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A universal estimation model of fractional vegetation cover for different crops based on time series digital photographs

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ABSTRACT

The green fractional vegetation cover (FVC) is an important parameter in monitoring crop growth and predicting aboveground biomass. In this study, we monitored crop growth with digital cameras installed at four automatic weather observation stations in different parts of China, from 2010 to 2016. With each station having a particular type of crop, nine color vegetation indices were calculated from the acquired time series digital photographs to arrive at an FVC estimation model applicable to sugarcane, maize, cotton and paddy rice. For individual crop types, our results show that the Excess Green (ExG) is the optimal color vegetation index for the estimation of sugarcane FVC, the Normalized Difference Index (NDI) is the optimal color vegetation index for the estimation of maize FVC, and the Vegetative (VEG) color vegetation index is optimal for the FVC estimation of cotton and paddy rice. However, owing to its higher coefficient of determination (R^2), and lower root mean square error (RMSE) and mean absolute error (MAE) of 0.9504, 0.0721 and 0.0545, respectively, the Color Index of Vegetation Extraction (CIVE) is found more universally applicable for FVC estimation of the four crop types under investigation. The CIVE index has therefore been proposed in this study to be optimal for FVC estimation in sugarcane, maize, cotton and paddy rice mixed cropping agro-systems which are especially common in small and highly fragmented agricultural landscapes such as those in urban and peri-urban areas.

1. Introduction

Vegetation cover is defined as the vertical projection of the crown or shoot area of vegetation canopies from the ground surface, and is expressed as a fraction or percent of the reference area (Purevdorj et al., 2010). Green fractional vegetation cover (FVC) is an important variable for controlling factors in transpiration, photosynthesis and other terrestrial biophysical processes (Jiapaer et al., 1923). FVC can be used as a direct input to crop growth models to predict or estimate crop yield, above-ground biomass, plant nutritional status, and in the estimation of evapotranspiration (Coy et al., 2016; Paton and Boag, 2007, Allen and Pereira, 2009). Based on the above, it is therefore apparent that the development of algorithms for routine investigation of FVC is extremely important in meeting the requirements of ecosystem applications and in modeling crop growth and productivity in the light of environmental management, sustainable development, precision agriculture and food security.

A number of studies have been conducted on the monitoring or estimation of crop green fractional vegetation cover (FVC). Traditional methods of FVC investigation include ground measurements and remotely-sensed data. Several ground measurement techniques for the estimation of percent ground cover of crops have been proposed, and two of the commonly used are described as follows: ① Some agronomists have estimated percent ground cover of vegetation based on visual interpretation (Armbrust, 1990; DUNCAN et al., 1993; Mueller-Dombois and Ellenberg, 2012; Torell and Glimskär, 2009). The major problem of this method is that the results are too subjective, as they are primarily based on the intuition of the observer. Hence, different

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observers could have different value judgments; ② Another method is based on shaded area measurements taken at-or-near noon (Adams and Arkin, 1977; Thalen, 1979). However, in addition to being time and labor consuming, this ruler or electronic method is also affected by weather conditions and orientation of the instrument during measurement (Zhao et al., 2009). Field measurements, even though relatively simple, are subjected to a variety of uncertainties and can be regarded inefficient especially for operational applications at large scales of FVC inventories (Cui et al., 2011).

With the development of computer technology and digital image analysis, estimating crop FVC using digital photography is becoming increasingly popular. The use of digital photography is providing much information on vegetation cover and growth conditions. Computer-aided vision techniques have been applied on digital photographs to segregate the green vegetation from the soil background (Liu et al., 2012). Using digital image analysis, an accurate color vegetation index is required to properly discriminate crop, soil and residue backgrounds for application in ecological monitoring and assessments, quantitative biophysical modeling, precision crop management, and weed control (Meyer and Neto, 2008).

Previous studies have documented a variety of color vegetation indices for separating crops from their background using digital images. The normalized difference index (NDI), which uses the green and red channels has been frequently used to separate the plant from the soil background in digital color images (Meyer, 1993; Pérez et al., 2000). Meyer et al.(1999), tested the excess green and excess red in segmenting plant pixels from the soil background under varying environmental and lighting conditions. Unsupervised fuzzy excess green and excess red have been developed and employed for identifying green plants from soil and residue backgrounds, but they are however, not suitable for wheat-straw backgrounds (Meyer et al., 2004). A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object a grade of membership ranging between zero and one (Zadeh, 1965). The ExG − ExR index has been successfully tested using two commercial color digital cameras to separate plants from their backgrounds under greenhouse field lighting conditions with a fixed zero threshold (Meyer and Neto, 2008). The vegetative index (VEG) has been used to identify plant pixels (Hague et al., 2006). The CIVE index has been mainly used to separate the green plant portion from the soil background (Kataoka et al., 2003). Woebbecke et al. (1995a) selected the R-G, G-B and (G-B)/|R-G|, where the R, G, and B are the red, green, and blue chromatic coefficients for each pixel in the range of 0–1, to find the best optical contrast between plants and their background.

With the availability of inexpensive high-quality digital images, mapping vegetation cover by means of automated image analysis is becoming more common (Bauer and Strauss, 2014). In Zhou and Robson (2001), a method to estimate vegetation cover, density and background brightness parameters in a rangeland environment from low-altitude digital images was presented. In their study, a digital still-frame camera, mounted on a 5.2 m pole was used to acquire images of the ground. The acquired images were then processed using an unsupervised spectral–contextual classifier for the automatic extraction of quantitative measurements. In (Laliberte et al., 2007), ground photographs were acquired from 50 plots using an eight megapixel digital camera. The images were transformed from the RGB (red, green, blue) color space to the IHS (intensity, hue, saturation) color space. An object-based image analysis approach was employed to classify the images into soil, shadow, green vegetation, and senescent vegetation. Shadow and soil were effectively masked out by using the intensity and saturation bands, and a nearest neighbor classification algorithm was used to separate green and senescent vegetation using intensity, hue and saturation, as well as the visible bands. However, classifying leaves under shadows using digital images remains challenging and several classification errors are likely to occur. To address this problem, an automatic shadow-resistant algorithm in the Commission Internationaled'Eclairage L*a*b* color space (SHAR-LABFVC) based on a documented FVC estimation algorithm (LABFVC) has been proposed in (Song et al., 2015). LABFVC is the mean-shift-based color segmentation method and the Commission Internationaled'Eclairage L*a*b* (LAB) color space for the documented FVC estimation algorithm (Liu et al., 2012).

Previous studies have largely focused on the application of color vegetation indices to segment crops from their background (Hague et al., 2006; Meyer and Neto, 2008; Woebbecke et al., 1995a) and estimate nitrogen status (Jia et al., 2007; Lee and Lee, 2013; Wang et al., 2013). In most previous studies, only one crop type is investigated, posing limitations in FVC estimation under mixed cropping systems. In this study, an approach for FVC estimation is adopted based on the Probabilistic Superpixel Markov Random Field (PFMRF) algorithm presented in Ye et al. (2015), a brief description of which is provided in Section 2.3 of this paper. We utilized raw digital photographs as inputs to derive reference FVC, with which linear relationships are built with color vegetation indices to estimate the FVC of four crops.

To achieve the aforementioned aim, image data of sugarcane, maize, paddy rice and cotton were acquired from four automatic weather observation stations in China from 2010 to 2016. Through correlation analysis between FVC and color vegetation indices derived from the combined (all crops) data, we have proposed an FVC estimation model, capable of universal applicability to these four crop types which are generally characterized by overlapping growth periods and located in mixed agricultural systems most typical in urban and peri-urban areas.

2. Materials and methods

2.1. Study area

The data used in this study were obtained from four automatic weather observation stations in China, each station corresponding to a particular type of the crops under investigation. Fig. 1 shows the location of the four test sites. The agrotype of the respective automatic weather observation stations and details of image acquisition are shown in Table 1.

2.2. Image acquisition

As shown in Fig. 2, the images were captured from automatic observation devices designed by the Jiangsu Province Radio Scientific Institute Co., Ltd. The images were shot daily at hourly intervals throughout the year unless there is a system problem, such as system breakdown or power outage. The automatic observation devices consist of Charge Coupled Device (CCD) cameras, and wireless routers connecting the cameras to computers in each station. Image data of crops captured by the CCD cameras are transmitted through wireless launchers to remote computers using 3G network. Camera parameters differ amongst study areas as shown in Table 2.

All the digital color images were saved to 32 bit or 24 bit true color in the appropriate folder in accordance with the focal lengths and shooting time. In the end, we acquired the time series images of sugarcane, maize, paddy rice, and cotton. As images were acquired at different view angles, we selected the vertically shot images to calculate FVC.

2.3. Measurement of fractional vegetation cover (FVC)

In this study, we consider the FVC calculated by the PFMRF algorithm as the reference FVC of the four crops and the measured FVC of an image is calculated as the ratio of the number of pixels of all vegetation to the total number of pixels in the image (Song et al., 2015). Due to system transmission problems, some images were incomplete, and