TEMPORAL CHANGES IN NORWAY SPRUCE PHYSIOLOGICAL STATUS USING HYPERSPECTRAL DATA: A CASE STUDY OF MOUNTAINOUS FORESTS AFFECTED BY LONG-TERM ACIDIC DEPOSITIONS

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ABSTRACT

A decline in the Norway spruce forests of the Krušné Hory Mts., Czech Republic, has been reported since the early 1950's. It was attributed to the combination of severe atmospheric pollution and climatic conditions. The physiological status of the Norway spruce forests has been assessed using ground-truth data (biochemical and spectroscopic data) as well as two hyperspectral data sets acquired in 1998 (ASAS sensor, NASA Goddard Space Flight Center) and in 2013 (APEX sensor, developed by a Swiss-Belgian consortium on behalf of ESA, currently operated by VITO). The very first results coming from the analysis of the foliar chemistry indicate that the stands exhibit different physiological statuses corresponding to the pollution gradients in 1998 and 2013. Slight improvement of the Norway spruce physiological status was recorded in the eastern part of the mountains (e.g. total carotenoids to chlorophyll ratio), while the status of the western-located stands slightly worsened. These findings may correspond to a tremendous decrease in the atmospheric pollution which was most severe in the east. However, remains of the pollution can be still seen in the adverse soils conditions. Further linkages among foliar chemistry and reflectance and soil chemistry are currently under investigation.

INTRODUCTION

The physiological status of trees within forest ecosystems determines their proper functioning (1,2). The contents of foliar biochemical compounds, such as photosynthetic pigments, phenolic compounds or lignin, can be used as non-specific indicators of the physiological status and early pre-visual indicators of tree damage (1). Variations in leaf biochemical composition affect foliar optical properties and can be retrieved from continuous spectral data (3,4). There are two modelling approaches to link content of biochemical compounds or biophysical parameters of vegetation to spectra: empirical models (different regressions, e.g. (2)) and physical models (radiative transfer, e.g. (5)).

Due to coal burning power plants in the close vicinity of the Krušné Hory Mts. a strong gradient of acidic deposition leading from heavy (the eastern part) to light (the western part) developed during the 1970's and 1980's. Although the load of SO_2 has significantly decreased since 1991, the full recovery of forests damaged by previous acid deposition is a long term process. Thus, the main goal of the INMON project is to assess the temporal changes in the physiological status of Norway

DOI: 10.12760/02-2014-1-13

spruce in Krušné Hory Mts. using two hyperspectral data sets acquired in 1998 (ASAS sensor) and in 2013 (APEX sensor). In this paper, we will focus on three specific objectives:

i. to compare biochemical and biophysical needle parameters from trees sampled at the western part (Přebuz) and the eastern part (Kovářská) of the Krušné Hory Mts. between 1998 and 2013
ii. to construct the prediction models for photosynthetic pigments and water content based on laboratory spectroscopy
iii. to compare the geochemical conditions of study stands at the western part (Přebuz) and the eastern part (Kovářská) of the Krušné hory Mts. in 2012.

METHODS

The study sites were selected at two different localities in the Krušné Hory Mts. about 50 km apart. Přebuz located in the western part of the mountains was considered as healthy or slightly damaged in contrast to Kovářská located in the eastern part, which suffered from the heavy acidic load and the trees exhibited visible damage symptoms (2). Even-aged forest stands older than 60 years (15 sites at Kovářská and 22 sites at Přebuz in 1998) and older than 80 years (five sites at Kovářská and six sites at Přebuz in 2013) were selected. In 2013, the sites studied in 1998 were revisited if possible. In 2013, the sampled trees did not show any visible damage symptoms. The hyperspectral image data was acquired on 6th September 2013 using the APEX airborne imaging spectrometer. Simultaneously, a supportive calibration and validation ground campaign was organized to support the processing of the hyperspectral data.

Needle sampling for biochemical analyses was accomplished for five representative trees per site within the periods 15-28 August 1998 and 22-25 August 2013. In both years, the first three needle age classes were used for photosynthetic pigments (total chlorophylls, total carotenoids) determination using dimethylformamide extractions according to Porra (6), followed by spectrophotometric detection and calculations according to Welburn (7). The pigment concentrations were then expressed as mass of pigment per gram of needle dry mass (mg/g). The relative water content (*RWC*) was determined as the percentage of water in the fresh needles.

Simultaneously with the needle sampling in 2013 the spectral reflectance of spruce foliage was measured in the range between 350 and 2,500 nm using an ASD FieldSpec 4 Wide-Res spectrometer in combination with the fibre optic contact probe (similar to (4)). Branchlets consisting of only one age class were arranged in the same direction to create a consistent layer to fill in the field of view (spot size 10 mm) of the contact probe. Five independent spectra were taken on different parts of one sample and afterwards the median spectrum was calculated (altogether 165 median spectra: 11 sites $\times$ 5 trees $\times$ 3 needle age classes). Due to the noise in the spectra in the 350-450 nm regions, this interval was excluded from further analyses. Selected spectral indices were calculated from the spectra: Modified Chlorophyll Absorption in Reflectance Index *MCARI* (8), Transformed Chlorophyll Absorption Ratio Index / Optimized Soil Adjusted Vegetation Index *TCARI*/*OSAVI* (9), Triangular Vegetation Index *TVI* (10) for correlations with total chlorophyll and Water Index *WI* (11) and Normalized Difference Water Index *NDWI* (12) for correlations with *RWC*. Often used indices for carotenoids were calculated, but the regression model results were not significant. Also partial least square regressions (*PLSR*) using all reflectance values in the range of 450 - 2,500 nm for estimation of *RWC* and pigments were performed. The regression models were trained on four fifths of the dataset; data from one tree per site were used for model validation. All calculations were performed in R software with pls package or in Microsoft Excel 2007.

In each forest stand, representative sampling pits were chosen to collect soil samples. Material was collected from organic and mineral soil horizons. Exchangeable cations and selected trace elements were determined together with soil pH, TEA and total contents of C and N.

RESULTS

Total contents of photosynthetic pigments did not significantly differ between 1998 and 2013 either at Kovářská (eastern locality) or at Přebuz (western locality). However, the ratio between total carotenoids and total chlorophylls (Car/Cab) significantly decreased at Kovářská in contrast to a significant increase in Přebuz. This change in Car/Cab documents the different progress of tree physiological status between 1998 and 2013: Improvement at the eastern and worsening at the western part of the Krušné Hory Mts (Table 1). Relative water content (*RWC*) also significantly decreased, indicating much drier canopy conditions in 2013 (Table 1). Since *RWC* can vary strongly in relationship to temperature and humidity, we will further compare the meteorological conditions at both sites at the time of data collection.

Table 1: Differences in the foliar chemistry at two studied localities between 1998 and 2013 (Mann-Whitney test., Means and standard deviations (S.D.) are shown for each year and locality studied. Significant difference at α = 0.05, n.s. = not significant; d.m. needle dry mass.*

	Přebuz (Western part)			**Kovářská (Eastern part)**		
	1998	2013		1998	2013	
Needle parameter	Mean (S.D.)	Mean (S.D.)	*p*-value	Mean (S.D.)	Mean (S.D.)	*p*-value
Total chlorophyll (mg/g d.m.)	3.42 (0.815)	3.26 (0.666)	0.141812 n.s.	3.29 (0.837)	3.58 (0.589)	0.277424 n.s.
Carotenoids (mg/g d.m.)	0.43 (0.106)	0.42 (0.077)	0.517501 n.s.	0.45 (0.121)	0.451 (0.070)	0.893544 n.s.
Car/Cab	0.13 (0.011)	0.13 (0.009)	0.000578 *	0.14 (0.011)	0.13 (0.006)	0.000084 *
RWC (%)	60.80 (3.500)	57.50 (2.750)	0.000000 *	60.00 (4.920)	58.30 (2.730)	0.003330 *

Prediction models for photosynthetic pigments and water content based on different methods (indices and PLSR) calculated from laboratory spectra did not produce very strong correlation results (Table 2) in comparison with, for example, (2,3,9). The best results were achieved using the *TCARI*/*OSAVI* index (for photosynthetic pigments), *WI* (for water content) and *PLSR* (in accordance with (3)).

Table 2: Regression models between the spectra and biochemical and biophysical parameters (R2 – coefficient of determination, RMSE – root mean square error, comp. – number of components considered in the model)

	Total chlorophyll (mg/g d.m.)			**Carotenoids (mg/g d.m.)**			***RWC* (%)**	
Method	***R^2* ***	***RMSE***	**method**	***R^2* ***	***RMSE***	**method**	***R^2* ***	***RMSE***
MCARI	0.522	0.462	x	x	x	*WI*	0.501	1.746
TCARI/OSAVI	0.648	0.375	x	x	x	*NDWI*	0.482	1.976
TVI	0.494	0.489	x	x	x	x	x	x
PLSR	0.776 (6 comp.)	0.332	*PLSR*	0.774 (6 comp.)	0.038	*PLSR*	0.783 (8 comp.)	1.456

* *P-values for all the models were lower than $2.2 \cdot 10^{-16}$.*

Both study sites exhibited differences in soil geochemical conditions. Comparing Kovářská to Přebuz, the latter was characterized by lower base cation contents and the top organic horizon (O) had a very low pH (pH<3) (Figure 1). In general, soil environment at the Přebuz site represents less favourable conditions, in which selected trace elements (Hg, Pb) could be present at a mobile form.

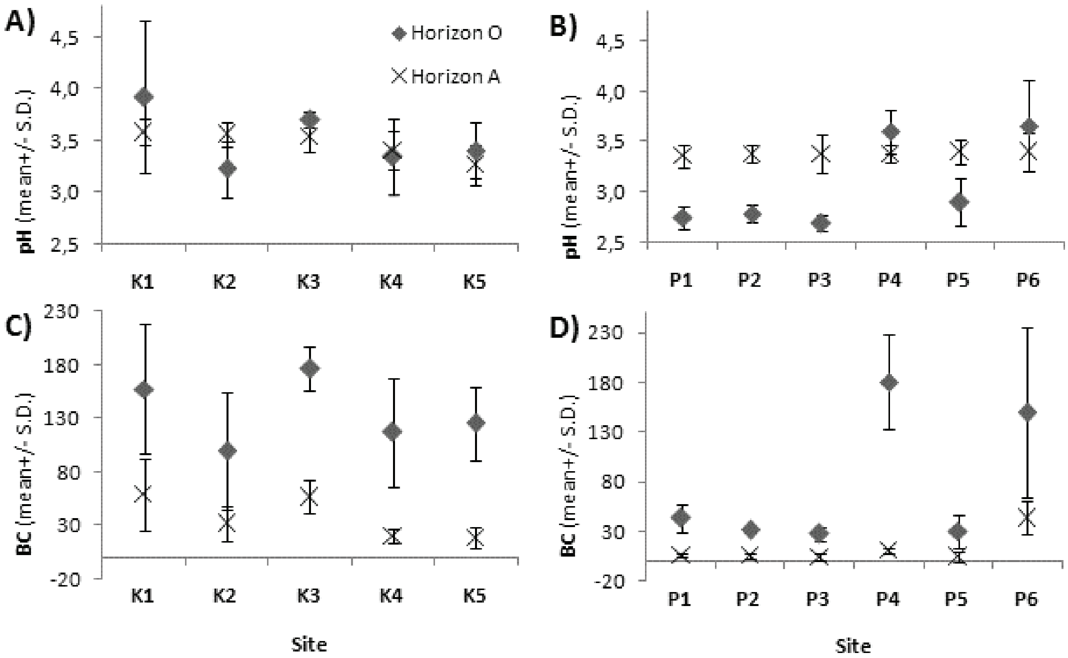

Figure 1: pH (A: Kovářská, B: Přebuz) and base cation (BC) content in (mmol·kg^{-1}) (C: Kovářská, D: Přebuz) and (SD: Standard Deviation).

CONCLUSIONS

The photosynthetic pigment content alone does not always clearly indicate changes in tree physiological status and a combination of several stress indicators is required (3). The carotenoids in needles protect the pigment-protein complexes from photodamage (13) and thus the increase in *Car*/*Cab* ratio indicates higher levels of tree stress at Přebuz, the western locality. The results of soil analyses also indicate less favourable conditions for trees at Přebuz. It appears that after removal of main acidic deposition sources in the 1990's, the soil acidification is now the main driving factor of the Norway spruce physiological status in Krušné Hory Mts. The improvement of forest soils damaged by previous acidic deposition is a long-term process and only slight recovery was observed after a decade in other mountainous regions of the Czech Republic (14).

In this paper, only preliminary results from foliar chemistry ground truth are presented. However, we will draw more complex conclusions about the temporal change in Norway spruce physiological status after processing the hyperspectral data providing the information on a larger spatial scale. We also plan to employ additional needle biochemical stress indicators (e.g. soluble phenolics, lignin) in our future work to better understand the Norway spruce physiological status and its response to soil conditions.

The next step of the project is to improve the predictive models for pigments and other biochemical stress indicators based on the spectral measurements using an integrating sphere. After that, upscaling from the foliar to the canopy level and classification of already acquired hyperspectral data (by APEX in 2013 and by ASAS in 1998) will be performed. The methodology for hyperspectral data processing to compare the health status of Norway spruce stands in the Krusne Hory Mts. in the end of the 1990's and at present will be adjusted. Also linking foliage chemical composition and spectral properties with soil chemical properties (basic cations, heavy metals, pH, C/N, DOC, DON, etc.) will continue.

ACKNOWLEDGEMENTS

The support by the Ministry of Education of the Czech Republic is acknowledged: LH12097. We are grateful to Drahomíra Bartáková and Monika Kovářová for laboratory analyses and to students who helped with needle sampling and spectral measurements.

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