of PROCOSINE-D. The structure parameter N is equal for both groups and continuously rising throughout the day. This is not realistic since the leaf structure does not change much during a single day and beech leaves usually have much lower N values of about 1.2. The probable reason for this is changing illumination during the day that is not completely captured by θ_i.

The rise of Cab and Ccx in retrieved values during the day is also unlikely to represent true changes of leaf pigments. But the inversion captures the differences between both groups that was also shown in previous studies [7, 8].

C_{Ant} and C_{brown} also show clear differences between well-watered and drought-stressed group. Figure 3 shows maps of the retrieved C_{Ant} values over the course of the day. As expected, the dry group exhibits higher values in both parameters throughout the day. Both parameters show stress or senescence so the higher values in the dry group clearly show that reflectance model inversion on hyperspectral data

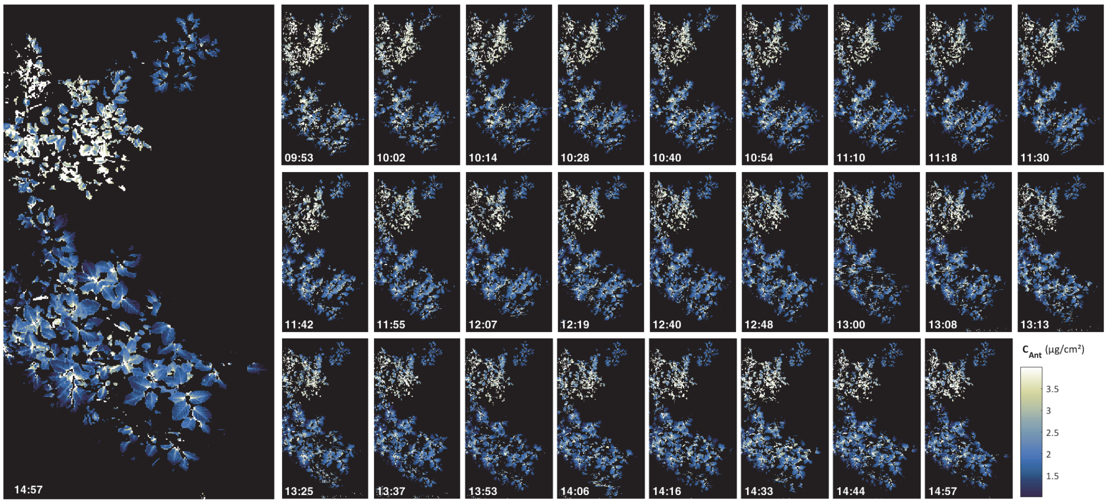

Figure 3: Maps of retrieved leaf anthocyanin content (C_{Ant}). The last image is shown enlarged at the left side.

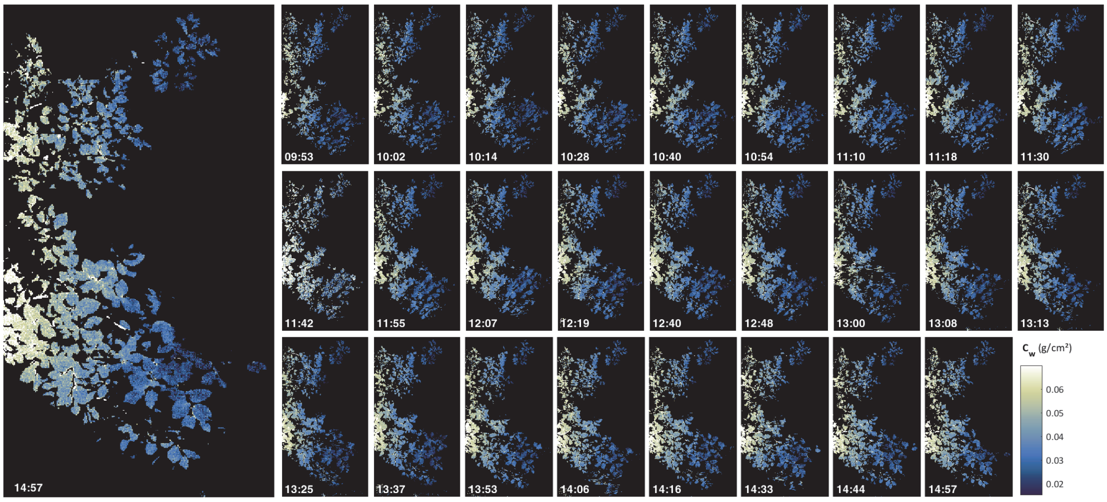

Figure 4: Maps of retrieved leaf water content (C_w) over the course of the day. The last image is shown enlarged at the left side.

can be used to detect these effects although the leaves of the stressed trees were still green.

C_w cannot be retrieved reliably in the considered wavelength range [9]. Although the leaves of the drought-stressed group have significantly lower water contents, this is not captured by the model inversion. Figure 4 shows the C_w maps resulting from the model inversion. It can be clearly seen that there is a gradient in retrieved C_w values from left to right. The spectral region sensitive to changes in C_w, suffers from a low signal to noise ratio and a large influence of smile effects in the HySpex VNIR sensor.

C_m is another parameter that is difficult to invert reliably, so interpreting the temporal course or the resulting maps is futile. Still it should be noted that the temporal behavior is not random.

The retrieved values for θ_i closely follow the solar zenith angle at the respective time of image recording, but the values are about 10° lower than the zenith angles. Values for both groups are nearly equal, which shows that this parameter really captures changes in illumination rather than foliar attributes.

The b_{spec} diurnal course is unique and it is another parameter that is hard to interpret but contains low noise levels. Both groups start at the same mean value and then diverge with rising values in the dry group and declining values in the well-watered group.

4. CONCLUSIONS

While not all parameters can be mapped reliably with the proposed approach, the high-resolution maps resulting from field imaging spectroscopy combined with reflectance model inversion have the potential to be quite helpful in precision agriculture contexts, especially in small environments like orchards or greenhouses. For larger areas, the technique may be transferred to other platforms like unmanned aerial vehicles although the very high resolution will be lost and probably other reflectance models like SAIL [10] or Inform [11] will be better suited.

The PROCOSINE model was designed for laboratory imaging spectroscopy of single leaves, but using it for field imaging spectroscopy of whole trees still leads to interesting results. We assume that some of the hard to explain effects like the temporal course of the leaf structure parameter can be explained by the violation of model pre-conditions, i.e. the fact that many pixels have leaf area indices greater than one.

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The maps in Figures 4 and 5 use the perceptually-uniform colour map “devon” (fabiocrameri.ch/devon.php).

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