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A rule-based approach for mapping macrophyte communities using multi-temporal aquatic vegetation indices

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ABSTRACT

Macrophytes are important components of freshwater ecosystems, playing a relevant role in carbon and nutrient cycles. Notwithstanding their widespread diffusion in temperate to subtropical shallow lakes, little effort has been performed so far in extensively mapping macrophyte communities at regional to continental scale. A rule-based classification scheme was implemented for mapping four macrophyte community types (helophyte, emergent rhizophyte, floating, and submerged-floating association). Input features were selected among multi-spectral reflectance and multi-temporal vegetation indices, based on Landsat data acquired over four test sites: Lake Taihu (China), Kis-Balaton wetland (Hungary), Lake Trasimeno and Mantua Lakes system (Italy). The best performing features were derived from Water Adjusted Vegetation Index (WAVI) computed at: early spring, maximum growth, and late autumn conditions. Overall accuracy (OA) and Kappa coefficient (k) of macrophyte maps produced with our approach over the ensemble of four sites were 90.1% and 0.865, respectively, with best performance in European temperate areas (OA = 93.6–94.2%, $k = 0.887$–0.916), and lower scores for subtropical Lake Taihu (OA = 82.8%, $k = 0.762$). Per-class accuracies were higher than 80% for all target classes, except for the submerged-floating association, with misclassifications concentrated in Taihu site. The robustness of the approach was tested over two independent validation cases: a different site (i.e. Lake Varese, Italy), and a different input dataset (i.e. AVNIR-2 data, for Mantua Lakes system). Consistent accuracy results were achieved: OA = 94.3% ($k = 0.922$) and OA = 85.6% ($k = 0.766$), with some misclassification due to spatial resolution of AVNIR-2 data.

1. Introduction

Macrophytes are important components of inland freshwater ecosystems (Jeppensen et al., 1997), playing a relevant role in the global carbon (e.g. gas fluxes, interactions with phytoplankton productivity) and nutrient (e.g. denitrification in sediments, nitrogen uptake) cycles (Wetzel, 1992; Jordan, Stoffer, & Nestlerode, 2011; Bolpagni et al., 2014), as well as in the provision of suitable niches for nursery and feeding activities for several aquatic faunal species and threatened taxa (e.g. amphibians, water birds and fish) (Schriver, Bogestrand, Jeppensen, & Sondergaard, 1995). All the more so, these roles could be further modified in the short term by the effects of the global change (Carmichael, Bernhardt, Brauer, & Smith, 2014; Jacobs & Harrison, 2014). Even if many evidences suggest an ambiguous role of climate warming on macrophytes, increments in growth rates and spatial distribution, as well as a general reinforcement of water eutrophication symptoms are expected (McKee et al., 2002; Kosten et al., 2011). This is especially true for shallow lakes and wetlands, in temperate to high latitude regions (Poff, Brinson, & Day, 2002; Dudgeon et al., 2006; Finlayson, Davis, Gell, Kingsford, & Parton, 2013).

As the Millennium Ecosystem Assessment (2005) has thoroughly assessed, in the last decades worldwide littoral lacustrine environments have experienced a dramatic reduction in extent and a sensible decline in water quality and functionality (e.g. Hicks & Frost, 2011; Bresciani, Bolpagni, Braga, Oggioni, & Giardino, 2012; Azzella, Rosati, Iberite, Bolpagni, & Blasi, 2014a). Water use and abuse for multiple human purposes, shoreline modification and reinforcement, and urban settlements development have heavily contributed to jeopardize the survival of riparian and littoral aquatic plant communities (Schmieder, 2004; Jeppesen et al., 2010).

Recent studies on marine coastal vegetated ecosystems (e.g. seagrasses, mangroves, salt marshes) have assessed both intensity and efficiency of carbon (C) fixation in vegetation and sediments and gave origin to the concept of the so called 'blue carbon' (Duarte, Middelburg, & Caraco, 2005; Mcleod et al., 2011; Duarte, Losada, Hendriks, Mazarrasa, & Marbà, 2013), relevant at global scale assessment of C budget. Concerning the terrestrial compartment, Abril et al. (2013) have demonstrated that flooded forests and wetlands play a crucial role in C fixation in the Amazon Basin. For inland freshwater ecosystems, the quantitative role of macrophytes communities in C cycle has

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been so far neglected, mainly due to the high spatial resolution needed to assess such processes from remote. Still, their role in terrestrial C cycling could be relevant, at least at watershed scale (Pinardi, Bartoli, Longhi, & Viaroli, 2011; Abril et al., 2013). Despite all this, little effort has been performed so far in extensively mapping aquatic vegetation cover and characteristics especially in shallow lakes, focusing on robust approaches to assess morpho-ecological gradients, structural complexity and functional status of macrophyte dominated habitats (Bolpagni et al., 2007; Ribaudo, Bartoli, Racchetti, Longhi, & Viaroli, 2011; Jacobs & Harrison, 2014). Macrophytes display a higher level of species diversity in temperate areas than in tropical ones, contrary to what happens for terrestrial plants (Crow, 1993), and show some cosmopolitan features, with 60% of known species being present on more than one continent (Sculthorpe, 1967); these two characteristics make macrophytes a very interesting target from regional to cross-continental studies at synoptic scale. Due to its repeatability and spatial coverage, Earth Observation (EO) can be considered an ideal tool to make large-scale inventories of wetland and aquatic vegetation communities across different ecosystems, and has long demonstrated theoretical capabilities and operational potential for such application (e.g. Penuelas, Gamon, Griffin, & Field, 1993; Caloz & Collet, 1997; Silva, Costa, Melack, & Novo, 2008; Xie, Sha, & Yu, 2008; Adam, Mutanga, & Rugege, 2010; Zlinszky, Mücke, Lehner, Briese, & Pfeifer, 2012; Klemas, 2013; Birk & Ecke, 2014). Tough, systematic, regional to global scale vegetation monitoring base on EO has been historically biased towards terrestrial vegetation, the main reason being that the vast majority of spectral vegetation analysis techniques have been designed on terrestrial vegetation (e.g. Carlson & Ripley, 1997; Pettorelli et al., 2005; Gray & Song, 2012; Yang, Weisberg, & Bristow, 2012). Moreover, most of the literature on macrophyte remote sensing focuses on the use of hyperspectral information (e.g., Williams, Rybicki, Lombana, O'Brien, & Gomez, 2003; Artigas & Yang, 2005; Giardino, Bartoli, Candiani, Pellegrini, & Bresciani, 2007; Hestir et al., 2008; Hunter, Gilvear, Tyler, Willby, & Kelly, 2010) or use multispectral imagery over limited targets, mostly consisting of a single study area (e.g. Munyati, 2000; Liira, Feldmann, Mäemets, & Peterson, 2010; Tian, Yu, Zimmerman, Flint, & Waldron, 2010; Albright & Ode, 2011; Dronova et al., 2012; Shuchman, Sayers, & Brooks, 2013), thus not completely assessing the capabilities of EO providing synoptic regional sampling with regular, operational data acquisitions. An exception is the work of Nelson, Cheruvelil, and Soranno (2006), that have used Landsat data to map four macrophyte groups in 13 small lakes with relatively low turbidity, all located in Michigan, U.S.; although they reached satisfying to good results over lakes used for model development (58–97% per-class concordance), when they validated the model over different lakes the mapping accuracy was drastically reduced (18–36% per-class concordance), failing to extend their approach to lakes not sampled in their training set.

The high discrimination capabilities demonstrated through the use of hyperspectral data is in fact balanced by the relatively high cost and low availability of such type of remote data, either from aerial or satellite platforms (e.g. Schaepman et al., 2009; Ben-Dor, Schlapfer, Plaza, & Malthus, 2013). Great potential in vegetation mapping applications has been shown by exploiting multi-temporal information, e.g. for assessing wetland vegetation in tidal marsh environments (e.g. Gilmore et al., 2008) and regularly flooded systems (e.g. Wang et al., 2012), as well as for mapping vegetation damage recovery patterns after extreme events (e.g. Villa, Boschetti, Morse, & Politte, 2012). The straightforwardness of spectral vegetation indices (VIs) has long demonstrated its advantages for large scale mapping of dynamic phenomena in both terrestrial (e.g. Huete, Justice, & Liu, 1994; Lunetta, Knight, Ediriwickrema, Lyon, & Worthy, 2006; Wardlow & Egbert, 2008) and aquatic environments (e.g. Hu, 2009; Hu et al., 2010; Villa, Duan, & Loiselle, 2015). In particular, Wang et al. (2012) showed capabilities and performance of temporal series of vegetation indices in mapping wetland vegetation groups on a functional basis over Lake Poyang, China, but more testing over different areas and cases need to be performed to reach consistent results beyond local, site-specific approaches.

The high spatial heterogeneity of macrophytes and their presence in relatively small water bodies and wetland areas, especially throughout temperate climates, needs to be monitored at a spatial resolution which is not supported by a majority of operational low resolution EO platforms (300–1000 m ground resolution) currently used for terrestrial vegetation applications at global scale (e.g. Fensholt & Proud, 2012; Brown, De Beurs, & Marshall, 2012; Liu, Dijk, McCabe, Evans, & Jeu, 2013; Hmimina et al., 2013). For this scope, medium resolution EO data (10–30 m ground resolution) is the best option in terms of balance between operational capabilities, large area coverage and spatial resolution for macrophyte monitoring applications that aim to go beyond the local scale with enough potential for detection capabilities from regional to global scales, and offers best capabilities when used for multivariate analysis in spectral and temporal domain (e.g. Villa, Lechi, & Gomarasca, 2009). Recently, spectral VIs specifically optimized for aquatic vegetation have been designed and tested using broadband spectral ranges currently available for an extended group of medium resolution EO sensors: i.e. the Normalized Difference Aquatic Vegetation Index (NDAVI, Villa, Laini, Bresciani, & Bolpagni, 2013; Villa, Mousivand, & Bresciani, 2014a) and the Water Adjusted Vegetation Index (WAVI; Villa et al., 2014a). Even if not as spectrally powerful as hyperspectral based one, a multispectral medium resolution mapping approach is at the moment showing the highest degree of flexibility and applicability in the context of macrophytes monitoring applications that aim to go beyond the local scale, as many applications in macrophyte analysis require (Farmer & Adams, 1989; Vis, Hudon, & Carignan, 2003). In this work, we re-adapted the functional group scheme proposed by Lacoul and Freedman (2006) for delineating four target macrophyte community types to be mapped, which are globally widespread and representative of temperate to subtropical environments: helophyte, emergent rhizophyte, floating (both free-floating and floating-leaved species), and submerged-floating association (i.e. the coexistence of floating and submerged species). We then assessed the efficiency of aquatic vegetation indices (NDAVI and WAVI) in capturing specific multi-temporal features of such community types. Based on this assessment, we eventually delivered a comprehensive rule-based approach for mapping macrophyte community types, relying on multi-temporal medium resolution data over a set of heterogeneous test and validation sites.

In this context, our study covers three main objectives, dealing with: i) assessing the performance of multi-spectral information compared to multi-temporal VIs and selecting the best VI for discriminating different macrophyte community classes; ii) exploiting the most efficient multi-temporal features for implementing a rule-based macrophyte community type mapping approach, and iii) validating the results derived from such approach over independent data and sites.

2. Test sites and rationale

We developed and tested our approach for macrophyte community types classification on five shallow water systems (average depth ranging from 2 to 11 m), featuring abundant and variegate macrophyte vegetation: Lake Taihu (eastern China), Kis-Balaton wetland (western Hungary), Lake Trasimeno (central Italy), Mantua Lakes system and Lake Varese (northern Italy). The five sites are located in the northern hemisphere and represent a gradient of environmental conditions, ranging from continental (including perialpine and Mediterranean regions) to subtropical climates, as well as limnological characteristics, from small, artificial wetlands to large hypertrophic lakes (Fig. 1).

Lake Taihu (central-eastern China; 31°14′ N, 120°12′ E), located in subtropical Yangtze Delta, is the third largest Chinese lake (surface of 2338 km^2; mean depth of ~2 m). The lake is subjected to severe eutrophication and suffers from massive cyanobacteria blooms in summer-autumn seasons since at least three decades, mainly as a result of industrial development and urbanization (Ning, Pan, Chen, & Liu, 2013). The