Ecological Indicators 71 (2016) 317–326

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Determining critical light and hydrologic conditions for macrophyte presence in a large shallow lake: The ratio of euphotic depth to water depth

Xiaohan Liu[a,b,c], Yunlin Zhang[a,*], Kun Shi[a], Junfang Lin[c], Yongqiang Zhou[a,b], Boqiang Qin[a]

[a] Taihu Laboratory for Lake Ecosystem Research, State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, 210008, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] School for the Environment, University of Massachusetts Boston, Boston, MA 02125, USA

ARTICLE INFO

Article history:
Received 6 December 2015
Received in revised form 8 July 2016
Accepted 11 July 2016
Available online 22 July 2016

Keywords:
Underwater light
Euphotic depth
Water depth
Macrophyte
Shallow lake

ABSTRACT

Light determines macrophyte distribution, community composition and biomass in shallow lakes. Therefore, it is vital to determine the critical underwater light climate thresholds for macrophyte degradation and recovery. In this study, we first proposed a novel index, defined as the ratio of euphotic depth (Z_{eu}) to water depth (WD), as a measure of the underwater light supply for macrophytes. The underwater light environment in Lake Taihu (a large, shallow, eutrophic lake) was then characterized based on this index (Z_{eu}/WD) using field measurements collected from 2006 to 2013 (8 years × 4 seasons × 32 sites). The distribution of the macrophyte presence frequency (MPF, the number of investigations that identified macrophytes divided by the total number of investigations) was greater than 0.70 in Xukou Bay and East Lake Taihu over the 32 investigations, followed by the other sites distributed in East Lake Taihu. The proportion of macrophyte coverage increased with the increase in Z_{eu}/WD. A significant relationship was observed between Z_{eu}/WD and MPF for the 19 sites with macrophytes ($r^2 = 0.48$, $p < 0.001$, $n = 19$). In the region with high nutrient concentrations and serious water pollution, better underwater light conditions are required for the growth of macrophytes. A Z_{eu}/WD value of 0.80 can be regarded as the critical underwater light threshold for the growth of macrophytes in Lake Taihu. The region with Z_{eu}/WD ranging between 0.57 and 0.80 was usually covered by sparse macrophytes; this region should be vital for macrophyte recovery and environmental management in Lake Taihu. The distribution of Z_{eu}/WD was further obtained using MODIS satellite-derived Z_{eu} from June to October in 2003 and 2013. Xukou Bay and Guangfu Bay in the southern part of Lake Taihu could be regarded as potentially crucial regions for the recovery of macrophytes from the perspective of underwater light and nutrient levels.

1. Introduction

Macrophytes are important primary producers in lake and estuarine ecosystems around the world and provide a critical habitat for a number of fish, shrimp and zooplankton (Coen et al., 1981; Lauridsen and Lodge, 1996; Meerhoff et al., 2003). Macrophytes also play important roles in biogeochemical processes, sediment stability and water quality improvement, in addition to having numerous other functions in many shallow lakes (Liu et al., 2013; Lyons et al., 2015). Because of the perceived importance of macrophytes for maintaining a healthy lake ecosystem, many scientists and management agencies have focused on protecting and restoring macrophytes to the greatest extent possible (Hilt et al., 2006; Novak and Chambers, 2014).

Shallow lakes and wetlands cover vast areas of the world and are the most numerous lentic ecosystems on earth (Downing et al., 2006). Shallow lakes are among the most dynamic aquatic ecosystems in the world, and they have garnered increased attention because of their ability to exist in two alternative stable states, macrophyte-dominated and phytoplankton-dominated states; moreover, they play an important role in the terrestrial nutrient and carbon cycles (Downing et al., 2006; Sánchez et al., 2015; Scheffer and Nes, 2007).

* Corresponding author.
E-mail address: ylzhang@niglas.ac.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.ecolind.2016.07.012
1470-160X/

However, these systems are frequently under threat from dredging, eutrophication and other consequences of human activity (Egertson et al., 2004; Kirk, 2011). The many potential causes of macrophyte disappearance include increases in nutrients, changes in water levels, and phytoplankton blooms resulting from nutrient enrichment (Barko et al., 1986; Krause-Jensen et al., 2008). All of these factors influence the underwater light regime to some extent and therefore are reflected in aquatic plant distributions (Barko et al., 1986; Dennison et al., 1993; Schwarz et al., 2000; Søndergaard et al., 2013). As a key factor in macrophyte distribution, light availability sometimes explains approximately 75% of the variation in macrophyte distribution (De Boer, 2007). Therefore, determining the optimal light requirement threshold to enable macrophyte growth is essential for macrophyte recovery and aquatic system management (Collier et al., 2012).

The underwater light environment in aquatic systems, including the intensity and spectral composition, varies greatly with depth and the composition and concentration of optically active substances (Shi et al., 2014; Zhang et al., 2012). One commonly used parameter to quantitatively describe the underwater light environment, the diffuse attenuation coefficient for downward irradiance, K_d, is defined in terms of the exponential decrease in downward irradiance with depth (Kirk, 2011; Shi et al., 2014). Photosynthetically active radiation (PAR), which refers to the light available spectrum in the visible wavelength (400–700 nm), contributes significantly to the growth of phytoplankton and macrophytes in aquatic systems (Wang et al., 2009). The rate at which light diminishes with depth is generally measured as the diffuse attenuation coefficient of PAR with depth, K_d(PAR). An accurate estimation of K_d(PAR) in the water column is critical for understanding physical processes, such as heat transfer and sediment resuspension in the upper layers of the ocean and deep lakes, and biological processes, such as phytoplankton photosynthesis, algal species distribution and macrophyte growth in the euphotic zone (Sánchez et al., 2015; Saulquin et al., 2013). Another useful index in aquatic biology is euphotic depth (Z_{eu}) because significant phytoplankton photosynthesis occurs only down to this depth (Kirk, 2011). Z_{eu} is closely related to K_d(PAR) and is the point at which downward irradiance between PAR falls to 1% of that just below the surface (Kirk, 2011). The depth of the euphotic zone is affected by various factors, including chromophoric dissolved organic matter (CDOM), phytoplankton and suspended particles, and shading by riparian vegetation, periphyton and aquatic plants (Lacoul and Freedman, 2006).

Light drives photosynthesis, leading to the production of oxygen and carbohydrates required for plant growth (Ralph et al., 2007). The availability of light is an important factor controlling the maximum depth of macrophytes (Z_c) in aquatic ecosystems (Zhang et al., 2007), and macrophytes are able to grow only at water depths less than the Z_c. Water depth influences the distribution of macrophytes according to two interacting factors (Lacoul and Freedman, 2006): *a*, light availability as directly affected by water color and suspended matter; and b, the exponential attenuation of irradiance with depth. In general, a strong positive relationship exists between water clarity and Z_c (Kemp et al., 2004). Numerous statistical models have described the relationship between Z_c and the water clarity measured by K_d or Secchi depth (Middelboe and Markager, 1997; Nielsen et al., 2002; Saulquin et al., 2013; Vant et al., 1986). Studies also exist on the relationship between Z_c and water optically active substances, such as chlorophyll a (Chl*a*), CDOM and total suspended matter (TSM) (Dennison et al., 1993; Søndergaard et al., 2013). Compared to Z_c, which is predicted by water clarity or optically active substances, Z_{eu} is a much more synthetic parameter indicating the light penetrating capability between PAR bands and is therefore more suitable for evaluating underwater light conditions. A comparison of Z_{eu} and actual water depth could provide a potential measurement of the underwater light supply for a specific location, and thus, the ratio of Z_{eu} to water depth (Z_{eu}/WD) would be an excellent evaluation index.

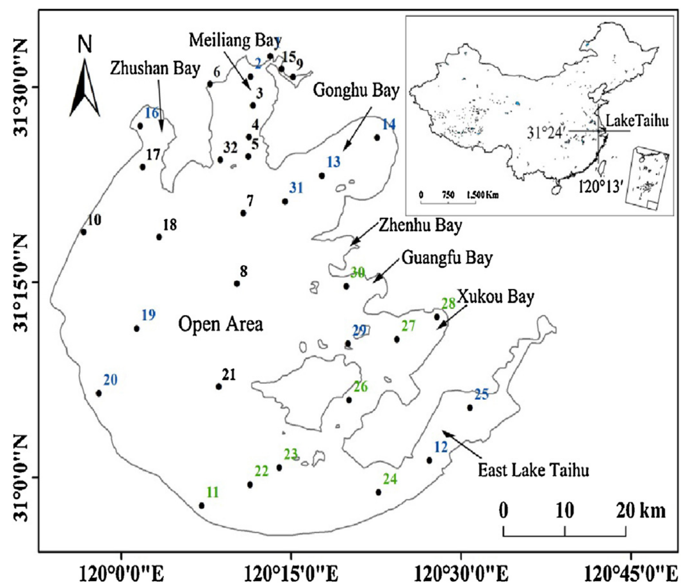

Fig. 1. Distribution of the sampling sites. The sites with green labels were covered with relatively permanent macrophytes and had low nutrient levels; the sites with blue labels were covered with relatively temporary macrophytes and had high nutrient levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Lake Taihu is the third largest freshwater lake in China. It has a total water area of 2338 km^2 and a mean depth of 1.89 m (Qin et al., 2007) and is located in the South Yangtze River Delta. As a shallow, eutrophic lake, Lake Taihu is known to simultaneously have both macrophyte- and phytoplankton-dominated regions (Liu et al., 2013; Qin et al., 2013). Lake Taihu can be divided into six areas based on shoreline geometry, environmental factors and human activities: Zhushan Bay, Meiliang Bay, Gonghu Bay, Xukou Bay, East Lake Taihu and the open area (Zhang et al., 2014) (Fig. 1). The macrophyte-dominated regions, such as Xukou Bay and East Lake Taihu, have better water quality (Yin et al., 2011) and abundant aquatic vegetation. The macrophytes of Lake Taihu can be grouped into three types: submerged (*Potamogeton maackianus*, *Potamogeton malaianus*, *Vallisneria natans*, *Ceratophyllum demersum*, *Hydrilla verticillata* var. *roxburghii*, *Elodea nuttallii*, *Myriophyllum verticillatum*, and *Najas minor*), floating-leaved (*Nymphoides peltatum, Trapa incisa var. sieb.,* and *Furctus Trapae Quadricaudatae*), and emergent (*Zizania caduciflora* and *Phragmites australis*) (Liu et al., 2015). However, the phytoplankton-dominated areas, such as Zhushan Bay and Meiliang Bay in the north, experience frequent algal blooms caused by eutrophication (Qin et al., 2010). In recent decades, the excessive input of nutrients has caused severe eutrophication and algal blooms (*Microcystis* spp.). The algal blooms have gradually extended their coverage during this period and have persisted for longer durations (Deng et al., 2014). In addition, the distribution of macrophytes in Lake Taihu has changed dramatically (Zhao et al., 2013), largely because of light limitations and nutrient enrichment (Zhang et al., 2016, 2007).

Here we propose a new index to assess the underwater light availability at the bottom for the survival of macrophytes. The ratio of Z_{eu} to water depth (Z_{eu}/WD) was calculated as a measure of the ability of the surface light to reach the water bottom. By analyzing the long-term investigations of macrophyte distribution and Z_{eu} in Lake Taihu, we aimed to (1) determine the critical light threshold for the survival of macrophytes using the ratio of Z_{eu}/WD; (2) evaluate the potential relationship between Z_{eu}/WD and the pres-