TRANSACTIONS OF THE CHINESE SOCIETY FOR AGRICULTURAL MACHINERY
Vol. 47, No. 9, 2016

doi:10.6041/j.issn.1000-1298.2016.09.046

# Prediction of Winter Wheat Tiller Number Based on 4-waveband Crop Monitor with Spectral Reflectance

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**Abstract**: The number of tillers has a significant effect on the winter wheat field management and the prediction of winter wheat yield. However, the traditional manual counting method of the tiller counting is inefficient. With the development of spectral technology and the application of low altitude remote sensing technology in agriculture, a method was provided for monitoring the number of tillers and growth of the winter wheat by calculating crop canopy reflectance and vegetation index. A 4-waveband crop monitor with spectral reflectance was used to carry on the experiment (Tainong 18). The instrument can obtain the crop canopy reflecting signals at 550 nm, 650 nm, 766 nm and 850 nm simultaneously. After that the crop canopy reflectance was first calculated and then nine vegetation indexes: OSAVI, MSAVI, SAVI, EVI2, TVI, NDGI, NDVI, RVI and DVI, were also calculated. The relationship between the tillering of winter wheat and each index of nine vegetation indexes was analyzed in both regreening and erecting stages. In regreening stage, the correlation between OSAVI (650, 850) and tillers was the highest ($R^2$ is 0.85, RMSE is 118.93), while in erecting stage, the correlation between EVI2 (650, 850) and tillers was the highest ($R^2$ is 0.84, RMSE is 73.04). The results of the test showed that there was a significant relationship between the winter wheat tillers and the two vegetation indexes. This may help the development of the instrument for winter wheat tillers counting based on canopy spectral reflection. The conclusions can be used in rapid predicting of wheat tillering and giving suggestions to field precision management.

**Key words**: wheat; tiller number; canopy spectral reflectance; OSAVI; EVI2

## 0 Introduction

The number of tillers and spike rate determine the robust degree of individual development, thereby affect the final yield. Currently, extensive researches had been launched against the regular pattern of the wheat tillering domestic and international. Studies have shown that the tillering of winter wheat is strong between turning-green stage to early jointing stage. Well field management during this period has very important significance to wheat nutrition and reproductive growth[1-7].

At present, manual counting is still being used in obtaining the number of tillers in the filed in China. It is time-consuming and cannot be automated, unavailable for large-scale farmland. With the development of spectral technology and the application of low altitude remote sensing technology in agriculture, a new method was provided for monitoring the number of tillers and growth of the winter wheat by calculating crop canopy reflectance and vegetation index.

In the field of advanced sensors on crop spectrum, domestic and foreign scholars have made a lot of practical results. USA ASD company developed FieldSpec HH portable visible/near-infrared spectrometer, which measures the wavelength range of 325 ~ 1 075 nm, spectral resolution of 1nm, mainly used for on-line monitoring of crop canopy hyperspectral data[8]. Oklahoma State University and the US N-tech company successfully developed GreenSeeker canopy spectral reflectance measurement

Received date: 2016 – 02 – 29 Accepted date: 2016 – 03 – 29
Supported by National Natural Foundation of China (Grant No. 31501219), Special Fund for Agro-scientific Research in the Public Interest (Grant No. 201303109) and China Scholarship Council Postgraduate Scholarship Program (201406350177)
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apparatus using 656 nm and 770 nm light source emitting alternately which can obtain crop canopy reflectance in two bands more accurate, and calculate crop NDVI index [8-9]. ZHU, et al.[10-12] designed and developed a dual-band sensor for crop growth information monitoring and verified by monitoring the growth of wheat. LI, et al.[13-14] developed a crop reflectance spectrum meter based on 2-band and 4-band daylight to get the crop canopy reflectance in real-time and calculate the NDVI, RVI and other vegetation index, and established model for wheat, rice crop nutrition diagnosis. Domestic and foreign scholars apply the above instruments has achieved fruitful results in the chlorophyll content and other nutrition indicators detection of crop like wheat and corn [10-16].

Domestic and foreign scholars have carried out relevant researches in the use of vegetation index to forecast wheat tillers. PHILLIPS, et al.[17] conducted a preliminary exploration in using NDVI index for winter wheat tillers forecast and provided basis for decision making of variable fertilization prescription. FLOWERS, et al.[18-19] used NDVI, RVI, DVI, SAVI and other vegetation index and color infrared aerial to predict tillers of winter wheat. WU, et al.[20] studied the relationship between NDVI and RVI index and early growth of winter wheat tillers to give a preliminary correlation model. These studies show that the use of existing advanced crop spectrum sensing equipment used to fast monitor and evaluate the wheat tillering state is feasible. This paper selects wheat tillering state between turning-green stage to erecting stage as object to study, because the early winter wheat (before flowering) has strong vegetative growth and tillers monitoring is more important at this stage. Using spectral measuring instruments to conduct spectral scanning on winter wheat canopy between turining-green stage and erecting stage and calculate a plurality of vegetation index. Selecting the best detection index and response band combination of winter wheat at different growth stages by analysis of the correlation between different vegetation indices and winter wheat tillers. Finally, establishing fast online forecasting model of winter wheat tillers. Fast real-time detection of winter wheat tillering at different growth stage could be done by the model and could provide a basis and support for the further development of winter wheat tillering on-line detection equipment.

## 1 Materials and methods

### 1.1 Experiment area

This study was conducted from October 2013 to June 2014 in academy of agricultural sciences experimental farm (118.002 103°E, 36.904 988 84°N), Zibo city, China. The experiment included one variety, five nitrogen levels, three repeated times, a total of 15 cells. This experiment uses a split-plot design (Tab. 1), the experiment species (V) is Tainong 18, residential setting different levels of nitrogen levels (N): N1 (0 kg/hm$^2$), N2 (84.375 kg/hm$^2$), N3 (168.75 kg/hm$^2$), N4 (253.125 kg/hm$^2$) and N5 (337.5 kg/hm$^2$). 50% as basal fertilizer was applied before planting; 50% more fertilizer was applied at jointing stage. The cell acreage is 1.5 m × 10 m, carriageway width is 0.5 m. In addition, the base fertilizer $P_2O_5$ fertilizer is 195 kg/hm$^2$ and $K_2O$ fertilizer is 127.5 kg/hm$^2$, watering at 0 ~ 60 cm soil layer to 50% of the maximum water holding capacity. Other management is the same as large-scale farmland high yield cultivate management. At the same time, observing the wheat growing conditions during the experiment, recording ambient temperature and humidity and sis situation.

**Tab. 1 Field experiment design**

| Repeat times | Nitrogen levels | | | | |
|---|---|---|---|---|---|
| 1 | N1 | N2 | N3 | N4 | N5 |
| 2 | N3 | N4 | N5 | N1 | N2 |
| 3 | N5 | N1 | N3 | N2 | N4 |

### 1.2 Spectral data measuring of crop canopy

The experiment is conducted in early March 2014, wheat turning-green stage and early April 2014, wheat erecting stage, once each. Crop canopy spectral measurement using a 4-band and 8-channel crop reflectance spectra measuring instrument which is independent developed by China Agricultural University[11]. Schematic diagram is shown in Fig. 1.

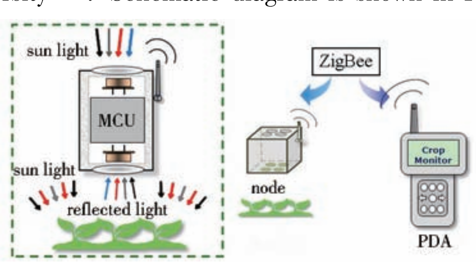


Fig. 1 Diagram of crop reflectance measuring instrument

Meter is divided into two parts: the measurement nodes and handsets, using ZigBee wireless transmission between the two parts. Wherein the measurement node can simultaneously detect 550 nm (G), 650 nm (R), 766 nm (R), 850 nm (NIR) 4 bands of sunlight incident and vegetation reflected light. Handheld terminal uses 32-bit embedded central controller which could calculate 4 bands crop reflectivity in real time[11]. For 15 cells, each experiment cell randomly selected three 1 m × 1 m plots as a duplication, and selected plots central location for winter wheat canopy scanning. During the test, the distance from measurement node to the canopy is about 50 cm, canopy and node are parallel. Before data collection, using whiteboard measuring to calibrate the instrument to minimize the impact of changes of sunlight to the generated spectrum data. The experiment collected 45 group data in total. Based on four measurement wavelength reflectance, nine vegetation indices are calculated combinatory. The formulas are shown in Tab. 2.

**Tab. 2 Spectral vegetation indices**

| Vegetation indices | Formula |
|---|---|
| $I_{OSAVI}$ | $I_{OSAVI} = 1.16(V_{NIR} - V_R)/(V_{NIR} + V_R + 0.16)$ [21] |
| $I_{EVI2}$ | $I_{EVI2} = 2.5(V_{NIR} - V_R)/(1 + V_{NIR} + 2.4V_R)$ [22] |
| $I_{TVI}$ | $I_{TVI} = 0.5[120(V_{NIR} - V_G) - 200(V_R - V_G)]$ [23] |
| $I_{MSAVI}$ | $I_{MSAVI} = 0.5[2V_{NIR} + 1 - \sqrt{(2V_{NIR} + 1)^2 - 8(V_{NIR} - V_R)}]$ [24] |
| $I_{SAVI}$ | $I_{SAVI} = 1.5(V_{NIR} - V_R)/(V_{NIR} + V_R + 0.5)$ [25] |
| $I_{NDGI}$ | $I_{NDGI} = (V_G - V_R)/(V_G + V_R)$ [26] |
| $I_{NDVI}$ | $I_{NDVI} = (V_{NIR} - V_R)/(V_{NIR} + V_R)$ [27] |
| $I_{RVI}$ | $I_{RVI} = V_{NIR}/V_R$ [28] |
| $I_{DVI}$ | $I_{DVI} = V_{NIR} - V_R$ [29] |

### 1.3 Winter wheat tillers collection

The experimental farm had 15 cells and each cell randomly selected three points. Using "Hundred Thousandth Sample Segment Method" in each point, which means using 0.1 $m^2$ sample segment. Cell seeding line spacing is 20 cm, so the sample segment length is 50 cm. Mark at both ends of the segment, and then use one end as starting point, count the number of tillers in the sample segment one by one. Each sample segment is measured double lines per point, counted separately, calculating the average as the number of tillers in the sample segment. Collected 45 group of data in total.

## 2 Results and analysis

### 2.1 Trend of tillers number under different nitrogen levels

By the twice experiments, the comparison of the mean number of tillers under different nitrogen levels in turning-green stage and erecting stage are shown in Fig. 2. The detailed statistical results of number of tillers under different nitrogen levels in turning-green stage and erecting stage are shown in Tab. 3. According to Fig. 1, nitrogen levels affected tillering greatly in turning-green stage and erecting stage. With the increasing amount of nitrogen, the total amount of winter wheat tillers showed "single peak" type which increases at first and the decreases. This may be because of nitrogen as the main element of the synthesis of chlorophyll and photosynthesis-related enzymes, when less supply, crop weak, fewer tillers or no tiller; when oversupply, also did not increase in winter wheat tillering.

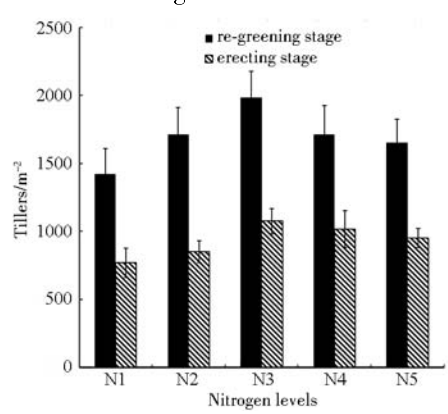


Fig. 2 Average quantities of tillers between re-greening and erecting stage under different nitrogen levels

**Tab. 3 Tillers of winter wheat re-greening and erecting stage in different nitrogen levels**

quantity/$m^2$

| Growth stage | N level | Average | Median | SE | CV |
|---|---|---|---|---|---|
| Turning-green stage | N1 | 1 421.4 | 1 381.4 | 188.6 | 0.132 693 |
| | N2 | 1 713.5 | 1 680.1 | 194.7 | 0.113 604 |
| | N3 | 1 981.4 | 1 920.0 | 195.4 | 0.098 612 |
| | N4 | 1 710.0 | 1 799.8 | 214.9 | 0.125 684 |
| | N5 | 1 651.6 | 1 650.0 | 170.6 | 0.103 323 |
| Erecting stage | N1 | 766.3 | 744.0 | 106.0 | 0.138 345 |
| | N2 | 849.4 | 862.8 | 81.1 | 0.095 532 |
| | N3 | 1 073.9 | 1 050.0 | 94.6 | 0.088 094 |
| | N4 | 1 017.0 | 1 001.2 | 135.3 | 0.133 075 |
| | N5 | 951.1 | 930.0 | 69.6 | 0.073 177 |

According to Tab. 3, the entire plots tiller number variation coefficient in the range [0.073, 0.138], standard deviation range [69.6, 214.9] are within the statistically acceptable range, data reliable.

Comprehensive Fig. 2 and Tab. 3, the tillers number in erecting stage was decrease by 40% to 50% according to turning-green stage under different nitrogen levels, and both reached the maximum number of tillers at N3 level. This may be because with the development of winter wheat, growth and nutrition centers transform, and the generated tillers gradually "polarization": early tillers continues to develop into a spike, while younger tillers and little tillers gradually become invalid tillers apoptosis eliminated, resulting in decrease in the number of tillers. At the same time a reasonable amount of nitrogen can promote tillering, too little or too much are not conducive to carry out tiller.

## 2.2 Vegetation index distribution characteristics under different nitrogen levels

Calculating the average of each vegetation indices under different nitrogen levels, and the results are shown in Tab. 4. Analysis of data in Tab. 4 shows that: each vegetation index showed a "single peak" type curve in turning-green stage and erecting stage under different nitrogen levels, with the increase of nitrogen application, each vegetation index increased first and then decreased. This variation consistent with the foregoing number of tillers under different nitrogen levels, indirectly prove the validity of the collected spectral data.

**Tab. 4 Distribution characteristics of vegetation index under different nitrogen levels**

| Vegetation index average | Turning-green stage | | | | | Erecting stage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N1 | N2 | N3 | N4 | N5 | N1 | N2 | N3 | N4 | N5 |
| OSAVI(650,850) | 0.567 | 0.651 | 0.780 | 0.756 | 0.731 | 0.577 | 0.699 | 0.805 | 0.730 | 0.710 |
| OSAVI(650,766) | 0.583 | 0.658 | 0.718 | 0.702 | 0.685 | 0.518 | 0.655 | 0.740 | 0.696 | 0.652 |
| MSAVI(650,850) | 0.485 | 0.634 | 0.765 | 0.740 | 0.647 | 0.543 | 0.682 | 0.780 | 0.730 | 0.689 |
| MSAVI(650,766) | 0.492 | 0.569 | 0.674 | 0.610 | 0.600 | 0.470 | 0.535 | 0.730 | 0.670 | 0.634 |
| EVI2(650,850) | 0.549 | 0.608 | 0.781 | 0.723 | 0.647 | 0.421 | 0.622 | 0.784 | 0.700 | 0.649 |
| EVI2(650,766) | 0.500 | 0.554 | 0.688 | 0.613 | 0.573 | 0.420 | 0.502 | 0.681 | 0.628 | 0.514 |
| NDVI(650,850) | 0.741 | 0.811 | 0.892 | 0.832 | 0.775 | 0.712 | 0.842 | 0.891 | 0.862 | 0.791 |
| NDVI(650,766) | 0.540 | 0.791 | 0.860 | 0.810 | 0.750 | 0.688 | 0.830 | 0.884 | 0.853 | 0.770 |
| NDGI(550,650) | 0.402 | 0.440 | 0.574 | 0.501 | 0.481 | 0.483 | 0.541 | 0.669 | 0.594 | 0.588 |
| DVI(650,850) | 0.267 | 0.328 | 0.432 | 0.407 | 0.386 | 0.310 | 0.333 | 0.467 | 0.393 | 0.371 |
| DVI(650,766) | 0.225 | 0.285 | 0.366 | 0.356 | 0.352 | 0.258 | 0.292 | 0.426 | 0.362 | 0.346 |
| SAVI(650,850) | 0.602 | 0.630 | 0.656 | 0.641 | 0.606 | 0.634 | 0.672 | 0.715 | 0.704 | 0.692 |
| SAVI(650,766) | 0.545 | 0.563 | 0.581 | 0.568 | 0.546 | 0.538 | 0.557 | 0.607 | 0.611 | 0.596 |
| TVI(650,850) | 25.183 | 26.950 | 28.910 | 27.878 | 25.402 | 28.155 | 31.365 | 34.670 | 33.821 | 32.913 |
| TVI(650,766) | 21.692 | 22.612 | 23.856 | 23.110 | 21.808 | 22.413 | 23.790 | 26.902 | 27.240 | 26.195 |
| RVI(650,850) | 7.512 | 9.614 | 15.852 | 13.623 | 10.631 | 7.632 | 8.525 | 12.152 | 10.982 | 9.773 |
| RVI(650,766) | 6.078 | 8.623 | 14.188 | 11.840 | 8.146 | 5.856 | 6.320 | 9.978 | 8.860 | 8.523 |

## 2.3 Correlation analysis of winter wheat vegetation index and tillering number

According to Tab. 3 and Tab. 4, it could be qualitatively obtained the relevant between the number of tillers of winter wheat at turning-green stage and erecting stage and vegetation indices. Then directly calculating the coefficient between the number of tillers and vegetation indices, quantitatively describing the correlation between them. The result is shown in Tab. 5. Nine vegetation indices and the tillers in two growth stage have higher correlation.

According to Tab. 5: in turning-green stage, the correlation coefficient of the same band combination vegetation index and tiller numbers in descending order are OSAVI, MSAVI, NDVI, EVI2. The values of NDWI, DVI, SAVI, TVI, RVI are lower than the previous four and little difference between them. This may be because in turning-green stage, group coverage is low, soil background noise is the main source of noise, atmospheric conditions, sun angle, terrain and other noise sources are the secondary source of noise. OSAVI is better able to filter out the soil background noise while other vegetation indices are not enough, which is same as the results of previous studies[17]. In erecting stage, the correlation coefficient of the same band combination vegetation index and tiller numbers

**Tab. 5 Coefficient of determination between vegetation index and tillers**

| Vegetation index | Turning green tillers | Erecting tillers |
|---|---|---|
| OSAVI(650,850) | 0.911 9 ** | 0.865 4 ** |
| OSAVI(650,766) | 0.840 9 ** | 0.843 1 ** |
| MSAVI(650,850) | 0.874 3 ** | 0.840 1 ** |
| MSAVI(650,766) | 0.821 6 ** | 0.798 6 ** |
| EVI2(650,850) | 0.856 7 ** | 0.908 4 ** |
| EVI2(650,766) | 0.817 6 ** | 0.849 8 ** |
| NDVI(650,850) | 0.861 8 ** | 0.819 3 ** |
| NDVI(650,766) | 0.836 2 ** | 0.749 7 ** |
| NDGI(550,650) | 0.813 8 ** | 0.793 7 ** |
| DVI(650,850) | 0.853 9 ** | 0.686 6 ** |
| DVI(650,766) | 0.764 1 ** | 0.659 3 ** |
| SAVI(650,850) | 0.832 5 ** | 0.799 1 ** |
| SAVI(650,766) | 0.802 7 ** | 0.768 8 ** |
| TVI(650,850) | 0.826 1 ** | 0.789 3 ** |
| TVI(650,766) | 0.811 4 ** | 0.776 7 ** |
| RVI(650,850) | 0.853 9 ** | 0.777 6 ** |
| RVI(650,766) | 0.796 7 ** | 0.721 2 ** |

in descending order are EVI2, OSAVI, MSAVI, NDVI. EVI2 index increased sensitivity. This may be because when entering to erecting stage, although tiller number is decreased, the early tillers and strong tillers growth are better, the biomass accumulation. EVI2 is sensitive to crop group biomass and the index reduces background and atmospheric noise at the same time. So the correlation between the index and the number of tillers is improved representing to turning-green stage. Soil background noise and atmospheric effects are still obvious in other vegetation indices at this stage, the sensitivity of vegetation coverage is not enough, not suitable for the present phase of the monitoring. For the same vegetation index, combination (650, 850) is better than combination (650, 766). This may be because 850 nm band is in the vegetation NIR "platform" with high and stable reflectivity and 766 nm band is at the vegetation NIR "red edge" with unstable reflectivity and easy affect by the surrounding environment, which is the same as the results of previous studies [14].

To sum up, at different growth stages, winter wheat population density differences, different vegetation indices have different sensitivity to tiller number. In this study, two prediction models were established for two different growth stages of winter wheats tiller numbers.

### 2.4 Forecasting model of winter wheat tillering in turning-green stage and erecting stage

According to the experimental data and conclusions, combined with the development of embedded systems and rapid online testing needs, selected OSAVI (650, 850) as a parameter for turning-green stage tillers to conduct unary linear regression and EVI2 (650, 850) as a parameter for erecting stage tillers to conduct unary linear regression. There are 35 sample point in modeling set and 10 point in validation set. Establishing prediction model for tillering numbers and relating vegetation index respectively for turning-green stage and erecting stage:

$$y_1 = 3\,102.4x_1 - 408.62 \quad (1)$$

$$y_2 = 1\,457.9x_2 + 28.451 \quad (2)$$

In which: $y_1$ means predictive value of winter wheat tillers in turning-green stage; $x_1$ means OSAVI(650, 850) parameter value; $y_2$ means predictive value of winter wheat tillers in erecting stage; $x_2$ means EVI2 (650,850) parameter value.

According to Fig. 3 and Fig. 4, the determination coefficient $R_c^2$ of calibration model for tillers at turning-green stage is 0.85, the determination coefficient $R_v^2$ of validation model is 0.79; the determination coefficient $R_c^2$ of calibration model for tillers in erecting stage is 0.84, the determination coefficient $R_v^2$ of validation model is 0.75.

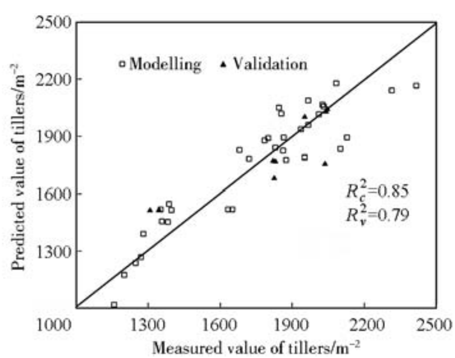


Fig. 3 Correlation between measured tillers and predicted tillers in re-greening stage

The results show that using the crop spectral reflectance measuring instrument for Tainong 18, the tillers number could be forecasted accurately with index OSAVI (650, 850) at turning-green stage and EVI2 (650, 850) at erecting stage. The study will continue for multi-year continuous experiments and spectroscopy diagnosis to validate and improve the applicability of the model. The model will be embedded into the

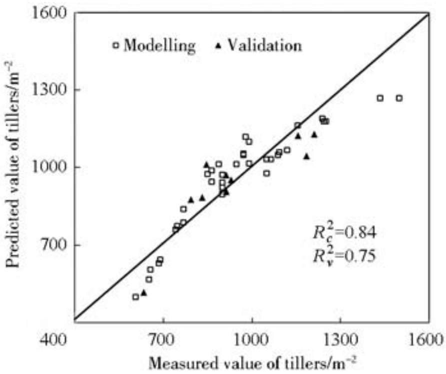


Fig. 4 Correlation between measured tillers and predicted tillers in erecting stage

central controller of the instrument and combined with previous crop nutrition diagnosis model to design a rapid diagnostic instrument for complex parameters including wheat tillers and nutrition indicators.

## 3 Conclusions

(1) According to the experiments for Tainong18, under the same circumstances sowing, the amount of nitrogen fertilizer has a significantly affect in winter wheat tillering. Too much or too little nitrogen will reduce the growth of tillers in turning-green stage and erecting stage. In this experiment, the optimum amount of nitrogen fertilizer is about N3 (168.75 kg/hm$^2$).

(2) The experiment analysis the correlation relationship between nine kinds of vegetation indices (OSAVI, MSAVI, EVI2, NDVI, NGVI, RVI, DVI, TVI) and winter wheat tillering. The results show that at turning-green stage, while tillers is grow strong, using OSAVI (650,850) for regression analysis, the coefficient of determination is up to 0.85 and the root mean square error is 118.93, the forecast accuracy is higher. At erecting stage, using EVI2 (650,850) for regression analysis, the coefficient of determination is up to 0.84 and the root mean square error is 73.04, the forecast accuracy is higher.

(3) At turning-green stage and erecting stage of winter wheat, (650,850) band combination can better reflect the correlation between vegetation index and tillering situation, which provides the basis and supports for the design and application of winter wheat tillers on-line detection equipment based on the principle of spectral reflectance. In the future, multi-year experiment will be conducted in a variety of winter wheat varieties to improve the system suitability.

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doi:10.6041/j.issn.1000-1298.2016.09.046

# 基于 4 波段作物光谱测量仪的小麦分蘖数预测

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**摘要**：使用 4 波段(550 nm、650 nm、766 nm 和 850 nm)便携式作物反射光谱测量仪对泰农 18 型冬小麦分蘖状态进行自动监测与建模，通过分析植被指数与分蘖数的相关关系实现了对分蘖数的建模预测。首先利用仪器获得小麦冠层在 4 个波段的反射信号，计算对应波段的作物冠层反射率，经校正后计算得到 OSAVI、MSAVI、SAVI、EVI2、TVI、NDGI、NDVI、RVI 和 DVI 9 种多波段组合的植被指数。然后分析以上 9 种植被指数与小麦分蘖数之间的相关关系，确定了可用于该类型小麦分蘖状态监测和评价的植被指数类型。2013—2014 年在山东省淄博市和桓台县开展了田间试验，计算了不同氮素水平下泰农 18 型小麦返青期和起身期分蘖数以及其两个生育期分蘖数与 9 种植被指数之间的相关系数，OSAVI(650,850)指数与返青期茎蘖数相关系数最高，决定系数最高为 0.85，均方根误差为 118.93；EVI2(650,850)指数与起身期茎蘖数相关系数最高，决定系数最高为 0.84，均方根误差为 73.04；以上试验结果表明，在冬小麦返青期和起身期利用 OSAVI(650,850)和 EVI2(650,850)两种植被指数可以快速预测小麦分蘖状态，可为田间精细管理提供科学依据。

**关键词**：小麦；分蘖数；冠层反射率；OSAVI；EVI2

**中图分类号**：O657.3；S126　　**文献标识码**：A　　**文章编号**：1000-1298(2016)09-0341-07

# Prediction of Winter Wheat Tiller Number Based on 4-waveband Crop Monitor with Spectral Reflectance

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**Abstract**: The number of tillers has a significant effect on the winter wheat field management and the prediction of winter wheat yield. However, the traditional manual counting method of the tiller counting is inefficient. With the development of spectral technology and the application of low altitude remote sensing technology in agriculture, a method was provided for monitoring the number of tillers and growth of the winter wheat by calculating crop canopy reflectance and vegetation index. A 4-waveband crop monitor with spectral reflectance was used to carry on the experiment (Tainong 18). The instrument can obtain the crop canopy reflecting signals at 550 nm, 650 nm, 766 nm and 850 nm simultaneously. After that the crop canopy reflectance was first calculated and then nine vegetation indexes: OSAVI, MSAVI, SAVI, EVI2, TVI, NDGI, NDVI, RVI and DVI, were also calculated. The relationship between the tillering of winter wheat and each index of nine vegetation indexes was analyzed in both regreening and erecting stages. In regreening stage, the correlation between OSAVI(650,850) and tillers was the highest ($R^2$ is

收稿日期：2016-02-29　修回日期：2016-03-29

**基金项目**：国家自然科学基金项目(31501219)、公益性行业(农业)科研专项(201303109)和国家留学基金委公派研究生项目(201406350177)

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0.85, RMSE is 118.93), while in erecting stage, the correlation between EVI2(650,850) and tillers was the highest ($R^2$ is 0.84, RMSE is 73.04). The results of the test showed that there was a significant relationship between the winter wheat tillers and the two vegetation indexes. This may help the development of the instrument for winter wheat tillers counting based on canopy spectral reflection. The conclusions can be used in rapid predicting of wheat tillering and giving suggestions to field precision management.

**Key words**: wheat; tiller number; canopy spectral reflectance; OSAVI; EVI2

## 引言

冬小麦分蘖数量与成穗率决定了个体发育的健壮程度,进而影响最终产量。目前国内外已经针对小麦分蘖规律展开了大量研究,研究表明在冬小麦返青期至拔节前期,小麦分蘖旺盛,此期间进行良好的田间管理对后期小麦营养生长和生殖生长具有极其重要的意义[1-7]。

但是在田间获取茎蘖数这一环节上,目前国内仍多采用人工计数方法,费时费力且无法实现自动化,也无法在大规模农田中使用。近年来随着光谱技术在精细农业生产中的应用推广,将光谱参数与农学参数相结合,运用先进传感器获取作物光谱反射数据,建立基于各种植被指数的小麦分蘖预测模型,为实现对冬小麦分蘖数快速无损在线测量提供了新方法。

在作物光谱先进传感器领域,国内外学者已经取得了许多实用化成果。美国ASD公司研发了FieldSpec HH便携式可见/近红外光谱仪,其测量的波长范围为325~1 075 nm,光谱分辨率1 nm。主要用于在线监测作物冠层高光谱数据[8];俄克拉荷马州立大学与美国N-tech公司研制成功GreenSeeker冠层光谱反射率测量装置,利用656 nm和770 nm光源交替发光可以较为准确地获取作物冠层在两个波段的反射率,并计算得到作物NDVI指数[8-9];朱艳等[10-12]设计开发了用于作物生长信息监测的双波段传感器并对小麦生长监测进行了验证;李修华等[13-14]研发了分别基于日光的2波段和4波段作物反射光谱测量仪,可以实时获得作物冠层反射率,计算NDVI、RVI等植被指数,并对小麦、水稻作物建立了营养诊断模型。国内外学者,应用上述仪器在小麦、玉米等作物氮素、叶绿素含量等营养指标检测中取得了丰硕的成果[10-16]。

在运用植被指数预测小麦茎蘖数方面,国内外学者也进行了相关研究。PHILLIPS等[17]采用NDVI指数对冬小麦茎蘖数预测进行了初步探索,并为变量施肥处方提供了决策依据;FLOWERS等[18-19]利用NDVI、RVI、DVI、SAVI等多种植被指数和彩红外航片对冬小麦茎蘖数进行了预测;吴军华等[20]研究了NDVI和RVI指数与冬小麦生长前期的分蘖相关关系,得到了初步的相关模型。

以上研究表明,利用已有的作物光谱传感仪器快速监测评价小麦分蘖状态是可行的。由于冬小麦前期(开花期前)营养生长旺盛,在此阶段对茎蘖数进行监测具有更重要意义,因此本文选择返青期和起身期冬小麦分蘖作为研究对象。采用光谱测量仪器对返青期和起身期冬小麦冠层进行光谱扫描,并计算多个植被指数,通过分析不同植被指数与冬小麦分蘖数相关关系,筛选出冬小麦不同生长期的最佳检测指数和响应波段组合,最后建立冬小麦茎蘖数快速在线预测模型。通过该模型可以实时快速检测冬小麦不同生长期分蘖情况,并为进一步开发冬小麦茎蘖数在线检测仪提供依据和支撑。

## 1 材料与方法

### 1.1 试验区域

于2013年10月—2014年6月在淄博市农业科学院试验农场(118.002 103°E,36.904 988 84°N)进行试验。试验设1个品种和5个施氮水平,3次重复,共计15个小区。采用裂区设计(表1),试验品种为泰农18,小区设不同等级施氮水平(N):N1、N2、N3、N4、N5,施氮量分别为0、84.375、168.75、253.125、337.5 kg/hm$^2$。50%作基肥,在播种前施入;50%作追肥,在拔节期施入。小区面积为1.5 m×10 m,行道宽0.5 m。此外,基施$P_2O_5$肥料195 kg/hm$^2$和$K_2O$肥料127.5 kg/hm$^2$,在0~60 cm土层土壤含水率降到最大持水量的50%时浇水。其他管理同大田高产栽培管理。同时试验期间观察小麦长势情况,记录环境温湿度和虫病情况。

表1 试验设计

Tab.1 Field experiment design

| 重复次数 | 施氮水平 | | | | |
| --- | --- | --- | --- | --- | --- |
| 1 | N1 | N2 | N3 | N4 | N5 |
| 2 | N3 | N4 | N5 | N1 | N2 |
| 3 | N5 | N1 | N3 | N2 | N4 |

### 1.2　作物冠层光谱数据测量

试验于 2014 年 3 月初小麦返青期和 2014 年 4 月初起身期各进行一次。作物冠层光谱测量采用中国农业大学自主研发的 4 波段 8 通道作物反射光谱测量仪[11]。原理图如图 1 所示。

测量仪分为两部分：测量节点和手持终端，测量节点与手持终端之间采用 ZigBee 无线传输。其中测量节点可以同时检测 550 nm（绿光 G）、650 nm（红光 R）、766 nm（红光 R）、850 nm（近红外 NIR）4 个波段的太阳光入射光和植被反射光。手持终端采用 32 位嵌入式中央控制器，可以实时计算出 4 个波段的作物反射率[11]。针对 15 个小区，每个试验小区随机选择 3 个 1 m×1 m 样方作为重复，选择样方中心位置进行冬小麦冠层扫描。试验时，测量节点距小麦冠层约 50 cm，节点与冠层保持平行，采集数据前对测量仪进行白板标定，尽可能减小太阳光变化对光谱数据产生的影响。试验共采集得到 45 组数据。基于测定的 4 个波长处反射率，组合计算了 9 种植被指数，计算公式如表 2 所示。

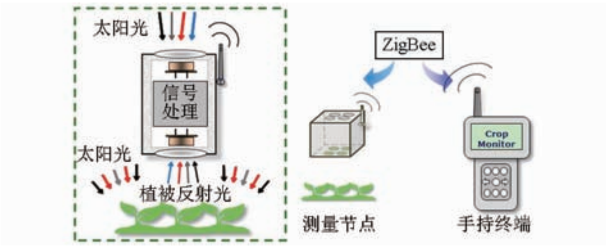


图 1　作物反射光谱测量仪测量原理示意图

Fig. 1　Diagram of crop reflectance measuring instrument

表 2　光谱植被指数

Tab. 2　Spectral vegetation indices

| 植被指数 | 计算公式 | 文献序号 |
|---|---|---|
| 优化土壤调整植被指数（$I_{OSAVI}$） | $I_{OSAVI}=1.16(V_{NIR}-V_R)/(V_{NIR}+V_R+0.16)$ | [21] |
| 增强型植被指数Ⅱ（$I_{EVI2}$） | $I_{EVI2}=2.5(V_{NIR}-V_R)/(1+V_{NIR}+2.4V_R)$ | [22] |
| 转换型植被指数（$I_{TVI}$） | $I_{TVI}=0.5[120(V_{NIR}-V_G)-200(V_R-V_G)]$ | [23] |
| 修正土壤调整植被指数（$I_{MSAVI}$） | $I_{MSAVI}=0.5[2V_{NIR}+1-\sqrt{(2V_{NIR}+1)^2-8(V_{NIR}-V_R)}]$ | [24] |
| 土壤调整植被指数（$I_{SAVI}$） | $I_{SAVI}=1.5(V_{NIR}-V_R)/(V_{NIR}+V_R+0.5)$ | [25] |
| 归一化差异绿度指数（$I_{NDGI}$） | $I_{NDGI}=(V_G-V_R)/(V_G+V_R)$ | [26] |
| 归一化差异植被指数（$I_{NDVI}$） | $I_{NDVI}=(V_{NIR}-V_R)/(V_{NIR}+V_R)$ | [27] |
| 比值植被指数（$I_{RVI}$） | $I_{RVI}=V_{NIR}/V_R$ | [28] |
| 差值植被指数（$I_{DVI}$） | $I_{DVI}=V_{NIR}-V_R$ | [29] |

注：$V_{NIR}$、$V_R$、$V_G$ 分别代表相应波段范围内近红外、红光、绿光的反射率。

### 1.3　冬小麦茎蘖数采集

该试验田共 15 个小区，每个小区随机选取 3 个点。每个采集点使用“十万分之一样段法”，即采用 0.1 $m^2$ 样段。小区苗行间距 20 cm，因此样段长 50 cm。在样段两端作标记，然后以一端为起点，逐一数出样段内小麦茎蘖数。每个样段测量均为每点双行，分别计数，计算平均值为该样段总茎蘖数。总共采集得到 45 组数据。

## 2　结果与分析

### 2.1　不同氮素水平下冬小麦茎蘖数变化趋势

通过 2 次试验，返青期与起身期不同施氮水平下茎蘖数的均值对比如图 2 所示。返青期和起身期不同施氮水平下茎蘖数详细统计结果如表 3 所示。

通过图 1 知，冬小麦返青期和起身期的分蘖受施氮水平影响很大，随着施氮量的不断提高，冬小麦总茎蘖数呈现出先增加后减少的“单峰”型。这可能是因为氮素作为合成叶绿素及相关光合作用酶的主要元素，供给较少时，作物长势孱弱，分蘖少或无分蘖；供给过多时，冬小麦也并没有增加分蘖。

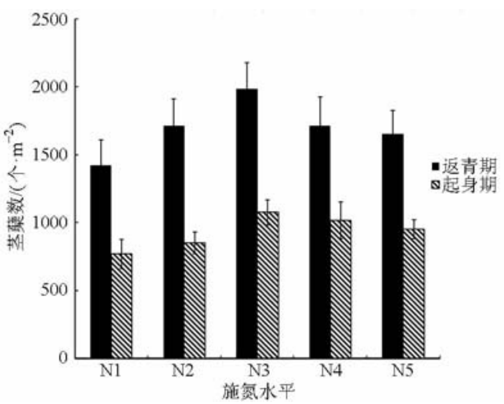


图 2　冬小麦返青期与起身期不同施氮水平下茎蘖数的平均值对比

Fig. 2　Average quantities of tillers in re-greening and erecting stages under different nitrogen levels

通过表 3 知，整块试验田茎蘖数变异系数范围为[0.073,0.138]，标准差范围[69.6,214.9]，均在统计学可接受范围内，数据可靠。

综合图 2 和表 3 知，各施氮水平下起身期小麦分蘖数比返青期分蘖数均分别降低了 40%～50%，且均在N3水平下达到最大分蘖数。这可能是因为

表3 冬小麦返青期和起身期不同施氮水平下茎蘖数结果

Tab.3 Tillers of winter wheat in re-greening and erecting stages under different nitrogen levels 个/$m^2$

| 生育期 | 施氮水平 | 平均值 | 中位数 | 标准差 | 变异系数 |
|---|---|---|---|---|---|
| 返青期 | N1 | 1 421.4 | 1 381.4 | 188.6 | 0.132 693 |
| | N2 | 1 713.5 | 1 680.1 | 194.7 | 0.113 604 |
| | N3 | 1 981.4 | 1 920.0 | 195.4 | 0.098 612 |
| | N4 | 1 710.0 | 1 799.8 | 214.9 | 0.125 684 |
| | N5 | 1 651.6 | 1 650.0 | 170.6 | 0.103 323 |
| 起身期 | N1 | 766.3 | 744.0 | 106.0 | 0.138 345 |
| | N2 | 849.4 | 862.8 | 81.1 | 0.095 532 |
| | N3 | 1 073.9 | 1 050.0 | 94.6 | 0.088 094 |
| | N4 | 1 017.0 | 1 001.2 | 135.3 | 0.133 075 |
| | N5 | 951.1 | 930.0 | 69.6 | 0.073 177 |

随着冬小麦的发育,生长和营养中心发生转移,已经生成的分蘖逐渐“两极分化”:早生分蘖继续发育成穗,而晚生分蘖和小蘖成为无效蘖逐渐凋亡淘汰,最终导致分蘖数下降。同时合理的施氮量能促进分蘖的发生,过少或过多均不利于分蘖进行。

## 2.2 不同氮素水平下植被指数分布特征

计算不同氮素水平下各植被指数的平均值,结果如表4所示。

分析表4数据可知:返青期和起身期各植被指数在不同氮素水平下均呈现“单峰”型变化曲线,即随着施氮量的增加,各植被指数先增大后减小。这与前述不同氮素水平下茎蘖数的变化规律吻合,间接地证明了所采集光谱数据的有效性。

表4 不同氮素水平下植被指数平均值

Tab.4 Average value of vegetation index under different nitrogen levels

| 植被指数 | 返青期 | | | | | 起身期 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N1 | N2 | N3 | N4 | N5 | N1 | N2 | N3 | N4 | N5 |
| OSAVI(650,850) | 0.567 | 0.651 | 0.780 | 0.756 | 0.731 | 0.577 | 0.699 | 0.805 | 0.730 | 0.710 |
| OSAVI(650,766) | 0.583 | 0.658 | 0.718 | 0.702 | 0.685 | 0.518 | 0.655 | 0.740 | 0.696 | 0.652 |
| MSAVI(650,850) | 0.485 | 0.634 | 0.765 | 0.740 | 0.647 | 0.543 | 0.682 | 0.780 | 0.730 | 0.689 |
| MSAVI(650,766) | 0.492 | 0.569 | 0.674 | 0.610 | 0.600 | 0.470 | 0.535 | 0.730 | 0.670 | 0.634 |
| EVI2(650,850) | 0.549 | 0.608 | 0.781 | 0.723 | 0.647 | 0.421 | 0.622 | 0.784 | 0.700 | 0.649 |
| EVI2(650,766) | 0.500 | 0.554 | 0.688 | 0.613 | 0.573 | 0.420 | 0.502 | 0.681 | 0.628 | 0.514 |
| NDVI(650,850) | 0.741 | 0.811 | 0.892 | 0.832 | 0.775 | 0.712 | 0.842 | 0.891 | 0.862 | 0.791 |
| NDVI(650,766) | 0.540 | 0.791 | 0.860 | 0.810 | 0.750 | 0.688 | 0.830 | 0.884 | 0.853 | 0.770 |
| NDGI(550,650) | 0.402 | 0.440 | 0.574 | 0.501 | 0.481 | 0.483 | 0.541 | 0.669 | 0.594 | 0.588 |
| DVI(650,850) | 0.267 | 0.328 | 0.432 | 0.407 | 0.386 | 0.310 | 0.333 | 0.467 | 0.393 | 0.371 |
| DVI(650,766) | 0.225 | 0.285 | 0.366 | 0.356 | 0.352 | 0.258 | 0.292 | 0.426 | 0.362 | 0.346 |
| SAVI(650,850) | 0.602 | 0.630 | 0.656 | 0.641 | 0.606 | 0.634 | 0.672 | 0.715 | 0.704 | 0.692 |
| SAVI(650,766) | 0.545 | 0.563 | 0.581 | 0.568 | 0.546 | 0.538 | 0.557 | 0.607 | 0.611 | 0.596 |
| TVI(650,850) | 25.183 | 26.950 | 28.910 | 27.878 | 25.402 | 28.155 | 31.365 | 34.670 | 33.821 | 32.913 |
| TVI(650,766) | 21.692 | 22.612 | 23.856 | 23.110 | 21.808 | 22.413 | 23.790 | 26.902 | 27.240 | 26.195 |
| RVI(650,850) | 7.512 | 9.614 | 15.852 | 13.623 | 10.631 | 7.632 | 8.525 | 12.152 | 10.982 | 9.773 |
| RVI(650,766) | 6.078 | 8.623 | 14.188 | 11.840 | 8.146 | 5.856 | 6.320 | 9.978 | 8.860 | 8.523 |

注:表中(650,850)表示9种植被指数在(650,850)波段组合下的平均值,下同。

## 2.3 冬小麦植被指数与茎蘖数的相关性分析

通过表3和表4可以定性地得到冬小麦返青期和起身期茎蘖数与各植被指数之间具有相关性的结论。然后计算二者相关系数,定量地描述二者相关关系,结果如表5所示,9种植被指数与两个生育期茎蘖数均有较高相关性。

通过表5可知:在返青期,同一波段组合植被指数与茎蘖数的相关系数由大到小依次为:OSAVI、MSAVI、NDVI、EVI2,而NDGI、DVI、SAVI、TVI、RVI这5种参数较前4种较低,且相差不大。这可能是因为在返青期,群体覆盖度较低,土壤背景噪声为主要噪声来源,大气条件、太阳角、地形等噪声来源为次要噪声来源,OSAVI能比较好地滤除土壤背景噪声,而其他几种植被指数对主要噪声来源滤除不够,这与前人研究结果相同[17]。在起身期,同一波段组合植被指数与茎蘖数的相关系数由大到小依次为:EVI2、OSAVI、MSAVI、NDVI。EVI2指标敏感性提高,这可能是因为进入起身期,虽然茎蘖数下降,但是早生蘖和壮蘖生长较好,各器官生物量累积,EVI2对作物群体生物量较为敏感同时还减少了背景和大气噪声影响,故其与茎蘖数相关系数较返青期高。其他植被指数在该阶段受土壤背景噪声和大气影响仍较为明显,对植被覆盖敏感度不够,不适宜用于本阶段监测。同一种植被指数,(650,850)组合优于(650,766)组合,这可能是因为850 nm波长处于植被近红外反射“平台”处,反射率很高且稳

表 5　植被指数与茎蘖数之间的相关性分析

Tab. 5　Coefficient of determination between vegetation index and tillers

| 植被指数 | 返青期茎蘖数 | 起身期茎蘖数 |
|---|---|---|
| OSAVI(650,850) | 0.911 9 ** | 0.865 4 ** |
| OSAVI(650,766) | 0.840 9 ** | 0.843 1 ** |
| MSAVI(650,850) | 0.874 3 ** | 0.840 1 ** |
| MSAVI(650,766) | 0.821 6 ** | 0.798 6 ** |
| EVI2(650,850) | 0.856 7 ** | 0.908 4 ** |
| EVI2(650,766) | 0.817 6 ** | 0.849 8 ** |
| NDVI(650,850) | 0.861 8 ** | 0.819 3 ** |
| NDVI(650,766) | 0.836 2 ** | 0.749 7 ** |
| NDGI(550,650) | 0.813 8 ** | 0.793 7 ** |
| DVI(650,850) | 0.853 9 ** | 0.686 6 ** |
| DVI(650,766) | 0.764 1 ** | 0.659 3 ** |
| SAVI(650,850) | 0.832 5 ** | 0.799 1 ** |
| SAVI(650,766) | 0.802 7 ** | 0.768 8 ** |
| TVI(650,850) | 0.826 1 ** | 0.789 3 ** |
| TVI(650,766) | 0.811 4 ** | 0.776 7 ** |
| RVI(650,850) | 0.853 9 ** | 0.777 6 ** |
| RVI(650,766) | 0.796 7 ** | 0.721 2 ** |

注：**表示在 0.01 水平上显著相关。

定，而 766 nm 波长处于植被反射“红边”处，反射率不稳定受周围环境影响较大，这与前人研究结果相同[14]。

综上，在不同生育期，冬小麦群体密度差异较大，不同植被指数对茎蘖数的敏感性不同，因此接下来针对两个生育期分别建立冬小麦茎蘖数预测模型。

## 2.4　冬小麦返青期与起身期茎蘖数预测模型

根据上述试验数据与结论，同时结合嵌入式系统开发及快速在线检测需求，优选 OSAVI(650,850)作为参数对返青期茎蘖数进行一元线性回归，EVI2(650,850)作为参数对起身期茎蘖数进行一元线性回归。利用建模集 35 个采样点，验证集 10 个采样点，分别建立返青期和起身期茎蘖数与相关植被指数预测模型为

$$y_1 = 3\,102.4x_1 - 408.62 \quad (1)$$

$$y_2 = 1\,457.9x_2 + 28.451 \quad (2)$$

式中　$y_1$——冬小麦返青期茎蘖数预测值

$x_1$——OSAVI(650,850)参数值

$y_2$——冬小麦起身期茎蘖数预测值

$x_2$——EVI2(650,850)参数值

如图 3 和图 4 所示，返青期茎蘖数标定模型决定系数 $R_c^2$ 为 0.85，模型验证决定系数 $R_v^2$ 为 0.79；起身期茎蘖数标定模型决定系数 $R_c^2$ 为 0.84，模型验证决定系数 $R_v^2$ 为 0.75。

结果表明，应用该作物反射光谱测量仪针对泰

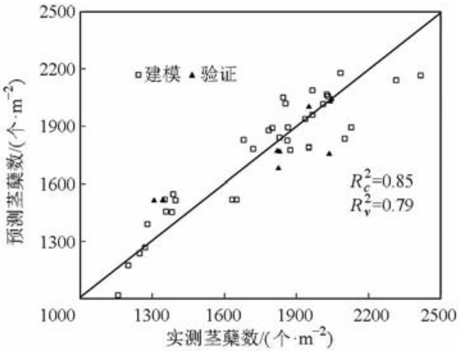


图 3　返青期茎蘖数预测值与实测值建模结果

Fig. 3　Correlation between measured tillers and predicted tillers in re-greening stage

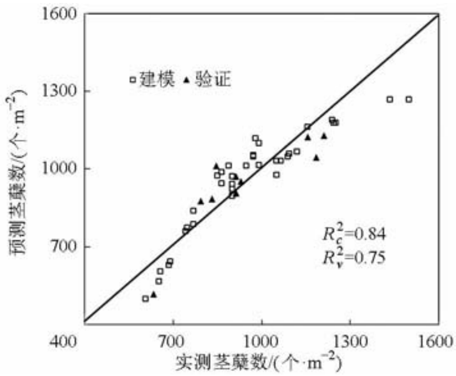


图 4　起身期茎蘖数预测值与实测值建模结果

Fig. 4　Correlation between measured tillers and predicted tillers in erecting stage

农 18 小麦在返青期和起身期分别采用 OSAVI(650,850)和 EVI2(650,850)指数均可对茎蘖数进行较高精度的预测。未来研究将继续针对不同株型品种冬小麦作物的分蘖数进行多年份的连续试验和光谱学诊断研究，继续验证并提高模型适用性。将模型嵌入到仪器中央控制器中，并结合前期作物营养诊断模型，设计成小麦茎蘖数和营养指标复合参数的快速诊断仪。

## 3　结论

(1)通过对泰农 18 冬小麦分区试验可知，相同播种情况下，氮肥施用量显著影响冬小麦分蘖数，在返青期和起身期，过多或过少施用氮素均会降低分蘖的生长，本试验中最佳氮肥使用量为 N3 (168.75 kg/hm²) 左右。

(2)试验分析了 OSAVI、MSAVI、EVI2、NDVI、NGVI、RVI、DVI、TVI 这 9 种指数与泰农 18 冬小麦茎蘖数相关关系，结果表明在返青期分蘖旺盛时，采用 OSAVI(650,850)指数进行回归分析，其决定系数最高达到 0.85，均方根误差为 118.93，预测精度较高；在起身期，优先考虑应用 EVI2(650,850)指数进行回归分析，其决定系数最高达到 0.84，均方根

误差为73.04,预测精度较高。

(3)在冬小麦返青期和起身期,(650,850)波段组合能比较好地反映植被指数与分蘖情况的相关关系,为基于光谱反射原理的冬小麦茎蘖数在线检测仪器的设计与应用提供了依据和支撑,未来还将对多种冬小麦品种进行多年份测试验证以提高系统适用性。

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