Analysis of Accuracy Differences in Monitoring Maize Canopy Height Across Different Growth Stages Using UAV Imagery: A Postprint

Authors: Yang Jin, Mingbo, Yang Fei, Honggen Xu, Li Lulu, noble, Liu Chaowei, Wang Keru, Li Shaokun

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Abstract

To clarify the accuracy and influencing factors of monitoring maize population plant height using UAV imagery, this study constructed a field maize population Digital Elevation Model (DEM) based on UAV-borne optical imaging equipment, and investigated the accuracy differences in maize population plant height monitoring across different growth stages. For plant height-differentiated populations constructed from 3 maize varieties and 8 sowing date treatments, a multi-rotor UAV equipped with a high-resolution RGB camera and multispectral imaging device was used to collect high-resolution RGB and multispectral imagery of the experimental area, obtain maize population digital elevation information (DEM) and plant heights in each treatment zone, and analyze the correlation between UAV-based and manually measured plant heights under different variety and sowing date treatments. The experimental results showed that DEMs obtained from both the high-resolution RGB camera and multispectral imaging device could reflect height differences in maize populations. The plant height monitoring accuracy of the high-resolution RGB camera was superior to that of the multispectral imaging device, but the plant height monitoring accuracy was insufficient to reflect smaller plant height differences in maize populations. Different growth stages had a significant impact on maize plant height monitoring accuracy; when the canopy had not fully covered the ground in early growth stages or when plants senesced with yellowing and drooping leaves in late growth stages, the population plant height was severely underestimated due to the influence of bare soil. This study analyzed the factors affecting the accuracy of monitoring maize plant height using UAV-borne imaging equipment, which can provide guidance for the application of this method in field production.

Full Text

The Accuracy Differences of Using Unmanned Aerial Vehicle Images for Monitoring Maize Plant Height at Different Growth Stages

YANG Jin, MING Bo, YANG Fei, XU Honggen, LI Lulu, GAO Shang, LIU Chaowei, WANG Keru, LI Shaokun*

Institute of Crop Sciences, Chinese Academy of Agricultural Sciences/Key Laboratory of Crop Physiology and Ecology, Ministry of Agriculture and Rural Affairs, Beijing 100081, China

Abstract: To clarify the accuracy and influencing factors of using unmanned aerial vehicle (UAV) imagery for monitoring maize population plant height, this study constructed a digital elevation model (DEM) of field maize populations based on UAV-borne optical imaging equipment to investigate the precision differences in maize population height monitoring across different growth stages. For maize populations with differentiated plant heights constructed from three varieties and eight sowing date treatments, a multi-rotor UAV equipped with a high-definition camera and multispectral imaging device was used to collect high-definition RGB and multispectral images of the experimental area, obtaining maize population digital elevation information and plant height data for each treatment zone. The correlation between UAV-based and manually measured plant heights was analyzed under different variety and sowing date treatments. Results demonstrated that both high-definition RGB cameras and multispectral imaging equipment could reflect height differences in maize populations. However, the plant height monitoring accuracy was insufficient to capture smaller height differences within maize populations. Growth stage significantly influenced maize plant height monitoring accuracy. During early growth stages when the canopy had not fully covered the ground surface, or during late growth stages when plants senesced with yellowing and drooping leaves, population plant height was severely underestimated due to exposed soil surface effects. This study analyzed the factors affecting the accuracy of UAV imaging equipment for monitoring maize plant height, providing valuable insights for applying this method in field production.

Keywords: accuracy difference; UAV; plant height measurement; maize; multispectral

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1 Introduction

Plant height is a crucial indicator characterizing crop growth status, with wide applications in growth monitoring, water and fertilizer regulation decisions, and lodging risk prediction. Traditional plant height measurement methods rely on manual measurements using rulers or other length measurement tools in the field or on sampled whole plants, which suffer from low operational efficiency and subjective errors due to non-standardized procedures.

To improve the efficiency and precision of plant height measurement, numerous studies have attempted to construct accurate plant height measurement methods for controlled environments using machine vision and laser triangulation (LiDAR) techniques, enhancing objectivity and accuracy. However, these methods require standardized detection environments and cannot be applied in open field conditions, limiting their practicality and measurement efficiency.

In recent years, UAV platforms equipped with digital imaging devices, hyperspectral/multispectral imaging sensors, and LiDAR have formed flexible and efficient farmland monitoring systems, becoming important tools for crop population growth and nutrition monitoring. For plant height measurement, LiDAR equipment offers high point cloud density and excellent accuracy with clear advantages. However, high cost, heavy weight, demanding UAV payload requirements, and complex data processing constrain its expansion from a research tool to agricultural production applications. In contrast, low-altitude monitoring platforms combining high-definition RGB cameras or spectral imaging instruments with UAVs can utilize Structure from Motion (SfM) algorithms to generate sparse point clouds of photographed objects, reconstruct three-dimensional models, and ultimately obtain digital surface models (DSM) for plant height measurement across various crops. To eliminate terrain effects on plant height measurements, soil DSM data from pre-planting periods without crops must be differenced with crop population DSM data from measurement periods. Additionally, imaging device distortion and SfM algorithms affect crop population 3D reconstruction and DSM calculation accuracy, which can be improved through geometric correction using ground control points with high-precision geographic coordinates.

As a relatively widely spaced crop, maize undergoes significant morphological and structural changes during growth, development, and senescence that substantially alter its population and canopy surface structure, creating difficulties for UAV imaging equipment in reconstructing crop population 3D structures and calculating DSM. This study monitored maize population plant height using UAV-borne RGB and spectral imaging equipment to analyze the effects of different maize varieties, growth stages, and imaging device resolution factors on plant height monitoring accuracy. The feasibility of using UAV imagery for plant height difference monitoring in field maize production was evaluated to provide references for developing rapid, non-destructive, flexible, and low-cost plant height monitoring methods suitable for field crop applications.

2 Materials and Methods

2.1 Experimental Design

The experiment was conducted in 2018 at the Henan Xinxiang Comprehensive Experimental Station of the Chinese Academy of Agricultural Sciences (35°07 52 N, 113°45 37 E). The experimental field was flat with elevation ranging from 61.84 to 61.87 m (Figure 1 [Figure 1: see original paper], DEM of bare soil in the experimental area obtained on May 11, 2019). Three maize varieties with different plant heights were selected: Fengken 139 (FK139), Jingnongke 728 (JNK728), and Zhengdan 958 (ZD958). Eight sowing date treatments were established within 2018: April 20 (B1), April 30 (B2), May 10 (B3), May 24 (B4), June 3 (B5), June 13 (B6), June 23 (B7), and July 3 (B8), totaling 24 treatments arranged in large plots. Each plot covered 162 m^2 (22.5 m × 7.2 m) with row spacing of 0.6 m and planting density of 75,000 plants/ha. Field management followed standard commercial practices. The variety and sowing date treatment layout is shown in Figure 2 [Figure 2: see original paper].

2.2 UAV Image Acquisition and Processing

2.2.1 UAV Image Acquisition Under clear, cloudless conditions with wind speed less than level 2, high-definition digital RGB and multispectral images of the 24 plots were acquired between 10:00–13:00 on July 25 and August 27, 2018, using a DJI M600 Pro six-rotor UAV equipped with a high-definition digital camera (SONY $ $7 , 24.3 million effective pixels, maximum resolution 6000 px × 4000 px, SONY Sonnar T* FE 35mm f/2.8 ZA fixed-focus lens) and a multispectral camera (Micasense Rededge MX, maximum resolution 1280 px × 960 px). Flight altitude was set at 70 m with 85% forward overlap and 80% side overlap. On July 25, treatments were between jointing and grain-filling stages when population height differences among sowing date treatments were maximal. On August 27, all treatments had reached silking stage when height differences were minimal.

2.2.2 UAV Image Processing Agisoft PhotoScan Professional software was used to mosaic UAV images and generate RGB and multispectral digital elevation models (DEM) of the experimental field. RGB images were mosaicked based on Position and Orientation System (POS) data recorded by the DJI M600 Pro flight control system during image acquisition. Multispectral data were mosaicked based on GPS navigation data from the Rededge-M device. The mosaicking process involved: (1) pixel matching between adjacent images based on spatial attitude data and feature pixels with subsequent pose optimization; (2) gradual generation of sparse and dense point clouds with precise spatial information attributes; (3) construction of monitoring area surface geometry and DSM to calculate surface elevation information for different maize populations. Plant height for each treatment plot was extracted from the DSM by collecting elevation points for the plot, removing the highest and lowest 15% of data points, and using the average elevation of the remaining 70% as the plot’ s plant height measurement. ArcMap software was used for DSM data processing and mapping.

2.3 Manual Plant Height Measurement Method

In each treatment plot, 20 maize plants were randomly selected as fixed measurement samples, uniformly distributed throughout the plot. Plant height was measured using extendable rulers on the same day as UAV image acquisition. For plots not yet at silking stage, plant height was measured as the distance from the highest point of the natural plant canopy to the ground surface. For plots at or past silking stage, height was measured from the plant apex to the ground surface. The average of the 20 samples was used to approximate the population plant height for that treatment. The growth stages of each treatment at measurement time are shown in Table 1 .

On July 25, treatments B1-B5 for all varieties had reached silking stage, with the early-maturing variety FK139 at 41 days after silking in the B1 treatment, where some plants showed withered and drooping leaves. Treatments B6-B8 for all three varieties remained at different vegetative growth stages with substantial height differences. On August 27, all sowing date treatments for all varieties had reached silking stage, with most plants showing withered and drooping leaves for early-maturing FK139 in treatments B1-B4, and the stay-green variety ZD958 showing leaf senescence in treatment B1.

2.4 Analysis and Statistical Methods

The relationship between UAV-monitored and manually measured plant heights was analyzed after normalizing both datasets using Formula (1):

$$H_n = \frac{H - \min H}{\max H - \min H}$$

where H_n is the normalized image-based canopy height or manually measured population height (dimensionless), H is the raw data to be normalized (m), $\min H$ is the minimum measured plant height (m), and $\max H$ is the maximum measured plant height (m). UAV-monitored canopy relative height is denoted as $H_n(i)$, and manually measured population relative height as $H_n(t)$. After normalization, canopy heights for all treatments are expressed as relative heights within the range [0, 1].

Data analysis of variance (ANOVA) and graphing were performed using SPSS 20.0 and Microsoft Excel 2010.

3 Results

3.1 Plant Height Differences Among Treatments and Image Performance

Manual measurements of average plant height for each plot under different variety and sowing date treatments are shown in Table 2 . Population plant heights generally showed a trend of increasing then decreasing from north to south. Significant differences in plant height existed among different sowing date treatments for the same variety due to different growth stages. On July 25, the three maize varieties in treatments B1-B5 had reached silking stage with fixed plant heights, and all varieties showed that B1 and B2 treatments had significantly lower population heights than B3-B5. Treatments B6-B8 were at vegetative stages V6-V14 with lower heights than B1-B5, showing large height differences among B6-B8 treatments but smaller differences among varieties than among sowing dates. On August 27, all treatments had reached silking stage (Table 1), yet height differences among treatments were still observable.

The DEM generated from single images represents elevation information of the maize canopy top, comprising both plant height and ground elevation components. Since the experimental field was flat with minimal relief, ground elevation was essentially consistent across treatments, making canopy elevation differences equivalent to plant height differences. However, altitude information recorded in UAV flight paths represents barometric altimeter height, causing inconsistencies across collection dates. To ensure comparability between UAV-measured canopy heights and manually measured plant heights, both datasets were normalized using Formula (1).

After masking the original DSM images by plot, DSM images for each treatment were obtained (Figure 3 [Figure 3: see original paper]). Height variations among treatments in both RGB images (Figures 3a and 3c) and multispectral images (Figures 3b and 3d) from the two monitoring periods showed the same trends as manually measured plant heights (Table 2), indicating that UAV image-based methods can reflect population height differences.

3.2 Relationship Between Image-Monitored and Manually Measured Plant Heights

Normalized average heights from RGB and multispectral images ($H_n(UAV)$) were correlated with normalized manually measured plant heights ($H_n(L)$) for each treatment. Results are shown in Figure 4 [Figure 4: see original paper]. On July 25, due to different growth stages among sowing date treatments, large differences existed among population heights, which were clearly expressed in images. The normalized average height from RGB images ($H_n(UAV)$) showed extremely significant correlation with normalized manually measured height ($H_n(L)$) on July 25 (Figure 4a, $r = 0.839$). On August 27, when all treatments had reached maximum height and inter-treatment differences were smaller, the correlation between RGB image-based canopy height $H_n(UAV)$ and manually measured height $H_n(L)$ remained significant (Figure 4c) but with a lower correlation coefficient of 0.461. Similar relationships existed for multispectral imagery: on July 25, the correlation was extremely significant (Figure 4b) but with a lower correlation coefficient ($r = 0.587$) than RGB images, indicating that sensor precision affects measurement accuracy beyond treatment differences. On August 27, when treatment height differences were minimal and sensor precision limitations applied, multispectral image-based height monitoring performed poorly, with no significant correlation to manually measured heights (Figure 4d). These results demonstrate that both high-definition RGB and multispectral cameras can measure population heights when large differences exist among treatments, with RGB image accuracy superior to multispectral cameras. However, when height differences among treatments decrease, measurement errors for both camera types increase, particularly for multispectral cameras.

3.3 Analysis of Factors Affecting Image-Based Height Monitoring

Under variety and sowing date treatments, significant differences existed among plot plant heights (Table 2). Correlation analysis between normalized image-based canopy heights ($H_n(UAV)$) and normalized manually measured plant heights ($H_n(L)$) for the two measurement periods (Table 3) showed that RGB image monitoring results correlated more strongly with actual plant heights than multispectral images, with variations between measurement periods and varieties. In July 25 measurements, $H_n(UAV)$ from RGB images showed extremely significant correlations with $H_n(L)$ for JNK728 and ZD958 varieties, with correlation coefficients exceeding 0.9, while FK139 showed significant correlation ($r = 0.818$). For multispectral images, only JNK728 and ZD958 showed significant correlations ($r = 0.774$ and 0.737, respectively), while FK139 showed no significant correlation ($r = 0.486$). In August 27 measurements, RGB image $H_n(UAV)$ and $H_n(L)$ were significantly correlated only for ZD958 ($r = 0.797$), with no significant correlations for the other two varieties. For multispectral images, none of the three varieties showed significant correlations between $H_n(UAV)$ and $H_n(L)$. These results indicate that maize variety type and developmental stage affect plant height measurements by both camera types, while also demonstrating that RGB image-based population height monitoring has better adaptability to variety and developmental stage variations.

Differences in plant height among different sowing date treatments essentially reflect height variations caused by different developmental stages or different light and temperature conditions during growth, which can be well expressed through imaging methods. On July 25, RGB image results under different sowing date conditions showed extremely significant correlation with manually measured plant heights, with correlation coefficients reaching 0.9. On August 27, the normalized correlation between image-based population heights and manually measured heights weakened. Comparing developmental stages across treatments between the two measurement periods revealed that on July 25, treatments ranged from V6 to 41 days after silking, with all plants immature and canopy leaves green. On August 27, treatments ranged from 2 to 72 days after silking, with eight treatments exceeding 50 days after silking (i.e., mature). Mature maize had numerous yellow leaves that may have affected measurement results, representing a primary reason for degraded multispectral camera performance. These findings demonstrate that measurement timing significantly affects image-based plant height measurement.

4 Discussion

Using UAV-borne optical imaging equipment for crop growth and nutrition diagnosis is a current hotspot in precision agriculture research, with plant height monitoring being an early-developed and relatively mature application. SfM is a 3D reconstruction method that achieves 3D reconstruction from motion. UAVs capture time-series crop image sets during flight, and through key steps including feature extraction, image registration, global optimization, and data fusion, can reconstruct 3D models of ground crop populations. Combined with spatial attitude and position information provided by onboard Inertial Measurement Unit (IMU) and GPS systems, crop canopy DSM can be obtained. Compared with other plant height monitoring methods, this approach features low equipment cost, acceptable monitoring precision, non-destructive and efficient operation, and potential for large-scale production applications.

This study obtained population DSM data using widely applied high-definition digital cameras and multispectral imaging equipment in current precision agriculture research, comparing DSM differences in maize population plant heights across different varieties and sowing date treatments. Results showed that population height differences reflected in DSM information were significantly correlated with measured plant height differences, with height difference data obtained from high-definition RGB cameras showing higher correlation with measured plant heights and superior monitoring precision compared to multispectral imaging equipment. During the first monitoring period (July 25), due to different growth processes among sowing date treatments, population height differences were pronounced, and DSM data from both imaging devices showed significant correlation with measured plant heights. During the second monitoring period (August 27), all sowing date treatments had reached silking stage with no further plant height changes. At this stage, population height differences were caused by climatic environmental factors during key growth stages, with most inter-treatment height differences within 40 cm. DSM height differences from both devices showed no significant correlation with measured height differences during the second monitoring period, likely related to insufficient monitoring precision for reflecting small height differences.

UAV plant height monitoring precision is influenced by multiple factors including image quality, positioning information accuracy, and SfM 3D model reconstruction algorithms. Imaging device resolution and lens distortion significantly affect subsequent crop 3D model reconstruction. High-resolution images without obvious distortion provide richer crop image details that facilitate feature point matching in image sequences. SfM methods can generate finer point cloud information, thereby improving crop 3D model reconstruction effectiveness. Establishing a marker system with precisely measured elevation and positioning coordinates on the ground can help SfM methods correct image distortion and, to some extent, eliminate DSM elevation data bias caused by insufficient POS information accuracy in image sets, representing an effective means to improve UAV monitoring precision.

Under equivalent measurement conditions, high-definition digital cameras possess the precision advantage of higher pixel resolution, with estimated population heights showing better correlation with measured heights than multispectral image analysis. DSM-based population elevation includes both soil elevation and crop population height information. In fields with large elevation variations, interpolation analysis combining bare soil DEM and multi-temporal DSM after population development is a necessary step for obtaining plant height information. However, elevation data recorded in image POS information represents UAV barometric altimeter height, with substantial differences between monitoring dates. Without ground control point assistance for correction, accurate matching of elevation differences between soil DEM and crop DSM is difficult, causing challenges in plant height monitoring.

3D model reconstruction precision is closely related to point cloud density generated from image sequence matching. Limited by image resolution and SfM algorithm precision, details of upper canopy organs are often overlooked due to lack of matching feature points, causing DSM detail loss and plant height underestimation. This study found that during early or late growth stages when plants are small or leaves are withered and drooping, resulting in sparse populations, DSM-based population height estimation precision significantly decreases. The DEM generated from monitoring on May 11, 2018 reflected field flatness (Figure 1 [Figure 1: see original paper]). Although two sowing date treatments had been planted and emerged, the small and relatively sparse seedlings resulted in almost no elevation differences in the measured soil DEM between sown and unsown areas. When maize populations reached physiological maturity, yellow and drooping leaves increased canopy surface roughness, affecting 3D reconstruction precision. During the first monitoring period, plant height estimates for FK139 in sowing date 1 treatment were nearly identical to monitoring elevation for sowing date 8 treatment, which remained at the V6 stage. Therefore, during growth stages with small, non-dense populations and during mid-to-late stages with withered and drooping leaves, UAV SfM methods exhibit serious monitoring precision degradation for plant height measurement.

5 Conclusion

This study analyzed the precision and existing problems of using UAV imaging equipment for monitoring population plant heights in field production. By obtaining crop population DSM through aerial image analysis, average DSM elevations for different variety and sowing date treatment zones showed extremely significant correlation with measured plant heights. Results demonstrated that single-temporal DSM can qualitatively analyze population plant height differences in flat fields, but monitoring precision significantly decreases for sparse populations with small individual plants or withered stems and leaves. Under identical conditions, images obtained from imaging equipment with higher pixel resolution showed stronger correlation between estimated population heights and measured heights. The study analyzed factors affecting UAV imaging equipment monitoring of maize plant height, providing reference for applying this method in field production.

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Note: Figure translations are in progress. See original paper for figures.