VARIABILITY IN LEAF OPTICAL PROPERTIES OF NORWAY SPRUCE CROWNS

Z. Malenovský [a, c] *, Z. Lhotáková [b], J. Albrechtová [b], J.G.P.W. Clevers [a], M.E. Schaepman [a], P. Cudlín[c]

[a] Centre for Geo-Information, Wageningen University, Droevendaalsesteeg 3/PO Box 47, 6700 AA Wageningen, The Netherlands – (zbynek.malenovsky, jan.clevers, michael.schaepman)@wur.nl

[b] Dept. of Plant Physiology, Faculty of Science, Charles University, Viničná 5, 128 44 Prague 2, Czech Republic - zuza.lhotak@seznam.cz, albrecht@natur.cuni.cz

[c] Dept. of Forest Ecology, Institute of Systems Biology and Ecology, Academy of Sciences of the Czech Republic, Na Sádkách 7, 370 05 České Budějovice, Czech Republic - pavelcu@usbe.cas.cz

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ABSTRACT:

Norway spruce (*Picea abies* /L./ Karst.) growing in montane and/or boreal environment is continuously exposed to the influence of multiple environmental stress impacts. Stress factors increase nutritional demands imposed on a tree, leading to initial destabilization of its functions, followed by normalization and improved resistance or resilience depending on the stress intensity and duration. The objective of this study is to investigate the optical variability in Norway spruce needle categories collected from primary and secondary shoots throughout juvenile (upper) and production (middle) functional crown parts of stress resistant and stress resilient trees. Needles of three past generations were included into the analyses; however, spectral differences due to the leaf ageing were not statistically examined. The needle optical properties, i.e. hemispherical-directional reflectance, transmittance and absorption, of five defined needle categories were statistically tested for their quantitative and qualitative differences within the wavelength range from 505-800 nm. Spectral analyses were followed by laboratory measurements of needle pigment concentration (chlorophyll *a*+*b* and total carotenoids) and dry matter content. Results indicated no spectral variability within the observed spruce functional crown parts of one stress class, no matter whether they were stress resistant or resilient. However, significant optical differences were discovered in the visible (green and red) and the red edge wavelengths when comparing needles of primary shoots of two stress response classes. These differences were statistically related to the changes in the concentration of both examined foliar pigments, which proved to decrease in the needles of resilient trees. No significant variability was found within the near infrared wavelengths of tested needles.

1. INTRODUCTION

1.1 Leaf optical properties

Understanding the leaf optical properties is an important step to comprehend the radiative transfer through complex vegetation canopies (Myneni and Ross, 1991). The leaf optical properties are defined as the reflectance $\rho(\lambda)$, transmittance $\tau(\lambda)$ and absorption $\alpha(\lambda)$ of the photons by and/or within the leaf tissues (Despan and Jacquemoud, 2004). A number of studies has been focused on the leaf spectral properties in connection with their biochemical content and anatomical structure (Curran, 1989; Fourty et al., 1996; O'Neill et al., 2002). These studies provided basis for the leaf radiative transfer modelling (Jacquemoud and Baret, 1990; Dawson et al., 1998; Ganapol et al., 1998) which in turn allowed the non-invasive estimation of the leaf biochemistry (Curran et al., 1992; Jacquemoud et al., 1996; Demarez et al., 1999). Leaf optical properties, being the inputs of the vegetation canopy radiative transfer models (Gastellu-Etchegorry et al., 2004; Pinty et al., 2004), facilitate estimations of the biochemical vegetation parameters from airborne or spaceborne remotely sensed image data (Gastellu-Etchegorry and Bruniquel-Pinel, 2001; Gascon et al., 2004). Therefore, use of inappropriate leaf optical properties may directly lead to under- or over-estimation of the modelled reflectance at the shoot and/or canopy level (Asner et al., 1998) and subsequently to under- or over-estimations of the retrieved biochemical concentrations.

1.2 Categories of Norway spruce needles

The variability of evergreen coniferous leaf optical properties is driven by the leaf actual leaf physiological status, which does not only depend on the leaf age, but also on the environmental conditions including the stress agents. Environmental stress factors often affect the forest stands in combination, creating an influence defined as multiple stress (Mooney et al., 1991). Two types of environmentally stressed Norway spruce (*Picea abies* /L./ Karst.) trees can be distinguished based on their stress response classes: i) *stress resistant* (RN) and ii) *stress resilient* (RT) (Cudlin et al., 2001). Crowns of the RN trees are formed mainly by the *primary* structure of the assimilative apparatus, while RT crowns are mostly composed by the proventitious *secondary* shoots, often formed in successive series (Gruber, 1994). The upper part of the crown, named *juvenile* part, has the dominant function of colonizing new space above the forest canopy. The middle crown part, called *production* functional part, is responsible for production of the main portion of energy and biomass within the crown. The production part mainly consists of the primary shoots in case of the RN crowns, while secondary shoots are formed within the RT crowns at a different rate according to the ratio of degradation and

* Corresponding author.

regenerative processes (Cudlín et al., 1999). The lower branches represent the so-called *saturation* crown part, which is characterized by a low rate of all metabolic processes due to lower availability of solar irradiation, because of shadows of the adjacent trees. This part is therefore not very important for production and regeneration of the tree, thus it was not included in our experiment.

All the combinations created out of two functional crown parts, two stress response classes and three shoot formations resulted in the following needle categories: i) primary-juvenile-stress resistant (J_RN), ii) primary-production-stress resistant (P_RN), iii) primary-juvenile-stress resilient (J_RT), iv) primary-production-stress resilient (P_RT), and v) secondary-production-stress resilient (S_RT) needles. Notice that the variability in spruce needle stress categories is increased by the physiological and anatomical differences between the needle generations.

1.3 Study objectives

Both the statistically and the physically based remote sensing approaches to estimate the leaf biochemical concentrations have been predicated on the assumption that the leaf optical properties vary little with location in the canopy, and thus a randomly collected foliar sample is assumed to be representative for a whole crown. Knowing the high physiological (anatomical) variability in Norway spruce needles, a detailed study investigating spatial variability of the leaf optical properties within the tree crowns is required to approve or reject this assumption. Therefore, the objectives of this study were focused on examination of the quantitative and qualitative differences in leaf optical properties of five Norway spruce needle categories as defined above. Spectral differences in needle age-classes, explored in previous studies (e.g. Hoshizaki et al., 1988; Rock et al., 1988), were not analyzed in this study. Nevertheless, a balanced number of needle samples of the last three generations was taken into account during the sampling so that the variability caused by the leaf ageing was considered. Finally, the leaf spectral characteristics were statistically related to concentrations of the basic foliage pigments, chlorophyll *a*+*b* (C_{ab}) and total carotenoids (C_{xc}), and dry matter content (C_m).

2. MATERIAL AND METHODS

2.1 Study site and sample collection

A dataset of leaf optical properties along with biochemical and biophysical characteristics of spruce needles was acquired within the mountain forest stands located at the Šumava Mts. (National Park in the southern Czech Republic), near the village Modrava (48° 59' N, 13° 28' E). Fifteen RN and fifteen RT Norway spruce trees were selected there and two branches were cut off by a tree-climber from the south side of each sample crown during the period of September 5th till September 15th 2002. The first branch was always taken from the *juvenile* functional crown part and the second branch from the upper level of the *production* crown part. The architecture of each branch was described immediately after collection and sunlit shoots of the last three year-classes were detached and placed into zip-lock plastic bags together with a wet pulp paper. All the samples (n=221) were stored and transferred to the laboratory in a dark portable cooler with frozen blue ice (about -4°C). There they were kept in a dark and cold chamber (-16°C) and spectrally measured within 24 hours.

2.2 Laboratory determination of the foliar pigments

Immediately after the branch detachment, parallel needle sets (coming from the same shoots that were selected for the spectroscopic examination) were collected for the foliar pigment analysis. These samples were placed inside plastic vials, transported to the laboratory in a dark portable cooler, and preserved at -70°C until processed. The foliar pigments were extracted in dimethylformamide (DMF) according to Porra et al. (1989). The amount of photosynthetic pigments (C_{ab} – chlorophyll *a* + *b* and C_{xc} – total carotenoids) was determined spectrophotometrically. The total amount of individual pigments was determined according to equations of Lichtenthaler (1987). The concentration of pigments, originally expressed as weight of pigment per gram of needle dry mass, was transformed into the micro-grams per needle hemispherical-surface projection [$\mu g/cm^2$] in order to work with the units that are commonly used in quantitative remote sensing applications.

2.3 Needle optical and biophysical properties

The hemispherical-directional reflectance and transmittance of the sampled Norway spruce needles were measured between 400-1100 nm with a wavelength interval of 5 nm using the LI-COR spectroradiometer LI-1800-22 (Li-Cor, Inc., Lincoln, NE, USA) coupled with an integrating sphere LI-1800-12 (Li-Cor, 1983). The original method proposed by Daughtry (1989) and extended by Mesarch et al. (1999) was improved and adapted for the Norway spruce needles. The hemispherical-directional reflectance, transmittance and absorption of needle samples were computed according to the following equations:

$$\text{Reflectance} = \rho(\lambda) = \frac{\left(\dfrac{R_{TOTAL} - STR}{REF - STR}\right)}{(1 - GF_R)} \quad (1)$$

$$\text{Transmittance} = \tau(\lambda) = \left[\left(\frac{T_{TOTAL}}{REF - STR}\right) - (\rho_W GF_T)\right] \frac{1}{(1 - GF_T)} \quad (2)$$

$$\text{Absorption} = \alpha(\lambda) = 1 - \rho(\lambda) - \tau(\lambda) \quad (3)$$

where R_{TOTAL} = flux of radiation reflected from the sample in reflectance mode
STR = flux of the stray light radiation
REF = flux of the radiation reflected from a $BaSO_4$ reference standard in reference mode
GF_R = gap fraction of the sample in reflectance mode
T_{TOTAL} = flux of the radiation transmitted through the sample in transmittance mode
ρ_W = reflectance of the wall of the integrating sphere
GF_T = gap fraction of the sample in transmittance mode.

The stray light inside the integrating sphere was measured as a radiation flux of the empty illuminated sample port in reflectance mode. The reflectance of the integrating sphere wall ρ_W was set to 0.955 according to Zwinkles and Dodd (1990). Unfortunately, some of the spectral measurements were erroneous due to inappropriate arrangement of needles within the sample port, causing overestimation of the gap fractions between the needles (GF_R and GF_T). In total 78 erroneous measurements were rejected so the final spectral dataset contained 143 optical properties (48 of current, 46 of one year, and 49 of two years old needles representing 30 of J_RN, 30 of J_RT, 30 of P_RN, 24 of P_RT, and 29 of S_RT samples).

Finally, the spectrally examined needle samples were oven-dried at 60°C for 48 hours and their dry biomass was weighted. The weight of dry biomass was expressed against a needle hemispherical-surface projection in order to obtain the dry matter concentration (C_m) in [mg/cm^2]. The hemispherical-surface projection was calculated as a needle projected area multiplied by a universal conversion factor of 1.285, derived experimentally for Norway spruce needles by Waring (1983).

2.4 Quantitative assessment of the needle optical properties

The quantitative validation of the needle optical properties was done by looking at the intensity (magnitude) of the reflectance, transmittance, and absorption within the specific wavelength intervals. The noise-free wavelengths of the optical properties were divided into the four specific spectral intervals: green (505-600 nm), red (600-685 nm), red edge (RE; 685-760 nm), and near-infrared (NIR; 760-800 nm). The wavelength intervals of 400-505 nm and 800-1100 nm were excluded because of their high contamination due to random noise. The area under the reflectance, transmittance, and absorption curve (*AUC*) was integrated within the specified wavelengths according to:

$$AUC(\rho,\tau,\alpha)=\sum_{i=1}^{n} f(\lambda_i^*)(\lambda_i-\lambda_{i-1})$$
(4)
$$f(\lambda_i^*)=(h(\lambda_i)+h(\lambda_{i-1}))/2$$
(5)

where $f(\lambda_i^*)$ = mean height h of the spectral function intensity at wavelength interval of two successive spectral bands $(\lambda_i-\lambda_{i-1})$
n = number of integrated wavelengths within defined spectral interval.

2.5 Qualitative evaluation of the needle optical properties

The qualitative spectral analysis of the needle optical properties was performed by highlighting changes in shape (pattern) of the measured spectral features. A technique called *continuum removal* was applied to investigate qualitative changes in needle optical properties of defined stress response classes between the wavelengths of 505-800 nm. Kokaly and Clark (1999) used this technique for absorption features of the reflectance measured over dried and ground leaves to estimate the concentrations of nitrogen, lignin, and cellulose. Curran et al. (2001) refined the Kokaly and Clark methodology and test it within assessment of 12 foliar biochemical concentrations of dried and ground slash pine needles.

Computation of the spectral continuum removal used in this study is described in figure 1. First, the continuum line was linearly interpolated between the wavelengths of 505 and 800 nm. Then the continuum removed (*CR*) values of needle reflectance, transmittance and absorption, respectively, were computed according to the following formula:

$$CR(\lambda)=1-\left(\frac{\rho(\lambda)}{R(\lambda)}\right)$$
(6)

where $\rho(\lambda)$ = reflectance at the wavelength λ
$R(\lambda)$ = corresponding value at the interpolated continuum line.

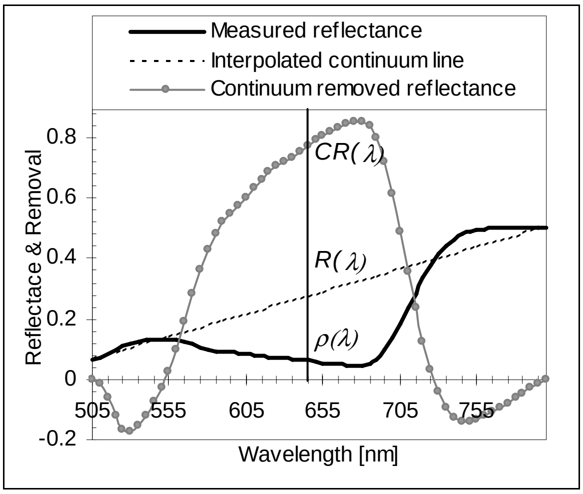

Figure 1. Diagrammatic description of the *continuum removal* for a reflectance signature between 505-800 nm.

2.6 Statistical tests

The statistically significant differences in the *AUC* and *CR* of defined needle categories were assessed using the one-way analysis of variance (ANOVA) combined with the Tukey-Kramer multiple comparison test in case of normal distribution of the input data. The Kuskal-Wallise (Bonferroni) multiple comparison test, validating significant differences between medians, was applied in case of a dataset without normal distribution of the inputs. The statistical relationships between the spectral derivatives and the needle pigment concentrations and dry matter content were tested by the correlation (Pearson correlation coefficient R) and linear regression tests (coefficient of determination r^2).

3. RESULTS AND DISCUSSION

3.1 Bio-chemical/physical differences

The concentrations of the foliar pigments (C_{ab} and C_{xc}) did not significantly differ between needles from the juvenile and production part of the stress resistant crowns. The same situation was observed in case of the stress resilient trees. Nevertheless, a significant difference (P=0.0005) was found in the amount of all examined foliar pigments between the RN samples (J_RN, P_RN) and the RT samples (J_RT, P_RT, and S_RT). The dry matter content (C_m) was statistically different between J_RN, P_RN and P_RT, S_RT needles, but J_RT needless did not significantly differ from any of those categories. As shown in table 1, the RT needles contained less photosynthetic pigments and also slightly less biomass than the RN needles.

	C_{ab} [µg/cm^2]		C_{xc} [µg/cm^2]		C_m [mg/cm^2]	
Cat.	Mean	SE	Mean	SE	Mean	SE
J_RN	69.55	2.96	10.21	0.54	27.62	0.60
J_RT	56.52	2.96	8.34	0.54	26.61	0.60
P_RN	67.41	2.96	10.07	0.54	27.40	0.60
P_RT	49.33	3.31	7.27	0.61	24.52	0.67
S_RT	53.84	3.01	7.82	0.55	24.93	0.61

Table 1. Means and standard errors (SE) of the foliar pigment concentrations (C_{ab}, C_{xc}) and dry matter content (C_m) per needle category (*Cat.*).

3.2 Differences in *AUC* of the optical properties

Most of the statistically significant *AUC* differences in optical properties of the needle categories were identified within the green, red and RE wavelengths (505-760 nm). No statistically significant difference was found in the NIR spectral part (figure 2).

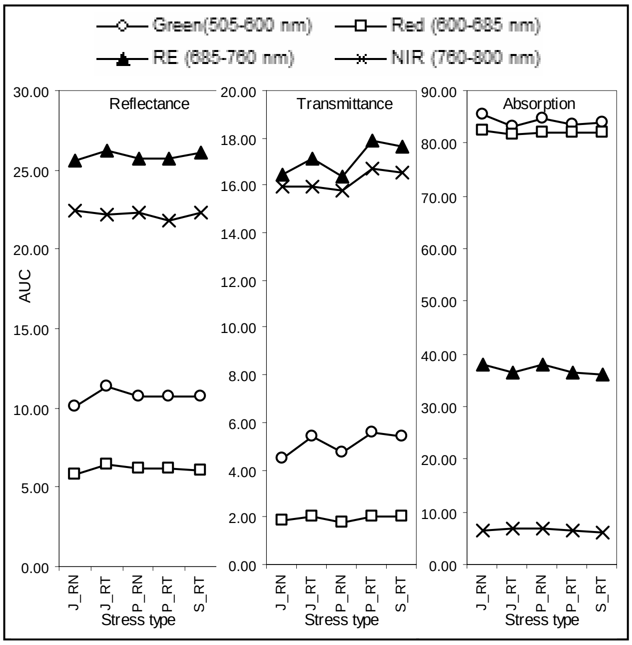

Figure 2. Area under curve (*AUC*) computed for the optical properties of defined spectral intervals per needle category.

The *AUC* of green and red reflectance of the J_RN samples was statistically smaller than the *AUC* for reflectance of the J_RT samples. Complementarily, the *AUC* of green absorption of the J_RN needles was significantly larger than green absorption *AUC* of the J_RT needles. Finally, the *AUC* of green J_RN transmittance appeared to be smaller than the *AUC* of P_RT transmittance, and also the red edge *AUC* of J_RN and P_RN transmittance was smaller than the *AUC* of P_RT transmittance.

Concerning the statistical relationships, the *AUC* of green, red, and red edge spectral intervals were significantly correlated with the C_{ab} and C_{xc} leaf concentrations (Pearson coefficient R = 0.55-0.77, r^2 = 0.30-0.60). A positive correlation was revealed for the needle absorption whereas a negative one was found for the reflectance and transmittance of both visible and red edge wavelengths. Lower C_{ab} and C_{xc} concentrations of the RT samples resulted in their lower absorption and higher reflectance and transmittance between 505-760 nm, while opposite situation was observed for the RN samples. The correlations between intensities of the spectral signatures and dry matter content were weak (R = 0.10-0.60).

3.3 Variability in *CR* spectral signatures

Statistically significant differences of the needle category's continuum removed *(CR)* reflectance, transmittance and absorption was observed between green ρ (510-600 nm), τ (550-580 nm), α (510-575 nm) and red ρ (605-660 and 685 nm) of J_RN and J_RT samples. However, more differences in needle categories were discovered for the red edge wavelengths, particularly for the *CR* reflectance and transmittance at 710-745 nm, and absorption at 715-730 nm (table 2). No significant difference in *CR* spectral signatures in the NIR region was found, except for the reflectance at 760 and 765 nm where P_RN samples were different from S_RT samples. All the observed differences were consistent in the way that needles of RN trees were always different only from needles of RT trees, so no mutual difference in-between RN samples or in-between RT samples was recorded.

It is worth to mention that the strongest regression relationships between *CR* ρ, τ, and α, and measured foliar pigment concentrations in the visible spectral part were obtained for the wavelengths at about 530 nm (r^2 = 0.49-0.56). The strongest relationships within the red edge spectral region were computed for the wavelengths at 735 and 740 nm (r^2 = 0.63-0.66). Similarly to the spectral intensities, the correlations and regressions of the *CR* spectral wavelengths with the dry matter content were rather poor (r^2 = 0.13-0.36).

The qualitative differences were, as expected, consistent with the quantitative changes in needle categories, but more detailed in distinction of the stress classes. Our results about the optical properties of Norway spruce needles were consistent with some findings of O'Neill et al. (2002) concerning reflectance variation throughout a Sitka spruce (*Picea sitchensis* /Bong./ Carr.) canopy. Particularly, the strongest regressions were measured between C_{ab} or C_{xc} concentrations and optical properties at the red edge. The second highest ones were found between pigments and spectral signatures at the green wavelengths, but the red wavelengths of strong photosynthetic pigment's absorption (665-680 nm) did not reveal significant correlation with the C_{ab} and C_{xc} concentrations. This can be explained by the presumption that these wavelengths become saturated and consequently less sensitive to the changes in pigment's quantity (Daughtry et al., 2000). The dry matter content, while different between RN and RT stress classes, was not able to statistically explain the variability in intensities of the needle category's optical properties. The amount of biomass seems to have less influence on the needle optical properties than the pigment concentrations. Finally, the NIR optical properties remained invariant in all the examined needle categories and were not significantly related to any bio-chemical/physical needle characteristic. Based on the fact that the NIR leaf signatures are driven by the leaf anatomical structure, one can contemplate a hypothesis that structural properties of needles from RN and RT trees did not diverge enough to differentiate their spectral responses. Yet, more detailed anatomical analyses of spruce needle categories must be conducted to investigate the validity of this implication.

	Differences in *CR reflectance* per wavelength [nm]							
Cat.	710	715	720	725	730	735	740	745
J_{RN}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}
J_{RT}	J_{RN}	J_{RN}	J_{RN}	J_{RN} P_{RN}	J_{RN} P_{RN}	J_{RN}	J_{RN}	J_{RN}
P_{RN}				J_{RT} P_{RT}	J_{RT} P_{RT}	P_{RT}	P_{RT} S_{RT}	P_{RT} S_{RT}
P_{RT}	J_{RN}	J_{RN}	J_{RN}	J_{RN} P_{RN}	J_{RN} P_{RN}	J_{RN} P_{RN}	J_{RN} P_{RN}	J_{RN} P_{RN}
S_{RT}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN} P_{RN}	J_{RN} P_{RN}
	Differences in *CR transmittance* per wavelength [nm]							
Cat.	710	715	720	725	730	735	740	745
J_{RN}	J_{RT}	J_{RT} P_{RT}	J_{RT} P_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}	P_{RT} S_{RT}	P_{RT} S_{RT}
J_{RT}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	
P_{RN}							P_{RT}	
P_{RT}		J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN} P_{RN}	J_{RN}
S_{RT}				J_{RN}	J_{RN}	J_{RN}	J_{RN}	J_{RN}
	Differences in *CR absorption* per wavelength [nm]							
Cat.	710	715	720	725	730	735	740	745
J_{RN}		J_{RT}	J_{RT} P_{RT}	J_{RT} P_{RT} S_{RT}	J_{RT} P_{RT} S_{RT}			
J_{RT}		J_{RN}	J_{RN}	J_{RN}	J_{RN}			
P_{RN}								
P_{RT}			J_{RN}	J_{RN}	J_{RN}			
S_{RT}				J_{RN}	J_{RN}			

Table 2. Statistically significant differences (P = 0.03) in needle continuum removed spectra between 505-800 nm.

4. CONCLUSIONS

In this study we have found no significant optical differences between needles of juvenile and production functional crown parts for either stress resistant or stress resilient Norway spruce crowns. Therefore, we conclude that any foliage sample of a specific age collected from a randomly selected branch within the juvenile or production crown parts can be considered as being representative for all needles of the same age throughout both functional crown parts of the tree. Nevertheless, statistical comparison of the needle optical properties from stress resistant and stress resilient trees showed significant spectral differences in the red edge, green and partially red part of the electromagnetic spectrum. Most differences were identified for needles of the upper juvenile crown parts followed by the primary shoots of the middle production parts. Needles of the secondary shoots were mostly optically indifferent from the others. The optical differences found in the red edge and green spectral region were statistically related to the variability in the concentration of foliar pigments (chlorophyll *a*+*b* and total carotenoids), responding to the magnitude of environmentally imposed multiple stresses. We can therefore conclude that remotely sensed estimates of the Norway spruce leaf biochemical concentration should take into consideration the spectral differences between the actual tree stress classes, because they might have an impact on both: i) calibration and parameterisation of statistical or physical models, and ii) validation of their results. Additionally, the proved foliar pigment differences can be beneficially used by the imaging spectroscopy based methods at an appropriate spatial resolution for detection and mapping the actual Norway spruce stress response classes.

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