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Assessing macrophyte seasonal dynamics using dense time series of medium resolution satellite data

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ABSTRACT

The improved spatial and temporal resolution of latest-generation Earth Observation missions, such as Landsat 8 and Sentinel-2, has increased the potential of remote sensing for mapping land surface phenology in inland water systems.

The ability of a time series of medium-resolution satellite data to generate quantitative information on macrophyte phenology was examined, focusing on three temperate shallow lakes with connected wetlands in Italy, France, and Romania.

Leaf area index (LAI) maps for floating and emergent macrophyte growth forms were derived from a semi-empirical regression model based on the best-performing spectral index, with an error level of 0.11 $m^2 m^{-2}$. Phenology metrics were computed from LAI time series using TIMESAT to analyze the seasonal dynamics of macrophyte spatial distribution patterns and species-dependent variability. Particular seasonal patterns seen in the autochthonous and allochthonous species across the three study areas related to local ecological and hydrological conditions.

How characteristics of the satellite dataset (cloud cover threshold, temporal resolution, and missing acquisitions) influenced the phenology metrics obtained was also assessed. Our results indicate that, with a full-resolution time series (5-day revisit time), cloud cover introduced a bias in the phenology metrics of less than 2 days. Even when the temporal resolution was reduced to 15 days (like the Landsat revisit time) the timing of the start and the peak of macrophyte growth could still be mapped with an error of no more than 2–3 days.

1. Introduction

Although much has been learned about the long-term effect of climate change on the phenology of terrestrial ecosystems (Richardson et al., 2013; Yang et al., 2015), there is still little information available on aquatic ecosystems, and even less regarding aquatic plants. It is essential to improve our understanding of seasonal changes in macrophyte growth in order to shed light on the ecological drivers of aquatic system degradation, and promote effective conservation programs. Some studies have examined emergent macrophytes (Alahuhta et al., 2011), floating plants (Peeters et al., 2013), and their interaction with submerged macrophytes (Netten et al., 2011; Li et al., 2017). These studies were based largely on existing thematic cartography and in situ observations of vegetation density and biomass, so their conclusions are not generalizable across spatial and temporal scales. As recently stressed by Luo et al. (2016), large lakes and wetland ecosystems are difficult to survey, and that is why few data have been collected on the temporal dynamics of aquatic vegetation. Consistent, spatialized details of key phenological features, such as the timing of the start and end of the growing season, are needed to elucidate the main drivers behind the seasonal dynamics of aquatic vegetation (Wang et al., 2012; Sletvold and Ågren, 2015). A detailed knowledge of the seasonal dynamics of macrophyte communities is crucial to our understanding of the role in time and space of different functional groups, the competition with other primary producers (Bolpagni et al., 2014; Villa et al., 2015; Zhang et al., 2015), and the potential impact of invasive species (Wolkovich and Cleland, 2011). Furthermore, managers of natural resources and policy-makers demand increasingly extensive temporal and spatial

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Table 1
Key characteristics of the main target, floating and emergent macrophyte species in the study areas.

Study area	Species (common name)	Functional group[a]	Abundance	Origin of species
Mantua lakes system	*Nelumbo nucifera* (sacred lotus)	Emergent rhizophyte	Dominant (Superior Lake)	Allochthonous
	Trapa natans (water chestnut)	Free-floating pleustophyte	Dominant (Middle and Inferior lakes)	Autochthonous
	Nuphar lutea (yellow water lily)	Floating-leaved rhizophyte	Spread patches (all lakes)	Autochthonous
	Nymphaea alba (white water lily)	Floating-leaved rhizophyte	Small patches (Middle Lake)	Autochthonous
	Nymphoides peltata (yellow floating heart)	Floating-leaved rhizophyte	Small patches (Vallazza wetland)	Autochthonous
	Ludwigia hexapetala (water primrose)	Floating rhizophyte	Spreading (Superior and Middle lakes)	Allochthonous
Lac de Grand Lieu	*Nuphar lutea* (yellow water lily)	Floating-leaved rhizophyte	Co-dominant	Autochthonous
	Nymphaea alba (white water lily)	Floating-leaved rhizophyte	Co-dominant	Autochthonous
	Nymphoides peltata (yellow floating heart)	Floating-leaved rhizophyte	Small patches	Autochthonous
	Trapa natans (water chestnut)	Free-floating pleustophyte	Small patches	Autochthonous
	Ludwigia hexapetala (water primrose)	Floating rhizophyte	Spreading (riparian areas)	Allochthonous
	Ludwigia peploides (creeping water primrose)	Floating rhizophyte	Spreading (riparian areas)	Allochthonous
Fundu Mare island	*Nymphaea alba* (white water lily)	Floating-leaved rhizophyte	Co-dominant	Autochthonous
	Trapa natans (water chestnut)	Free-floating pleustophyte	Co-dominant	Autochthonous
	Nymphoides peltata (yellow floating heart)	Floating-leaved rhizophyte	Small patches	Autochthonous

[a] According to Villa et al. (2015).

information on phenological dynamics in order to address important issues relating to global environmental change (White and Nemani, 2003; Cleland et al., 2007).

In this setting, remote sensing has virtually ideal features in terms of spatial and temporal resolution, synoptic view and coverage, sensitivity to the structural and physiological features of vegetation, sampling rate, and repeatability (Malthus, 2017). Long-term, consistent satellite data can be used to monitor and quantify intra- and inter-annual trends in vegetation cycles (e.g. Villa et al., 2012; Fensholt et al., 2015). A large corpus of scientific literature on remote sensing applied to land surface phenology has been accumulated in the last decade, focusing particularly on terrestrial biomes (e.g. Reed et al., 1994; Zhang et al., 2003; Fisher and Mustard, 2007). Most of the studies used satellite data with a medium to low resolution, i.e. a pixel size larger than 1 km (e.g. Jenkins et al., 2002; Reed, 2006; Fisher et al., 2007). The particular characteristics of macrophytes (e.g. background conditions, canopy structures) and their ecosystems (mostly bodies of shallow water, with small surface areas and a great variety of plant species and forms) make them difficult to study using data with a coarse spatial resolution, and the techniques developed for terrestrial plants would need to be adapted and/or reparametrized. Some phenological analyses were conducted on macrophytes using the 30 m spatial resolution of the Landsat sensors (e.g. Hestir et al., 2015; Luo et al., 2016), but the 16-day revisit time could not ensure a sufficiently-detailed monitoring of the variability in macrophyte growth over time.

In July 2017, the Sentinel-2 satellite constellation managed by the ESA through the Copernicus initiative started to provide high-quality data with a 10–20 m resolution and a 5-day revisit time (Drusch et al., 2012). These characteristics make the Sentinel-2 data a powerful tool for monitoring macrophytes and their seasonal dynamics with a hitherto unknown level of detail.

This paper analyzes the capabilities of such a dense time series (with a 5- to 10-day revisit time) of medium-resolution (10–30 m) satellite data to provide information and metrics of macrophyte phenology. Data were collected and analyzed over three shallow European lakes with connected wetlands that host macrophyte communities of floating and emergent species common to temperate freshwater ecosystems.

In particular, our objectives were: i) to calibrate a semi-empirical model for deriving leaf area index (LAI) time series for floating and emergent macrophytes from satellite spectral reflectance data; ii) to map the macrophyte phenology metrics across our study areas, comparing their spatial distribution and species-dependent variability; iii) to examine how characteristics of the satellite dataset – i.e. maximum cloud cover, temporal resolution, and missing acquisitions – influenced the phenology metrics obtained.

2. Study areas

Three shallow freshwater bodies were considered, with their connected wetlands, which host macrophyte communities mainly comprising floating and emergent species (Table 1). The three areas share a temperate climate and are located in different parts of Europe. The Mantua lakes system (Italy) was the principal study area, where in situ data were extensively collected for the purpose of implementing our analysis. The Lac de Grand-Lieu (France), and Fundu Mare Island (Romania) are test sites for which less reference information was available.

2.1. Mantua lakes system

The Mantua lakes system lies in the Po river floodplain in northern Italy (45°10′ N, 10°47′ E; Fig. 1c), with a continental climate (Peel et al., 2007). The Superior, Middle and Inferior lakes are semi-artificial, created by dams installed on the Mincio River in the 12th century. The three fluvial lakes are small in surface area (~6 km^2), shallow (with an average depth of 3.5 m), and hypertrophic (with chlorophyll-a concentrations up to 100 $\mu g\,L^{-1}$). The water level in the Superior Lake remains constant (at 17.5 m a.s.l.) because water outflow is regulated by the Vasarone and Vasarina sluice gates (Pinardi et al., 2015). In the Middle and Inferior lakes, water levels are allowed to vary within a very narrow range (14.0–14.5 m a.s.l.) for safety reasons (to avoid flooding in the historical city center). The lakes are protected and form part of a Regional Natural Park. They are surrounded by two wetlands, called Valli del Mincio (VM) and Vallazza (VW), which are nature reserves. The Mantua lakes system is characterized by phytoplankton coexisting with macrophyte communities (Pinardi et al., 2011; Bolpagni et al., 2014; Villa et al., 2015). During the period from April to October, dense stands of an allochthonous emergent rhizophyte, *Nelumbo nucifera*, colonize the Superior Lake, together with some small patches of autochthonous floating species, *Nuphar lutea* and *Trapa natans*. The Middle Lake hosts dominant monospecific stands of *T. natans*, with small patches of nymphaeids (*N. lutea* and *Nymphaea alba*). The Inferior Lake mainly hosts small, isolated *T. natans* beds. In recent years, *Ludwigia hexapetala*, a very invasive, mat-forming allochthonous species, has spread in the littoral zones of the Superior and Middle lakes.

2.2. Lac de Grand-Lieu

The Lac de Grand-Lieu is a large, eutrophic, shallow freshwater lake in north-western France (Loire-Atlantique department, 47°05′ N, 1°41′ W; Fig. 1a), 25 km from the Atlantic coast. It extends over 63 km^2 in winter, when the wet meadows, reed beds, and tree groves (*Salix* spp.,

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