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Detection of Spatio-Temporal Changes of Norway Spruce Forest Stands in Ore Mountains Using Airborne Hyperspectral Imagery

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Abstract: The Ore Mountains are an example of the region that suffered from severe environmental pollution caused by long-term coal mining and heavy industry leading to massive dieback of the local Norway spruce forests between the 1970's and 1990's. The situation became getting better at the end of 1990's after pollution loads significantly decreased. In 1998 and 2013, airborne hyperspectral data (with sensor ASAS and APEX, respectively) were used to study recovery of the originally damaged forest stands and compared them with those that have been less affected by environmental pollution. The field campaign (needle biochemical analysis, tree defoliation etc.) accompanied hyperspectral imagery acquisition. An analysis was conducted assessing a set of 16 vegetation indices providing complex information on foliage, biochemistry and canopy biophysics and structure. Five of them (NDVI, $NDVI_{705}$, VOG_1, MSR and TCARI/OSAVI) showing the best results were employed to study spatial gradients as well as temporal changes. The detected gradients are in accordance with ground truth data on representative trees. The obtained results indicate that the original significant differences between the damaged and undamaged stands have been generally levelled until 2013, although it is still possible to detect signs of the previous damages in several cases.

Keywords: forest health; tree physiological status, hyperspectral imagery, Norway spruce, Ore Mountains

1. Introduction

Forests belong to most crucial terrestrial ecosystems. However, they have recently faced increasing pressure not only in terms of human needs of wood and other resources, but also worsening of environmental conditions mainly by human industrial activities. The concerns of forest health status lead to numerous remote sensing applications focusing on monitoring the actual level of forest damage using multispectral data like Landsat TM/ETM+, e.g. [1-2]. Significant advances have been made with the use of the first generation of airborne hyperspectral sensors enabling identification of not only significant forest damage, but also the very initial phases of vegetation stress. [3-4].

The main aim of this paper is to assess spatio-temporal differences between the particular Norway spruce stands located in the western and central parts of the Ore Mts. using several vegetation condition sensitive vegetation indices extracted from the ASAS and the APEX imagery in combination with the set of ground supportive data. We would like to answer the question whether there is currently any significant difference in tree physiological status between the originally damaged and subsequently recovered stands at central Ore Mts. and the stands which have never been seriously damaged located in the western Ore Mts.

2. Methods

Our study took part in the Ore Mountains (western Bohemia), which is one example of the region which suffered by severe environmental pollution caused by coal mining and heavy industry leading to massive dieback of the local Norway spruce forests between 1970 and 1990. Two temporal hyperspectral and ground-truth datasets were analyzed to study temporal changes of selected forest stands. First dataset represents ASAS (Airborne Solid-state Array Spectrometer) imagery and extensive in-situ data on forest biochemistry and biophysics acquired at the end of Norway spruce forest dieback phase [4-5]. A new hyperspectral image (Airborne Prism Experiment – APEX) as well as in-situ data were acquired in 2013 to assess forest physiological status after 15 years of regeneration.

2.1. Study area

The study was performed at two locations situated in Ore Mountains region in Western Bohemia. Přebuz, situated in the western part of the Ore Mountains, has not been significantly affected by air pollution and the related phenomena and local forests show historically stable conditions with no or light damage level. Kovářská, situated in central Ore Mountains, suffered historically much higher loads of SO_2, NO_x and PM_{10} [6]. Local forests showed moderate to high level of damage at the end of 1990-ies. The stands have been recovered since 2000 and currently show no visual damage symptoms.

Figure 1. Norway spruce stands sampled at Přebuz and Kovářská localities in 1998. Background map ©ČUZK
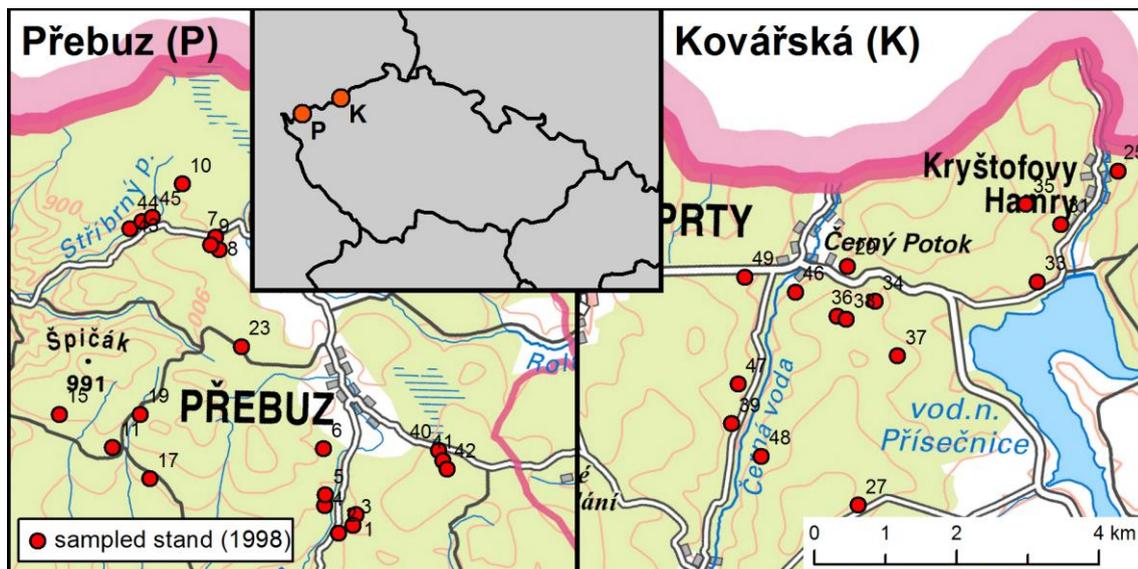
2.2. Airborne hyperspectral data

ASAS data were acquired between 20th August and 1st September 1998 consisting of 62 spectral bands (with FWHM ca. 10 nm) covering the spectral interval from 410 to 1032 nm. However, only the bands between approx. 550 – 850 nm were practically usable for the further analyses due to poor spectral performance of the sensor in the VIS-B and far NIR regions. The original ground spatial resolution of this dataset was 1.5×2.0 m.

The raw data were radiometrically calibrated and finally transformed to at-surface reflectance using the 6S atmospheric correction code as well as the in-situ ground level spectra of two selected calibration targets (dark asphalt and bright lime) taken by GER-2500 field spectroradiometer.

APEX data were acquired on 6th September 2013 consisting of 286 spectral bands (with FWHM ca. 7 nm) covering the spectral interval between approx. 430 and 2450 nm. The original ground spatial resolution of the dataset was 2.0 m.

Supportive calibration/validation ground campaign was organized simultaneously with the acquisition of hyperspectral imagery. Surface level spectra of several calibration and validation targets of adequate spatial extent and homogeneity were taken by ASD Fieldspec-4 spectroradiometer. The targets included water bodies (2×), asphalt (3×), concrete tiles (4×), bare soil/sand (1×), fresh grass (2×) and dry grass (1×).

Radiometric calibration, smile effect removal, geometric and atmospheric correction of the APEX dataset was performed by VITO. Radiometric calibration was conducted using the APEX Calibration Home Base data [7]. Geometric correction was performed using the data from GPS/IMU, boresight corrections and 5 m grid lidar-based digital elevation model. Atmospheric correction was conducted using the CDPC module [8] based on MODTRAN-4 radiative transfer code followed by algorithm described by [9].

Figure 2. (**a**) Hypercubes constructed from the ASAS data covering 410 – 1032 nm spectral range (A) and APEX data (B) covering 430 – 2450 nm range.
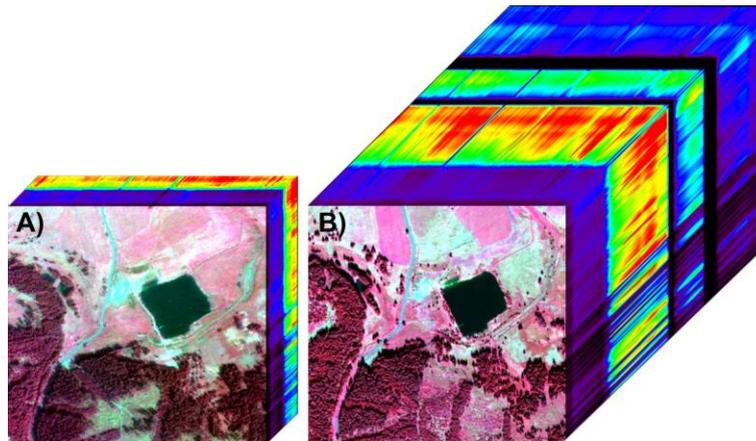
2.3. Ground supportive campaign

The ground supportive campaign was organized simultaneously with the ASAS data acquisition in late August 1998. In total, 38 even aged mature Norway spruce stands (21 at Přebuz and 17 at Kovářská sites) were selected for evaluation of tree physiological status using five-grade damage class scale as described in Table 1. The classification scheme is based on defoliation degree and presence of chlorosis rising from the practice used in the Czech Republic on that time [4]. In addition, five trees were selected at each stand for needle sampling to determine content of photosynthetic pigments (chlorophylls and carotenoids). The foliar pigments content was determined spectrophotometrically according to [10] after extraction in dimethylforamide according to [11] and normalized by dry sample weight (mg·g^{-1}). All the sampled trees fallen within the area of 30 × 30 m whose centroid was localized by differentially corrected GPS [4].

In 2013, a new ground campaign was organized simultaneously with the APEX data acquisition. Eleven Norway spruce stands were selected for a detailed study, from which 8 coincided with the stands selected during the 1998 campaign (stands P_9, P_{10}, P_{11}, P_{40}, K_{25}, K_{37}, K_{46} and K_{47}). Similar sampling design was applied in this case using five sampling trees per stand for foliar pigments content assessment. All stands were classified into DC_0 and DC_1 classes at both Přebuz and Kovářská sites as they did not show any severe symptoms of damage.

Table 1: Forest health status classification scheme used during the campaign in 1998 adopted from [4].

damage class	vitality status	canopy defoliation (%)		% of stands (1998)	
		chlorosis absent	chlorosis present	Přebuz	Kovářská
DC0	healthy	0 – 10	X	55	0
DC1	initial damage	11 – 25	0 – 10	45	0
DC2	moderate damage	26 – 60	11 – 25	0	36
DC3	heavy damage	61 – 80	26 – 60	0	64
DC4	ecosystem collapse	81 - 100	61 - 100	0	0

2.4. Stand definition

The Norway spruce stands defined during the 1998 field campaign were considered essential as healthy ($DC_0 - DC_1$; located at Přebuz area) and damaged ones ($DC_2 - DC_3$; located at Kovářská area) were clearly distinguished [4]. Note that no stand was classified into the DC_4 class neither at Přebuz nor at Kovářská site.

The original number of stands was reduced due to several issues such as cloud coverage, timbering (stands were cut-off in the 1998 – 2013 period) etc. Some other stands were out of the extent of the ASAS dataset. Finally, 16 stands defined in 1998 could have been found in both the ASAS and the APEX datasets, 14 at Přebuz (P_1, P_2, P_3, P_4, P_5, P_6, P_9, P_{10}, P_{11}, P_{15}, P_{17}, P_{43}, P_{44}, P_{45}) and 2 at Kovářská sites (K_{33} and K_{37}).

The forest health status analysis was performed at two levels of spatial resolution: original (2.0 m) considering individual tree crowns, and generalized (6.0 m) considering whole forest stands. The stands were defined by 30 m buffer zone. The pixels representing sunlit parts of Norway spruce crowns defined by Mahalanobis distance classificator were taken in into account in case of the original resolution data (Figure 3), whereas all the pixels within the defined buffers were used in case of the generalized level data.

Figure 3. Definition of the Norway spruce sampling stands in the original APEX data (A) and binary mask of the sunlit crowns (B).
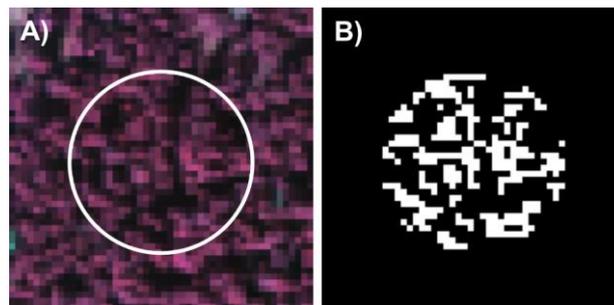
2.5. Vegetation indices and stands separability

In case of the ASAS dataset, only the bands between 550 – 850 nm were usable for further processing. This limited the number of vegetation indices (VIs) that can be calculated from these data (e.g. all the indices requiring the VIS-B bands had to be excluded). APEX data were resampled to the spectral resolution of the ASAS data prior the calculation of VIs to ensure their comparability. The vegetation indices used within this study are listed in Table 2.

Table 2. Vegetation indices used for the spatio-temporal analysis of Norway spruce physiological status.

Table 2: Vegetation indices	
NDVI$_{705}$ [12]	MCARI [19]
VOG$_1$ and VOG$_2$ [13]	TVI [20]
REP [14]	TCARI [21]
NDVI [15]	OSAVI [22]
RDVI [16]	TCARI/OSAVI [21]
MSR [17]	N$_{704}$, N$_{714}$, N$_{724}$ [4]
MSAVI [18]	D$_{714}$/D704, D$_{724}$/D$_{704}$ [4]

In the first step, a simple separability index was calculated between the healthy and damaged forest stands for the all VIs to check their sensitivity on forest damage. The SI was calculated using the following formula used in [23]:

$$SI = \frac{|\mu_h - \mu_d|}{\sigma_h + \sigma_d} \quad (1)$$

where: SI is the value of separability index; μ_h and σ_h are mean and standard deviation calculated from the pixels within the healthy (undamaged) forest stands; μ_d and σ_d are mean and standard deviation calculated from the pixels within the damaged forest stands.

The original values of the given VIs obtained from the ASAS dataset are not directly comparable to the ones extracted from the APEX dataset. This is mainly due to technological differences between ASAS and APEX sensors, differences in atmospheric correction applied on the ASAS and APEX datasets etc. The original VIs values were therefore normalized to allow their mutual comparability using the following formula:

$$VI'_x = \frac{VI_x - VI_\mu}{VI_\sigma} \quad (2)$$

where: VI'$_x$ is the normalized value of vegetation index VI for pixel x; VI$_x$ is the original value of vegetation index VI for pixel x; VI$_\mu$ and VI$_\sigma$ are mean and standard deviation values of vegetation index VI calculated from the all pixels representing sunlit crowns within the all buffer areas representing the selected forest stands.

2.6. Detection of spatial and temporal differences

Student's two-sample test was used to analyze spatial differences as well as temporal changes. In the first case we tested whether there are any significant differences in VIs values extracted from the healthy and damaged stands. In the second case, the relativized VI' values describe the relative distance of the given pixel from the global mean (calculated from all pixels). We thus analyzed whether any significant change of the relative distance to the global mean occurred at the given stand. The tests were performed at the 95% significance level ($\alpha = 0.05$).

2.7. Evaluation of changes in content of photosynthetic pigments

Two physiological photosynthetic pigment markers were used as the indicators of tree physiological status: chlorophyll-a to chlorophyll-b ratio (C_a/C_b) and total carotenoids to total chlorophylls ratio (C_x/C_{ab}). Worsening of tree physiological status is usually exhibited by increase in C_a/C_b ratio as chlorophyll-b is regarded to be more sensitive to vegetation stress than chlorophyll-a [24]. Similarly, stress conditions lead to increasing in C_x/C_{ab} ratio [25].

Temporal differences in photosynthetic pigments contents and their ratios were evaluated for the stands sampled in both years (1998 and 2013) and covered by both hyperspectral image datasets. Two-way ANOVA (considering differences as significant in $p < 0.05$) was used for evaluation the differences between the localities (Přebuz and Kovářská) and the temporal changes. The differences between localities in particular years were determined by Tukey-Kramer multiple comparison test.

3. Results

The performed sensitivity analysis proved that majority of the used VIs is highly sensitive to vegetation health status and forest damage. The separability scores for the most sensitive indices are shown in Table 3.

Table 3: Separability scores (SI) of the five most sensitive indices for the original (2 m) and generalized (6 m) spatial resolution ASAS data.

dataset	ASAS (1998)	
resolution	2 m (crown level)	6 m (stand level)
1.	VOG_1: 1.87	N_{714}: 1.92
2.	NDVI: 1.55	VOG_1: 1.88
3.	TCARI/OSAVI: 1.52	TCARI/OSAVI: 1.88
4.	MSR: 1.48	MSR: 1.85
5.	$NDVI_{705}$: 1.44	$NDVI_{705}$: 1.80

Significant differences were detected for the VIs values between damaged stands located at Kovářská (central Ore Mts.) and healthy ones located at Přebuz (western Ore Mts.) in both original (2 m) and generalized (6 m) spatial resolutions of the ASAS dataset (p-values were far less than 0.01 in all cases). Moreover, these differences were detectable also in case of the APEX 2013 data although they were not as noticeable as in case of the 1998 dataset.

The temporal changes were studied using primarily the VOG_1 index as it was showing high and stable sensitivity to forest damage for both considered spatial resolutions. Significant changes of the relativized VI' values were proved at major part of the studied stands except of P_5 (p-value 0.28) and P_{17} (p-value 0.46).

A simple visualization was developed to facilitate interpretation of the obtained results (Figure 4). The charts show the relative distance of the particular stands (defined by local mean of the given VI) from the baselines (defined by the global mean of the given VI) in both time horizons. Four possible situations can be defined from this point of view:

- **positive stagnation** (+/+)**:** local mean of the relativized VI' values was positive in both time horizons. The given stand was above the global mean in both years.
- **negative stagnation** (–/–)**:** local mean of the relativized VI' values was negative in both years. The stand was below the global mean in both years.
- **recovery** (–/+)**:** local mean of the relativized VI' values was negative in 1998, but positive in 2013. The stand was below the global mean in 1998, but above the global mean in 2013.
- **worsening** (+/–)**:** The given stand was above the global mean in 1998 but below the global mean in 2013.

The biochemical analysis did not prove significant differences in total chlorophyll a and b content in Norway spruce needles sampled on either locality in 1998 and 2013. Nevertheless, differences were detected in the ratios of photosynthetic pigments (C_a/C_b and C_x/C_{ab}). However, these differences were statistically significant only in 1998 dataset corresponding to higher degree tree and stand damage observed in central Ore Mts. (Figure 6).

Figure 4. Visualization of Norway spruce health status temporal change between 1998 and 2013 at Přebuz (P) and Kovářská (K) sites using VOG_1 vegetation index constructed for original (A) and generalized (B) spatial resolution of image data.
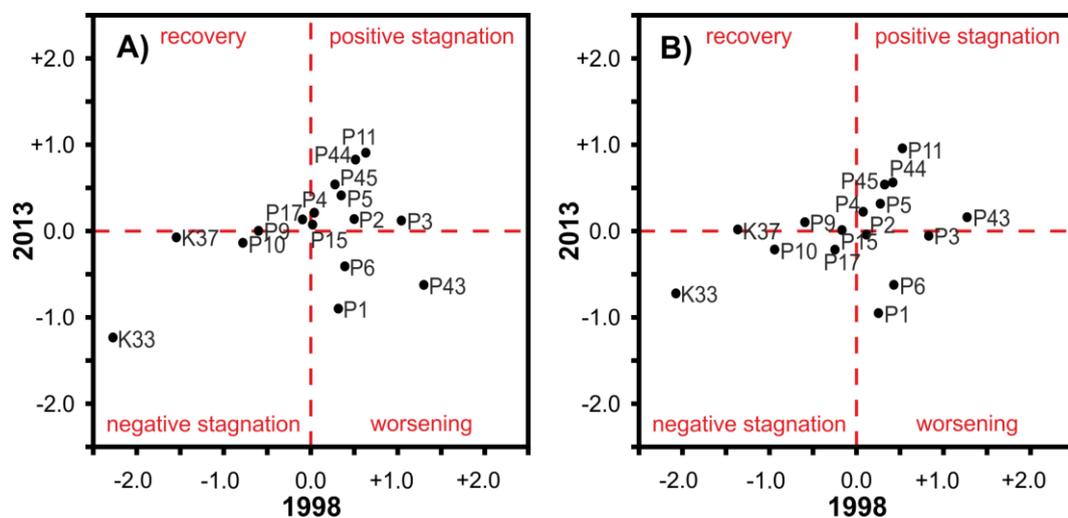
Figure 5. Spatio-temporal changes (comparison of 1998 and 2013 data for Přebuz and Kovářská sites) in the ratios of photosynthetic pigments by the Tukey-Kramer multiple comparison test: A) chlorophyll-a to chlorophyll-b ratio; B) total carotenoids to total chlorophylls ratio. Different letters above the mean/standard deviation columns correspond to significant difference at α = 0.05.
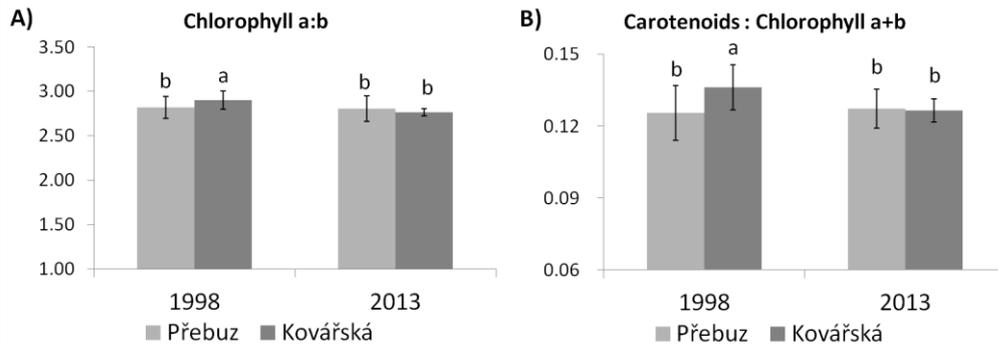
Figure 6. Relativized values of the VOG_1 vegetation index calculated from the ASAS (1998) and APEX (2013) hyperspectral image data in original 2 m spatial resolution for P_{11} and K_{37} stands.
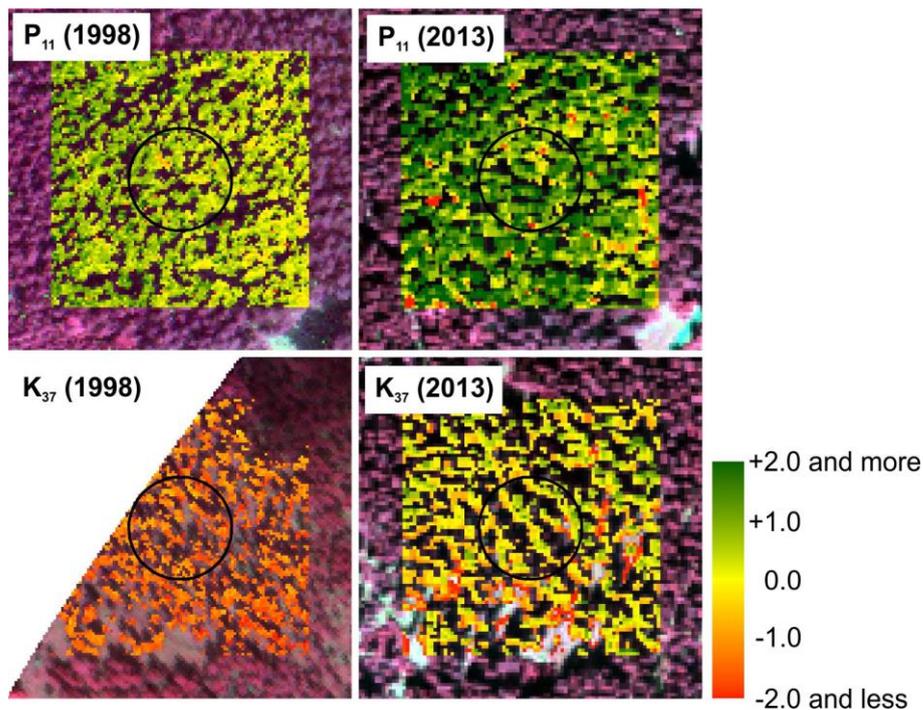
4. Discussion

Based on the above studied indicators of forest health status we can conclude that in 1998 significant differences were observed between damaged (central Ore Mts. – Kovářská) and undamaged (western Ore Mts. – Přebuz) stands. This result is in good agreement with the general gradient of air pollution within the Ore Mountains region due to prevailing wind direction which brought more pollution to the central and eastern parts of the Ore Mts. compared to their western part. The observed gradient of vegetation damage is also in accordance with previous studies [26, 27, 5].

In 2013, the stands at Kovářská exhibited VI' values much closer to the global mean (compared to 1998) indicating improvement of health status of the local Norway spruce forests. It demonstrates that the stands at Kovářská responded more positively to sharp decrease in air pollution loads compared to the stands at Přebuz. Nevertheless, there are still minor differences between the stands at Kovářská and Přebuz which are detectable by the majority of the used VIs. This demonstrates ability of the chosen

VIs in detecting not only high level of forest damage, but also slight differences in physiological status, which do not have any visible symptoms (such as high defoliation level etc.).

Ratios of photosynthetic pigments are sensitive indicators of air pollution [25, 27]. The differences in C_a/C_b and C_x/C_{ab} ratios generally corresponded with the spatial gradient of forest physiological status observed by the used VIs in both compared years 1998 and 2013. In 2013, the analysis confirmed a slight improvement in Norway spruce physiological status for Kovářská stands whereas the values for western-located Přebuz stands remained the same. Thus there are currently no significant differences in physiological photosynthetic pigment markers between the studied.

5. Conclusions

Several of the tested VIs proved to be highly sensitive to vegetation health status and forest damage, particularly VOG_1, TCARI/OSAVI, MSR and $NDVI_{705}$. The VOG_1 index was showing high and stable sensitivity to forest damage for both considered spatial resolutions (the original and generalized; 2 and 6 m respectively) and thus it was selected for a study of the spatio-temporal changes. Selected sensitive VIs also demonstrated ability to detect not only high level of forest damage, but also slight differences in physiological status, which do not have any visible symptoms (such as high defoliation level etc.).

Generally, we conclude that forest recovery appeared in Ore Mts. during the observed period 1998 – 2013. Regarding spatio-temporal changes in forest status, in 1998 significant differences were observed between damaged (central Ore Mts. – Kovářská) and undamaged (western Ore Mts. – Přebuz) stands, while in 2013 sort of "averaging" of the health status of Norway spruce stands has been observed: surviving trees in the central part improved their health status remarkably while originally undamaged stands in the western part showed symptoms of chronic damage. Since adverse soil conditions are longer persisting and improving only slowly comparing to air conditions and pollution, forests in the Ore Mts. are still exposed to acid soil conditions. The pollution load, particularly of sulfur, was reduced tremendously, however, the acid deposition in coniferous stands in the Ore Mts. still plays an important role, particularly due to nitrate deposition, which is currently exceeding critical load in 87 – 90 % [28]. We suppose that the full recovery of Norway spruce forest in the Ore Mountains will not occur in the nearest future due to persisting adverse soil conditions.

The presented study has character of methodical demonstration due to limited spatial extent of hyperspectral imagery acquired in 1998. Nevertheless, the obtained results seem to be promising and demonstrate great potential for further use of the proposed workflow (e.g. broader spatial area covered with multi-temporal hyperspectral data allowing more representative forest health status analysis). Higher temporal resolution of hyperspectral data (e.g. one acquisition per each vegetation season) would positively affect our knowledge on forest recovery processes. The main environmental drivers affecting forest productivity and services are currently regarded climate change together with anthropogenic pressure including air pollution [29, 30]. Since forests represent a key component in carbon cycling, the effective large-scale methods of remote sensing to detect their physiological status and capability of carbon sequestration are becoming crucially important. Our study demonstrates capability of highly sensitive VIs derived from hyperspectral data to facilitate this demand for spruce forests.

Acknowledgments

Conflicts of Interest

The authors declare no conflicts of interest as well as no direct financial profit arising from the publication of this study.

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