UAV-Based Digital Camera Aerial Photography for Nitrogen Nutrition Diagnosis in Wheat and Corn (Postprint)

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Abstract

Precision fertilization is one of the important technologies for reducing agricultural non-point source pollution, and soil nutrient testing and crop nutritional diagnosis serve as the technical guarantee for its implementation. Particularly under large-scale agricultural management models, there is an urgent need to develop rapid, economical, and non-destructive techniques for crop nitrogen nutritional diagnosis. Building upon research on nitrogen nutritional diagnosis in winter wheat and summer maize using digital images, this study mounted digital cameras on unmanned aerial vehicles (UAVs) to acquire crop canopy digital images through UAV aerial photography technology. The study investigated the differences in retrieving nitrogen nutritional status of winter wheat and summer maize from canopy image-related color parameters at various flight altitudes, aiming to determine optimal flight altitudes and sensitive color parameters, and to establish models for diagnosing nitrogen nutritional status in winter wheat and summer maize using UAV aerial digital images. The research results indicate that: during the winter wheat jointing stage, the optimal flight altitude is 16 m, the sensitive color parameter is the Visible Atmospherically Resistant Index (VARI), and the diagnostic model is: winter wheat stem base nitrate concentration = 2.103 4e18.874VARI; during the summer maize trumpet stage, the optimal flight altitude is 50 m, the sensitive color parameter is the blue light normalized value [B/(R+G+B)], and the diagnostic model is: summer maize first fully expanded leaf vein nitrate concentration = 1.526 1032 [B/(R+G+B)]50.445. Based on the established aerial photography method and diagnostic models, nitrogen status monitoring validation was conducted for winter wheat and summer maize respectively. The results showed that the coefficients of determination between the diagnostic results and measured data were 0.80 and 0.85 for winter wheat and summer maize respectively, both significantly correlated at $P<0.01$ level. Finally, the research results were applied to generate nitrogen topdressing operation maps for winter wheat and summer maize. Using UAV-mounted digital cameras for nitrogen nutritional diagnosis in winter wheat and summer maize is simple and feasible, but some technical details still need to be refined to improve the practicality of this technology.

Full Text

Diagnosis of Nitrogen Nutrition in Winter Wheat and Summer Corn Using Images from a Digital Camera Equipped on an Unmanned Aerial Vehicle

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Abstract: Precision fertilization represents a critical technology for reducing agricultural non-point source pollution, with soil nutrient testing and crop nutrition diagnosis serving as its technical foundation. Particularly under large-scale agricultural management models, there is an urgent need to develop rapid, economical, and non-destructive techniques for crop nitrogen nutrition diagnosis. Building upon previous research employing digital imagery for nitrogen nutrition diagnosis in winter wheat and summer corn, this study mounted a digital camera on an unmanned aerial vehicle (UAV) to acquire canopy digital images via aerial photography. We investigated differences in using canopy image color parameters obtained at various flight altitudes to retrieve nitrogen nutritional status in winter wheat and summer corn, aiming to determine optimal aerial heights and sensitive color parameters for establishing diagnostic models. Results indicated that for winter wheat at the jointing stage, the appropriate aerial height was 16 m, with the Visible Atmospherically Resistant Index (VARI) serving as the sensitive color parameter. The diagnostic model was: winter wheat stem base nitrate concentration = $2.1034e^{18}.^{874}$VARI. For summer corn at the large trumpet stage, the optimal aerial height was 50 m, with the normalized blue value [B/(R+G+B)] as the sensitive parameter. The diagnostic model was: summer corn first fully expanded leaf vein nitrate concentration = $1.526 \cdot 10^{32} \cdot [B/(R+G+B)]^{50}.^{445}$. Validation experiments demonstrated strong agreement between predicted and measured values, with determination coefficients of 0.80 and 0.85 for winter wheat and summer corn, respectively (both significant at $P<0.01$). The methodology was subsequently applied to generate nitrogen topdressing prescription maps for both crops. While UAV-based digital camera diagnosis of nitrogen nutrition in winter wheat and summer corn proved simple and feasible, further refinement of technical details is needed to enhance practical applicability.

Keywords: precision fertilization; unmanned aerial vehicle (UAV); digital camera; color parameters; aerial height; nitrate concentration; nitrogen nutrition diagnosis; winter wheat; summer corn

Introduction

China faces the dual challenge of a large population and limited arable land, necessitating substantial increases in crop yield per unit area to ensure food security. Chemical fertilizer application has become a crucial and straightforward measure to meet this demand, with China's consecutive grain production growth in recent years heavily dependent on fertilizer use. However, high fertilizer input coupled with low nutrient use efficiency has generated significant environmental impacts, drawing widespread attention to the relationship between food security policies and agricultural non-point source pollution. In response, the Ministry of Agriculture proposed the "Action Plan for Zero Growth of Chemical Fertilizer Use by 2020," with precision fertilization as a key component. The prerequisite for implementing precision fertilization is soil nutrient testing and crop nutrition diagnosis. While soil testing techniques are relatively mature, as evidenced by the nationwide promotion of soil testing and formula fertilization, traditional laboratory methods for crop nitrogen nutrition diagnosis remain time-consuming and labor-intensive, failing to meet the demands of rapid nitrogen management during critical growth periods. Consequently, developing fast, economical, and non-destructive methods for crop nitrogen nutrition diagnosis holds significant value for optimizing nitrogen application, improving crop quality, increasing farmer income, and reducing pollution.

Non-destructive nitrogen diagnosis has evolved from qualitative or semi-quantitative approaches to precise quantitative methods, encompassing chlorophyll meters, remote sensing technology, fluorescence diagnostics, and canopy color analysis. Canopy color analysis, based on leaf color changes under nitrogen deficiency, represents a particularly promising approach. Historical agricultural texts such as *Shen' s Agricultural Book* documented nitrogen topdressing recommendations based on rice leaf color. In the early 1960s, Tao Qinnan et al. evaluated rice leaf color using color cards and investigated the physiological basis of color variations. Recent advances in digital photography have enabled precise quantitative research on canopy color analysis across multiple crops. Zhang Lizhou et al. established relationships between wheat and corn canopy digital image color parameters and conventional nitrogen nutrition indicators, identifying normalized green and blue values for diagnostic purposes. Wang Lianjun et al. found that the green/blue ratio could diagnose grape nitrogen status. Wei Quanquan employed normalized red values from winter rapeseed canopy images for nitrogen diagnosis. Digital image-based nitrogen diagnosis has also been studied in potato, strawberry, cotton, and other crops, demonstrating its potential as a supporting technology for optimized fertilization and precise nitrogen management.

With increasing rural land transfer and the expansion of appropriately scaled agricultural operations, meeting the demand for large-area nitrogen diagnosis has become critical. Even with digital image techniques, the workload for manual photography across extensive areas remains substantial, particularly for tall crops like corn where field access is difficult. UAV technology offers a viable platform for low-altitude remote sensing, providing solutions for rapid image acquisition. Gao Lin et al. accurately estimated winter wheat leaf area index using a digital camera mounted on a rotary-wing UAV. Zhu Jinxia employed rotary-wing UAV platforms for rice nitrogen nutrition diagnosis. The high timeliness, resolution, and cost-effectiveness of UAV remote sensing demonstrate excellent prospects for field-scale crop monitoring and decision-making. However, aerial canopy photography differs fundamentally from ground-based imaging, requiring careful determination of flight altitude, speed, and camera parameters to ensure image clarity, complete coverage without excessive overlap, and operational efficiency. Further research is needed on aerial imaging techniques, nitrogen diagnostic indicator selection, and image processing methods to meet practical production requirements, though such studies remain limited.

Based on this research foundation and technical demand, this study employed UAV-mounted digital cameras to aerially photograph winter wheat and summer corn canopies. Combined with conventional nitrogen analysis, we analyzed aerial digital images to determine optimal flight altitudes, identify sensitive color parameters, and achieve precise diagnosis of crop nitrogen nutritional status, aiming to provide technical support for precise nitrogen management in large-scale agricultural operations.

1 Materials and Methods

1.1 Field Experimental Design

To monitor differential responses of leaf color to varying nitrogen deficiency levels, experiments were conducted within long-term fertilizer positioning trial plots. The experimental site was located at the Luancheng Agricultural Ecosystem Experimental Station of the Chinese Academy of Sciences (37.88°N, 114.68°E), representing a typical semi-humid monsoon climate zone in the North China Plain with cinnamon soil. The cropping system follows a winter wheat-summer corn rotation. The fertilizer positioning trial, initiated in 1997 and continuing to present, includes four nitrogen levels: 0, 200 $\mathrm{kg(N) \cdot hm^{-2} \cdot a^{-1}}$, 400 $\mathrm{kg(N) \cdot hm^{-2} \cdot a^{-1}}$, and 600 $\mathrm{kg(N) \cdot hm^{-2} \cdot a^{-1}}$; three phosphorus levels: 0, 32.5 $\mathrm{kg(P) \cdot hm^{-2} \cdot a^{-1}}$, and 64 $\mathrm{kg(P) \cdot hm^{-2} \cdot a^{-1}}$; and two potassium levels: 0 and 150 $\mathrm{kg(K) \cdot hm^{-2} \cdot a^{-1}}$. An orthogonal incomplete design yielded 16 treatments with three replications each (48 total plots). To avoid severe phosphorus deficiency effects, phosphorus-applied treatments were selected as experimental plots, with 33 plots participating in sampling and analysis.

1.2 UAV Platform and Aerial Photography Method

This study employed a DJI S900 six-rotor UAV equipped with a Nikon D7000 digital camera for canopy photography. A custom-designed vibration damping platform was fabricated to mount the camera on the UAV [Figure 1: see original paper]. To minimize vibration effects on image quality, shock-absorbing balls were installed at connection points between rods, the UAV, and the platform. The platform utilized carbon fiber materials to ensure structural strength while minimizing weight and avoiding reduced flight time. The camera was horizontally embedded into the platform and secured during flight to prevent sliding or falling. As the camera lacked a GPS module, a dedicated GPS receiver provided latitude and longitude information recorded in the image EXIF data for subsequent processing.

UAV flights were programmed using ground station software to plan take-off/landing points, flight trajectories, altitudes, and ascent/horizontal speeds, enabling automatic aerial photography along fixed routes and altitudes. To maintain a nadir perspective for orthorectified images, horizontal flight speed was set at 3 $\mathrm{m \cdot s^{-1}}$. Photography was conducted under clear, cloudless conditions with minimal wind between 11:00–13:00 to avoid cloud and solar intensity variations. The Nikon D7000 was fitted with an 18-300 mm f/3.5-5.6G lens, with focal length set to 18 mm and images saved in JPG format.

Aerial photography was performed in 2015 and 2016 at the fertilizer positioning trial site, and in 2017 at Nanpi County. The 2015 data were used for parameter screening and model development, while 2016 data served for validation. Photography timing targeted the winter wheat jointing stage (April 9, 2015 and April 8, 2016) and summer corn large trumpet stage (July 28, 2015 and July 22, 2016). To examine altitude effects on nitrogen status retrieval, winter wheat was photographed at 8 m, 10 m, 12 m, 14 m, 16 m, and 55 m, while summer corn was photographed at 10 m, 15 m, 20 m, and 50 m. The camera automatically captured images at 2-second intervals, with digital markers placed in the trial field to correlate images with ground sampling data. On April 14 and July 27, 2017, aerial photography was conducted in Dongwubo Village, Nanpi County, Hebei Province (38.068°N, 116.825°E) to apply the developed diagnostic method for nitrogen topdressing recommendations and guide precision fertilization.

1.3 Conventional Crop Nitrogen Information Collection

Nitrogen content was measured synchronously with aerial photography across 33 plots. A SPAD-502 chlorophyll meter measured the middle portion of the first fully expanded winter wheat leaves, with 30 leaves measured per plot and averaged as the plot SPAD value. A reflectometer and nitrate test strips measured stem base nitrate concentrations (hereinafter referred to as winter wheat stem base nitrate concentration). For summer corn, the midrib of the first fully expanded leaf was squeezed for sap, with vein nitrate concentration measured using the same method (hereinafter referred to as corn vein nitrate concentration).

1.4 Canopy Image Processing and Parameter Analysis

Canopy images reflect crop leaf optical properties through red (R), green (G), and blue (B) channels. UAV aerial photography maximizes information capture from top expanded leaves. However, due to light shading and other factors, images contain non-leaf information such as shadows, bare soil, and dead leaves. If entire images participate in color parameter analysis, this interference affects sensitive parameter selection. Therefore, filtering thresholds must be applied to exclude non-leaf pixels.

Multiple color parameters can be derived from R, G, and B channel combinations. Analyzing all parameters against conventional nitrogen measurements would be prohibitively labor-intensive. Referencing related studies and considering the noise reduction benefits of ratio-based parameters under varying light conditions, we pre-selected normalized red value [R/(R+G+B)], normalized green value [G/(R+G+B)], normalized blue value [B/(R+G+B)], and Visible Atmospherically Resistant Vegetation Index [(G−R)/(G+R−B), VARI] as candidate indicators for correlation analysis with synchronized crop nitrogen measurements to determine optimal aerial heights and diagnostic color parameters.

2 Results

2.1 Non-Crop Canopy Pixel Removal

Non-winter wheat and non-summer corn leaf pixels in aerial images interfere with parameter selection and diagnosis, requiring exclusion to ensure only crop leaf color parameters participate in statistical analysis. By analyzing color parameters of leaves and interfering objects in aerial images, three color parameters —G/(R+G+B), R/(R+G+B), and R—were selected for threshold-based image filtering. The rule for filtering non-leaf pixels was: $G/(R+G+B) > 0.37$ AND $R/(R+G+B) < 0.42$ AND $R > 20$, where G/(R+G+B) and R/(R+G+B) selected leaf pixels while $R > 20$ filtered shadows. [Figure 2: see original paper] compares aerial images with filtered mask images, showing that bare soil, markers, debris, and shadows were successfully removed, enhancing subsequent color parameter analysis accuracy.

Using the generated leaf mask file (0 and 1 values) and three-channel data for each leaf pixel, R/(R+G+B), G/(R+G+B), B/(R+G+B), and VARI were calculated for each pixel. Based on ground marker numbers identifying each plot' s aerial image, color parameters were averaged across all leaf pixels per plot and correlated with synchronized winter wheat and summer corn nitrogen status measurements to screen optimal aerial heights and sensitive color parameters for diagnostic model development.

2.2.1 Sensitive Parameter Selection

The handheld SPAD-502 chlorophyll meter enables rapid, simple, and non-destructive measurement of relative chlorophyll content, with applications in nitrogen diagnosis and fertilization recommendations for wheat, corn, cotton, rice, and other crops. This study analyzed correlations between color parameters from different aerial heights and synchronized SPAD measurements across winter wheat plots [Figure 3: see original paper]. SPAD values showed clear linear correlations with all candidate color parameters, being negatively correlated with R/(R+G+B) and positively correlated with the other three parameters, with all correlations significant at $P<0.01$. Coefficients of determination (R^2) between SPAD and R/(R+G+B), G/(R+G+B), B/(R+G+B), and VARI were 0.9269, 0.3062, 0.7929, and 0.8989, respectively. R/(R+G+B) showed the strongest correlation, followed by VARI.

However, SPAD values are susceptible to multiple influencing factors and exhibit saturation effects, limiting high-precision nitrogen diagnosis. Therefore, winter wheat stem base nitrate concentration was further analyzed against candidate color parameters to identify the most sensitive parameter for nitrogen status diagnosis. As shown in [Figure 4: see original paper], canopy color parameters from different aerial heights exhibited power function relationships with stem base nitrate content, with R/(R+G+B) showing the best correlation ($R^2 = 0.78$), followed by B/(R+G+B) and VARI (both $R^2 = 0.76$). Considering both SPAD and nitrate correlation analyses, R/(R+G+B) emerged as the most sensitive parameter for reflecting crop nitrogen status, followed by VARI.

R/(R+G+B) ranged from 0.27 to 0.38 (amplitude = 0.11), while VARI ranged from 0.01 to 0.36 (amplitude = 0.35). From a model robustness perspective, R/(R+G+B) showed low data dispersion (coefficient of variation = 0.11) and high uncertainty, potentially producing outliers. VARI exhibited a coefficient of variation of 0.39, with substantially lower uncertainty. Although VARI' s correlation coefficients were slightly lower than R/(R+G+B) for both SPAD and stem base nitrate, its superior uncertainty characteristics made it more suitable for monitoring winter wheat nitrogen nutrition.

2.2.2 Determination of Suitable Aerial Height

UAV photography at different altitudes affects image color parameters through resolution and viewing angle variations. To examine these effects on winter wheat nitrogen monitoring, flights were conducted at 8 m, 10 m, 12 m, 14 m, 16 m, and 55 m under identical conditions (camera settings, flight speed, etc.). Extracted VARI values were correlated with synchronized stem base nitrate measurements [Figure 5: see original paper]. Stem base nitrate concentration showed clear exponential relationships with VARI from all heights, with similar fitted curves. Coefficients of determination were 0.84, 0.84, 0.80, 0.84, 0.82, and 0.78 for 8 m, 10 m, 12 m, 14 m, 16 m, and 55 m, respectively. VARI responses to winter wheat nitrogen were similar across 8-16 m heights, with correlation decreasing noticeably at 55 m. Therefore, 8-16 m represents a suitable altitude range for winter wheat nitrogen diagnosis. Considering operational safety and obstacle avoidance (trees, poles), 16 m is recommended as the standard aerial height.

2.2.3 Winter Wheat Nitrogen Diagnosis Index Determination

Given that 8-16 m is suitable for winter wheat photography with similar VARI values and good nitrate correlations across this range, VARI values from these altitudes were averaged per plot and regressed against synchronized stem base nitrate measurements to develop an aerial image-based diagnostic model [Figure 6: see original paper]. The averaged VARI showed strong exponential correlation with stem base nitrate concentration, yielding the diagnostic equation: winter wheat stem base nitrate concentration = $2.1034e^{18}.^{874}$VARI.

After retrieving stem base nitrate concentration from VARI, nitrogen topdressing rates corresponding to different VARI values can be calculated based on nitrogen balance principles and target yields [21], enabling precision nitrogen management. provides reference topdressing rates for winter wheat under different VARI values and yield targets.

2.3 Summer Corn Nitrogen Nutrition Diagnosis Analysis

Aerial photography at 10 m, 15 m, 20 m, and 50 m was conducted during the summer corn large trumpet stage to examine altitude effects on parameter sensitivity. Non-leaf pixels were removed using masking methods, and plot-level R/(R+G+B), G/(R+G+B), B/(R+G+B), and VARI were extracted and correlated with synchronized vein nitrate measurements to identify sensitive parameters and optimal altitude .

Statistical analysis revealed substantial differences in correlations between the same color parameter and vein nitrate concentration across altitudes, indicating parameter variations due to resolution and viewing angle changes affecting captured canopy information. Among fitted equations, B/(R+G+B) from 50 m altitude showed the highest coefficient of determination ($R^2 = 0.92$, significant at $P<0.01$). Therefore, 50 m was selected as the suitable aerial height for summer corn, with B/(R+G+B) as the most sensitive nitrogen status parameter. The diagnostic equation was: summer corn vein nitrate concentration = $1.526 \cdot 10^{32} \cdot [B/(R+G+B)]^{50}.^{445}$. After retrieving vein nitrate concentration, conventional summer corn nitrogen topdressing methods [22] enable fertilizer rate estimation based on B/(R+G+B) , achieving precision nitrogen management.

2.4 Diagnostic Index Validation

To verify model accuracy, aerial photography at 16 m (winter wheat) and 50 m (summer corn) was conducted on April 8 and July 22, 2016, at the fertilizer positioning trial site. Canopy images were used to retrieve crop nitrogen status, with stem base and vein nitrate concentrations measured at identical sampling points. Comparisons between measured and predicted values are shown in [Figure 7: see original paper]. The 2016 validation demonstrated excellent agreement, with determination coefficients of 0.80 for winter wheat stem base nitrate and 0.85 for summer corn vein nitrate (both significant at $P<0.01$), confirming the feasibility of the established diagnostic indices.

2.5 Application of UAV Aerial Photography for Nitrogen Nutrition Diagnosis

The developed aerial method and diagnostic models were applied in 2017 to approximately 30 hm^2 of farmland in Dongwubo Village, Nanpi County, Cangzhou City, Hebei Province (38.068°N, 116.825°E). Photography was conducted at winter wheat jointing and summer corn large trumpet stages. A batch processing system was developed for rapid, automated processing of aerial image coordinates, leaf masks, color parameters, and nitrogen topdressing recommendations to meet field management requirements. Using inverse distance weighted interpolation, nitrogen topdressing rates were generated for each field block. [Figure 8: see original paper] presents prescription maps using urea as an example, where white dots indicate image trajectories and rectangles represent field plots. Ground surveys and farmer interviews confirmed that spatial distributions of recommended nitrogen rates aligned well with actual crop growth conditions.

3 Discussion and Conclusion

Addressing agricultural dependence on chemical fertilizers and associated non-point source pollution to achieve zero-growth targets requires practical crop nutrient diagnosis and fertilization technologies, particularly rapid, non-destructive, and low-cost nitrogen diagnostic methods. Leaf color diagnosis is simple and has long been employed by Chinese farmers, but remains overly qualitative and experience-dependent. Digital cameras enable quantitative analysis of differential light absorption in red, blue, and green bands, tracing these differences to nitrogen abundance/deficiency causes and achieving non-destructive, low-cost quantitative analysis and decision-making [23]. With land transfer and appropriately scaled agricultural operations becoming mainstream, large-area nitrogen diagnosis must be accommodated. Even digital image methods face substantial workload challenges, particularly for tall crops like corn where field access is difficult.

In response to these production demands, this study built upon digital image diagnosis research by developing a custom camera mounting platform for UAV aerial photography. Through route planning and automatic photography, rapid canopy image acquisition was achieved. For winter wheat and summer corn, optimal aerial heights and sensitive color parameters were systematically investigated. Results showed that VARI from 8-16 m altitude was highly sensitive to winter wheat nitrogen status, with 16 m recommended for operational safety. For summer corn, $B/(R+G+B)$ from 50 m altitude showed the best correlation with vein nitrate concentration, serving as the diagnostic basis. Validation in 2016 confirmed satisfactory monitoring accuracy for both crops.

Compared with traditional laboratory analysis, digital image diagnosis offers greater convenience, but mature field application requires further research and technical refinement. This study focused on single varieties under long-term fertilizer positioning trials; inter-varietal leaf color differences require consideration. While ratio-based color parameters were used to mitigate lighting effects, Wang Juan et al. [24] employed gray board calibration to eliminate brightness differences in cotton images across growth stages for improved water content diagnosis—a method warranting reference. Additionally, drought-induced changes in leaf color and nitrate concentration may affect diagnostic accuracy, and potential color parameter saturation requires investigation. These issues will be prioritized in future work to further refine UAV aerial nitrogen diagnosis methods, extend applications to other crops, and promote precision fertilization implementation.

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