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Research Paper

Using spectral reflectance to estimate leaf chlorophyll content of tea with shading treatments

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Some stresses are utilised to improve qualities of agricultural products. Low light stress increases the chlorophyll content of tea leaves, which improves appearance. Although chlorophyll content estimation is one of the most common applications of hyperspectral remote sensing, previous studies were based on measurements under relatively low stress conditions. In this study, two methods, machine learning algorithms and the inversion of a radiative transfer model, were evaluated using measurements from tea leaves with shading treatments. According to the ratio of performance to deviation (RPD), PROSPECT-D inversion (RPD = 1.71–2.31) had the potential for quantifying chlorophyll content, although it required some improvements. Overall, the regression models based on machine learning had high performances. The kernel-based extreme learning machine had the highest performance with a root mean square error of 3.04 ± 0.52 μg cm^{-2} and RPD values from 3.38 to 5.92 for the test set, which was used for assessing generalisation error.

1. Introduction

Green tea is a very healthy beverage because its consumption is associated with reduced mortality, and it has attracted a great deal of attention (Kuriyama et al., 2006). Green tea-flavoured sweets have even become popular. Some techniques have been developed for increasing chlorophyll content, which is important for improving tea leaf appearance. Chlorophyll content is strongly related to the colour of dry tea leaves (Wang, Park, Chung, Baik, & Park, 2004) and the flavour of tea is principally determined by chemical components. Chlorophyll content is positively correlated with the total quality score as well as the scores for appearance and infused leaf (Wang et al., 2010). Therefore, various methods are used to increase the chlorophyll content of tea leaves during growth (Lee et al., 2013). The control of light transmission by shade treatment is the most effective method for increasing chlorophyll content in tea plants (De Costa, Mohotti, & Wijeratne, 2007) and shading nets (70–95% shading) have been used in Shizuoka, Japan to increase the chlorophyll content of tea leaves and to improve appearance (Sonobe, Miura, Sano, &

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Horie, 2018a). However, excessive shading tea can lead to early mortality due to the excessive environmental stresses caused by reducing natural photosynthesis in the leaves. Both quantifying chlorophyll content and detecting environmental stresses using field measurements are required for better tea tree management, and no applicable approach has been established.

As destructive methods, spectrophotometric measurements using ultraviolet and visible (UV–VIS) spectroscopy and high-performance liquid chromatography (HPLC) measurements have been used to quantify pigment content in leaves (Prado-Cabrero et al., 2016). However, these techniques are expensive, labour-intensive and not always applicable for in-situ measurements. Alternately, the SPAD-502 Leaf Chlorophyll Meter (Konica Minolta Inc.) has been used for field measurements of leaf chlorophyll content (le Maire, Francois, & Dufrene, 2004; Elarab, Ticlavilca, Torres-Rua, Maslova, & McKee, 2015). However, light intensity also influences leaf thickness (Murchie, Hubbart, Peng, & Horton, 2005) and that makes the output of the meter obscure (Yamamoto, Nakamura, Adu-Gyamfi, & Saigusa, 2002). In contrast, remote sensing using hyperspectral reflectance has been used to evaluate biochemical properties (Whetton, Hassall, Waine, & Mouazen, 2018), especially chlorophyll content estimation, which has received special attention since chlorophyll pigments closely relate to protective activity against a variety of degenerative diseases as well as the photosynthetic process (Korus, 2013). Furthermore, because remote sensing is a non-destructive method that can cover large areas and reflect the spatial variability of crop canopies using sensors mounted on airborne drones or satellites, this technique is useful for improving fertiliser management (Gabriel et al., 2017).

The numerical inversion of radiative transfer models (RTMs) has been proposed to estimate chlorophyll content using hyperspectral remote sensing (Li et al., 2015; Masemola, Cho, & Ramoelo, 2016). PROpriétés SPECTrales (PROSPECT) is one of the most famous RTMs and has been widely used to assess the biochemical properties of broadleaf species and herbs (Féret et al., 2008; Hernandez-Clemente, Navarro-Cerrillo, & Zarco-Tejada, 2014; Jacquemoud et al., 1996; Sonobe, Miura, Sano, & Horie, 2018b; Sun et al., 2018). The latest version, PROSPECT-D, has an improved ability to estimate pigment content (Féret, Gitelson, Noble, & Jacquemoud, 2017). Although le Maire et al., (2004) pointed out that the previous versions of PROSPECT were not accurate enough to evaluate broad leaf chlorophyll content, this version has not been fully evaluated.

Another recent option for estimating chlorophyll content from hyperspectral reflectance is based on machine learning algorithms (Liang et al., 2016; Chemura et al., 2017). Random forests (RF) is specifically mentioned as a successful classification and regression method (Biau & Scornet, 2016), and has been widely used for evaluating the aboveground biomass of C3 and C4 grasses (Shoko, Mutanga, Dube, & Slotow, 2018). Support vector machine (SVM) has also been a very effective approach and is appropriate to express the relationship between reflectance and leaf water status (Das et al., 2017). In addition, the high performances of kernel-based extreme learning machine (KELM) have been shown in some previous studies for solving regression problems (Sonobe et al., 2018a). Therefore, the machine learning algorithms RF, SVM and KELM were applied to estimate the chlorophyll content of shade grown tea from hyperspectral reflectance. Notably, the disadvantages of machine learning algorithms are that they require training data for prediction and not enough training data leads to overfitting and the models could be unsuitable. In this study, machine learning algorithms that possess only two hyperparameters were evaluated.

Vegetation indices have also been widely used to emphasise the features of vegetation (Sonobe et al., 2018c) and a number of vegetation indices have been developed for evaluating chlorophyll content. Most vegetation indices for chlorophyll content are based on wavelengths ranging from 400 to 860 nm, which corresponds to photosynthetically active radiation. There are reflectance values or derivative-based indices and feature-based indices, mainly based on the properties of the red edge. However, most indices are only applicable to the specific species or specific leaf types, such as sunlit or shaded leaves, from which they were developed (Sonobe & Wang, 2017a). In this study, regression models using vegetation indices were evaluated as well as regression models based on original reflectance and their accuracies were compared.

In leaves, there are two types of chlorophyll pigments (chlorophyll *a* and *b*) and the chlorophyll *a*/*b* ratio is positively correlated with the ratio of photosystem II cores to light harvesting chlorophyll–protein complex (Terashima & Hikosaka, 1995). As a result, the cultivation using shading treatments imposes environmental stress on vegetation and changes the balance among chlorophyll *a* and *b* content. However, some previous studies have used datasets composed of measurements taken under relatively low light-stress conditions (e.g. the coefficients of linear regression models for estimating chlorophyll *a* content from carotenoid content were 2.99 (Hosgood et al., 1994, p. 21) to 3.45 (Féret et al., 2008)). Therefore, some approaches in previous studies for estimating chlorophyll content are not valid for evaluating the chlorophyll content of shade grown tea, and these approaches were evaluated in this study.

The objective of this study was to examine the potential of hyperspectral remote sensing approaches including radiative transfer model inversion and machine learning algorithms for quantifying chlorophyll content of tea that was grown under low-light stress.

2. Materials and methods

2.1. Measurements and datasets

The first flush of leaves, which are harvested from mid-April to mid-May, have the highest quality and, therefore, we focused on this period. The experiments were conducted at the Institute of Fruit Tree and Tea Science, National Agriculture and Food Research Organization, Shimada, Japan. Daily temperatures and precipitation varied between 12.5 and 19.2 °C and 0–17.5 mm, respectively, during the experiment (Japan Meteorological Agency, 2017). Four shading treatments were conducted using no net (0% shading), shading net #410 (35% shading), #1210 (75% shading) and #1220 (90% shading)