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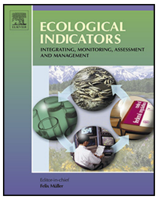

Remote estimation of canopy height and aboveground biomass of maize using high-resolution stereo images from a low-cost unmanned aerial vehicle system

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ABSTRACT

Canopy height (H_{canopy}) and aboveground biomass (AGB) of crops are two basic agro-ecological indicators that can provide important indications on the growth, light use efficiency, and carbon stocks in agro-ecosystems. In this study, hundreds of stereo images with very high resolution were collected to estimate H_{canopy} and AGB of maize using a low-cost unmanned aerial vehicle (UAV) system. Millions of point clouds that are related to the structure from motion (SfM) were produced from the UAV stereo images through a photogrammetric workflow. Metrics that are commonly used in airborne laser scanning (ALS) were calculated from the SfM point clouds and were tested in the estimation of maize parameters for the first time. In addition, the commonly used spectral vegetation indices calculated from the UAV orthorectified image were also tested. Estimation models were established based on the UAV variables and field measurements with cross validation, during which the performance of the UAV variables was quantified. Finally, the following results were achieved: (1) the spatial patterns of maize H_{canopy} and AGB were predicted by a multiple stepwise linear (SWL) regression model ($R^2 = 0.88$, rRMSE = 6.40%) and a random forest regression (RF) model ($R^2 = 0.78$, rRMSE = 16.66%), respectively. (2) The UAV-estimated maize parameters were proved to be comparable to the field measurements with a mean error (ME) of 0.11 m for H_{canopy}, and 0.05 kg/m^2 for AGB. (3) The SfM point metrics, especially the mean point height (H_{mean}) greatly contributed to the estimation model of maize H_{canopy} and AGB, which can be promising indicators in the detection of maize biophysical parameters. To conclude, the variations in spectral and structural attributes for maize canopy should be simultaneously considered when only simple RGB images are available for estimating maize AGB. This study provides some suggestions on how to make full use of the low-cost and high-resolution UAV stereo images in precision agro-ecological applications and management.

1. Introduction

Canopy height (H_{canopy}) and aboveground biomass (AGB) of crops are two basic agro-ecological indicators for the study of environmental processes and precision agriculture. The H_{canopy} and AGB of crops provide important indications on the growth, light use efficiency, and carbon stocks in agro-ecosystems (Li et al., 2015a), which are closely related to the yield production and human living. A rapid, economical and quantitative estimation of crop biomass is important for accessibility risk management, global markets, policy-making, and decision-making (Becker-Reshef et al., 2010). The most direct way quantitatively to capture the values of crop height and biomass is to measure the plant height by tape and to oven dry the plants to constant weight by destructive harvest, respectively. Thus, it is challenging and time consuming for ecologists and agronomists to conduct long-term measurements of crop height and biomass over large-scale areas.

In recent decades, remote sensing has gained weight in the estimation of large-scale distributions of crop biophysical parameters due to its ability to collect non-destructive multi-temporal information at regional and global scales. Satisfactory relationships have been found between the remotely sensed spectral variables

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and vegetation parameters such as phenology indicators (Gonsamo et al., 2013; Wu and Chen, 2013), light use efficiency (Wu et al., 2012), leaf area index (LAI) (Kross et al., 2015), and AGB (Coltri et al., 2013; Liu et al., 2010). Nevertheless, the spectral signals of remotely sensed images tend to saturate with vegetation biomass in areas with dense canopies. In addition, most satellite-based images can hardly provide the vertical structure information of vegetation canopy. To obtain the vertical height of vegetation, photogrammetric techniques have been developed and applied to groups of stereo images (Ni et al., 2014, 2015). However, it is costly and difficult to acquire so many satellite-based stereo images, because the visiting cycle of most open-access satellite data is too long for photogrammetric analysis. The later-presented airborne laser scanning (ALS) or light detection and ranging (LiDAR) technique helped to overcome the saturation problem because of its high penetration capability. The layered features of vegetation canopy like plant height can be directly obtained from the returned laser signals. Both airborne and terrestrial laser scanning (TLS) systems have been widely employed in the study of forest vegetation (Höfle et al., 2012; Hyyppa et al., 2012; Listopad et al., 2015). As the growth status of crops varies a lot during the growing season compared with forest, the TLS system is preferred in the multi-temporal monitoring of crops because it is more cost efficient. Detailed geo-information of crops like maize, whose canopy height is short can be provided by TLS even at the individual plant level (Höfle, 2014). Despite the high cost, the ALS data were proved to have great potential in estimating the canopy height and biomass of maize in the peak growing season based on our previous studies, and the estimated error varied from 0.15 to 0.17 m for H_{canopy}, and 0.29–0.49 kg/m^2 for AGB (Li et al., 2015a,c). In addition, the full-waveform of ALS has been proved to be more powerful in the height extraction of maize height compared with discrete point clouds (Gao et al., 2015). This is important for large-scale monitoring of precision farming as ALS can provide a larger measuring scale than TLS. However, ALS tends to overestimate canopy LAI and underestimate canopy height especially for short vegetation types like maize (Li et al., 2015a). In addition, both ALS and TLS datasets are difficult to acquire in terms of practicality and cost for vegetation detection, because repeat acquisitions are usually needed with an increased cost (Mathews and Jensen, 2013; Omasa et al., 2007). The point density of ALS data can be significantly increased with repeat airborne flights, giving a better description of the interactions between laser pulses and targets.

The recent advent of unmanned aerial vehicles (UAVs) seems to be a promising trade-off between airborne and terrestrial remote sensing in the study of precision agriculture and ecological management. Compared with manned airborne and terrestrial systems, an evident advantage of UAV systems is that they can work at low flight heights that are close to the targets with no risk to human life in different and inaccessible areas. In addition, it can provide a much larger ranging scope than TLS. The low cost and high flexibility have led to UAV systems rapidly being employed in agriculture (Geipel et al., 2014; Link et al., 2013) and forestry management (Getzin et al., 2014; Jaakkola et al., 2010). Detailed discussions on the evolution and state-of-the-art of the use of UAV systems have been reviewed by Colomina and Molina (2014). Both imaging and non-imaging sensors can be mounted on a small UAV, providing various types of remotely sensed data (Aasen et al., 2015). Hundreds of images with centimeter spatial resolution can be collected by a small and lightweight UAV system controlled by pre-programmed flying plans (Lisein et al., 2013), which can be used for applications at different scales. The structure of motion (SfM) technique has been proved to be a very efficient approach to organize and process the many overlapped UAV images based on the principles of photogrammetry. The SfM approach greatly improved the automation of the photogrammetric workflow so that very dense point clouds at sub-pixel accuracy can be produced in near real-time at low cost (Leberl et al., 2010). The SfM point clouds are usually of much higher point density than ALS and TLS, which is important for precision study of vegetation structure. Most of the previous studies of vegetation based on UAV mainly focused on the application of three-dimensional digital models and the spectral variables including the raw digital numbers and vegetation indices (VIs) (Aasen et al., 2015; Bendig et al., 2015; Candiago et al., 2015). However, considerably fewer studies explored the direct use of SfM point clouds. According to Mathews and Jensen (2013), metrics generated from the SfM point clouds (point heights, number of points, etc.) can be efficiently used to predict the canopy LAI of vineyard vegetation. In fact, these types of metrics calculated from ALS point clouds have been used in estimating biophysical parameters of vegetation (Li et al., 2015b; Luo et al., 2015). Comparisons on the similarities and differences between ALS and UAV SfM point clouds have been conducted on the extraction of forest inventory attributes (White et al., 2013). For the UAV detection of maize, spectral VIs calculated from the RGB color space have been used as the main proxies to predict maize parameters (Liebisch et al., 2015; Pena et al., 2013; Zaman-Allah et al., 2015). This is probably because of the good responses of biophysical and biochemical canopy components to solar radiation at different spectral wavelengths. To the best of our knowledge, few studies have employed or compared the ability of the SfM point cloud metrics in the estimates of maize biomass for the same dataset. In addition, the contribution and performance of different types of UAV variables during the estimation still need quantitative evaluation. With the rapid advent of UAV data, we believe that the SfM point cloud metrics will be widely used in future estimations of vegetation parameters.

Therefore, this study aimed to further explore the UAV detection of two maize parameters, namely, H_{canopy} and AGB. In addition to the spectral VIs, ALS-similar metrics were also calculated from the UAV SfM point clouds (denoted as SfM point metrics hereafter). It is expected that the addition of these point metrics will help to increase the estimation accuracy of maize parameters. The performance and contribution of these SfM point metrics and the spectral VIs were tested and quantified in the estimation of maize parameters. Estimation models were established and cross-validated by field measurements, and were further used to predict the spatial patterns of maize parameters. Based on the analysis in this study, we hope to provide some suggestions on how to make full use of the low-cost and high-resolution UAV stereo images in precision agro-ecological applications and management.

2. Materials

2.1. Study site

The study site called Huailai area is located in the Huailai-Yanqing Basin with a quite flat terrain, along the south of Guanting Reservoir, 84 km north of Beijing, China. Maize is the dominant crop type in this area, usually sowed in late May, flowering near late July, and harvested between middle and late September (Gao et al., 2013). The mean elevation is 30 m above sea level, and the mean annual temperature is 9.1 °C with the coldest temperature in January and the hottest in July. Precipitation is distributed unevenly in the four seasons with an average annual precipitation of 396 mm, the greatest precipitation occurring in summer.

2.2. UAV flight and data processing

The UAV flights were conducted on August 9, 2015. Detailed flight plans were made before data acquisition. A multiple rotor-wing UAV system was used for the collection of stereo images with an overlap set to 80% longitudinal and 40% lateral. The UAV platform