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Assessment of ecophysiology of lake shore reed vegetation based on chlorophyll fluorescence, field spectroscopy and hyperspectral airborne imagery

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ABSTRACT

Since the beginning of the 1960s an escalating deterioration of reed beds in parts of Europe has been often observed. Hence, the 'reed die-back' as it was later named, has been a phenomenon of great scientific interest and concern to conservationists worldwide and intensively studied by field ecologists. Imaging spectroscopy has frequently been employed for vegetation mapping, but this paper is the first explicit analysis of the spectral information content for reed and an assessment of the potential for detecting the areas affected by the reed die-back syndrome using hyperspectral data at the near infrared and the chlorophyll absorption spectral regions. Leaf reflectance spectra and photophysiological information were acquired using a Hand-Held ASD spectroradiometer, a portable fluorometer and a chlorophyll metre *in-situ* concurrently from leaf samples along a transect perpendicular to the lake shore of Central Europe's largest inland lake in terms of area, Lake Balaton in Hungary. A strong correlation between narrowband spectral indices and chlorophyll fluorescence parameters indicates the potential of hyperspectral remote sensing in assessing plant stability. Canopy hyperspectral data were collected from an airborne AISA Eagle sensor (400–1000 nm). An application of the findings from the field data analysis to airborne hyperspectral imagery reveals important information about reed condition at the study area. Y(II) values, regarded as a proxy of photosystem activity, have been calculated from high R^2 combination of spectral ratio 612/516 representing Fs and 699/527 representing Fm′. ETR values are estimated based on the calculated Y(II) and the spectral ratio 463/488 for Photosynthetically Active Radiation. This research underpins the development of methods for the spectral discrimination of reed patches affected by stress caused by environmental conditions, and subsequently the reed die-back syndrome. A comparison with empirical vegetation indices from the literature shows significantly higher R^2 values of the proposed indices for the specific application. We recommend spectral indices at leaf level for evaluating reed ecological status based on spectroscopic data to support the identification of affected vegetation patches and present R^2 maps that can aid the selection of indices tailored to specifications of remote sensors.

1. Introduction

Phragmites australis (Cav.) Trin. ex Steudel (common reed) is one of the most widespread vascular plants on the Earth, growing in all continents except Antarctica (Tucker, 1990). It is a tall rhizomatous perennial grass (Haslam, 1969) typically encountered in wetland environments and more frequently in land–water interface zones (Tucker, 1990). Acting as a buffer zone between terrestrial and aquatic ecosystems (Brix, 1999), it holds an important role as the key species of temperate wetlands and delivers valuable ecosystem services such as maintaining the shore stability (Engloner, 2009). Since the beginning of the 1960s a widespread, non-reversible and abnormal retreat of reed areas has been observed in parts of Europe (Brix, 1999; Van der Putten, 1997). The phenomenon was first reported 60 years ago from Hürlimann (1951), cited in Ostendorp (1989) and on Lake Balaton from Tóth et al. (1961). Since then an increasing scientific interest and environmental concern has been raised. Typical indicative expressions reported include reduced plant height, weaker culms, abnormal rhizomes, formation of clumps (Fogli et al. 2002), gradual thinning, and eventually natural degeneration and retreat from relatively deep water (Van der Putten, 1997). These factors signifying an abrupt reduced stability are collectively reported in the literature as the 'reed die-back syndrome'. However, contrary to the typical stress manifestation in the leaf structure of most plants, identification of die-back conditions is not

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straightforward when using macroscopic visual assessment especially at an early stage, because of the connection of individual shoots by underground rhizomes allowing sharing of nutrients. Thus, while the entire plant may be in a state of die-back, the leaves do not necessarily show typical signs of deterioration.

Vegetation photosynthetic systems are very sensitive to environmental induced stress. The first exhibition of leaf stress, preceding morphometric changes, is reduced photosynthetic performance and more specifically damage the Photosystem-II (PSII) (Maxwell & Johnson, 2000) which is quantitatively correlated to chlorophyll fluorescence yield. Thus photochemical parameters measured *in-situ* can provide an early diagnostic indicator of plants' stress and it is a well-studied fact that production of plants can be easily and non-intrusively estimated by chlorophyll fluorescence. Photochemical parameters usually relate to the apparent (Fs) and maximum (Fm′) values of fluorescence yield (Maxwell & Johnson, 2000). Genty et al. (1989) proposed a widely used formula to estimate changes in quantum yield defined as:

$$Y(II) = \frac{\Delta F}{F_{m'}} = \frac{F_{m'} - F_s}{F_{m'}} \quad (1)$$

Y(II) represents the ratio of open to close PSII centres at given irradiance, which is the proportion of energy used between photosynthesis and other processes, relating directly to plant stress. More specifically it is a measurement of the transfer of electrons between photosystems within the process of photosynthesis. Since during photosynthesis 4 electrons must be transported for every assimilated CO_2 molecule, Y(II) represents the potential possible driving force of photosynthesis. Therefore it relates to net photosynthesis, however in a curvilinear way because unknown stress factors, light dissipation and others might influence Y(II) values. Another factor related to production of photosynthesis is the Electron Transport Rate (ETR) which is defined as

$$ETR = \frac{\Delta F}{F_{m'}} \times PAR \times AF \times 0.50 \quad (2)$$

where 0.5 accounts for distributing the energy between PSI and PSII and AF is the absorption factor for the leaves. ETR within the PSII can be measured by PAM fluorometry and translates directly into production of photosynthesis, aparameter which provides significantly enhanced information in comparison to the photosynthetic activity at the given environmental conditions and time. When measured in a context of a correct methodological approach, it allows to measure both potential and apparent photosynthetic activity and photosynthetic efficiency. The comparison of these parameters could reveal the processes within the PSII, where the electron transport was decoupled, which sheds light on the effect of the apparent environmental conditions on the process of photosynthesis. For a comprehensive explanation of chlorophyll fluorescence the reader is referred to Krause and Weis (1991) and Baker (2008).

Remote sensing applications for the mapping of reed condition in Europe have been reported in the literature but their function so far has been limited to a tool for assessing the distribution of vegetation species and sometimes the plant health categorically; however quantification of reed stress physiological indicators has not been attempted. For example, Bresciani et al. (2009) used remotely sensed data to monitor reed vigour represented by the Leaf Area Index (LAI) in three environmentally sensitive Italian lakes. Liira et al. (2010) estimated the macrophytic expansion in a eutrophic Lake based on a Landsat TM and ETM + time series. Hunter et al. (2010) mapped the distribution of macrophytes in a clear British shallow lake. Onojeghuo and Blackburn (2011) demonstrated the synergistic use of hyperspectral and Light Detection and Ranging (LiDAR) data for mapping reed bed habitats and Bresciani et al. (2011) estimated the LAI from field and satellite data in the context of reed conservation. Lately, Zlinszky et al. (2012) used discrete return LiDAR to categorize aquatic vegetation and stressed reed in Lake Balaton, Hungary and Villa et al. (2013) presented an approach to monitor reed conservation status of Lake Garda in Italy with a variety of remotely sensed datasets. Remote sensing inherently has the capacity of species distribution mapping in lake-shore environments, however, macrophyte physiological status has not been yet investigated thoroughly from a remote sensing perspective. Despite the fact that chlorophyll fluorescence is one of the most powerful stress detection methods in plant ecophysiology (Maxwell & Johnson, 2000), coupling with remote sensing has not yet been widely examined.

Attempts to relate leaf spectral information with several physiological and morphological parameters have been widely reported in the literature, such as with chlorophyll, nitrogen, water or biomass content and leaf density. While some of these parameters have been proven to correlate highly with spectral indices, chlorophyll fluorescence provides significantly more information on the photosynthetic activity of plants than the aforementioned parameters.

The coupling between physiological parameters and spectral information is often established by building indices in the form of mathematical formulae integrating spectral bands. These spectral indices are typically developed on the basis of empirical observations or experimental processes as a proxy to vegetation characteristics. For instance, Zarco-Tejada et al. (2001) propose that the ratio of the reflectance of 750 nm and 710 nm is a good indicator of chlorophyll content at leaf level. Gitelson and Merzlyak (1996) suggest that the indices R_{750}/R_{550} and R_{750}/R_{700} are highly proportional (correlation $R^2 > 0.95$) to chlorophyll concentration in leaves. In a similar manner Vogelmann et al. (1993) propose R_{740}/R_{720} as well as the ratio of first derivative values D_{715}/D_{705}. Stagakis et al. (2010) in a thorough investigation of chlorophyll indices suggest that mNDVI (Sims & Gamon, 2002), PSRI (Merzlyak et al. 1999) and SIPI (Peñuelas et al. 1995) perform well in chlorophyll estimation. Finally, Thenkabail et al. (2000) present a study on the relationship between vegetation indices and agricultural crop characteristics where they suggest that remarkably strong relationships are found in specific narrow bands.

This paper presents the first investigation of the potential of hyperspectral remote sensing for characterizing the ecophysiological status of reed in a lake shore environment based on fluorometric in-situ measurements. Imaging spectroscopy has lately been emerging as a promising technique for vegetation-related applications and scientific improvements are needed to sustain the potential for advancement in this field (Thenkabail et al. 2012). Lake Balaton, Hungary is the largest (596 km^2) and a relatively shallow (mean water depth 3.25 m) freshwater lake in Central Europe (Virág, 1997). It encompasses a total area of ca. 11 km^2 of reed stands stretching along 112 km of the 254 km of the shoreline, with the majority situated on the north shore, part of which has suffered intense reed die-back from 1970s onwards (Kovács et al., 1989). In this study we attempt to assess the spectral signatures of reed samples of different inundation levels from a perpendicular transect at a relatively stable basin of the lake. We used statistical analysis to quantify the association between chlorophyll fluorescence kinetics and hyperspectral signatures of reed leaves. We identified spectral indices correlating significantly to fluorescence yield, and thus vegetation stability. An application of lake-shore vegetation status assessment based on hyperspectral airborne collected imagery demonstrates the potential of remote sensing for reed stability quantification.

2. Materials and methods

In-situ and airborne datasets were collected in the Kerekedi bay (46° 58′ 2.84″ N, 17° 55′ 4.34″ E), the easternmost mesotrophic basin of Lake Balaton, Hungary (Fig. 1). The field measurements were collected on August 14th, 2012 at the climax of the growing period in the area of study and under clear sky conditions between 11:00 and 13:00 local time (Central European Time). Fluorescence, chlorophyll and hyperspectral measurements were recorded concurrently from the middle of leaf samples collected along a transect aligned perpendicular to the