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Mapping species of submerged aquatic vegetation with multi-seasonal satellite images and considering life history information

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ABSTRACT

Spatial information of the dominant species of submerged aquatic vegetation (SAV) is essential for restoration projects in eutrophic lakes, especially eutrophic Taihu Lake, China. Mapping the distribution of SAV species is very challenging and difficult using only multispectral satellite remote sensing. In this study, we proposed an approach to map the distribution of seven dominant species of SAV in Taihu Lake. Our approach involved information on the life histories of the seven SAV species and eight distribution maps of SAV from February to October. The life history information of the dominant SAV species was summarized from the literature and field surveys. Eight distribution maps of the SAV were extracted from eight 30 m HJ-CCD images from February to October in 2013 based on the classification tree models, and the overall classification accuracies for the SAV were greater than 80%. Finally, the spatial distribution of the SAV species in Taihu in 2013 was mapped using multilayer erasing approach. Based on validation, the overall classification accuracy for the seven species was 68.4%, and kappa was 0.6306, which suggests that larger differences in life histories between species can produce higher identification accuracies. The classification results show that *Potamogeton malaianus* was the most widely distributed species in Taihu Lake, followed by *Myriophyllum spicatum, Potamogeton maackianus, Potamogeton crispus, Elodea nuttallii, Ceratophyllum demersum and Vallisneria spiralis.* The information is useful for planning shallow-water habitat restoration projects.

1. Introduction

Submerged aquatic vegetation (SAV) has important impacts on the physical, chemical and biological structure and function of aquatic ecosystems, particularly in shallow lakes (Barko et al., 1991; Gumbricht, 1993; Hu et al., 2010). Studies indicated that shallow aquatic systems that are dominated by SAV often have better water quality (clarity, total suspended solid, pH, chlorophyll *a* (Chl-a), total phosphorus (TP) and yotal nitrogen (TN) than other systems (Luo et al., 2014), and SAV can cause aquatic ecosystems to shift from a turbid algae-dominated state to a clear-water plant-dominated state (Folke et al., 2004; Soana et al., 2012), because it can inhibit the growth of algae, absorb the excessive nutrients, reduce water currents, accelerate the sedimentation of suspended materials, stabilize sediments and prevent them from re-suspending (Depew et al., 2011; Hilt et al., 2006; Luo et al., 2014; Shuchman et al., 2013), In addition, it can provide food and shelter for wildlife, and habitat for spawning aquatic animals.

In recent decades, as a consequence of rapid urbanization and human activities, most of the urban and suburban shallow lakes and rivers in China have experienced accelerating eutrophication followed by the loss or degradation of SAV due to high total suspended matter (TSM) concentration and low water transparency (Duan et al., 2012; Shi et al., 2015). The restoration of SAV in phytoplankton-dominated lakes is crucial for transforming the turbid states of these shallow lakes (Dong et al., 2014; Hilt et al., 2006). In addition, studies have indicated that SAV can help inhibit the growth of phytoplankton by competing for nutri-

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ents and light (Dong et al., 2014; Lombardo and Cooke, 2003). The re-establishment of SAV has been recognized as a valuable ecological engineering technique g for improving aquatic systems in China. Efficient SAV restoration planning requires reliable information about the physical habitat requirements of the species (Angradi et al., 2013). For SAV restoration projects, mapping the spatial distribution of the SAV species is important for acquiring the most suitable ecology and environment conditions for the growth of the dominant SAV species. Additionally, an accurate knowledge of the spatial distribution of dominant species of SAV is highly valuable to many scientific and management goals, including the improved parameterization of shallow lake ecosystem processes and models (Zhang et al., 2013).

Surveying the distribution of SAV and species at a large scale is very labour intensive and time-consuming due to the restriction of working in the water environment. Satellite remote sensing techniques have become powerful and effective tools for mapping aquatic vegetation (Liu et al., 2015; Ma et al., 2008; Zhao et al., 2013). For example, Zhao et al. (2013) and Luo et al. (2014) proposed methods for identifying of emergent, floating-leaved and submerged vegetation and mapping their distribution in Taihu Lake using Landsat TM and HJ-1A/1 B CCD images, respectively. Brooks et al. (2015) developed a satellite-based algorithm to map SAV and then successfully mapped the distribution of SAV in the Laurentian Great Lakes, Lakes Michigan and Ontario. Therefore, multispectral satellite remote sensing can be used to accurately map and identify emergent, floating-leaved and submerged vegetation in shallow coastal waters or lakes due to the large spectral difference among them.

For identifying SAV species, a limited number of exploratory research programs have been conducted using hyperspectral remote sensing data. For example, Han and Rundquist (2003) studied the spectral responses of *Ceratophyllum demersum* at varying depths in both clear and algae-laden water using a hyperspectral hand-held spectroradiometer. Pinnel (2007) gathered airborne hyperspectral remote sensing data for the spectral discrimination of submerged vegetation in Southern Germany. Yuan and Zhang (2006) investigated the spectral characteristics of the SAV plant species *Potamogeton crispus, Myriophyllum spicatum and Potamogeton malaianus* with the same coverage and found that their red edge peaks and valleys are different. These studies suggested that there are tiny spectral differences among SAV species, and it is only possible to recognize them using hyperspectral remote sensing data with abundant spectral information.

However, considering the cost and availability of hyperspectral satellite data, it is infeasible to use them to continuously monitor and identify SAV species. It appears to be impossible to map and identify SAV species using only multispectral satellite image because the spectral differences among the SAV species are tiny and therefore difficult to capture using broadband remote sensing data. Fortunately, different SAV species have different phonological characteristics and life histories, which has made it possible to map and identify SAV species using multiseasonal and multispectral satellite remote sensing data based on information on their life histories, and it has been proven to be effective to identify terrestrial vegetation types based on multi-temporal satellite remote sensing data (Leite et al., 2011; Liu et al., 2006; Murthy et al., 2003) and phenological information. However, the method has not been used and tested for mapping aquatic vegetation species.

Therefore, in this study, using ArcGIS spatial analysis technology, we developed a multilayer erasing flow for mapping SAV species in Taihu Lake by combining their life history characteristics and multi-seasonal satellite remote sensing data. To our knowledge, it is the first study to map the dominant SAV species using satellite images.

2. Materials and methods

2.1. Study area

Taihu Lake (30°55′40″–31°32′58″N, 119°52′32″–120°36′10″E) is one of the five largest freshwater lakes in China and covers an area of approximately 2338 km^2. It is located at the core of the Yangtze Delta in the lower reaches of the Yangtze River in eastern China (Fig. 1). Taihu Lake is a typical shallow lake with a maximum depth of less than 3 m and an average depth of 1.9 m. The western and central parts of Taihu Lake belong to the algal-dominated zone, where the waters are consistently extremely turbid with high total nitrogen (TN), total phosphorus (TP) contents and suspended matter concentration. Algal blooms occur frequently in the algal-dominated zone (Duan et al., 2015). The eastern of Taihu Lake, including Meiliang, Gonghu, Zhenhu, Guhuanghu, Xukou, Doangshan and Dongtaihu Bays, are covered with hydrophytes and therefore belonged to a macrophyte-dominated zone with much lower TN and TP content and higher water transparency than did those in the algal-dominated zone (Luo et al., 2016). According to previous studies (Carr et al., 2010; Liu et al., 2015), no aquatic vegetation exists at water depth greater than 2.3 m in the Taihu Lake. Therefore, we exacted the region with water depths less than 2.3 m as the study area. Depth data was provided by Taihu Laboratory for Lake Ecosystem Research (Fig. 1).

There are four types of aquatic vegetation in the grass-type zone: emergent, free-floating, floating-leaving and submerged vegetation. Emergent and free-floating hydrophytes accounts for less than 5% of the total aquatic vegetation area and are mostly distributed in the littoral zone of Taihu Lake (Luo et al., 2014). In this study, we divided aquatic vegetation into floating-leaved and submerged vegetation. According to field survey and documentary records, there are approximately 17 SAV species in Taihu Lake, but only seven species are dominant: *Elodea nuttallii*, *Potamogeton crispus*, *Myriophyllum spicatum*, *Potamogeton maackianus, Ceratophyllum demersum* and *Vallisneria spiralis* (Ma et al., 2008; Qin, 2008; Ye et al., 2009).

2.2. Field data collection

Field surveys were conducted on 10–14 March, 22–24 May, 10–13 July, 17–22 August and 23–26 September in 2013. A total of 604 ground-truth samples were collected for open water and aquatic vegetation (100 samples in March, 102 samples in May, 112 samples in July, 143 samples in August and 179 samples in September) in macrophyte-dominated zone of Taihu Lake (Fig. 1), including 405 submerged vegetation samples and 231 floating-leaved vegetation samples. The aquatic vegetation sampling plots were limited to areas measuring at least 60–60 m (*i.e.*, four pixels of an HJ-CCD image) and that had a relatively uniform distribution of vegetation. We used a portable GPS receiver with an accuracy of 3 m to record the centre coordinates of each sample and recorded the type and percent coverage of aquatic vegetation. We also used GPS to record the boundary extent of the representative floating-leaved and submerged aquatic vegetation sample regions to generate a polygon vector file.

2.3. Remote sensing data collections and processing

HJ-CCD images recorded from the HJ-1A/1 B CCD cameras were acquired from the China Centre for Resources Satellite Data and Application (CRESDA). These cameras were onboard the HJ-1A and HJ–1 B satellites, which were launched by CRESDA on September 6, 2008. Their spectral ranges and spatial resolutions are similar to those of the first four bands of Landsat TM. The single CCD imagery width is 360 km, and the two satellites constellation provides a