Hyperspectral Estimation of Nitrogen Content in Winter Wheat Leaves Based on Unmanned Aerial Vehicles

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Abstract. Leaf nitrogen content is an important index of crop growth and plays an important role in crop growth and development. In this paper, the hyperspectral data of winter wheat and the leaf nitrogen content is used to study winter wheat on flagging stage, flowering stage and grain filling stage. The estimation model of nitrogen content in winter wheat leaves at different growth stages is constructed by using partial least squares method and verified by using a cross-validation method. The results showed that R2 and the RMSE of the three growth stages were 0.53, 0.68, 0.64 and 0.331%, 0.246% and 0.406% respectively, and R2 and RMSE of model validation were 0.44, 0.71, 0.64 and 0.369%, 0.235% and 0.410%. Both the prediction model and the verification model had high reliability. Therefore, it is feasible for UAV to carry hyperspectral monitoring system for retrieving nitrogen content of winter wheat leaves.

Keywords: Unmanned aerial vehicles · Hyperspectral · Winter wheat Leaf nitrogen content · Partial least squares method

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1 Introduction

Nitrogen is the most important mineral nutrient element in crop life, which can promote the growth of vegetative organs such as roots, stems and leaves, expand the area of photosynthesis and enhance the accumulation of photosynthetic products [1, 2]. The nitrogen content directly affects crop growth and yield [3]. Inversion of crop nitrogen content by remote sensing system is one of the quantitative agricultural remote sensing hotspots. In order to establish the relationship between wheat nitrogen content and spectrum, domestic and foreign scholars have studied the changes of sensitive spectral bands in different growth stages of wheat [4, 5]. Zhang et al. [6] put forward the sensitivity study of retrieving leaf nitrogen content of Winter Wheat with different spectral vegetation index. The results showed that Using Hyperspectral Vegetation index can effectively achieve nitrogen content inversion of crop leaves. Zhu et al. [7] have put forward a preliminary study on the use of SPAD to predict chlorophyll and nitrogen content in wheat leaves. It turned out that the SPAD value of wheat leaves is positively correlated with total nitrogen content, and the total nitrogen content could be estimated by SPAD value for wheat nitrogen nutrition. Li et al. [8] have proposed a quantitative relationship between nitrogen content and canopy reflectance index in wheat leaves, and the results showed that the red edge position of canopy reflectance spectrum could indicate the leaf nitrogen content of wheat varieties with different protein types. Sun et al. [9] have raised the establishment and validation of GRNN hyperspectral remote sensing model for retrieving nitrogen content in winter wheat leaves based on GA. The results showed that the selected spectral parameters and the corresponding model could reflect the relationship between total nitrogen in wheat leaves, and the effect is better than the stepwise regression model. Zhang et al. [10] proposed rice leaf nitrogen Hyperspectral Estimation and inversion based on the model. Results showed that there is a good correlation between leaf nitrogen content and tillering stage normalized vegetation index. Wang et al. [11] have put forward to use wheat canopy reflectance spectra to retrieve the vertical distribution of nitrogen by PLS algorithm, and the results showed that it is feasible to use PLS algorithm to estimate the vertical distribution of total nitrogen in wheat leaves. Ju [12] has used land-air hyperspectral remote sensing to monitor the nitrogen status and growth characteristics of wheat. The results showed that the sensitive bands of leaf nitrogen are mainly in the visible and near-infrared bands, among which the red-edge region is the most significant. Zhai et al. [13] have raised hyperspectral differences and monitoring model construction of nitrogen content in wheat leaves based on different soil texture, and it turned out that using NDSI (FD710, FD690), DSI (R515, R460) and RSI (R535, R715) as independent variables, the estimation model can well predict the nitrogen content of wheat leaves in sandy, loamy and clay 3 germplasms. Li et al. [14] have proposed the estimation of nitrogen content in winter wheat leaves with wide band reflectance of the simulated multispectral satellite. The results showed that the spectral index based on the composite index (TCARI/OSAVI) and the transformed chlorophyll absorption index (TCARI) has some advantages in monitoring the nitrogen content of wheat leaves during the whole growth period. Wang et al. [15] proposed to estimate the nitrogen nutrient index of Winter Wheat Based on hyperspectral. The results showed that the linear interpolation of the red edge position, the red edge correction single index, ratio index, simple ratio pigment index, index and spectral parameters in nitrogen have a good correlation, can be used for inversion of canopy nitrogen nutrition level. Yang et al. [16] have put forward the optimal regression model of plant nitrogen content at different growth stages based on the importance of variable projection - partial least squares - Akai information criterion integration model, and the results showed that the flag stage is the best period for monitoring the nitrogen nutrition of Winter Wheat by hyperspectral remote sensing. Liu et al. [17] have raised quantitative modeling for leaf nitrogen content of winter wheat using UAV-based hyperspectral data. The results showed that the predicted values are very good in jointing stage, flagging leaf stage, and flowering stage, while it is a little bit less in the filling stage.

This essay first analyzed the correlation between the original spectrum, the first derivative of the spectrum, the normalized spectral index (NDSI), the ratio spectral index (RSI) and the leaf nitrogen content, and then each growth period selects the spectra of the original spectral positive correlation maximum and negative correlation maximum, the spectra of first derivative positive correlation maximum and negative correlation maximum, a group of spectra with the greatest NDSI correlation value and a group of spectra with the greatest RSI correlation value, with a total of six parameters. Next, the estimation model of nitrogen content in winter wheat leaves is constructed by partial least squares method and verified by cross-validation method. So as to provide a new technical approach for hyperspectral remote sensing inversion of nitrogen content in winter wheat leaves.

2 Materials and Methods

2.1 Brief Introduction of Research Area

Field experiments were conducted at the National Precision Agriculture Research and demonstration base from 2014 to 2015. The base is located in the northeast of Beijing City, located at latitude 40°00′–40°21′, longitude 116°34′–117°00′. The Base covers an area of about 2500 acres, altitude 36 m, fertile land, flat terrain, and soil type is fluvo-aquic soil. The climate in the base area belongs to warm temperate semi-humid continental monsoon weather, four distinct seasons, cold and dry in winter, hot and rainy summer. The average temperature is 13 °C, and the average annual precipitation is 510 mm. At the end of September, early winter wheat is planted here (Fig. 1).

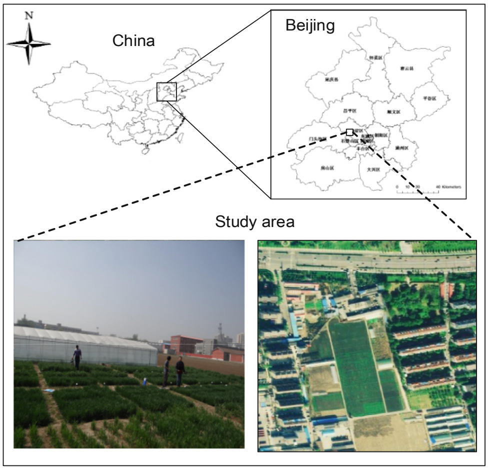

Fig. 1. National Precision Agriculture Research and demonstration base

2.2 Experimental Design

Using varieties, water, nitrogen fertilization orthogonal test; Wheat is divided into two varieties: Beijing 9843 (J9843), Zhongmai 175 (ZM175); There were 4 levels of fertilizer: 0 kg urea/acre (N1), 13 kg urea/acre (N2), 26 kg urea/acre (N3), 39 kg urea/acre (N4); Planting plots were processed 16 times and repeated 3 times. Field planting map (see below): From east to west, the total length is 84 m, and the total length is 32 m from south to North; The number of planting area is 48, and each area is 6 m * 8 m (Fig. 2).

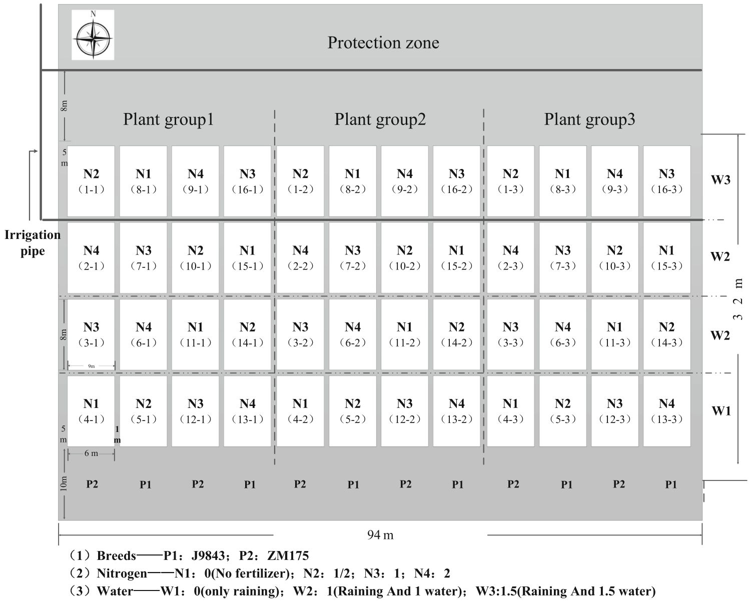

Fig. 2. Test plan

2.3 Data Acquisition and Processing

2.3.1 Leaf Nitrogen Content Data Acquisition

The nitrogen content of winter wheat leaves is collected at flagging stage (April 27, 2015), flowering stage (May 11, 2015) and grain filling stage (May 25, 2015). Twenty growing average winter wheat plants were selected as experimental samples for each plot. Firstly, The wheat samples were collected in paper bags and the leaves of wheat should be integral during collection. Next cut the wheat sample leaves separately in the test paper bag, and Put the paper bag in the 105 C oven for half an hour. Then we reduced oven temperature immediately and maintained oven temperature of 80 °C for drying samples, drying for more than 24 h, until the quality of the sample remained unchanged. After drying, the sample blades were weighed and crushed, and the nitrogen content of the sample blades is measured by Kjeldahl apparatus. The nitrogen content of the sample leaves is the product of the nitrogen mass fraction and the sample biomass. Finally, the average nitrogen content of winter wheat leaves in each plot is taken as the value of nitrogen content in winter wheat leaves.

2.3.2 Hyperspectral Data Acquisition

The experiment used UAV equipped with a UHD-185 remote sensor to sample spectral of winter wheat from 10am to 2pm Beijing time in Changping districts when the weather is sunny and windless. The hyperspectral remote sensing images were collected at flagging stage (April 27, 2015), flowering stage (May 11, 2015) and grain filling stage (May 25, 2015), using the same flight route. The UHD-185 hyperspectral measures a range of 454 to 950 nm, a sampling interval of 4 nm, and a cubic resolution of one megapixel. The spectral range of the spectrometer is narrow, and the spectral resolution of the visible light to near-infrared band is nanometer order, and the number of spectral bands is large, and the band is continuous, which can meet the requirement of inversion of nitrogen content in winter wheat leaves. The UHD-185 hyperspectral sensor carried by the unmanned aerial vehicle (UAV) had been denoised and lens distortion correction before used.

The experiment used Agisoft photoscan software to splice UAV hyperspectral remote image. The pre-processed hyperspectral images were introduced into the ArcGIS software, and the rectangular region of interest is selected from the hyperspectral remote sensing image in combination with the 48 experimental plots. Finally, the average spectral reflectance of each experimental plot is extracted to obtain 125 spectral average reflectances at wavelengths 454 to 950 nm.

2.4 Method

2.4.1 Vegetation Index Selection

The normalized difference index NDSI [18] and the ratio spectral index RSI [19] were constructed by referring to the normalized vegetation index and the ratio vegetation index in the study of vegetation canopy spectra. These formulas are as follows:

$$\mathrm{NDSI}(\lambda_1, \lambda_2) = \frac{R_{\lambda 2} - R_{\lambda 1}}{R_{\lambda 2} + R_{\lambda 1}} \tag{1}$$

$$\mathrm{RSI}(\lambda_1, \lambda_2) = \frac{R_{\lambda 2}}{R_{\lambda 1}} \tag{2}$$

Where λ_1 is wavelength 1 and λ_2 is wavelength 2. $R_{\lambda 1}$ represents spectral reflectance of winter wheat leaves at wavelength 1, and $R_{\lambda 2}$ represents spectral reflectance of winter wheat leaves at wavelength 2.

2.4.2 Partial Least Squares Method

Partial least squares [20] is a multivariate statistical data analysis method that minimizes the square of the error and finds the best matching function model for a set of data. It is generally used to study the regression model of dependent variables for multiple independent variables. The simplest form is the linear relationship between the variable Y and the independent variable X, the expression is:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + \cdots + a_n X_n \tag{3}$$

Where a0 is the intercept of the regression coefficient; ai is the regression coefficient; Xi is the independent variable 1–n.

2.5 Statistical Analysis

In this study, determination coefficient (R2) and root-mean-square error were regarded as indicators to interpret and quantify the relationship between LNC and vegetation index. Generally speaking, the higher R2, the smaller RMSE, and the better ability of the estimated model between the LNC and vegetation index, otherwise, the estimated ability is poor.

3 Data Processing and Analysis

3.1 Analysis of Correlation Between Original Spectrum and Leaf Nitrogen Content

The correlation between the average reflectance of the arbitrary band spectrum and the nitrogen content of the corresponding wheat leaves is analyzed in the winter wheat flagging stage, flowering stage and grain filling stage, and the graphs of wavelength and correlation coefficient were obtained. Each growth period sorted the correlation coefficients and selected the spectra of the original spectral positive correlation maximum and negative correlation maximum.

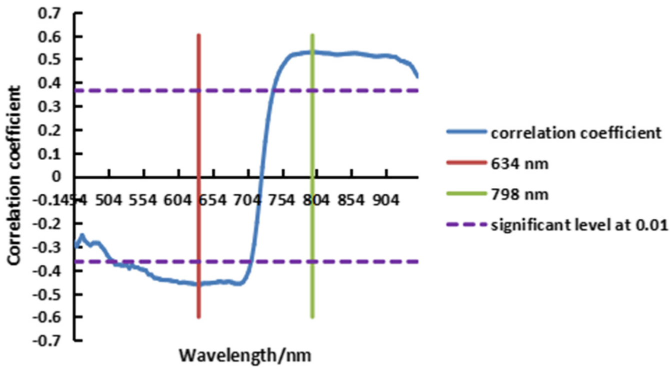

Fig. 3. Correlation between original spectrum and leaf nitrogen content at flagging stage

As shown in Fig. 3, In the range of 514 to 706 nm, the leaf nitrogen content is significantly negatively correlated with the original spectrum, and the correlation coefficient in the 634 nm band is the best, and the correlation coefficient is −0.46. In the range of 742 to 950 nm, the leaf nitrogen content is significantly positively correlated with the original spectrum, and the correlation coefficient in the 798 nm band is the best, and the correlation coefficient is 0.53. 634 nm band and 798 nm band are selected as the parameters for modeling the flagging stage of winter wheat.

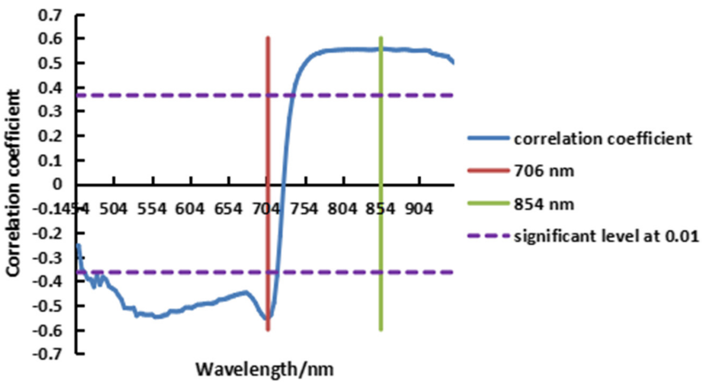

Fig. 4. Correlation between original spectrum and leaf nitrogen content at flowering stage

As shown in Fig. 4, In the range of 466 to 718 nm, the leaf nitrogen content is significantly negatively correlated with the original spectrum, and the correlation coefficient in the 706 nm band is the best, and the correlation coefficient is −0.55. In the range of 742 to 950 nm, the leaf nitrogen content is significantly positively correlated with the original spectrum, and the correlation coefficient in the 854 nm band is the best, and the correlation coefficient is 0.56. 706 nm band and 854 nm band are selected as the parameters for modeling the flowering stage of winter wheat.

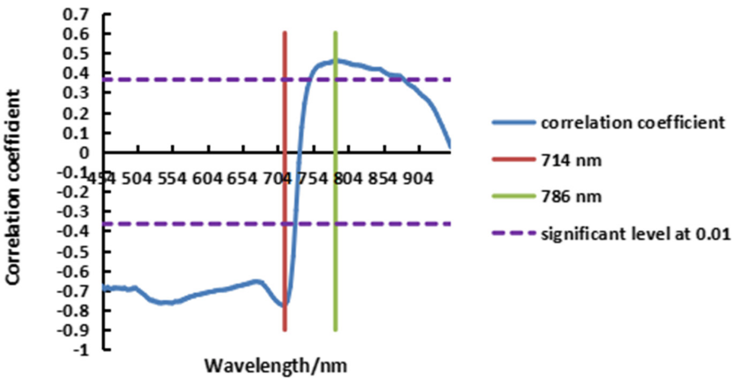

Fig. 5. Correlation between original spectrum and leaf nitrogen content at grain filling stage

As shown in Fig. 5, In the range of 454 to 726 nm, the leaf nitrogen content is significantly negatively correlated with the original spectrum, and the correlation coefficient in the 714 nm band is the best, and the correlation coefficient is −0.78. In the range of 750 to 882 nm, the leaf nitrogen content is significantly positively correlated with the original spectrum, and the correlation coefficient in the 786 nm band is the best, and the correlation coefficient is 0.46. 714 nm band and 786 nm band are selected as the parameters for modeling the grain filling of winter wheat.

3.2 Analysis of Correlation Between First Derivative of Spectrum and Leaf Nitrogen Content

The correlation between the first derivative of spectral average reflectance of the arbitrary band spectrum and the nitrogen content of the corresponding wheat leaves was analyzed in the winter wheat flagging stage, flowering stage and grain filling stage, and the graphs of wavelength and correlation coefficient were obtained. Each growth period Sorted the correlation coefficients and selected the spectra of first derivative positive correlation maximum and negative correlation maximum.

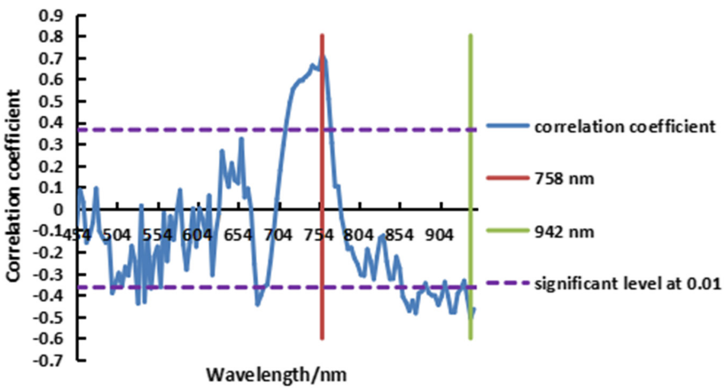

Fig. 6. Correlation between first derivative of spectrum and nitrogen content in leaves at flagging stage

As shown in Fig. 6, In the range of 714 to 766 nm, the leaf nitrogen content is significantly positively correlated with the first derivative of the spectrum, and the correlation coefficient in the 758 nm band is the best, and the correlation coefficient is 0.71. In the range of 858 to 882 nm, 890 to 906 nm, 914 to 930 nm, 938 to 930 nm and other sporadic spectrum, the leaf nitrogen content is significantly negatively correlated with the first derivative of the spectrum, and the correlation coefficient in the 942 nm band is the best, and the correlation coefficient is −0.51. 758 nm band and 942 nm band are selected as the parameters for modeling the flagging stage of winter wheat.

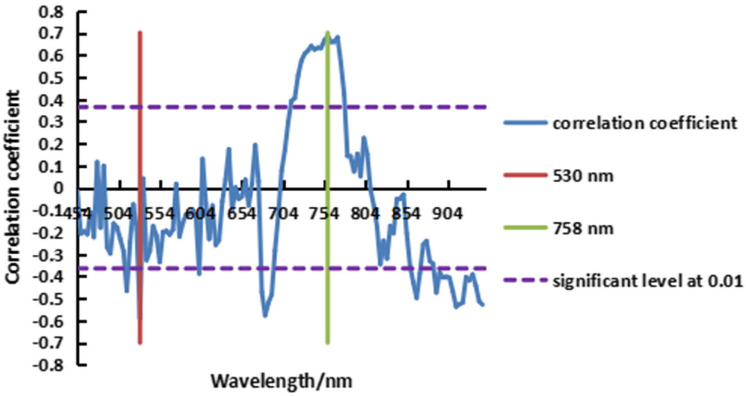

Fig. 7. Correlation between first derivative of spectrum and nitrogen content in leaves at flowering stage

As shown in Fig. 6, In the range of 714 to 778 nm, the leaf nitrogen content is significantly positively correlated with the first derivative of the spectrum, and the correlation coefficient in the 758 nm band is the best, and the correlation coefficient is 0.69. In the range of 530 nm, 678 to 690 nm, 862 to 870 nm, 890 to 946 nm and other sporadic spectrum, the leaf nitrogen content is significantly negatively correlated with the first derivative of the spectrum, and the correlation coefficient in the 530 nm band is the best, and the correlation coefficient is −0.59. 530 nm band and 758 nm band are selected as the parameters for modeling the flowering stage of winter wheat (Fig. 8).

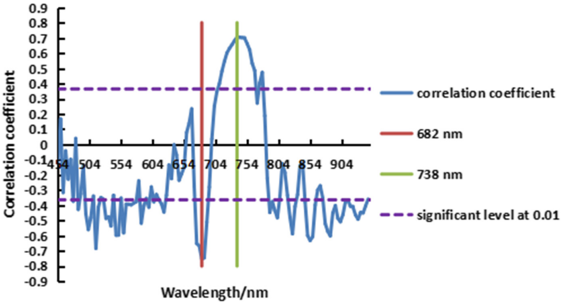

Fig. 8. Correlation between first derivative of spectrum and nitrogen content in leaves at grain filling stage

As shown in Fig. 7, In the range of 710 to 766 nm and 744 to 778 nm, the leaf nitrogen content is significantly positively correlated with the first derivative of the spectrum, and the correlation coefficient in the 738 nm band is the best, and the correlation coefficient is 0.71. In the range of 558 to 578 nm, 674 to 690 nm, 790 to 802 nm, 846 to 862 nm, 878 to 942 nm and other sporadic spectrum, the leaf nitrogen content is significantly negatively correlated with the first derivative of the spectrum, and the correlation coefficient in the 682 nm band is the best, and the correlation coefficient is −0.75. 682 nm band and 730 nm band are selected as the parameters for modeling the grain filling stage of winter wheat.

3.3 Analysis of Correlation Between NDSI and Leaf Nitrogen Content

Using the MATLAB program, the NDSI of the spectral reflectance of any two bands in the winter wheat flagging stage, flowering stage and grain filling stage was calculated. Then the coefficient of determination between NDSI and leaf nitrogen content is calculated, and the contour map of each growth period was obtained, as shown in Figs. 9, 10 and 11.

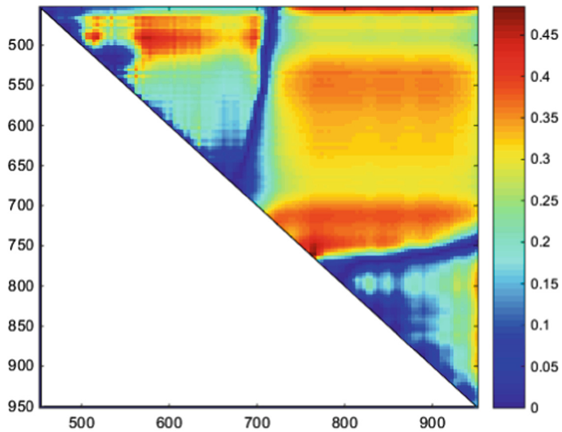

Fig. 9. Coefficient of determination between NDSI and leaf nitrogen content at flagging stage

As shown in Fig. 9, The leaf nitrogen content of winter wheat has a good correlation with NDSI in many bands during flagging stage. These bands are as follows: the range on the x-axis is 746 to 758 nm and the range on the y-axis is 762 to 766 nm. These regions show that the nitrogen content of leaf can be well estimated by using NDSI, and the coefficient of determination is above 0.45. NDSI[758, 762] has the best correlation, with a coefficient of determination of 0.48. NDSI[758, 762] is selected as the parameter for modeling at the flagging stage of winter wheat.

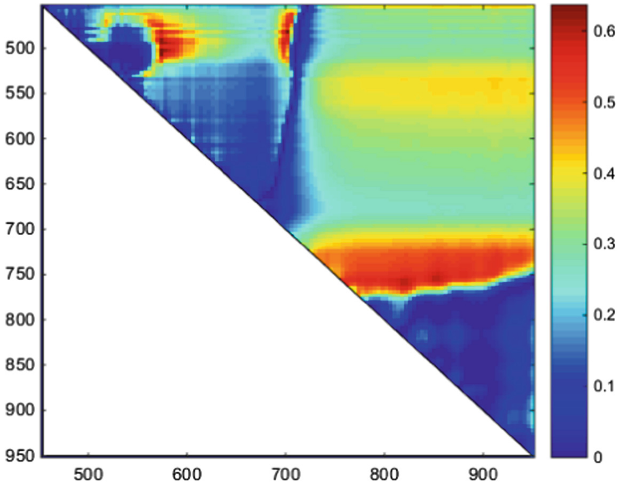

Fig. 10. Coefficient of determination between NDSI and leaf nitrogen content at flowering stage

As shown in Fig. 10, The leaf nitrogen content of winter wheat has a good correlation with NDSI in many bands during flowering stage. These bands are as follows: the range on the x-axis is 490 to 506 nm and the range on the y-axis is 574 to 578 nm. These regions show that the nitrogen content of leaf can be well estimated by using NDSI, and the coefficient of determination is above 0.6. NDSI[502, 574] has the best correlation, with a coefficient of determination of 0.64. NDSI[502, 574] is selected as the parameter for modeling at the flowering stage of winter wheat.

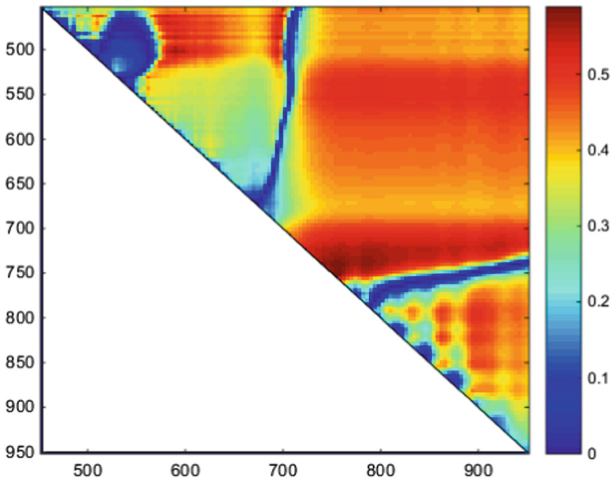

Fig. 11. Coefficient of determination between NDSI and leaf nitrogen content at grain filling stage

As shown in Fig. 11, The leaf nitrogen content of winter wheat has a good correlation with NDSI in many bands during grain filling stage. The band range is as follows: The range on the x-axis is 502 nm, and the range on the y-axis is 586 to 598 nm; the range on the x-axis is 718 to 726 nm, and the range on the y-axis is 750 to 850 nm; The range on the x-axis is 730 to 738 nm, and the range on the y-axis is 738 to 806 nm; the range on the x-axis is 742 to 750 nm, and the range on the y-axis is 754 to 766 nm. These regions show that the nitrogen content of leaf can be well estimated by using NDSI, and the coefficient of determination is above 0.55. NDSI[746, 754] has the best correlation, with a coefficient of determination of 0.59. NDSI[746, 754] is selected as the parameter for modeling at the flowering stage of winter wheat.

3.4 Analysis of Correlation Between RSI and Leaf Nitrogen Content

Using the MATLAB program, the RSI of the spectral reflectance of any two bands in the winter wheat flagging stage, flowering stage and grain filling stage was calculated. Then the coefficient of determination between RSI and leaf nitrogen content is calculated, and the contour map of each growth period was obtained, as shown in Figs. 12, 13 and 14.

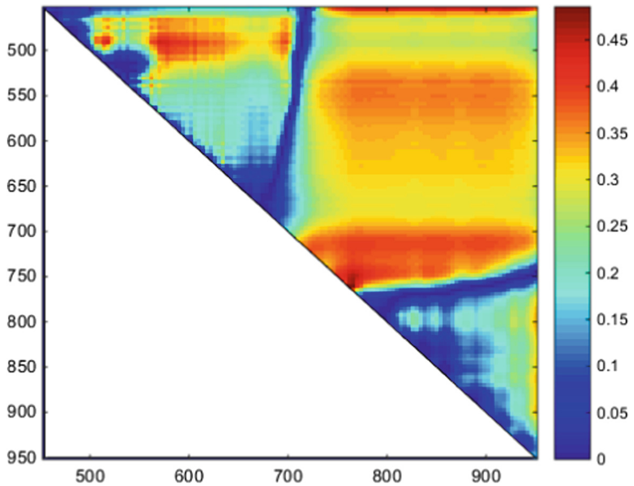

Fig. 12. Coefficient of determination between RSI and leaf nitrogen content at flagging stage

As shown in Fig. 12, The leaf nitrogen content of winter wheat has a good correlation with RSI in many bands during flagging stage. These bands are as follows: the range on the x-axis is 746 to 758 nm and the range on the y-axis is 762 to 766 nm. These regions show that the nitrogen content of leaf can be well estimated by using RSI, and the coefficient of determination is above 0.45. RSI[758, 762] has the best correlation, with a coefficient of determination of 0.49. RSI[758, 762] is selected as the parameter for modeling at the flagging stage of winter wheat.

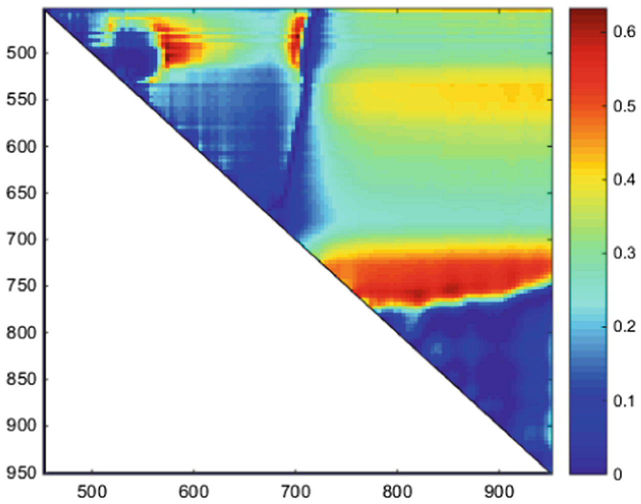

Fig. 13. Coefficient of determination between RSI and leaf nitrogen content at flowering stage

As shown in Fig. 13, The leaf nitrogen content of winter wheat has a good correlation with RSI in many bands during flowering stage. These bands are as follows: The range on the x-axis is 482 nm, and the range on the y-axis is 702 nm; the range on the x-axis is 490 nm, and the range on the y-axis is 574 nm; The range on the x-axis is 502 nm, and the range on the y-axis is 574 to 578 nm; the range on the x-axis is 508 nm, and the range on the y-axis is 574 nm. the range on the x-axis is 570 nm, and the range on the y-axis is 854 nm. These regions show that the nitrogen content of leaf can be well estimated by using RSI, and the coefficient of determination is above 0.6. RSI[502, 574] has the best correlation, with a coefficient of determination of 0.63. RSI[502, 574] is selected as the parameter for modeling at the flowering stage of winter wheat.

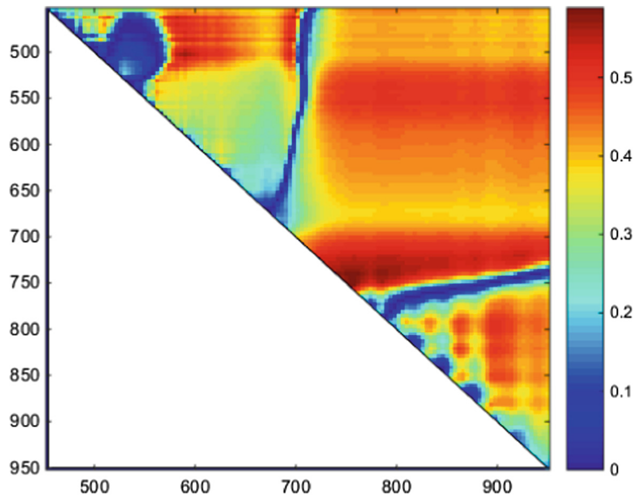

Fig. 14. Coefficient of determination between RSI and leaf nitrogen content at grain filling stage

As shown in Fig. 14, The leaf nitrogen content of winter wheat has a good correlation with RSI in many bands during flowering stage. These bands are as follows: The range on the x-axis is 502 nm, and the range on the y-axis is 586 to 594 nm; the range on the x-axis is 722 nm, and the range on the y-axis is 754 to 762 nm; The range on the x-axis is 722 nm, and the range on the y-axis is 782 to 802 nm; the range on the x-axis is 726 to 738 nm, and the range on the y-axis is 742 to 806 nm; the range on the x-axis is 726 to 734 nm, and the range on the y-axis is 810 to 818 nm. The range on the x-axis is 742 nm, and the range on the y-axis is 746 to 770 nm; the range on the x-axis is 742 nm, and the range on the y-axis is 778 to 798 nm; The range on the x-axis is 746 nm, and the range on the y-axis is 754 to 790 nm. These regions show that the nitrogen content of leaf can be well estimated by using RSI, and the coefficient of determination is above 0.55. RSI[502, 574] has the best correlation, with a coefficient of determination of 0.59. RSI[746, 754] is selected as the parameter for modeling at the grain filling stage of winter wheat.

4 Model Building and Accuracy Analysis

4.1 Model Building

At each stage of growth, we first selected the spectra of the original spectral positive correlation maximum and negative correlation maximum, the spectra of first derivative positive correlation maximum and negative correlation maximum, a group of spectra with the greatest NDSI correlation value and a group of spectra with the greatest RSI correlation value, with a total of six parameters. And then the partial least squares method was used to establish the estimation model of nitrogen content in leaves of winter wheat leaves at different growth stages. Finally, the relationship between the measured value and the predicted value was analyzed, as shown in Figs. 15, 16 and 17.

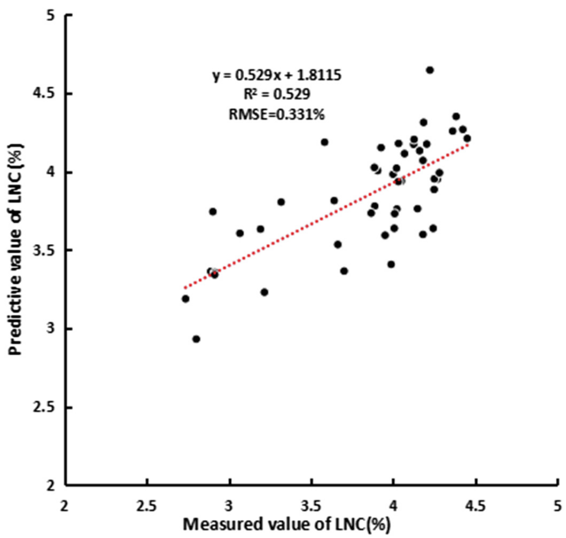

Fig. 15. Relationship between predicted LNC and measured LNC at flagging stage

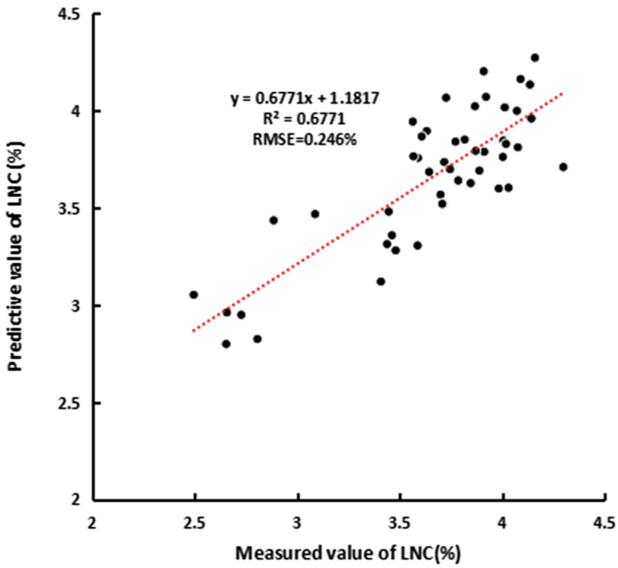

Fig. 16. Relationship between predicted LNC and measured LNC at flowering stage

After correlation analysis between spectral and leaf nitrogen content, the original spectral trough 634 nm and the peak 798 nm, spectral first derivative trough 942 nm and peak 758 nm, normalized spectral index maximum NDSI[758, 762] and ratio spectral index maximum RSI [758, 762] are chosen as modeling parameters at flagging stage. The equation between the predicted and measured values is y = 0.529x + 1.8115, and the value of R^2 and RMSE are 0.53 and 0.331% respectively.

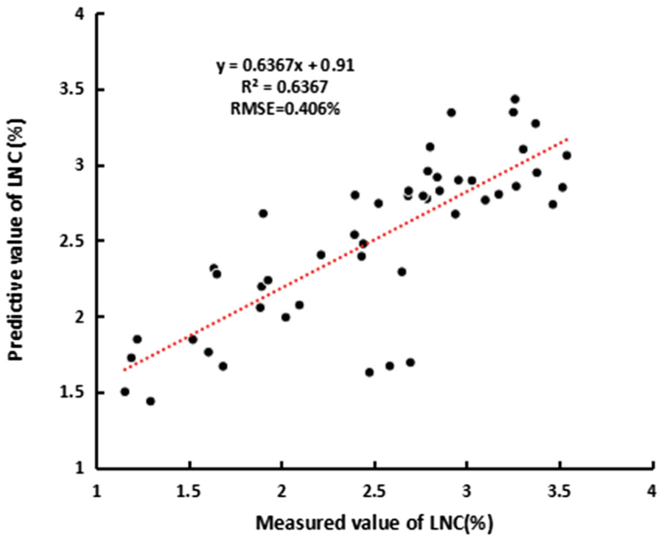

Fig. 17. Relationship between predicted LNC and measured LNC at grain filling stage

After correlation analysis between spectral and leaf nitrogen content, the original spectral trough 706 nm and the peak 854 nm, spectral first derivative trough 530 nm and peak 758 nm, normalized spectral index maximum NDSI[502, 574] and ratio spectral index maximum RSI [502, 574] are chosen as modeling parameters at flowering stage. The equation between the predicted and measured values is y = 0.6671x + 1.1817, and the value of R^2 and RMSE are 0.68 and 0.246% respectively.

After correlation analysis between spectral and leaf nitrogen content, the original spectral trough 714 nm and the peak 786 nm, spectral first derivative trough 682 nm and peak 738 nm, normalized spectral index maximum NDSI[746, 754] and ratio spectral index maximum RSI [746, 754] are chosen as modeling parameters at grain filling stage. The equation between the predicted and measured values is y = 0.6367x + 0.91, and the value of R^2 and RMSE are 0.64 and 0.406% respectively.

4.2 Model Validation

At each stage of growth, we first selected the spectra of the original spectral positive correlation maximum and negative correlation maximum, the spectra of first derivative positive correlation maximum and negative correlation maximum, a group of spectra with the greatest NDSI correlation value and a group of spectra with the greatest RSI correlation value, with a total of six parameters. And then the Leave a cross-validation method was used to validate the estimation model of nitrogen content in leaves of winter wheat leaves at different growth stages. The coefficient of determination (R2) and the root mean square error (RMSE) were chosen as the indexes to evaluate the validation accuracy (Fig. 18).

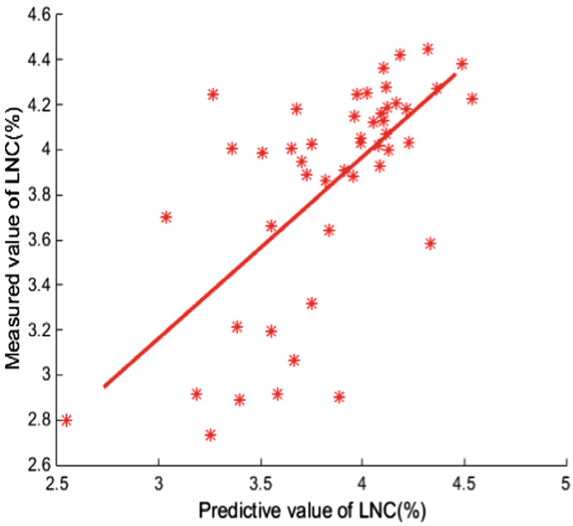

Fig. 18. Relationship between predicted LNC and measured LNC at flagging stage

At flagging stage, the original spectral trough 634 nm and the peak 798 nm, spectral first derivative trough 942 nm and peak 758 nm, normalized spectral index maximum NDSI[758, 762] and ratio spectral index maximum RSI [758, 762] are chosen as model validation parameters. The value of R2 and RMSE are 0.4381 and 0.3695% respectively (Fig. 19).

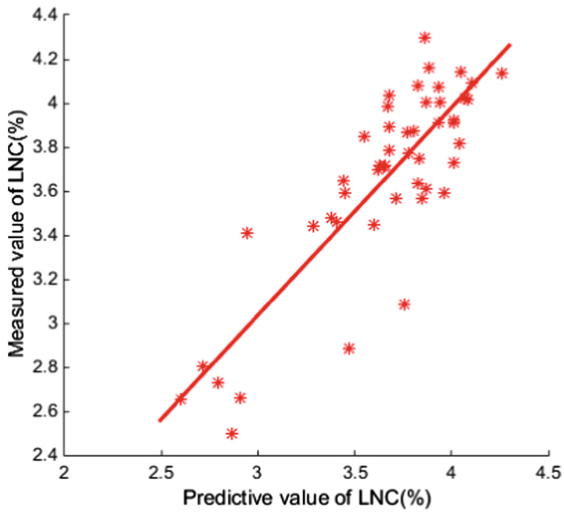

Fig. 19. Relationship between predicted LNC and measured LNC at flowering stage

At flowering stage, the original spectral trough 706 nm and the peak 854 nm, spectral first derivative trough 530 nm and peak 758 nm, normalized spectral index maximum NDSI[502, 574] and ratio spectral index maximum RSI [502, 574] are chosen as model validation parameters. The value of R2 and RMSE are 0.7085 and 0.2347% respectively (Fig. 20).

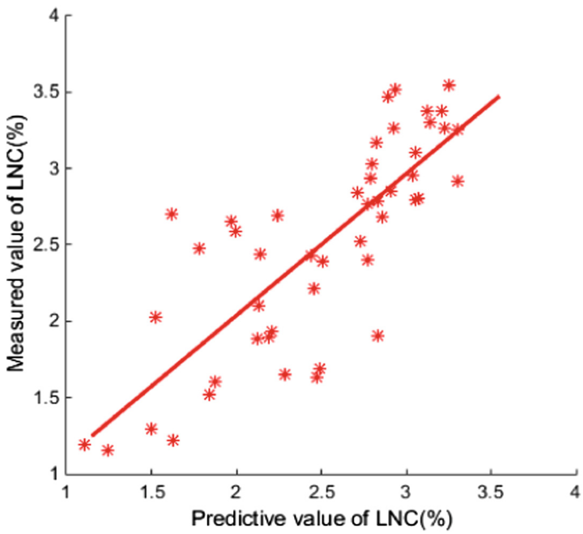

Fig. 20. Relationship between predicted LNC and measured LNC at grain filling stage

At grain filling stage, the original spectral trough 714 nm and the peak 786 nm, spectral first derivative trough 682 nm and peak 738 nm, normalized spectral index maximum NDSI[746, 754] and ratio spectral index maximum RSI [746, 754] are chosen as model validation parameters. The value of R2 and RMSE are 0.6352 and 0.40869% respectively.

5 Conclusions

(1) At different growth stages of winter wheat, we first analyze the correlation between the original spectrum, the first derivative of the spectrum, the normalized spectral index (NDSI), the ratio spectral index (RSI) and the leaf nitrogen content, and then screen out the best sensitive bands. these sensitive bands of the flagging stage are as follows: the original spectral 634 nm and 798 nm, spectral first derivative 942 nm and 758 nm, NDSI[758, 762] and RSI [758, 762]. these sensitive bands of the flowering stage are as follows: the original spectral 706 nm and 854 nm, spectral first derivative 530 nm and 758 nm, NDSI[502, 574] and RSI [502, 574]. these sensitive bands of the grain filling stage are as follows: the original spectral 714 nm and 786 nm, spectral first derivative 682 nm and 738 nm, NDSI[746, 754] and RSI [746, 754].

(2) For these three growth stages of flagging stage, flowering stage and grain filling stage, the coefficient of determination (R^2) and the root mean square error (RMSE) of the model building were 0.53, 0.68, 0.64 and 0.331%, 0.246% and 0.406% respectively. The modeling coefficient of determination of the flowering stage is the biggest in these three growth stages, indicating that the flowering stage is the best growth stage for monitoring the nitrogen nutrition of winter wheat leaves by hyperspectral remote sensing.

(3) For these three growth stages of flagging stage, flowering stage and grain filling stage, the coefficient of determination (R^2) and the root mean square error (RMSE) of model validation were 0.441, 0.71, 0.64 and 0.369%, 0.235% and 0.410% respectively. The results show that the estimation of the nitrogen content of winter wheat plant by using partial least squares method has high accuracy and good reliability. Therefore, it is feasible to monitor the nitrogen content of winter wheat by hyperspectral remote sensing image of UAV.

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