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Monitoring litchi canopy foliar phosphorus content using hyperspectral data

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ABSTRACT

Phosphorus (P) is an important element to litchi yield and fruit quality in addition to nitrogen (N) and potassium (K). This study was undertaken to explore the ability to predict P content using canopy reflectance. Some published indices and two ratio spectral indices (Ratio of reflectance index, RRI; Ratio of reflectance difference index, RRDI) developed by band interactive-optimization algorithms were investigated to determine their performance in predicting litchi canopy foliar P content. The results showed that optimal spectral indices selected by correlation analyses reached the highest level of accuracy in the retrieval of P content at each growth stage (R^2cv = 0.54–0.98, RMSEcv = 0.02–0.03). The particular wavelengths of importance in the significant RRIs and RRDIs changed with the growing stages, cultivars and planting conditions. The sensitive wavebands ranged from the visible to the short-wave infrared (SWIR) regions, which are related to the absorption features of pigments (e.g., anthocyanin, chlorophyll), proteins, nitrogen, starch, sugar, oil, cellulose, and lignin. And the wavebands in SWIR region were used in the optimal RRIs and RRDIs for growth stages. This study demonstrates that the optimal RRDI is useful in predicting litchi foliar P content. The successes of use of SWIR in foliar nutrient monitoring is important for precision agriculture.

1. Introduction

Information concerning the distribution of crop foliar biochemical contents is important to assess crop growth, implement the fine management and protect the environment (Duhan et al., 2017). P is a component of nucleic acids, lipid membranes, sugar phosphates and adenosine triphosphate (ATP), which all have important roles in photosynthesis and respiration (Li et al., 2006). P has been found to be one of the most important minerals for litchi growth, quality, and yield (Nath, 2014). The effective P supply in autumn shoot maturation stage (ASMS), flower bud morphological differentiation stage (FBMDS) and flowering stage (FS) are crucial to litchi blooming and fruiting. And an adequate phosphorus supply is necessary in fruit enlargement stage.

Attempts to estimate the foliar P variation using remote sensing data have yielded the promising results in various environments. And the P estimation have been used in quality assessment of forage (Knox et al., 2012), forest trees (Asner and Martin, 2008), field crops (Pimstein et al., 2011), and wetland vegetation (Wang et al., 2016).

Many studies have explored the relationships between foliar P and plant reflectance spectral characteristics and evaluated the ability of hyperspectral data to predict P contents. The bands useful for P prediction ranged from the visible to SWIR regions. Reflectance in the visible region is related to the P stress, especially for the bands in the blue, red and red-edge regions (Stein et al., 2014). Commonly used vegetation indices (e.g., normalized differential vegetation index) were also evaluated in foliar P estimation. Some publications indicated that P deficiency reduced leaf chlorophyll concentrations and changed the reflectance in the visible (400–700 nm) and infrared (700–1100 nm) wavelength range (Pacumbaba Jr. and Beyl, 2011). Plants exhibiting P deficiencies were characterized by purple discoloration in the leaf margins due to increased anthocyanin production (Marschner, 2013), which absorbed energy in the green region (Kumar et al., 2002).

Jacob and Lawlor (1991) showed that the initial amounts of P stress on corn, wheat, and sunflower increased in the number of small cells per unit of leaf area compared with a non-stressed plant, which affected the reflectance in near infrared region (Mahajan et al., 2014). A few studies found that the reflectance in SWIR region had the potential for predicting foliar P. The usage of wavelengths in the SWIR were mainly

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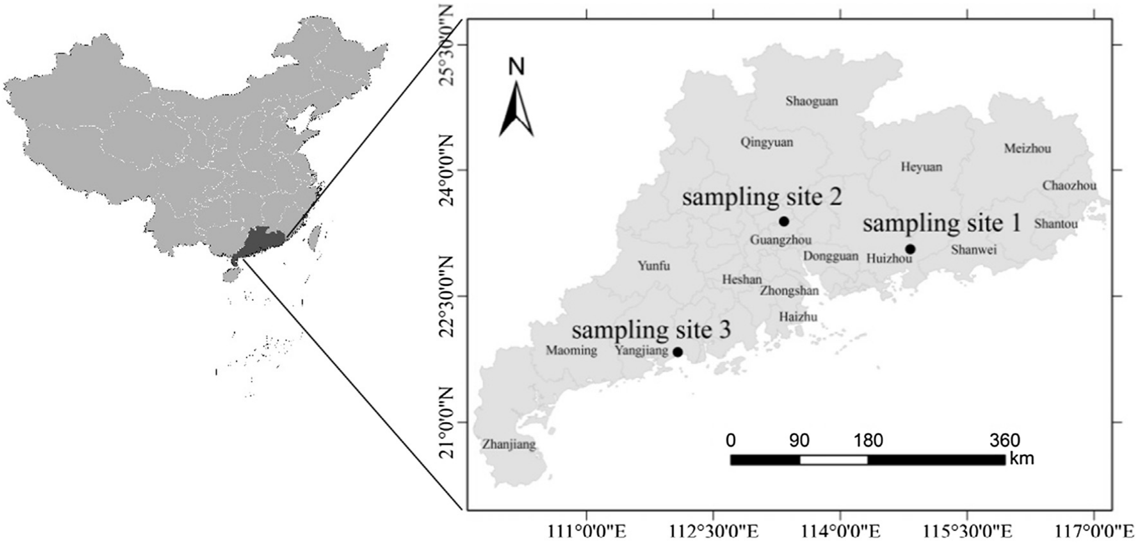

Fig. 1. The distribution of sampling sites in Guangdong Province of China. Sampling site 1: Huidong County; Sampling site 2: Baiyun District; Sampling site 3: Yangdong County.

associated with the absorptions of protein, nitrogen, cellulose, starch and sugar (Knox et al., 2011, 2012).

Spectral transformation techniques such as water removal, continuum removal, band depth, the first difference derivative, and log transformation were proposed to enhance the measurement of nutrient absorption features. Some variable selection methods were used for P estimation (Wang et al., 2016). Additionally, extensive research have been conducted to explore the multivariate statistical relationships between in situ biochemistry and the reflectance values of vegetation (Duhan et al., 2017).

Phenology plays a crucial role in foliar biochemical estimation using spectroscopy (Ramoelo et al., 2013). The selection of specific or known absorption features was not consistent over growing seasons (Knox et al., 2012). The developmental stages of a plant and differences in growth conditions and species were coupled with the changes in cell structure, canopy structure, biomass, water content, and biochemical functions (Schellberg et al., 2008), which in turn influenced the reflectance and the selection of absorption features over a period of plant development (Knox et al., 2012).

Although many studies have estimated crop foliar P by reflectance spectra, the effects of canopy structure and biochemistry on P estimation in different planting conditions have seldom been analyzed. Additionally, few studies have examined the correlation between litchi reflectance and phosphorus in the key growth stages (Chen et al., 2011). The objectives of this study are to develop a useful litchi foliar P estimation model using hyperspectral data, and try to explore the effects of canopy leaf area index (LAI), organic matter (OM), chlorophyll content, leaf nitrogen (N) content, potassium (K) content, calcium (Ca) content, and magnesium (Mg) content on P estimation model.

2. Materials and methods

2.1. Study site

Commercial litchi orchards under normal management by local farmers were investigated in the study. One is located in Huidong County (sampling site 1), one is located in the Baiyun District of Guangzhou City (sampling site 2), and the other is in Yangdong County (sampling site 3). The orchard fields are maintained under a wide range of agricultural management practices and environmental conditions in south China (Fig. 1). Three cultivars ("Huai-zhi", "Gui-wei", and "Shuang-jian-yu-he-bao") of litchi were used in this study. Fifteen samples of *Litchi chinensis* Sonn.cv. trees were collected in Huidong County on 23 Nov 2013 during the autumn shoot maturation stage (ASMS). A total of 54 samples of *Litchi chinensis* Sonn. cv. trees were collected on 15 Dec 2006, 24 Nov 2013, 24 March 2014 and 27 June 2014 in the Baiyun District of Guangzhou City during the flower bud morphological differentiation stage (FBMDS), autumn shoot maturation stage (ASMS), flowering stage (FS), and fruit maturation stage (FMS), respectively. In the flower spike stage (FSS), 20 samples of *Litchi chinensis* Sonn. cv. trees were investigated in Yangdong County on 12 March 2011. Digital images of litchi trees in each growth stage are shown in Fig. 2a–e. The leaves of the litchi canopy were evenly collected immediately after the canopy spectral measurements. Approximately 80 leaves from the canopy were grouped as one sample for biochemical analyses.

2.2. Experimental data

2.2.1. Canopy spectral measurements

Canopy reflectance spectra were measured under clear-sky conditions around midday (10:00–15:00 LST) using portable spectroradiometers (Fieldspec-FR@ 3, ASD Inc., USA). The spectral range of the sensor was 350–2500 nm, with a field of view of 25°. The resembling interval was 1 nm. Reflectance measurements were taken at a nadir-looking angle from 0.5 m above the canopy with the help of ladder. The canopy surface coverage in meters was about 0.22 m. Fifteen measurements were made for each observation. And around each canopy, the reflectance were measured five times from different canopy locations. Then the averaged spectra from the five measurements were calculated as the final canopy reflectance spectra. Spectral reflectance were derived as the ratio of reflected radiance to incident radiance estimated with a calibrated white reflectance material (Spectralon, Labsphere Inc.). The averaged canopy reflectance spectra for each dataset are shown in Fig. 2f.

2.2.2. Measurement of other variables

From each tree, one gram of fresh leaf samples was weighed and transferred into glass tubes with 10 ml of dimethyl sulphoxide for chlorophyll extraction. Absorbance of the clear extract was measured using a double beam Ultraviolet-visible spectrophotometer (Hitachi, Ltd., Japan.). The relative value of chlorophyll was measured with SPAD-502 Plus (Minolta Osaka Company, Ltd., Japan.). The fresh leaves were oven-dried at 60 °C for approximately 72 h to measure the dry