Ecological Informatics 37 (2017) 1–9

Contents lists available at ScienceDirect

Ecological Informatics

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

Hyperspectral indices for quantifying leaf chlorophyll concentrations performed differently with different leaf types in deciduous forests

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ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 20 November 2016
Accepted 21 November 2016
Available online 28 November 2016

Keywords:
Beech
Broadleaf
Chlorophyll content
Hyperspectral indices
WAIC

ABSTRACT

Chlorophyll content is among the most important indicators of plant photosynthetic activity and is increasingly being monitored through hyperspectral remote sensing. In this study, we have targeted the best hyperspectral indices for tracing chlorophyll content in cold temperate deciduous forests from a total of 86 published representative hyperspectral indices, including 71 reflectance-based indices, 10 derivative-based indices and five feature-based indices. These indices have been thoroughly evaluated using the datasets from a dominant species (*Fagus crenata*) in one alpine site along the Japanese sea coast (Naeba site) and another alpine site along the Pacific Coast (Nakagawane site) composed of 29 species other than beech. Evaluation results based on beech leaves from the Naeba site revealed that the DDn had the best performance ($R^2 = 0.57$), and its robustness has also been confirmed from the dataset obtained from the Nakagawane site ($R^2 = 0.47$) when all leaf types were dumped. However, the indices that performed best were different when leaf types were taken into account, for which CI ($R^2 = 0.73$) and D2 ($R^2 = 0.71$) were identified for sunlit and shaded leaves, respectively. Astonishingly, they performed poorly with the other leaf type ($R^2 = 0.23$ for CI with shaded leaves and 0.15 for D2 with sunlit leaves), suggesting the sensitivity of indices to different leaf categories. The measurements obtained from Nakagawane were also adopted to validate them based on the ratio of performance to deviation (RPD). For the sunlit leaf-oriented indices, the CI good again; however, those of the shaded-oriented indices were poor, and their robustness was not confirmed. As a result, there are no indices that are applicable for quantifying the chlorophyll concentrations of shaded leaves from different species; hence, it is required to develop a generally applicable index to express the differences in leaf type in future works.

1. Introduction

Chlorophyll pigments absorb sunlight and use their energy to synthesize carbohydrates from CO_2 and H_2O; their concentrations thus relate closely to primary production (Gitelson et al., 2006). Furthermore, chlorophyll also provides the information for assessing leaf nitrogen, an essential plant nutrient, due to the close relationship between leaf chlorophyll and leaf nitrogen (Bungard et al., 2000; Kokaly and Skidmore, 2015; Ramoelo et al., 2015). In addition, changes in the chlorophyll content of leaves are related to the effects of disease and nutritional and environmental stresses (Datt, 1999b). Chlorophyll content is thus one of the most important indicators of photosynthetic activity among all biochemical variables.

For large-scale monitoring of chlorophyll content, traditional approaches that generally require tremendous efforts for the collection of samples and laboratory chemical analyses are not feasible, although several handheld devices are useful for rapid non-destructive sampling of leaf chlorophyll content in situ. For example, the SPAD-502 Leaf Chlorophyll Meter (Konica Minolta Inc.) can quantify subtle changes or trends in vegetation locally, using a nondestructive method in a couple of seconds (Leon et al., 2007), but it is difficult to provide large-scale information. In contrast, hyperspectral remote sensing is proven to be an efficient way for large-scale chlorophyll content monitoring, from which a lot of easy-to-apply vegetation indices based on hyperspectral reflectance have been developed (Atzberger et al., 2010).

The hyperspectral remote sensing approaches to quantifying leaf chlorophyll concentrations generally rely on two techniques: one involves the numerical inversion of radiative transfer models (RTM), and the other is more empirical, such as spectral indices. Although the inversion approach may have advantages in providing inherent mechanisms, a famous "ill-posed" problem makes it a big challenge to be applied on a large scale (Li and Wang, 2013). As a comparison, empirical approaches such as spectral indices are convenient and may be potentially applied for large-scale monitoring if they are general ones that are robust to different biomes, species, and phenological stages.

Hyperspectral indices are generally based on a few narrow or broad spectral bands. Most hyperspectral indices for chlorophyll content use

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http://dx.doi.org/10.1016/j.ecoinf.2016.11.007
1574-9541/

wavelengths ranging from 400 to 860 nm, since the source of energy for driving the photosynthesis process, photosynthetically active radiation (PAR), covers this wavelength domain. They may roughly be categorized into two types: one is reflectance value or derivative-based indices, e.g., red/NIR ratios (Blackburn, 2007; le Maire et al., 2004; Zarco-Tejada et al., 2001); the other type is feature based, mainly on the properties of the red-edge, such as the point of maximum slope (Collins, 1978; Filella et al., 1996; Horler et al., 1983; Miller et al., 1990) or the sum of derivative values (Elvidge and Chen, 1995; Filella et al., 1995).

Although numerous vegetation indices for estimating chlorophyll content have been proposed, a general index that is applicable to different species has not yet reached a consensus. Most indices are unfortunately only applicable to limited ranges from which they were developed. While this may be worse for deciduous forests, since in general deciduous broadleaves consist of two distinctive leaf groups, namely shaded and sunlit leaves, which develop either under low irradiances or under high irradiances (Powles, 1984), respectively. Large structural discrepancies between the two types of leaves lead to differences in their spectral features and consequently lead to different performances of the same hyperspectral indices in quantifying the chlorophyll content of different leaf types.

In this study, the performances of hyperspectral indices were evaluated for both leaf types within beech canopies, a typical dominant species in the cold-temperate zone, as well as in 32 other deciduous species. The primary objective of this study is to identify a general applicable index for estimating chlorophyll content in both sun-shaded and sunlit leaves. We hypothesize that the best indices vary between sunlit and shaded leaves. This is based on extensive evaluations of 86 published hyperspectral indices in total using the measurements obtained from natural beech (*Fagus creanata*) leaves in Mt. Naeba (Niigata prefecture, Japan) and those from 29 deciduous species in Nakagawane (Shizuoka prefecture, Japan). The statistical criteria to evaluate the performance of these indices relied on the widely applicable information criterion (WAIC), which is a more fully Bayesian approach for estimating the out-of-sample expectation based on the log-pointwise posterior predictive density (Watanabe, 2010).

2. Materials and methods

2.1. Study area

The primary study area is located in the Naeba Mountains, Japan. Beech (*Fagus crenata*) forests dominate on the northern slope of Kagura Peak, ranging from elevations of 550 m to 1600 m (Fig. 1). This area is along the Japanese sea coast and has a typical alpine cold-temperate climate with plenty of snow in winter, an average annual temperature of 5.4–6.3 °C and annual precipitation of 2321–2391 mm (Japan Meteorological Agency, http://www.jma.go.jp/jma/index.html). In this study, beech leaves, including sunlit and shaded leaves sampled from 2007 to 2010 at 550 m (36°55′33″N, 138°45′47″E), 700 m (36°55′35″N, 138°46′05″E), 900 m (X1, 36°53′38″N, 138°46′01″E), 900 m (X5, 36°52′44″N, 138°46′04″E) and at 1500 m (36°50′44″N, 138°43′50″E) were used. A detailed description of the study sites can be found in (Wang et al., 2008). It is also an important SPECNet site (Gamon et al., 2006).

Another dataset was sampled from another alpine cold-temperate site in Nakagawane, one of the university forests of Shizuoka University. This site is located in a region along the Pacific Ocean coast, and its elevation varied from 390 to 1560 m above sea level (Fig. 1). This dataset also consisted of two leaf types: sunlit leaves were sampled from 3 species (*Styrax shiraianus*, *Acer rufinerve* and *Acer nipponicum*) and shaded leaves were sampled from 26 species (*Tilia japonica*, *Styrax japonica*, *Kalopanax septemlobus*, *Pterostyrax hispida*, *Acer argutum*, *Acer mono*, *Acer sieboldianum*, *Acer micranthum*, *Acer capillipes*, *Carpinus japonica*, *Lindera praecox*, *Lindera umbellata*, *Viburnum furcatum*, *Viburnum wrightii*, *Rhododendron quinquefolium*, *Enkianthus campanulatus*, *Rhododendron dilatatum*, *Symplocos coreana*, *Prunus buergeriana*, *Pourthiaea villosa* var. *zollingeri*, *Prunus maximowiczii*, *Euptelea polyandra*, *Quercus crispula*, *Magnolia obovata*, *Ilex macropoda*, *Clethra barbinervis*).

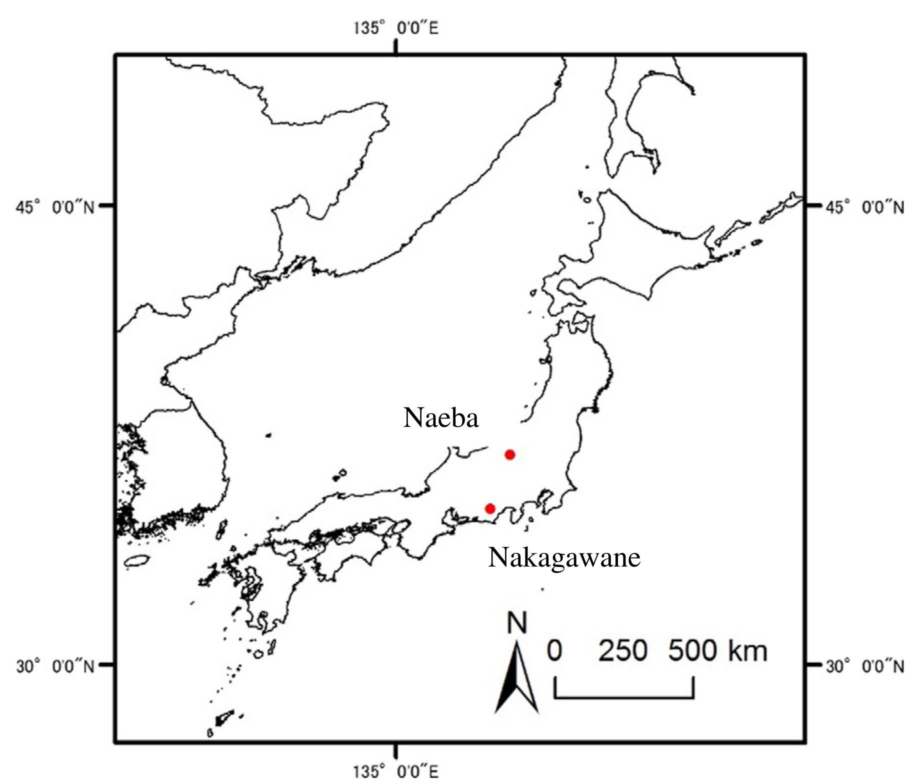

Fig. 1. Locations of study sites.