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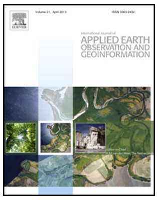

Using multi-date high spectral resolution data to assess the physiological status of macroscopically undamaged foliage on a regional scale

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ABSTRACT

Forests play an important role in regulation of the global climate; moreover, they provide human beings with a whole range of ecosystem services. Forest health and ecosystem functioning have been influenced by anthropogenic activities and their consequences, such as air pollution, surface mining, heavy metal contamination, and other biotic and abiotic stress factors, which had an especially serious effect on central Europe. Many aspects of the physiological state of trees are more or less related to the concentrations of two main groups of leaf photosynthetic pigments: chlorophylls and carotenoids. Therefore, their contents can be used as non-specific indicators of the actual tree physiological status, stress and the pre-visible tree damage. Variations in leaf biochemical composition affect foliar optical properties and can be assessed remotely using high spectral resolution data (hyperspectral data). These data were successfully used in earlier studies to detect vegetation stress and damage. However, only a few approaches have dealt with the use of hyperspectral remote sensing to assess vegetation physiological status on a regional scale. Moreover, little or no research has been done on assessing vegetation health while utilizing multi-date hyperspectral images.

In this study, the method for assessing forest health conditions using optical indices retrieved from hyperspectral data was applied to the two temporal HyMap date sets acquired in 07/2009 and 08/2010 to detect stress for the Norway spruce forests in Sokolov, NW Bohemia, a region affected by long-term extensive mining. The classification results were validated by ground truth data (total chlorophyll – Cab, carotenoids – Car and carotenoid to chlorophyll ratio – Car/Cab) and were associated with the geochemical conditions of the forest stands. Both biochemical analysis of the sampled foliage and classification of 2009 and 2010 hyperspectral image identified the same sites affected by vegetation stress. In addition to higher Car/Cab, which enabled detection of the stressed trees using hyperspectral image data, these sites showed critically low pH and lower values for the macronutrient parameters in both organic horizons and, in addition, both sites exhibit critically low base cation to aluminum ratios (Bc/Al) for lower organic and top mineral (0–20 cm) soil horizons.

The results of this study demonstrate (i) the potential application of hyperspectral remote sensing as a rapid method of identifying tree stress prior to symptom expression, and (ii) the added value of multi-temporal approaches for hyperspectral data and its further potential for monitoring forest ecosystems.

Abbreviations: AAS, atomic absorption spectrometry; ANOVA, analysis of variance; AOT, aerosol optical thickness; BRDF, bi-directional reflectance distribution function; Cab, total chlorophylls content; Car, total carotenoids content; Car/Cab, carotenoids to chlorophylls ratio; D_{718}/D_{704}, ratio of the 1st derivatives of refletance at 718 and 704 nm; DMF, dimethylformamide; expSIPI, exponentially transformed SIPI index; GPS, global positioning system; HCRF, hemispherical-conical reflectance factor; HS, hyperspectral; IMU, inertial measurement unit; IS, imaging spectroscopy; K–S, Kolmogorov–Smirnov test; MLC, maximum likelihood classification; MNF, minimum noise fraction; NDVI, normalized difference vegetation index; REP, red-edge position; SIPI, structure insensitive pigment index; TEA, total exchangeable acidity; WV, water vapor.

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1. Introduction

Forests play an important role in regulation of the global climate via the global carbon cycle, evapotranspiration, and earth surface albedo (Bonan, 2008; Jackson et al., 2008). Moreover, forests provide humans with a whole range of ecosystem services including provision of food and forest products, regulation of the hydrological cycle, protection of soil resources, etc. Forest health and ecosystem functioning have recently been influenced by anthropogenic activities and their consequences, such as air pollution, surface mining, heavy metal contamination (Aznar et al., 2009), and other biotic and abiotic stress factors such as pest invasions and soil acidification (Sebesta et al., 2011), which had an especially high effect on central Europe. Therefore, large-scale monitoring of forest health and its methodologies are in the forefront of interest for scientists as well as forest managers.

Many aspects of the physiological state of trees are more or less connected with the concentrations of two main groups of leaf photosynthetic pigments: chlorophylls and carotenoids (Ustin et al., 2009). Vegetation with a high concentration of chlorophyll is considered to be healthy, as the chlorophyll content is linked to greater light-use efficiency, photosynthetic activity and carbon dioxide uptake (Blackburn, 2007; Kramer, 1981; Wu et al., 2008). Chlorophyll generally decreases under stress and during senescence (Blackburn, 2007). Carotenoids play the main role in the process of incident light absorption, transportation of energy to the reaction center of the photosystems, and heat dissipation of energy in case of high irradiation (Demmig-Adams and Adams, 1996). Combination of the influences of chlorophylls and carotenoids is thus connected with light-use efficiency (Landsberg et al., 1997). However, higher carotenoid to chlorophyll ratios indicate vegetation stress and senescence (Demmig-Adams and Adams, 1996; Young and Britton, 1990).

Therefore, the content of biochemical compounds such as photosynthetic pigments can be used as non-specific indicators of the actual tree physiological status, stress and the pre-visible tree damage. Moreover, the contents of photosynthetic pigments are closely related to photosynthetic performance and can serve as non-specific stress indicators in a very early stage, when the needles do not yet show any microscopic or macroscopic damage symptoms (Lepedus et al., 2005; Soukupova et al., 2000; Tzvetkova and Hadjiivanova, 2006). When dealing with photosynthetic pigments as vegetation stress indicators, seasonal dynamics in pigment contents in evergreen conifers must be taken into account. Changes in pigment levels reflect the normal physiological responses in the plant as well as the responses to environmental stress (Gamon and Surfus, 1999; Gitelson et al., 2001, 2002; Grisham et al., 2010). The chlorophyll content in needles increases in the spring (from May/June) and during the summer (July–September) and then remains relatively constant until October, when it again decreases during the frost hardening process (Oquist and Huner, 2003). Some of the carotenoids (e.g., lutein, β-carotene) exhibit stable contents during the seasons in contrast to several groups of xanthopylls (e.g., antheraxanthin, zeaxanthin; Yatsko et al., 2011), which increase significantly during the winter and serve as effective protection of the photosynthetic apparatus under conditions of high irradiance and low temperature during the winter and spring (Maslova et al., 2009). The total carotenoid to total chlorophyll ratio decreases in parallel with the chlorophyll increase in the spring (Martz et al., 2007).

Conventional laboratory analyses of leaf biochemical parameters can be very precise, although they have a number of disadvantages (e.g., limited number of samples, high labor and cost demands). It has been demonstrated that variations in leaf biochemical composition affect foliar optical properties (Carter and Knapp, 2001; Clevers and Kooistra, 2012; Kokaly et al., 2009; Schlerf et al., 2010; Sims and Gamon, 2002; Ustin et al., 2009; Zhang et al., 2012). The spectral reflectance characteristics of plant canopies are influenced by the chemical composition, internal leaf structure and spatial distribution of the leaves (Asner, 1998; Ollinger, 2011; Zwiggelaar, 1998). Leaf pigments are well positioned to absorb incident light and can be assessed with spectral reflectance. The more important absorption pigments and their characteristic absorption wavelengths/wavebands were reviewed by Zwiggelaar (1998).

Modern remote sensing has become a novel tool not only for detecting target materials but also for monitoring dynamic processes and physical-property induced changes. The use of multispectral imagery has been demonstrated to effectively map the distribution of ecosystem types and vegetation systems (Everitt et al., 2002; Gould, 2000; Knorn et al., 2009; Lamb and Brown, 2001; Vogelmann et al., 2012); however, the low spectral resolution of multispectral imagery is a major limitation. On the other hand, imagery with higher spectral resolution (e.g., hyperspectral) provides sufficient spectral resolution to describe diagnostic absorption signatures and allows sufficiently detailed species discrimination and biochemical differentiation (Aspinall, 2002; Feret and Asner, 2013; Kokaly et al., 2009; Lass and Prather, 2004; Majeke et al., 2008; Odagawa and Okada, 2009; Underwood et al., 2003; Ustin et al., 2004; Zhao et al., 2013).

Data with very high spectral resolution – also referred to as imaging spectroscopy (IS) data, which is also known in the remote sensing community as hyperspectral data – has been successfully used in earlier studies to detect vegetation stress and damage (Campbell et al., 2004, 2007; Hamzeh et al., 2013; Hernandez-Clemente et al., 2011; Pu et al., 2008; Rathod et al., 2013; Romer et al., 2012; Sanches et al., 2013a; van der Meer et al., 2002; van der Werff et al., 2008). In the forestry context, most published precedents used IS data as a basis for identification of stress-sensitive wavelengths (e.g., Ahern, 1988, Masaitis et al., 2013; Sanches et al., 2013a), for development of stress-sensitive vegetation indices (e.g., Carter and Miller, 1994; Carter and Knapp, 2001; de Jong et al., 2012; Lausch et al., 2013) and for integrating stress-sensitive indices in more complex models (e.g., Fassnacht et al., 2012; Pontius et al., 2008; Shafri et al., 2012; Zarco-Tejada et al., 2004; Zhao et al., 2013).

In contrast, only a few approaches (Asner and Martin, 2009; Kampe et al., 2010) have dealt with the use of hyperspectral remote sensing (image spectroscopy) to assess the physiological status of vegetation on a regional scale, the term "regional" is understood to mean related or limited to a particular region, area or part, as of a country or the body. Moreover, little or no research has been done on assessing vegetation health utilizing multi-date hyperspectral image data, as a time-series of hyperspectral data and reliable methods to extract change/stress information for remotely sensed data analysis are still lacking. We recently proposed a new method for assessing forest health condition via normalization and further statistical integration of optical indices retrieved from HS image data (Misurec et al., 2012). To assess subtle changes in the physiological status of macroscopically undamaged foliage of Norway spruce, this method integrated the following HyMap derived parameters: quantitative retrieval of chlorophyll concentrations (Cab); Red-Edge Position (REP) (Curran et al., 1995) – the inflection point of the spectral curve in the red-edge region, which is shifted to shorter wavelengths under vegetation stress (e.g., the presence of heavy metals in the soil) (Chang and Collins, 1983; Clevers et al., 2002; Curran et al., 1995; Horler et al., 1983; Cho et al., 2012; Rock et al., 1988; Sanches et al., 2013b); and the Structure Insensitive Pigment Index (SIPI) (Penuelas et al., 1995) which is sensitive to the ratio of bulk carotenoids to chlorophyll. This method is easily applicable and, after further testing and confirming its general applicability, it has a potential to be adopted for other