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Full Length Article

Study on Photosynthetic Rate of Wheat under Powdery Mildew Stress using Hyperspectral Image

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Abstract

In order to monitor wheat powdery mildew in real time and identify crop diseases in a large range by remote sensing, the relationships of spectral reflectivity and net photosynthetic rate (Pn) with disease index of wheat were clarified under the stress of powdery mildew, and the variation of photosynthetic rate was predicted using spectral vegetation index. The experiemnt was conducted during the winter wheat growth season of 2016-2017, and the wheat variety Jimai 15 (control) susceptible to powder mildew, and Jimai 22 and Luyuan 502 resistant to powdery mildew, were used as the test materials. Based on the inoculation test of powdery mildew by plot test in field, the photosynthetic rate, spectral reflectivity and disease index of wheat flag leaves were measured and investigated every 7~12 days from heading stage to milk-ripe stage. It was found that the Pn of normal leaves of Jimai 22 and Luyuan 502 was larger than that of diseased leaves at flowering stage, and the spectral reflectivity of the leaf spots was higher than that of normal leaves at filling stage. The photosynthetic rate and spectral reflectivity of the control and Jimai 22 were positively correlated, while those of Luyuan 502 were significantly negatively correlated. In the visible light range, the spectral reflectivity increased with the increase of disease index. At the reflectivity platform, the spectral reflectivity decreased with the increase of disease index. The inversion models of photosynthetic rate were established based on the ratio vegetation index of the three cultivars, and their R^2 values were 0.551~0.994 and reached significant or extremely significant level. Therefore, using the ratio vegetation index to invert the photosynthetic rate could obtain better effect during the growth period of wheat.

Keywords: Estimation model; Hyperspectral imaging; Photosynthetic rate; Powdery mildew; Wheat

Introduction

Wheat powdery mildew is a worldwide disease that is spread in all major wheat-producing countries. Before 1970 in China, the morbidity was quite severe in the southwest and local areas of Shandong coastal areas, and then the extent of damage has been aggravated along with the increasingly expanded scope of occurrence (Cao *et al.*, 2009). *Erysiphe graminis* f. spp. *tritici* is an important living parasite, and the back side of leaves will be covered with a layer of white powdery mildew once the crop is infected. The mesophyll cell will be damaged, the content of water and chlorophyll will decrease, and leaves will be yellowing and dried-up, which will then reduce the production of wheat and lower the edible quality (Liu *et al*., 2000; Maxwell *et al*., 2009). The changes of infected crop in morphology and physiology may lead to the changes of corresponding spectra and photosynthesis. The crop spectral information can be used to accurately identify healthy crops and different types of crop diseases, providing possibilities of applying remote sensing technology for the real-time monitoring of wheat powdery mildew and the identification of crop disease in large scope (Wu *et al.*, 2008; Lu *et al.*, 2016). Previous studies have defined that the sensitive bands for the identification of pests and disease damage spectrum of different crops are mainly located in the visible and near-infrared bands, and the optimal sensitive bands differ due to crops and disease types (Huang *et al*., 2003; Zhang *et al*., 2012; Zhang *et al*., 2003). 630 ~ 687, 740 ~ 890 and 976 ~ 1350 nm are sensitive bands for remote sensing monitoring of stripe rust (Zhang *et al*., 2003); the stripe rust of wheat can be identified by using the distance between the red edge and yellow edge of the hyper-spectrum, and the precision of the forecasted DI will be the best when using the model taking REP-YEP as the variant (Huang *et al*., 2003); RVI and NDVI based on 690 nm and 850 nm can be used for the accurate inversion of disease index (Jiang *et al*., 2010); Yang Xiaobing and others (Yang and Zeng, 1988) have found the wheat stripe rust can restrict the net photosynthetic rate (Pn, μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$), and the asymptotic line of net photosynthetic rate of wheat leaf will be lower and lower along with the aggravation of the stripe rust. Yuan Lin and others (Yan *et al*., 2003) have conducted a research on the distinction between wheat powdery

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mildew and stripe rust and the disease inversion based on leaf spectrum analysis. Researches of Feng Wei and others (Feng *et al*., 2013) indicated that the spectral reflectance at 350 to 710 nm of visible light is on the rise along with the aggravation of disease, and 580 to 710 nm is the sensitive bands for remote sensing monitoring of powdery mildew. After the first derivative transformation, Lv Wei and others (Lv *et al*., 2017) have conducted analysis on correlation of original spectrum with the net photosynthetic rate (Pn), and the determined sensitive spectral range is between 750 to 925 nm, and the best hyper-spectrum analysis model for Pn of wheat flag leaf is the QPSR model after the reflectance of wheat leaf at 750 to 925 nm is performed with the first derivative transformation.

Previous studies mainly focused on the identification and spectral quantitative monitoring of wheat stripe rust and powdery mildew, and the impact of powdery mildew on the yield and each nutritive index; however, fewer scholars have conducted remote sensing inversion study on the photosynthetic rate of wheat leaf through the hyper-spectrum technology. This study is carried out to investigate the change of photosynthetic rate of wheat and hyperspectral estimation under stress of powdery mildew and build spectrum inversion model for photosynthetic rate of wheat, aiming at estimating the hotosynthesis rate of wheat using simple and damage-free remote sensing technology and providing theoretical foundation and technological support for remote sensing monitoring of wheat diseases, photosynthetic capacity and yield estimation in large area.

Material and Methods

Experimental Material

The experiment was conducted in Jiyang Test Base (East longitude 116°58′26″ and northern latitude 36°59′4″), Ji'nan, Shandong, from October, 2016 to June, 2017. The testing materials were susceptible wheat variety Jimai 15 (control group), and the disease-resistant wheat varieties Jimai 22 (JM22) and Luyuan 502 (LU502), which were sowed on October 15 and the seeding rate was 150 kg per hectare. Infection area and non-infection area (control area) were set. The sub-regions were set as per variety and three times' repeats for each variety. Previous crop was corn, soil was sandy loam soil, the amount of pure nitrogen for testing was 280 kg per hectare, and the dosage of phosphorus and potash fertilizer and cultivation and management measures were in comply with local practice. The testing time of leaf spectrum and photosynthesis was on April 28 (heading period), May 10 (flowering period), May 18 (grain filling period) and May 27 (milk-ripe period).

Powdery Mildew Inoculation

The strain of *Erysiphe graminis* f. spp. *Tritici* is the mixture of current popular physiological races. On March 13, 2017, spore spray and live-body inarching were used for the inoculation in the infection area. The inoculation was performed 2 meters every one meter along the inoculation line, and the moisture was maintained for more than 16 h after inoculation. The disease infection began in the poplar blossom period of wheat.

Testing Items and Methods

Wheat spectrum testing: Testing was performed in the SOC710VP Visible - Near-infrared Hyperspectral Imaging Spectroradiometer produced by America Surface Optics Corporation, whose spectral region is at 350 to 1050 nm and spectral resolution is 4.6875 nm. The spectrum testing was carried out under natural light of growing land. The field angle of the spectrograph is 25°, and the probe was in 0.50 m distance to the leaf to be tested. Take the leaf to be tested from the plant, place on the platform with black testing cover whose reflectance is almost 0° in flat, and test vertically downward and over against the middle part of the leaf. To eliminate external disturbance and ensure the precision, five pieces normal and five infected leaves were placed respectively for each group, and also 10 of normal and scabbed parts respectively, then their spectral reflectivity were tested, and the means were used as the reflectivity of normal and scabbed parts. The standard white plate rectification was conducted at the same time during measuring.

Photosynthesis Testing of Wheat

The CI-340 Portable Photosynthesis System made in America was adopted. The area of the leaf chamber was 6.5 cm^2, and the normal and scabbed flag leaves of winter wheat were selected. The test was performed at 10: 00 am to 14: 00pm (Beijing time). The leaf chamber was filled with leaf during the test, and the average Pn value of three times was taken as the Pn of this variety.

Disease Index (DI) Investigation

The disease degree of 20 wheat plants was investigated randomly from each sub-region, and the severity was divided into eight degrees, which were indicated as 1%, 5%, 40%, 60%, 80% and 100% respectively. If the state of disease was located between different degrees, the closer degree would be taken. If the plant suffered the disease but its severity was less than 1%, the severity still would be taken as 1%. The disease index was determined as the occurrence degree of wheat powdery mildew and the average disease index at the local onset peak of the disease, which was divided into five levels, that is, Level 1 (≤10%), Level 2 (20%≥DI>10%), Level 3 (30%≥DI>20%), Level 4 (40%≥DI>30%) and Level 5 (DI>40%). The number of wheat leaves with different degrees of severity was recorded respectively, and then the disease index was calculated as per the following formula (NY/T 613-2002, Ministry of Agriculture of the People's Republic of China):

Disease Index =Σ (leaf number of each degree × value of this degree)/(total number of leaves × rate of diseased leaves) ×100

Data Analysis

ENVI 4.7 was adopted for the handling of spectrum data, Matlab was used for the calculation of vegetation index, and relevant statistics and analysis were carried out in Excel. Refer to Table 1.

Results

Comparison of Photosynthetic Rate between Normal and Infected Flag Leaves

From Fig. 1, it is indicated that the photosynthetic rate of Jimai 22 is higher than that of Luyuan 502 during the flowering period, and for both varieties, the photosynthetic rate of normal leaves is higher than that of infected leaves. Based on the analysis, it is found that the actual area for photosynthesis is decreased due to the scab in the leaf. In addition, to the sori after infection cause the rupture of epidermis and lead to the water metabolism disorder of residual healthy parts and the resistance increase of CO_2 movement, and as a result, the photosynthesis of residual healthy parts is affected.

Characteristics of Spectral Reflectance of Normal and Scabbed Parts

Data presented in Fig. 2 shows that for both the Jimai 22 and the control group flag leaves during the grain filling period, the spectral reflectivity of the scabbed part is larger than that of normal leaf. For the visible light band of spectrum, the more absorbs the light, the lower the reflectance will be due to that the chlorophyll content per unit area of normal leaf is higher; Since the content of chlorophyll on scabbed part of leaves is quite lower per unit area, less light will be absorbed, and it will lead to a high reflectance. For wave band at 750 to 1050 nm, the spectral reflectivity of scabbed part on the leaf of wheat is higher than that of normal leaf, which is caused not only due to that chlorophyll and water content of the scabbed part has decreased rapidly, but also the mesophyll cell of the scabbed part has been damaged and dry matter is produced after cell death. All those have indicated that the internal structure of the leaf has been damaged under stress of disease, and has caused spectral characteristics of leaves to change correspondingly. During the milk-ripe period of wheat and within the scope of visible light band, changed conditions of spectral reflectance in control variety is that the normal leaf is larger than scabbed part, and the scabbed part of Jimai 22

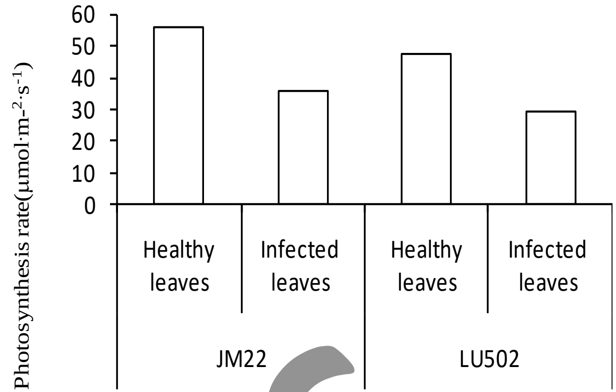

Fig. 1: Comparison of netphotosynthesis rate of wheat during the flowering period

is larger than that of normal leaf, which indicates that during the later stage of growth of wheat, the leaf tissue of the susceptible control variety has been damaged seriously while Jimai 22 with disease resistance complies with the rule of the grain filling period. Within the scope of near-infrared band, for the control group and Jimai 22, the spectral reflectivity of normal leaf is larger than that of scabbed part.

Comparison of KVI in Normal and Scabbed Parts of Wheat Leaf

Table 2 presents that plant indexes like the normalized differential vegetation index (NDVI), green normalized differential vegetation index (GNDVI), chlorophyll index at red edge ($CI_{red\text{-}edge}$), chlorophyll index at green wave band (CI_{green}), ratio vegetation index (RVI), RVI_{700} and others. The plant indexes of scabbed parts are less than those of normal leaf. For the photochemical reflectance index (PRI) and plant senescence reflectance index (PSRI), the values of scabbed parts are larger than those of normal parts of leaves. All these indicate that the disease and severity degree can be identified through spectral vegetation values. The change values of all plant indexes of Luyuan 502 normal and scabbed parts are lower than those of control group, which indicates that the disease infection degree of Luyuan 502 is low, and Luyuan502 is quite disease-resistant.

Correlation between Photosynthetic Rate and Spectral Reflectivity of Wheat

From Fig. 3, it can be found that the correlation between photosynthetic rate and spectral reflectance may vary for the different varieties of wheat in different growth periods. Within the wave band of 350-700nm, the photosynthetic rate and spectral reflectivity of the three varieties of wheat show a positive correlation in the heading period, and the correlation of Jimai 22 is more significant than that of the other two varieties, and Luyuan 502 shows significant negative correlation.

Table1: List of hyper-spectral parameters

Spectral parameter	Name	Formula	Reference
RVI	Ratio Vegetation Index	R_{890}/R_{670}	(Rouse *et al.*, 1974)
DVI	Difference Vegetation Index	R_{800}-R_{670}	(Jordan, 1969)
NDVI	Normalized Differential Vegetation Index	$(R_{800}-R_{670})/(R_{800}+R_{670})$	(Rouse *et al.*, 1993)
GNDVI	Green Normalized Differential Vegetation Index	$(R_{750}-R_{550})/(R_{750}+R_{550})$	(Elliott *et al.*, 2009)
$CI_{red\text{-}edge}$	Red Edge Chlorophyll Index	$R_{800}/R_{720}-1$	(Ciganda *et al.*, 2009)
RVI_{700}	Ratio Vegetation Index	R_{750}/R_{700}	(Mirik *et al.*, 2013)
PRI	*Photochemical Reflectance Index*	$(R_{570}-R_{531})/(R_{570}+R_{531})$	(Mirik *et al.*, 2013)
CI_{green}	Green Band Chlorophyll Index	$R_{800}/R_{550}-1$	(Ciganda *et al.*, 2010)
PSRI	Plant Senescence Reflectance Index	$(R_{680}-R_{500})/R_{750}$	(Deng and Chen, 2010)

Table 2: Comparison of spectral vegetation index between normal and scabbed parts of blades of wheat during grain filling period

Vegetation Index	CK			LU502		
	Normal	Scab	Variation	Normal	Scab	Variation
Ratio Vegetation Index (RVI)	6.298	2.776	3.522	12.048	7.734	4.314
Normalized Differential Vegetation Index(NDVI)	0.726	0.470	0.256	0.847	0.771	0.076
Green Normalized Differential Vegetation Index (GNDVI)	0.542	0.452	0.090	0.570	0.560	0.010
Red Edge Chlorophyll Index ($CI_{rededge}$)	0.546	0.371	0.175	0.872	0.749	0.123
Ratio Vegetation Index (RVI_{700})	4.163	2.577	1.586	4.679	3.418	1.261
Green Band Chlorophyll Index (CI_{green})	2.530	1.800	0.730	4.111	3.985	0.126
Photochemical Reflectance Index (PRI)	0.024	0.054	-0.03	0.029	0.049	-0.020
Plant Senescence Reflectance Index (PSRI)	0.008	0.124	-0.116	-0.048	-0.009	-0.039

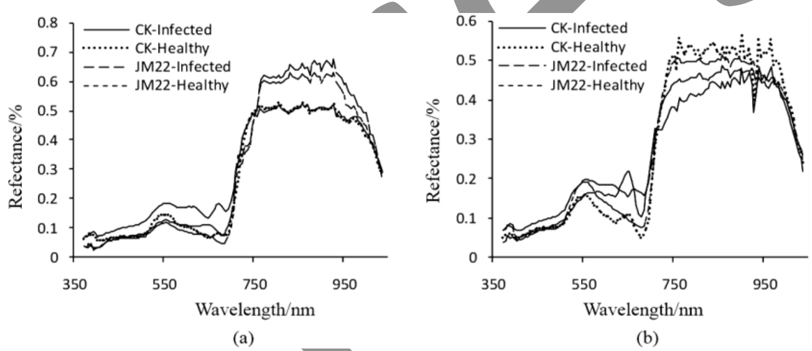

Fig. 2: Comparison of spectral reflectance between Jimai 22 to control scab and normal parts during the grain filling period (a) and milk-ripe period (b)

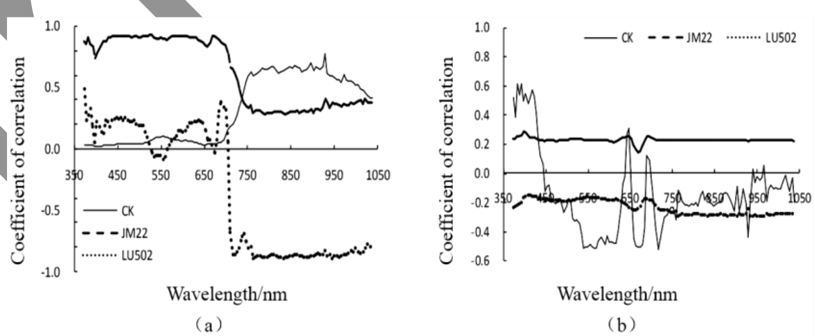

Fig. 3: Correlation between photosynthesis and spectral reflectance of wheat during heading period (a) and grain filling period (b)

During the grain filling period of Jimai 22 and Luyuan 502, the correlation between photosynthetic rate and spectral reflectivity of flag leaves is quite stable, and Jimai 22 shows positive correlation, while Luyuan 502 shows negative correlation. For the control variety, the correlation between photosynthetic rate and spectral reflectivity is unstable due to the heavy disease.

Change of Photosynthetic Rate of Wheat during the Growth Period along with the Disease Index

When plants are infected, the photosynthetic physiology process will be affected to some extent (Zhang *et al.*, 2006). According to Fig. 4, the change trends of photosynthetic rate of control group, Jimai 22 and Luyuan 502 are consistent: the infected degree of powdery mildew will be aggravated along with the advancing of the growth period, and the photosynthetic rate shows more significant downward trend than that of normal leaves.

Correlation Analysis of Disease Index and Photosynthetic Rate

The analysis on correlation between disease index and photosynthetic rate (Table 3) indicates that disease index and photosynthetic rate shows negative correlation. The correlation between disease index and photosynthetic rate of Jimai 22 and Luyuan 502 reaches the maximum in the grain filling period, then in milk-ripe period, and heading period to the minimum. The higher the disease index is, the more severe the disease and the lower the photosynthetic rate. Due to the degree of disease infection during the heading period is low, the correlation between disease index and photosynthetic rate is not quite close.

Changes of Spectral Reflectivity along with Disease Index of Wheat

The scope of visible light is the strong absorption band for leaves of plants, and both the reflection and projection are very low. The reflection peak will be formed in the visible light band due to the absorption of plant pigments, especially for the strong absorption of chlorophyll a and b. Date presented in Fig. 5 indicates that the spectral reflectivity of control group, Jimai 22 and Luyuan 502 have a peak value within the scope of the wave band from 350 to 700 nm, and the peak value will rise along with the increase of the disease index. At the position of the reflectance platform, the strength of spectral reflectivity depends on the internal structure of leaf, especially for the relative thickness between the mesophyll and the intercellular space. The figure shows that the spectral reflectivity will decrease along with the increase of the disease index within that wave scope due to that the absorption of pigment and cellulose is less than 10% in that wave scope. The lights are scattered for many times in the interior of leaf and almost 50% of light are reflected and almost 50% are scattered. The cellular structure of the infected leaf of wheat is damaged, and the number of normal cells becomes few. Therefore, the spectral reflectivity is reduced (Table 4).

Correlation Analysis on Disease Index and Vegetation Index

Vegetation index is a combination of spectral values in different wave bands and it has certain biochemical

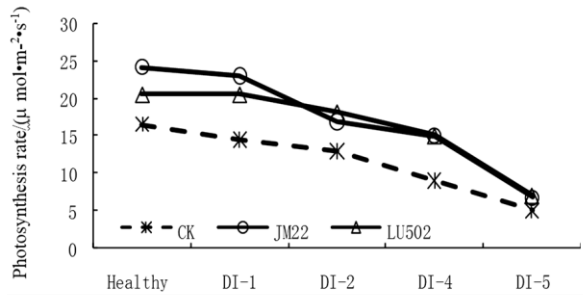

Fig. 4: Changes conditions of photosynthesis rate along with disease index

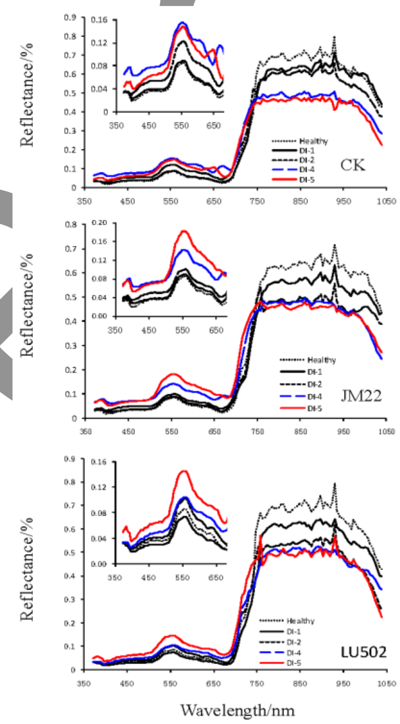

Fig. 5: Change of spectral reflectance with disease index of wheat

significance. The study selects the vegetation indexes related to stress of disease such as GNDVI, PSRI, Difference Vegetation Index (DVI) and RVI to perform a correlation analysis with disease index. It indicates that the trend of correlation between disease index and GNDVI for two varieties in different periods is consistent, and the correlation is negative in heading period but positive after grain filling period. For Luyuan 502 in the heading period, the correlations of disease index with all vegetation indexes are negative. Four kinds of vegetation indexes and the disease index of Jimai 22 and Luyuan 502 during the grain filling period show positive correlation, and the correlation of disease index of Jimai 22 with GNDVI and RVI_{700} reaches a very significant level. The DVI and disease index of Jimai 22 during the heading period show negative correlation, and the correlation coefficient reaches -0.934.

Table 3: Correlation between disease index and photosynthesis rate

	JM22			LU 502		
Growth period	Heading period	Grain filling period	Milk-ripe period	Heading period	Grain filling period	Milk-ripe stage
Correlation index	-0.3703	-0.6807*	-0.67794*	-0.6473*	-0.82502**	-0.7515*

Table 4: Analysis on the correlation between disease index to vegetation index

Variety	Growth period	Green Normalized Differential Vegetation Index (GNDVI)	Plant Senescence Reflectance Index (PSRI)	Difference Vegetation Index (DVI)	Ratio Vegetation Index (RVI_{700})
JM22	Heading period	-0.130	0.435	-0.934**	0.537*
	Grain filling period	0.950**	0.516	0.645	0.958**
	Milk-ripe stage	0.214	-0.277	-0.306	0.072
LU502	Heading period	-0.604*	-0.252	-0.472	-0.567*
	Grain filling period	0.097	0.646	0.645	0.479
	Milk-ripe period	0.287	-0.547	0.882**	-0.292

Note: *: Significant level of 0.05; **: Significant level of 0.01

Table 5: Photosynthesis rate model by vegetation index for wheat of different varieties at different periods (n=180)

Growth period	Variety	Vegetation index	Model	R^2
Heading period	CK	Green Normalized Differential Vegetation Index (GNDVI)	$y=-44504x^3+73492x^2-40372x+7394$	0.990**
		Plant Senescence Reflectance Index (PSRI)	$y=77278x^3+35203x^2+265.5x+14.05$	0.908**
		Difference Vegetation Index (DVI)	$y=-11743x^3+22049x^2-13768x+2875$	0.910**
		Ratio Vegetation Index (RVI)	$y=-0.642x^3+13.71x^2-96.36x+239.6$	0.986**
	JM22	Green Normalized Differential Vegetation Index (GNDVI)	$y=-96x^2+79.14x+14.28$	0.569*
		Plant Senescence Reflectance Index (PSRI)	$y=2281x^2+16.5x+26.85$	0.817*
		Difference Vegetation Index (DVI)	$y=69.31x^2-73.07x+45.91$	0.702*
		Ratio Vegetation Index (RVI)	$y=0.037x^2-1.118x+34.07$	0.667*
	LU502	Green Normalized Differential Vegetation Index (GNDVI)	$y=6157x^3-9955x^2+5333x-928.6$	0.608*
		Plant Senescence Reflectance Index (PSRI)	$y=6157x^3-9955x^2+5333x-928.6$	0.608*
		Difference Vegetation Index (DVI)	$y=-555.7x^3+903.8x^2-484.6x+103.6$	0.853*
		Ratio Vegetation Index (RVI)	$y=-0.009x^3+0.205x^2-1.326x+20.85$	0.574*
Grain filling period	CK	Green Normalized Differential Vegetation Index (GNDVI)	$y=-1E+07x^3+2E+07x^2-8E+06x+1E+06$	0.724*
		Plant Senescence Reflectance Index (PSRI)	$y=-41066x^3+8078x^2-420.1x+15.22$	0.967**
		Difference Vegetation Index (DVI)	$y=-2676x^2+1996x-360.2$	0.471
		Ratio Vegetation Index (RVI)	$y=-16.78x^2+150.5x-325.2$	0.949**
	JM22	Green Normalized Differential Vegetation Index (GNDVI)	$y=-3E+06x^3+4E+06x^2-2E+06x+31347$	0.716*
		Plant Senescence Reflectance Index (PSRI)	$y=23.69x^2-6.081x+24.28$	0.330
		Difference Vegetation Index (DVI)	$y=-2521x^3+2728x^2-978x+140.2$	0.103
		Ratio Vegetation Index (RVI)	$y=-20.43x^3+281x^2-1285x+1981.$	0.994**
	LU502	Green Normalized Differential Vegetation Index (GNDVI)	$y=463.8x^2-503.4x+156.4$	0.585*
		Plant Senescence Reflectance Index (PSRI)	$y=-42592x^3+9967x^2+128.5x+19.75$	0.391
		Difference Vegetation Index (DVI)	$y=-89464x^3+13217x^2-64962x+10644$	0.994**
		Ratio Vegetation Index (RVI)	$y=-0.980x^3+21.74x^2-154.8x+377.4$	0.953**
Milk-ripe period	CK	Green Normalized Differential Vegetation Index (GNDVI)	$y=-319x^2+294.6x-59.56$	0.735*
		Plant Senescence Reflectance Index (PSRI)	$y=-485.9x^2+47.27x+7.279$	0.658*
		Difference Vegetation Index (DVI)	$y=-166.5x^2+109.6x-9.973$	0.284
		Ratio Vegetation Index (RVI)	$y=1.172x^3-22.96x^2+147x-300.2$	0.932**
	JM22	Green Normalized Differential Vegetation Index (GNDVI)	$y=278.7x^2-265.3x+70.40$	0.213
		Plant Senescence Reflectance Index (PSRI)	$y=9036x^2-55.66x+7.366$	0.343
		Difference Vegetation Index (DVI)	$y=-464.1x^2+392.9x-75.13$	0.739*
		Ratio Vegetation Index (RVI)	$y=1.453x^3-26.81x^2+162.6x-316.0$	0.929**
	LU502	Green Normalized Differential Vegetation Index (GNDVI)	$y=9146x^3-12138x^2+5282x-744.1$	0.411
		Plant Senescence Reflectance Index (PSRI)	$y=-619x^2+94.98x+5.511$	0.944**
		Difference Vegetation Index (DVI)	$y=-540.6x^2+360.7x-50.73$	0.715*
		Ratio Vegetation Index (RVI)	$y=0.183x^2-2.374x+15.36$	0.551*

Note: *: Significant level of 0.05; **: Significant level of 0.01

Inversion Model of Photosynthetic Rate

The photosynthetic rates in different periods of wheat can be predicted by using the vegetation index which is highly correlated to the disease index. As showed in Table 5, when the photosynthetic rate of wheat during the heading period is simulated through GNDVI, PSRI, DVI and RVI, the correlation can reach the significant or extremely significant level, and the correlations of control group all reach the extremely significant level. During the grain filling period, the inversion model R^2 of GNDVI and RVI to photosynthesis rate of the three varieties reaches significant or extremely significant level. During the milk-ripe period, the inversion model R^2 of RVI to photosynthetic rate of the three varieties reaches significant or extremely significant level. Through the analysis of the whole growth period, the inversion effect of RVI to photosynthetic rate is the best.

Discussion

Powdery mildew is a perennial disease mainly infecting leaves and sheaths of wheat, and its occurrence could decrease yield in a certain degree. The net photosynthetic rate is an important index in measuring the vegetation productivity and embodying the overall growing status of plants. Photosynthesis is a unique physiological function peculiar to higher plants, and it can convert solar energy into chemical energy. Net photosynthetic rate is an important indicator in measuring the photosynthesis ability, and the higher the net photosynthetic rate is, the better the structure and function conditions of leaves of plants are. The current studies on net photosynthetic rate of plants are mainly based on sample-plot survey on the ground, which takes plenty of time and efforts and fails to reflect the status of net photosynthetic rate in large areas and large time span quickly. However, the remote sensing technology, especially the hyperspectral remote sensing developed in recent years has the advantages of being convenient and fast in large-scale and trans-regional monitoring, which can remedies shortcomings of the traditional methods. Therefore, how to establish the relationship between hyperspectral data and net photosynthetic rate is the key of the study (Lv *et al.*, 2017). Therefore, using the remote sensing to monitor the photosynthetic physiological indicators in a large area could provide technical supports for monitoring the growth trend and estimating the yield of wheat.

Due to the different absorption characteristics of vegetation to different spectral bands, the vegetation indexes can provide data collecting and handling methods that are convenient, fast, effective and damage-free for the quantification testing of physiological parameters of vegetation. The strength of photosynthesis is closely related to physiological and biochemical parameters of the vegetation growth, especially for the chlorophyll content of leaves which will affect the absorption and transition of light energy by vegetation. Zhang Qiuying and others (Zhang *et al.*, 2005) studied the change rules of chlorophyll content and photosynthesis rate of leaves of winter wheat and pointed out the trend of both were consistent with season changes and there was a significant correlation. At present, there were few studies and reports on the remote sensing monitoring of vegetation physicochemical parameters after vegetation is suffered with relevant insects damage, and there is no any report on spectrum estimation of photosynthetic physiological indexes of wheat under stress of powdery mildew. Through monitoring the photosynthesis and spectral characteristics of wheat under stress of powdery mildew, we compared the change of spectrum and photosynthesis between normal leaves and scabbed leaves, analyzed the correlation of disease index with photosynthesis and spectrum of wheat, established the relationship between net photosynthetic rate and spectral vegetation index in different periods, discussed whether hyperspectral data can be used to simulate the photosynthetic rate of plants, and provided new thoughts and theoretical basis for the psychological study of plant photosynthesis.

The spectral changes of wheat powdery mildew and the correlation between the photosynthetic rate of flag leaves and the first-order derivative of wheat spectral reflectivity had been studied (Feng *et al.*, 2013; Lv, *et al.*, 2017). The relationship between hyperspectral data and Pn is the focus of this study under powdery mildew infection. The relationships of photosynthetic rate of wheat flag leaves and spectral reflectivity with disease index were comprehensively analyzed, and the relationship model between photosynthetic rate and vegetation index was established. So the variation of photosynthetic physiological indicators of wheat was clarified under the stress of powdery mildew. It provided theoretical bases for the monitoring of crop growth in large areas. It was found that the Pn of Jimai 22 and Luyuan 502 decreased after powdery mildew infection, and the spectral reflectivity of flag leaf spot during filling period was higher than that of normal leaves. There was a significant negative correlation between disease index and photosynthetic rate, and the photosynthetic rate decreased with the increase of disease index. With the increase of disease index, the spectral reflectivity increased in the visible light range and dicreased at the reflectance platform. Using the RVI to invert the photosynthetic rate could achieve better effect during the growth period. This study is a further step forward in previous studies. Because the photosynthetic rate of plants is closely related to the indices of intercellular CO_2 concentration and stomatal conductivity, it lays a foundation for the study on preventing the occurrence and harm degree of powdery mildew using non-destructive monitoring spectral indicators.

Conclusion

In this study, we monitored the changes of spectrum and photosynthetic physiological indicators of wheat from heading to milk-ripe periods using the imaging spectrometers and portable photo converters. The results showed that the photosynthetic rate of Jimai 22 and Luyuan 502 decreased with the increase of disease index, and the Pn of normal leaves was greater than that of diseased leaves. The spectral reflectivity increased within the wave bands of 350~700 nm but decreased at the reflectance platform with the increase of disease index. The spectral reflectivity of disease spot of flag leaves was higher than that of normal leaves during grain filling period. The vegetation indexes such as NDVI, RVI, GNDVI and

RVI700 of diseased parts were less than those of normal parts, while the values of PSRI and PRI of the diseased parts were larger than those of normal parts. In order to construct the model between photosynthetic rate and spectral indexes, we studied their correlations. The correlation between RVI and photosynthetic rate of the three varieties reached significant or extremely significant levels. So it was concluded that better effect could be achieved when using RVI to predict the photosynthetic rate during the growth period. All these results provided theoretical bases for monitoring wheat growth physiological indexes or diseases in a large area by remote sensing.

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