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Distinguishing surface cyanobacterial blooms and aquatic macrophytes using Landsat/TM and ETM + shortwave infrared bands

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ABSTRACT

Satellite remote sensing can be considered a suitable approach to monitor the extent of cyanobacterial blooms compared with conventional ship surveys because of the patchiness and high spatial and temporal variability of the blooms. However, most of the existing algorithms are not capable of distinguishing cyanobacterial blooms and aquatic macrophytes due to their similar spectral characteristics in the red and near infrared (NIR) wavelengths. In this study, we conducted in situ spectral measurements and satellite data analyses for cyanobacterial blooms and aquatic macrophytes to find an effective method to distinguish them using medium-resolution Landsat satellite images. The reflectance spectra were measured for lake waters and cyanobacterial blooms with 13 different chlorophyll-a concentration levels (from 54 to 21,736 μg L^{-1}) and four types of aquatic macrophytes (two emerged and two floating-leaved macrophytes) in the wavelength range from 350 to 2500 nm. In addition, seven Landsat images were collected for nine lakes in Japan or Indonesia. We calculated several selected indices, i.e., the normalized difference vegetation index (NDVI), five types of normalized difference water index (NDWI), and the floating algal index (FAI) to find an appropriate index for distinguishing cyanobacterial blooms and aquatic macrophytes.

The results showed that the spectral characteristics of cyanobacterial blooms were significantly different from those of aquatic macrophytes in the short-wave infrared (SWIR) region, indicating that the SWIR bands are important for distinguishing cyanobacterial blooms and aquatic macrophytes. The results also showed that the combination of FAI and $NDWI_{4,5}$ was an effective method for classifying lake areas. We first used the FAI for extracting lake waters, and we then used the $NDWI_{4,5}$ to classify the remaining areas as cyanobacterial blooms or aquatic macrophytes. The results also showed that the threshold of $NDWI_{4,5}$ was less sensitive to the effects of both the atmosphere and mixed pixels compared to the other indices. Our application of the FAI threshold of 0.05 and the $NDWI_{4,5}$ threshold of 0.63 to six lakes in Japan and Indonesia showed that the proposed method could successfully distinguish lake water, cyanobacterial blooms, and aquatic macrophytes.

1. Introduction

Cyanobacterial blooms are one of the most serious problems in inland waters due to their negative effects on human activities. Increased turbidity due to a cyanobacterial bloom causes the deterioration of water quality for drinking, agricultural, and industrial uses (Klapper, 1991). An unfavorable appearance or unpleasant odor due to the bloom is a nuisance that affects recreational activities such as boating and swimming (Dodds et al., 2009). In addition, cyanobacterial toxins (cyanotoxins) have become a concern for human health and animal poisoning (Codd, 2000). Cyanobacterial blooms have a great impact on aquatic environments, including reduced transparency, elevated pH, and oxygen depletion (Carpenter et al., 1998; Havens, 2007). These effects also influence the community structure and biodiversity of aquatic flora and fauna. For example, oxygen depletion can preclude fish and other biota (e.g., macroinvertebrate) from the hypolimnion and bottom sediments, bringing about changes in their taxonomic structure (Havens, 2007).

In many lakes, the presence of aquatic macrophytes is another concern. Invasion by mats of free-floating plants is an important threat to the function and biodiversity of freshwater ecosystems (Janse & Van Puijenbroek, 1998). Dark, anoxic conditions under a thick floating macrophyte cover can cause tremendous damage to animals and plants (Scheffer & Van Nes, 2007). In tropical lakes, the water hyacinth (*Eichhornia crassipes*) has dramatic negative impacts on fisheries and boat traffic (Gopal, 1987; Mehra, Farago, Banerjee, & Cordes, 1999).

Since the early 1970s, satellite remote sensing has been widely used to monitor the cyanobacterial blooms (e.g., Kahru, Leppänen, & Rud, 1993; Kahru, Savchuk, & Elmgren, 2007; Kutser, Metsamaa, Strömbeck, & Vahtmäe, 2006; Subramaniam, Brown, Hood, Carpenter, & Capone, 2002). A valuable tool, satellite remote sensing obtains more reliable information about the extent of cyanobacterial blooms compared to conventional ship survey because of their patchiness and

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high spatial and temporal variability (Kutser, 2004). Several indices for monitoring algal blooms (e.g., diatom, dinoflagellate, and cyanobacterial blooms) have been suggested, such as the maximum chlorophyll index (MCI; Gower, King, Borstad, & Brown, 2005), the cyanobacteria index (CI; Wynne et al., 2008), the maximum peak height (MPH) algorithm (Matthews, Bernard, & Robertson, 2012) and the floating algal index (FAI; Hu, 2009). These indices were developed based on a linear baseline algorithm, relying on three bands (one band corresponds to the reflectance peak often present in the red to near-infrared (NIR) region, and the other two bands are one shorter and one longer than the wavelength of the first band; Gower, 1980; Letelier & Abbott, 1996).

The MCI, CI, and MPH algorithm can be used with a medium-resolution imaging spectrometer (MERIS), and are calculated from the combination of red and NIR bands with the narrow wavelength range; for example, band 8 (677.5–685.0 nm), band 9 (700.0–710.0 nm), and band 10 (750.0–757.5 nm). In contrast, the FAI was developed for used with a moderate-resolution imaging spectroradiometer (MODIS) based on the red, NIR and short-wave infrared (SWIR) bands with broad wavelength ranges; i.e., band 1 (620–670 nm), band 2 (841–876 nm) and band 5 (1230–1250 nm). This band combination can be also applied to many medium-resolution satellite sensors (e.g., Landsat/TM, ETM + and OLI; EO-1/ALI; Terra/ASTER; SPOT/HRVIR and HRG; and ResourceSat/LISS-III), which makes it possible to monitor small lakes and ponds at low cost.

One problem with the FAI is that it is unable to distinguish cyanobacterial blooms and aquatic macrophytes. This is because they have similar spectral characteristics around the NIR region (Dekker et al., 2001; Gower et al., 2005) and thus show similar FAI values. Although the wavelength around 620 nm, which has a absorption peak due to phycocyanin (a specific photosynthetic pigment in cyanobacteria), could be used to distinguish cyanobacterial blooms from aquatic macrophytes (e.g. Dash et al., 2011; Dekker, Malthus, & Goddijn, 1992; Simis, Peters, & Gons, 2005; Tyler et al., 2009), only a few satellite sensors such as MERIS, OCM (Ocean Colour Monitor) and hyperspectral sensors (e.g., Hyperion and CHRIS (Compact High Resolution Imaging Spectrometer)) provide this band, and thus this absorption peak cannot be used with a multispectral satellite sensor. On the other hand, although Landsat-style imaging has only limited spectral bands, it has an advantage over sensors like MERIS because of its high spatial resolution, and making it useful for mapping small-scale features.

The objectives of the present study were: (1) to understand the spectral characteristics of cyanobacterial blooms and aquatic macrophytes by comparing their in situ reflectance measurements; (2) to propose an effective method to distinguish cyanobacterial blooms and aquatic macrophytes using medium-resolution Landsat satellite sensors; and (3) to test the proposed method using Landsat/TM and ETM + images obtained in different periods and lakes.

2. Methods

2.1. In situ data collection

Field investigations were carried out on August 2 and 3, 2012 in three Japanese lakes (Lakes Kasumigaura, Inba-numa and Tega-numa; Fig. 1). In this period, cyanobacterial blooms (mainly *Mycrocystis* spp.) were observed in the western part of Lake Kasumigaura. The waters with different chlorophyll-a (Chl-a) concentrations in the lake are shown in Fig. 2a–e. Here, we defined 'cyanobacterial bloom' as a state the cyanobacteria had begun to accumulate at the water surface (Fig. 2b–e).

We measured reflectance spectra at 13 water areas with different levels of Chl-a concentration in Lake Kasumigaura (10 for cyanobacterial blooms and three for lake waters). The reflectance spectra for cyanobacterial blooms with high aggregations were measured from the shore of Lake Kasumigaura.

Water samples were taken immediately after the spectral measurements, using a clear cylinder sampler (15-cm diameter, 50-cm length). The cylinder sampler was slowly lowered into the water to minimize the disturbance to the cyanobacterial blooms. The sampling volume was kept constant (from the surface to 20 cm deep) at all stations because the concentration of cyanobacteria can be easily changed with the sampling volume when the cyanobacteria are aggregating on the water surface.

The water samples were brought back to the laboratory and then used for the Chl-a measurements by a spectrophotometric method. An amount of particles was collected by filtering the water sample onto a Whatman GF/F glass-fiber filter (47-mm diameter, 0.7-mm pore size). Methanol (100%) was used to extract Chl-a, and the extract was incubated at 4 °C for 24 h in the dark. The extract was then centrifuged at 3000 rpm for 5 min and analyzed with a spectrophotometer (UV-1600, Shimadzu, Kyoto, Japan). The optical density (OD) of the chlorophyll extract was measured at four wavelengths: 750, 663, 645 and 630 nm, and Chl-a concentrations were calculated using SCOR-UNESCO equations (SCOR-UNESCO, 1966).

We also measured the reflectance spectra for two emerged macrophytes (*Nelumbo nucifera* and *Phragmites communis*) in Lake Tega-numa and two floating-leaved macrophytes (*Nymphoides peltata* and *Trapa natans*) in Lakes Kasumigaura and Inba-numa, respectively (Fig. 2f–i). Spectral measurements were conducted using a FieldSpec FR spectroradiometer (Analytical Spectral Devices, Boulder, CO) with the wavelength range from 350 to 2500 nm. We conducted the measurements of the upwelling radiance (L_u) (W m^{-2} sr^{-1}) ten times at the same station, and we used the averaged radiance values for the reflectance calculation. We measured the downwelling radiances (L_d) using a Spectralon reflectance panel (12.5 cm × 12.5 cm, Labsphere, Reflectance Calibration Laboratory, North Sutton, NH) before and after the upwelling radiance measurements, and these values were also averaged for the reflectance calculation by the following equation:

$$R(\lambda)=\frac{L_u(\lambda)}{L_d(\lambda)}\times Cal(\lambda) \quad (1)$$

where R is the reflectance, λ is the wavelength, and Cal is the calibration coefficient of the reflectance panel. We ignored the skylight effects for the reflectance calculation in Eq. (1) because our main purpose was to compare the relative relation between reflectances of cyanobacterial blooms and those of aquatic macrophytes. In addition, since the sky conditions were clear and the wind speeds were low (less than 1 m s^{-1}) during the field surveys, the skylight would have had little effect on the measured reflectances (Mobley, 1999). The spectral reflectances were recalculated to Landsat/TM reflectances using the following equation:

$$R_{Bi}=\frac{\sum_m^n (L_u(\lambda)\times SRF_{\mathrm{Bi}}(\lambda))}{\sum_m^n (L_d(\lambda)\times SRF_{\mathrm{Bi}}(\lambda))} \quad (2)$$

where Bi is the TM ith band, SRF is the spectral response function for each TM band, and m and n are the start and end wavelengths of the SRF for each TM band, respectively.

2.2. Satellite data collection

We collected seven Landsat/TM and ETM + images for nine lakes as training and validation data. The nine lakes include five Japanese lakes and four Indonesian lakes (Table 1). Heavy *Microcystis* blooms were observed during the image acquisition periods for Lakes Suwa, Sutami, and Maninjau (Park, Yokoyama, & Okino, 2003; UNESCO/IHP, 2005). In contrast, floating-leaved macrophytes (*T. natans*) have been highly

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