Mapping cotton plant height using digital surface models derived from overlapped airborne imagery

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Abstract. *High resolution aerial images captured from unmanned aircraft systems (UASs) are recently being used to measure plant height over small test plots for phenotyping, but airborne images from manned aircraft have the potential for mapping plant height more practically over large fields. The objectives of this study were to evaluate the feasibility to measure cotton plant height from digital surface models (DSMs) derived from overlapped airborne imagery and compare the image-based estimates with the data from a tractor-mounted ultrasonic distance sensor. An airborne imaging system consisting of a red-green-blue (RGB) camera and a modified near-infrared (NIR) camera mounted on a Cessna 206 aircraft was flown along six flight lines over a 27-ha field at peak cotton growth and again with tilled bare soil. Images were captured at 370 m above ground level to achieve a ground pixel size of 0.09 m and side/forward overlaps of about 85%. The ultrasonic distance sensor and a centimeter-grade GPS receiver were mounted on a high-clearance tractor to collect cotton plant height data from every 8th row at 1-s intervals. The images taken on the two dates were processed to create orthomosaics and DSMs. Plant height was estimated from the difference between the two DSMs. Results showed that a significant linear relation existed between image-based and ground-based plant height estimates with a* R^2 *value of 0.657 and a standard error of 0.11 m. The preliminary results from this study indicate that DSMs derived from overlapped airborne imagery have the potential to estimate and map plant height for monitoring crop growth conditions.*

Keywords. *airborne image, digital surface model, orthomosaic, plant height, ultrasonic sensor.*

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Introduction

Plant height is an important crop canopy characteristic that is directly related to crop biomass and yield potential (Bendig et al., 2014; Hoffmeister et al. 2015; Tilly et al. 2015). Therefore, measuring plant height during the growing season provides useful crop growth information for precision management and phenotyping. For cotton, plant height is a particularly important parameter for site-specific applications of plant growth regulators (PGRs) (Bethel et al. 2003; Sharma et al. 2008). PGRs are often needed to shift cotton from vegetative to reproductive growth, maintain proper plant size, and promote boll set and early maturity. Information on plant height and growth stages is important for PGR recommendations.

Manual methods and electronic sensors such as ultrasonic sensors have been traditionally used for measuring plant height. An ultrasonic sensor determines the distance between the sensor and the object by measuring the time difference between the transmission of high frequency sound waves and the reception of the reflected echo. Ultrasonic sensors are usually mounted on ground vehicles along with other electronic sensors (i.e., spectral and thermal) to measure plant height and other canopy characteristics for crops (Sui and Thomasson 2006; Escola et al. 2011; Sharma and Ritchie 2015; Bai et al. 2016).

Lidar has been used for canopy characterization in tree crops for many years (Tumbo et al. 2002; Llorens et al. 2011). This technology has recently gained attention in precision agriculture and phenotyping for modeling crop plant 3D structure so that various canopy characteristics (i.e. height, canopy cover, volume, and biomass) can be extracted (Lin 2015; Sun et al. 2018). Lidar, also called LIDAR or LiDAR, measures distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target. Lidar systems are available onboard different platforms, but ground-based stationary and mobile terrestrial Lidar has been commonly used for mapping crops (Saeys et al. 2009; Zhang and Grift 2012). Unmanned aerial vehicle (UAV) based LiDAR is developing quickly and has been evaluated for fine-scale mapping of vegetation (Lin 2015).

Ground-based data acquisition can provide accurate results, but is costly and time-consuming and may not have continuous sampling for every area of the field. Moreover, ground vehicles can cause damage to the crop and compaction to the soil. Therefore, airborne non-destructive methods of measuring crop canopy characteristics are more attractive. Vegetation indices derived from airborne multispectral imagery have been traditionally used to estimate crop height, biomass and yield (Yang and Anderson 1999; Plant et al. 2000).

Recent advances in unmanned aircraft systems (UASs) allow digital cameras to be flown at low altitudes to capture very high resolution imagery. As the ground coverage of the UAS-based images is relatively small, a large number of overlapped images need to be acquired along multiple flight lines to cover a field. With the high resolution overlapped images, it is possible to create high resolution 3D point cloud models similar to those derived from Lidar. Structure-from-motion (SfM) photogrammetry is an image-based 3D reconstruction method for automatic creation of digital surface models (DSMs) and orthomosaics from overlapping images (Westoby et al. 2012).

A number of studies evaluated SfM methods to estimate crop height from UAS-based images over the growing season (Bendig et al. 2014; Holman et al. 2016; Varela et al. 2017). Several studies also compared UAS-based images and ground Lidar for estimating plant height (Madec et al. 2017; Malambo et al. 2018). Results from these studies showed significant correlations between UAS-based estimates and ground or Lidar data. However, estimation accuracy varied with camera types, image resolution, flight parameters, and other imaging and crop growing conditions.

Despite the encouraging UAS-based results, almost all the studies were conducted over small test plots with different crop varieties or treatments. There is no report on the use of UAS-based images for mapping crop height on normal crop fields. Moreover, due to UAS flight height restrictions and resolution requirements, images are usually captured at very low altitudes above ground (as low as 20 m), resulting in very high resolution (<10 mm) and large numbers of images (100s or over 1000) for a small area. Consequently, image processing can take hours or days. For the SfM-based approach to be practical, it should be tested with images taken at higher altitudes from normal crop fields.

Therefore, the objectives of this study were to 1) evaluate the feasibility to estimate plant height from DSMs derived from overlapped airborne imagery for a cotton field; and 2) compare image-based estimates with data from a tractor-mounted ultrasonic distance sensor.

Materials and methods

Study site

This study was conducted on a 27-ha field (30°31'50"N, 96°25'55"W) at the Texas A&M University AgriLife Research Farm near College Station, Texas. Cotton was planted to the field with a row spacing of 1.016 m. The field was irrigated with a center-pivoted irrigation system.

Aerial image acquisition

An airborne imaging system consisting of two consumer-grade cameras (Nikon D810, Nikon Inc., Melville, NY) with a 7360 x 4912 pixel array was used for image acquisition. One camera captured red-green-blue (RGB) color images, while the other camera was equipped with an 830-nm long-pass filter to obtain near-infrared (NIR) images. A Cessna 206 aircraft was used to fly the imaging system along six flight lines over the field at peak cotton growth on September 12, 2016 and with tilled bare soil on October 30, 2017. Images were captured at approximately 370 m above ground level to achieve a ground pixel size of 0.09 m and side/forward overlap of about 85%.

Plant height measurements with an ultrasonic sensor

A plant height sensing system, consisting of an ultrasonic distance sensor (TSPC-15S, Senix Corporation, Bristol, VT), a centimeter-grade GPS receiver (GEO 7X, Trimble Navigation Limited, Sunnyvale, CA) and a data logger (GeoSCOUT, Holland Scientific, Inc., Lincoln, NE), was used to collect plant height data. The ultrasonic senor and the GPS receiver were configured to transmit distance count values and GPS data, respectively, at 1-s intervals. The system was mounted on a high-clearance tractor and data were collected from the cotton field every 8th row on September 12, 2016. The count values were converted to distance in meters by a scale factor and plant height was calculated by subtracting the scaled distance from the height of the sensor above the ground level. The GPS data were converted to the Universal Transverse Mercator (UTM), World Geodetic System 1984 (WGS-84), Zone 14, coordinate system.

Creation of orthomosaics and DSMs from images

The images with and without cotton plants were processed to create orthomosaics and DSMs using Pix4DMapper Pro (Pix4D SA, Lausanne, Switzerland). To improve the accuracy of mosaicked images and DSMs, 10 and 15 white panels were placed around the field during image acquisition with and without cotton plants, respectively. The geographic coordinates (X, Y, Z) for the centers of these panels were measured with the centimeter-grade GPS receiver and the panel centers were used as ground control points (GCPs) during image processing. The root mean square error was less than 0.1 m in both horizontal and vertical directions for the two DSMs.

Comparison of DSM-based plant height and ultrasonic data

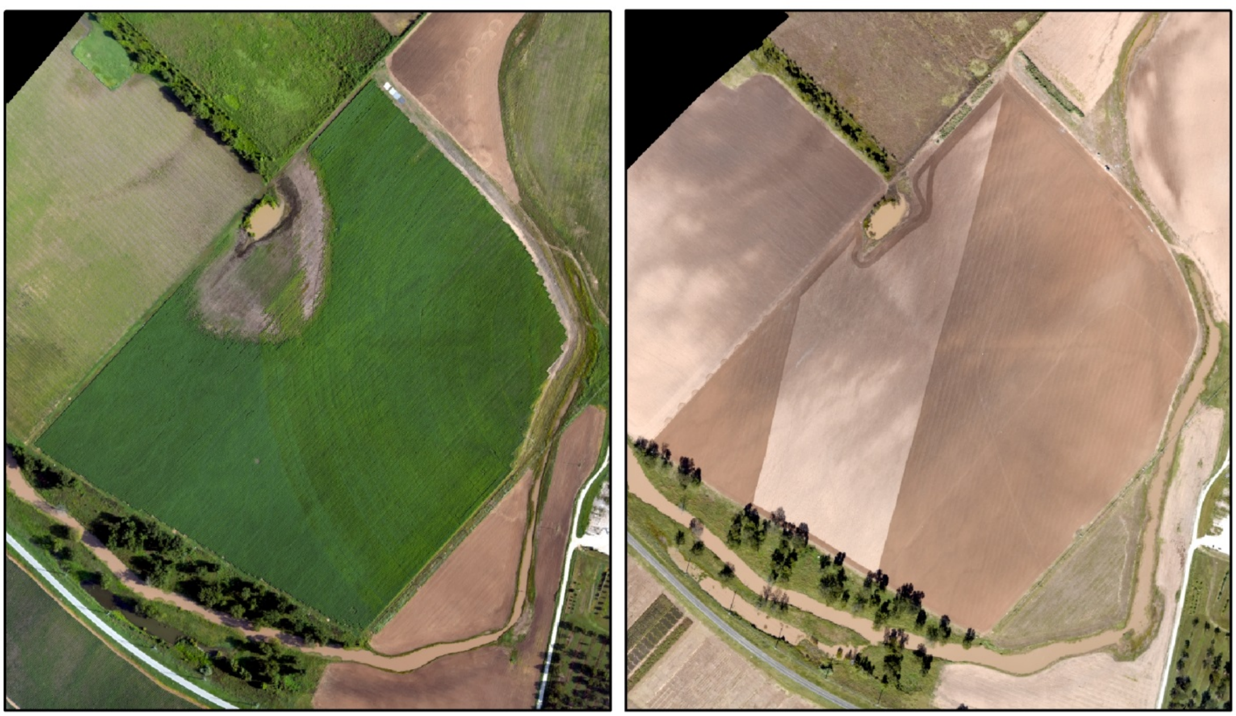
The DSMs for cotton plants and bare soil were imported to Erdas Imagine (Intergraph Corporation, Madison, AL). The image for plant height was then derived from the difference between the two DSMs. A field boundary was defined as an area of interest (AOI). Since plant height by the ultrasonic sensor was measured at 1-s intervals and from every 8th row, the effective swath width was 8.128 m and the average ground speed was approximately 9 km/h or 2.5 m/s. Thus each plant height data point represented a rectangular area of 8.128 m by 2.5 m. The ground data evidently had much coarser spatial resolution than the 0.09-m image data.

For spatial and correlation analysis, an aggregation function was applied to the image to degrade the pixel resolution to 8 m. The value for each output pixel of the reduced-resolution image was the mean of all the input pixels that the 8 m × 8 m output pixel encompassed. The ground plant height value for each corresponding output pixel was the mean of the discrete plant height samples falling within the 8 m × 8 m output pixel. Consequently, the total number of data samples for the field was reduced to 3854. Linear regression analysis was performed to determine the relation between image-based and ground-based plant height.

Results and discussion

Orthomosaics and DSMs

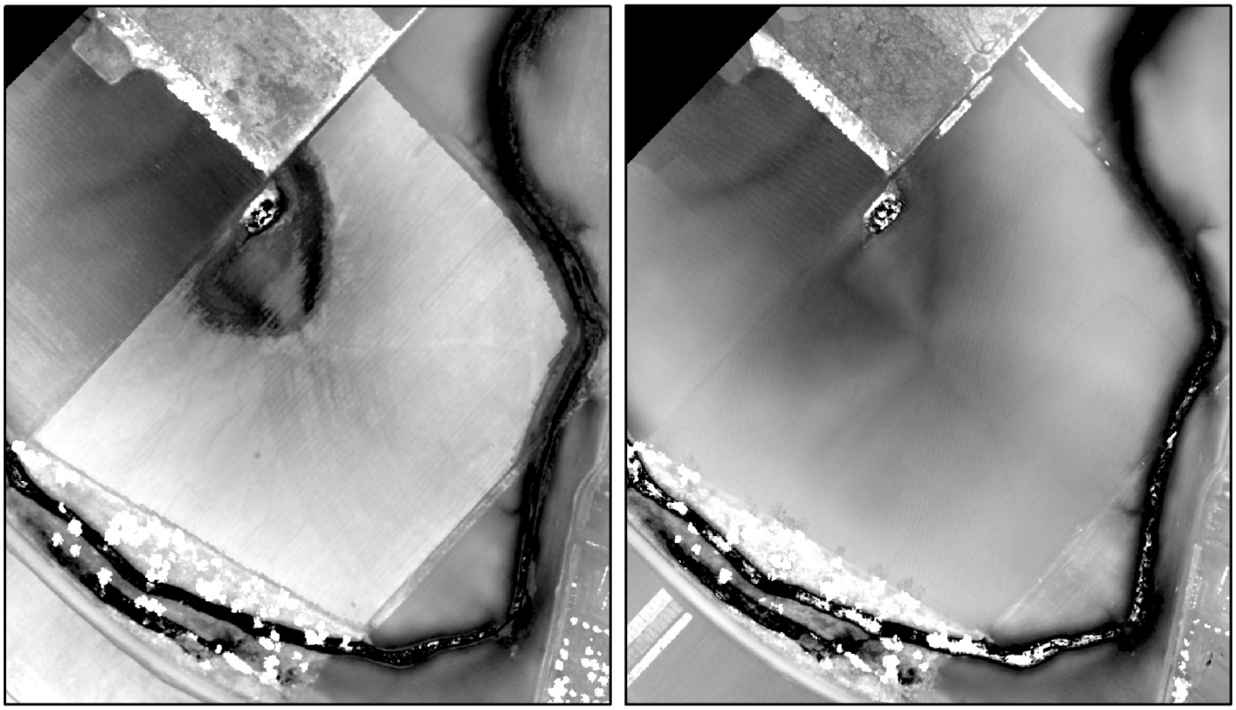
Fig. 1 shows the RGB orthomosaic images for cotton plants and bare soil for the 27-ha field. The orthomosaic image for cotton plants were created from the images taken around peak plant growth during the 2016 growing season, while the orthomosaic for bare soil was based on images taken after the field was tilled in 2017. As shown in the cotton plant image, the canopy cover was full for the field except for the low area along the northwest boundary. The very poor plant stand was caused by excessive water in the area. The bare soil image shows that the field was partially disked at the imaging time in 2017.



(a) Cotton plants (b) Bare soil

Fig. 1. RGB orthomosaic images for (a) cotton plants and (b) bare soil for a 27-ha cotton field near College Station, Texas.

Fig. 2 shows the DSMs for cotton plants and bare soil for the cotton field. The very bright areas represent tall bushes and trees around the field, while the very dark areas depict low and drainage areas. Clearly, the field looks brighter with cotton plants than with bare soil. The field is generally flat with an elevation range of about 1.5 m.



(a) Cotton plants (b) Bare soil

Fig. 2. Digital surface models for (a) cotton plants and (b) bare soil for a 27-ha cotton field near College Station, Texas. Light gray color represents high elevation, whereas dark gray color depicts low elevation.

(a) Image-based (b) Ground-based

Fig. 3. Plant height estimates based on (a) digital surface models with and without cotton plants and (b) data from an ultrasonic sensor for a 27-ha cotton field near College Station, Texas.

Comparision of image-based and ground-based plant height

Fig. 3 shows plant height estimates based on the DSMs and the ultrasonic data for the cotton field. Although plant height appeared relatively uniform except for the flooded low area, there existed some spatial variability within the field. Table 1 presents the simple statistics for both image-based and ground-based plant height estimates. Plant height ranged from 0.02 m to 1.27 m with a mean of 0.88 m for image-based estimates and from 0 to 1.36 m with a mean of 0.90 m for ground-based estimates. The coefficient of variation was 24.4% and 20.5%, respectively, for image-based and ground-based estimates.

Table 1. Simple statistics for image-based and ground-based plant height estimates for a 27-ha cotton field near College Station, Texas.

Simple statistic	Image-based	Ground-based
No. of samples	3854	3854
Minimum (m)	0.02	0.00
Maximum (m)	1.27	1.36
Mean (m)	0.88	0.90
Standard deviation (m)	0.22	0.18
Coefficient of variation (%)	24.4	20.5

Fig. 4 shows the scatterplot between image-based and ground-based plant height estimates for the field. The linear regression equation and R^2 value along with the y = x line are also given on the figure. Clearly, a significant linear relation existed between the two sets of plant height estimates with a R^2 value of 0.657 and a standard error around the regression line of 0.11 m. It can be seen from Fig. 4 that low plant height below 0.6 m tended to be overestimated by the DSMs.

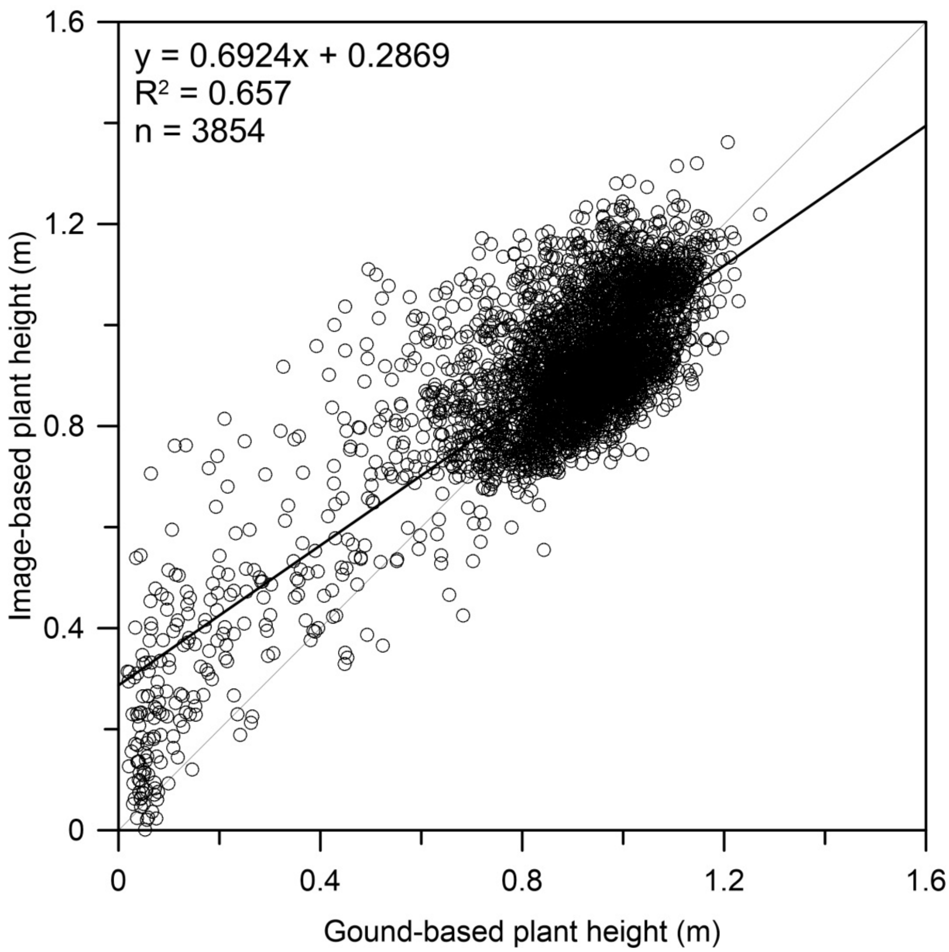


Fig. 4. (a) Relation between image-based and ground based plant height estimates for a 27-ha cotton field near College Station, Texas.

Conclusions

Preliminary results from this study demonstrate that DSMs derived from overlapped airborne images have the potential for estimating crop plant height. Nevertheless, estimation accuracy is yet to be improved. More research is needed to evaluate how image resolution, amount of overlap, image processing parameters and other factors affect the accuracy for plant height estimation.

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