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Abstract. Many studies on remote sensing monitoring of plant diseases have been conducted. Remote sensing (RS) has played an important role in monitoring some kinds of plant diseases and making decisions for the management of the diseases. Progress on remote sensing monitoring of wheat stripe rust in China was summarized from four aspects including remote sensing monitoring stripe rust of single wheat leaves and monitoring this disease using ground, aerial and space remote sensing technologies. The phenomena of same object with different spectra and different objects with same spectrum, the lowest threshold of disease prevalence for remote sensing monitoring, the spectral information distilling technologies, and the methods to develop inversion models based on spectral information were also discussed. Moreover, the development trends of multi-pest remote sensing, space remote sensing and integrated utilization of RS, geographical information system (GIS) and global positioning system (GPS) in monitoring wheat stripe rust were prospected.

Keywords: Wheat stripe rust, remote sensing, monitoring.

1 Introduction

Remote sensing (RS) is to acquire spectral information or images of an object in a far distance by receiving electromagnetic waves that the object reflects or radiates using either recording or real-time sensing devices. Since the 1960s, remote sensing technologies have being developed quickly. In the 1980s, with the rise of hyperspectral remote sensing, more and narrower wavebands of electromagnetic waves could be used to acquire related information from certain object, and then the application areas of remote sensing technologies were broadened further [1]. Now remote sensing technologies have been widely applied in many disciplinary fields, such as geography, geology, meteorology, ecology, oceanography and agronomy.

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When plant disease occurs, biochemical components and organization structure inside plant leaves would be induced to change. Accordingly, the changes of the spectral characteristics of the plants and remote sensing images would be caused, and would show some specificity, which provides a basis for remote sensing monitoring of plant diseases [2], [3]. Generally, either crop plant pests, fruit tree pests, forest pests or grassland pests that could cause discoloration or deformation of the leaves, or produce residues on the leaf surfaces, could be monitored using remote sensing technologies [4]. There have been many reports about remote sensing monitoring of plant diseases in the world [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]. The reports about remote sensing monitoring of wheat stripe rust caused by *Puccinia striiformis* f. sp. *tritici*, were almost published by Chinese researchers.

In China, stripe rust is the most important disease of wheat [15]. The four most destructive epidemics of this disease occurred in 1950, 1964, 1990 and 2002, which caused yield losses up to 6.0, 3.2, 1.8 and 1.3 million metric tons, respectively [15], [16]. Prevention and control of the disease is very important for wheat production and even for food security in China. In order to control wheat stripe rust effectively, it is necessary to carry out disease monitoring to obtain the information on the incidence of the disease timely and accurately. Traditionally, monitoring of this disease in China mainly relies on field surveys by human power, which is time-consuming and energy-consuming. The subjectivity of the monitoring results and a certain hysteretic nature of the acquired information seriously affect the accuracy of disease forecast. The development of remote sensing technologies could make quickly, conveniently, economically and accurately real-time monitoring wheat stripe rust come true. In recent years, a lot of funds have been invested in the studies on remote sensing technologies for monitoring wheat stripe rust in China and a lot of results have been obtained. In this paper, the progress on remote sensing monitoring of wheat stripe rust in China was reviewed from four aspects, namely, remote sensing monitoring stripe rust of single wheat leaves and ground, aerial and space remote sensing monitoring of wheat stripe rust. Furthermore, some problems in the studies were discussed and the development trends of remote sensing monitoring wheat stripe rust were prospected.

2 Monitoring Single Wheat Leaves Infected by Stripe Rust Using Remote Sensing Technologies

The studies on monitoring single wheat leaves infected by stripe rust using remote sensing technologies could provide theoretical basis for remote sensing monitoring the prevalence of this disease. The results obtained by Huang et al [17] indicated that the wavebands in 446-725 nm as well as 1380-1600 nm were sensitive to the severity level of wheat stripe rust. In their study, using the established mathematical models (shown in Table 1) with designed spectral angle index (*SAI*), designed absorption area index (*AAI*), absorption depth and absorption area as independent variable, respectively, the disease severity level of winter wheat leaf could be inversed with high accuracy. It has been found that spectral reflectance of diseased areas of wheat leaves was positively correlated with disease severity when the wavelength was in 350-1600 nm [18]. On the wave band from 670 nm to 690 nm where reflectance rate was correlated with disease severity significantly, regression model (P<0.0001) (shown in Table 1) elucidating the relationship between wavelength and disease severity was established [18]. Wang et al [19] applied support vector machine (SVM) to process hyperspectral data obtained from 88 leaves including healthy leaves and infected leaves over a range of disease severity levels. The identification model was built based on 44 proof-read samples to estimate 44 proof-test samples and the identification accuracy was totally 97%. The results indicated that SVM could be used in the classification and identification of severity of wheat stripe rust based on obtained spectral data.

Table 1. Remote sensing inversion models of disease severity (S) of wheat leaves infected by *Puccinia striiformis* f. sp. *tritici*.

Selected wave band	Inversion model	Independent variable
666 nm, 758 nm	S=1/tgθ×SAI	SAI =7.289×R_{666nm}-R_{758nm}, in which R_{666nm} and R_{758nm} mean the reflectance rates on 666 nm and 758 nm, respectively.
540-740 nm	S=- 3.494 *Depth* + 2.827	*Depth* means absorption depth in 540-740 nm.
540-740 nm	S=- 0.014 *Area* + 1.532	*Area* means absorption area in 540-740 nm.
540-740 nm	S= 2.459AAI- 0.019	AAI means absorption area index.
685 nm, 690 nm	S=-0.5768+0.7953R_{685nm}-0.6036R_{690nm}	R_{685nm} and R_{690nm} mean the reflectance rates on 685 nm and 690 nm, respectively.

Note: The first four models were established by Huang et al [17] and the last one was established by An et al [18].

3 Monitoring Wheat Stripe Rust Using Ground Remote Sensing Technologies

There have been many studies on monitoring wheat stripe rust using ground remote sensing technologies. They mainly focused on canopy spectral properties, inversion of disease index (DI), changes and inversion of biochemical parameters of wheat infected by stripe rust. Some spectral indexes (shown in Table 2) were used to analyze spectral properties, and some inversion models of wheat stripe rust were built based on spectral information (shown in Table 3). The inversion effects of the models were relatively insensitive to wheat varieties [21], [22]. Therefore, these models could be applied to monitor stripe rust on different wheat varieties. The studies clarified the mechanism of remote sensing monitoring of wheat stripe rust and provided the theoretical basis for monitoring this disease by using aerial and space remote sensing technologies.

The relationship between canopy reflectance and DI of wheat infected by stripe rust has been analyzed. Different results were obtained in different studies. Huang et al [20] found that 630-687 nm, 740-890 nm and 976-1350 nm were sensitive bands to DI of winter wheat stripe rust and the red edge position of diseased wheat shifted to the blue. The study conducted by Cai et al [26] showed that 769-938 nm was the sensitive band to DI. It has been found that DI of wheat stripe rust was highly correlated with the first derivative data of the canopy reflectance of winter wheat in the regions of 432-582 nm, 637-701 nm and 715-765 nm [22], [23]. The results obtained by Li et al [24] and Jiang et al [25] showed that the first derivative values of winter wheat infected by stripe rust increased at the green edge (500-560 nm), while decreased at the red edge (680-760 nm) with *DI* increasing. The ratio of the sum of derivative within the red region (*SDr*) and that within the green region (*SDg*) and the ratio of *SDr′* and *SDg′* were both highly correlated with *DI* of wheat stripe rust, and could be used to identify the disease effectively twelve days before symptoms appearing [24], [25]. The study conducted by Guo et al [21] indicated that *DI* has positive correlation with canopy reflectance in visible region and that it has significant negative correlation in the near infrared region and has stable negative correlation with the first derivative in the region of 700-760 nm. Zhang et al [27] found that with *DI* increasing, canopy reflectance in 600-703 nm decreased distinctively and that in 770-930 nm increased distinctively. Wang et al [30] used partial least square (PLS) to build a regression model for disease severity inversion based on canopy reflectance, and analysis results of regression coefficients of PLS showed that the first derivatives on the two sides of the chlorophyll absorption valley (505-550 nm, 640-670 nm, 680-700 nm) were very important for the assessment of disease severity.

Table 2. Some spectral indexes used in the studies on monitoring wheat stripe rust using ground remote sensing technologies.

Spectral index	Definition	References
NDVI	Normalized differential vegetation index	[20], [21]
RVI	Ratio vegetation index	[20], [21]
TVI	Transformed vegetation index	[20]
SDb	Sum of first derivative within blue region	[21], [22], [23]
SDg	Sum of first derivative within green region	[21], [22], [23], [24]
SDr	Sum of first derivative within red region	[22], [21], [23], [24]
SDr′	Sum of first derivative within red peak region	[22], [25]
Dx	First derivative value of reflectance in *x* nm	[22], [23]
Dr	The maximum of first derivative in red region	[22], 23]
Dg	The maximum of first derivative in green region	[22]
SDg′	Sum of first derivative within green peak region	[22], 25]
Rx	Reflectance in *x* nm	[21], [26], 27]
DSr	Thinness of the first derivative of red edge spectra	[28]
Ar	Asymmetry of the first derivative of red edge spectra	[28]
REP	Red edge position	[29]
YEP	Yellow edge position	[29]

Wang et al [28] put forward two new red-edge indexes (*DSr* and *Ar*) to predict wheat stripe rust. *DSr*, an index describing thinness of the first derivative of red edge spectra (*D*red) of winter wheat infected by stripe rust, was defined as the ratio of maximum value of *D*red and sum of *D*red. Ar, an index describing asymmetry of *D*red, was defined as $(S_2\text{-}S_1)$ /(S_2+S_1), where S_1 and S_2 were the sums of *D*red in 680-700 nm and 701-775 nm, respectively. Jiang et al [29] analyzed the relationship between *DI* and two spectral features, namely, the red edge position (*REP*) and yellow edge position (*YEP*) of the first derivative values. The results showed that with disease severity increasing, *REP* gradually shifted to the short-wave band, and the *YEP* gradually shifted to the long-wave band, however, the variable (*REP*-*YEP*) quickly became smaller. The model built using *REP*-*YEP* as independent variable has the best estimation precision for *DI* than that built using *REP* or *YEP*.

Table 3. Some inversion models of wheat stripe rust for monitoring wheat stripe rust using ground remote sensing technologies.

Inversion model	References	Inversion model	References
DI=-143.11$NDVI$+165.41	[20]	DI =752.477R_{690}-167.356R_{850}+66.966	[21]
DI=-7.288RVI+111.74	[20]	DI =696.934R_{690}-233.908R_{850}+108.023	[21]
DI =-304.16TVI+398.17	[20]	DI =148.657R_{690}-60.547R_{850}+26.385	[21]
DI =-4.6208RVI+55.496	[21]	DI =530.009R_{690}-131.489R_{850}+55.063	[21]
DI =-3.4151RVI+32.161	[21]	DI =-42.341R_{690}-234.475R_{850}+111.813	[21]
DI =-2.2092RVI+29.582	[21]	DI =46.637R_{690}-85.05R_{850}+46.745	[21]
DI =113.142-143.01Dr	[23]	DI =116.739-11.924×(D_{731}/D_{525})	[22]
DI =126.16-3.648SDr	[23]	DI =118.523-12.234×(Dr/Dg)	[22]
DI =-10.035+86.602SDb	[23]	DI =117.507-11.012×(SDr'/SDg')	[22]
DI =-229.03SDr+106.11	[21]	DI =115.557-7.576×(SDr/SDg)	[22], [23]
DI =-275.87SDr+127.4	[21]	DI =153.787×exp[-0.034×(SDr/SDb)]	[22], [23]
DI =-79.056SDr+33.574	[21]	DI =549.302×exp[-0.627×(SDg/SDb)]	[22], [23]
DI =-149.09SDr+76.168	[21]	DI =-489.43+1806.08×[(SDr-SDg)/ (SDr+SDg)]-1421.3×[(SDr-SDg)/ (SDr+SDg)]^2	[22], [23]
DI =-236.63SDr+80.265	[21]	DI =-533.34+2801.06×[(SDr-SDb)/ (SDr+SDb)]^2-2276.0×[(SDr-SDb)/ (SDr+SDb)]^3	[22], [23]
DI =-92.751SDr+41.246	[21]	DI =152.456-173.95×[(SDg-SDb)/ (SDg+SDb)]	[22], [23]
DI =-273.71$NDVI$+251.1	[21]	DI =137.682-26.602×(D_{725}/D_{702})	[23]
DI =-454.68$NDVI$+403.7	[21]	DI=-11.805×(SDr'/SDg')+117.8	[25]
DI =-113.99$NDVI$+96.975	[21]	DI =-2.5173R_{930nm} +1.2217	[26]
DI =-253.68$NDVI$+216.35	[21]	DI=13.03R_{650nm}-0.67R_{850nm}+10.22	[27]
DI =-118.24$NDVI$+96.078	[21]	DI=48.63R_{650nm}-2.41R_{850nm}-41.51	[27]
DI =-97.558$NDVI$+85.853	[21]	DI=24.42R_{650nm}-5.10R_{850nm}+67.77	[27]
DI =-6.697RVI +93.292	[21]	DI=-111.3DSr^2+314.1DSr-134.1	[28]
DI =-6.937RVI+101.96	[21]	DI=-567.1Ar^2+504.9Ar-36.5	[28]
DI =-2.9087RVI+32.279	[21]	DI=-2419.2+37.216×(REP-YEP)-0.1383×(REP-YEP)^2	[29]

The studies on monitoring the changes of biochemical components of wheat infected by stripe rust were also conducted by using ground remote sensing technologies. The canopy reflectance spectral data of winter wheat at the wavelength of 550-1160 nm had good correlation with *DI* of stripe rust and some physiological parameters such as chlorophyll content and water content, and chlorophyll content and water content can be used as two important indicators in remote sensing monitoring of the disease [31]. Chlorophyll fluorescence sensing based on Fraunhofer lines could be used to detect wheat stripe rust [32]. The model established by Jiang et al [33] could be used to estimate the contents of chlorophyll a, chlorophyll b and carotenoid in the diseased wheat with good accuracy. The regression model with satisfactory accuracy was established between the content of wheat chlorophyll and the hyperspectral data of wheat infected by stripe rust [34]. The inversion model with the first derivative index (D_{750}-D_{550})/(D_{750}+D_{550}) as independent variable could be used to estimate canopy chlorophyll densities (CCDs) [35]. Jiang et al [36] found that the leaf total nitrogen (LTN) of the wheat infected by stripe rust gradually decreased with disease aggravating, and there was high correlation between LTN and first derivative data of canopy reflectance in 430-518 nm, 534-608 nm, 660-762 nm and 783-893 nm, and that the model established with the ratio of sum of the first derivative within red edge and sum of the first derivative within blue edge （*SDr*/*SDb*） had satisfactory accuracy. The canopy spectral reflectance of winter wheat under stripe rust stress gradually decreased in the near-infrared region (900-1300 nm) with the reduction of relative water contents, while that gradually increased in the short-wave-infrared region (1300-2500 nm) [37].

4 Monitoring Wheat Stripe Rust Using Aerial Remote Sensing Technologies

The studies focusing on aerial remote sensing monitoring of wheat stripe rust have been done in recent years. A study was done to obtain the reflectance data of the wheat infected by stripe rust in field at a fire-balloon flight and near ground, respectively [38]. The results showed that the reflectance data from the fire-balloon were dramatically higher than that from near ground in the visible region, while the sum of first derivatives of the reflectance data from the fire-balloon was lower than that from near ground in 537-582 nm and 700-1000 nm. This study provided some certain basis for further studies on monitoring wheat stripe rust by using aerial remote sensing technologies. Liu et al [39] analyzed the multi-temporal hyperspectral airborne image data acquired from winter booting stage to milking stage using pushbroom hyperspectral imager (PHI) on Yun-5 plane. The results showed that compared with normal wheat, the image spectral reflectance of diseased wheat was higher in 560-670 nm bands, lower in near infrared bands and the absorption depth of chlorophyll well in red band and the height of chlorophyll peak in green band were relatively reduced. The model built to inverse *DI* was fitted well to the practical disease index and occurrence ranges. Yang and Guo [40] analyzed the multi-temporal PHI airborne wheat image data, and the information of wheat stripe rust was recognized in PHI images in terms of wheat spectral features and spectral angle mapping (SAM) technique. The analyses of the PHI images conducted by Luo et al [41] showed that red bands (620-718 nm) and near infrared bands (770-805 nm) were the sensitive bands to wheat stripe rust. With the inversion model established using the mean reflectance of red bands and near infrared bands as independent variables and the observed disease indexes as dependent variable, wheat stripe rust was monitored successfully based on PHI images.

5 Monitoring Wheat Stripe Rust Using Space Remote Sensing Technologies

Fruitful results have been obtained in monitoring forest pests and crop insect pests by using space remote sensing technologies in the world [42], [43]. However, the studies on monitoring crop diseases using space remote sensing technologies are less, especially for wheat stripe rust. Huang [44] reported that the sensitive spectral bands to *DI* were similar for three wheat varieties with different susceptibility including Jing 411, 98-100 and Jingdong 8, and that the bands included TM2 (520-600 nm), TM3 (630-690 nm) and TM4 (760-900 nm) of Landsat/TM. Thus, it is possible to monitor wheat stripe rust using the Landsat/TM remote sensed data, and meanwhile the wheat variety parameter could be neglected. Preliminary studies on remote sensing monitoring of wheat stripe rust based on SPOT5 image have been conducted by the researchers from China Agricultural University [45], [46]. They found that SPOT satellite remote sensing spectral information could be used to monitor wheat stripe rust, and the third band of SPOT image or normalized difference vegetation index (*NDVI*) and *RVI* calculated using the reflectance values extracted from SPOT image were useful for further studies. Zhang et al [47] used three PHI images that included different severity levels of stripe rust as a medium to establish the spectral knowledge base of relationships between *DI* and the simulated reflectance of TM bands by using the empirical inversion model of *DI* and the relative spectral response (RSR) function of TM-5 sensor. And then Mahalanobis distance or SAM was used to monitor and identify winter wheat stripe rust. The results showed that the infected pixels could be identified accurately from the simulated TM pixels in pustulation and milk stages of winter wheat. Liu et al [48] used multi-temporal remote sensed data to monitor and evaluate the diseases including stripe rust and powdery mildew and the yield of winter wheat. Four Landsat TM images used to analyze were acquired at erecting stage, booting stage, anthesis stage and grain filling stage. The results showed that both the spectral reflectance of diseased wheat at visible and short infrared regions and the red edge position decreased, and that the spectral reflectance at near-infrared region increased. An early yield prediction model developed using the Landsat TM images acquired at the erecting and booting stages was used to evaluate wheat yield loss.

6 Problems in the Studies on Remote Sensing Monitoring of Wheat Stripe Rust

6.1 The Phenomena of Same Object with Different Spectra and Different Objects with Same Spectrum

The acquisition of remote sensing spectral data of wheat stripe rust is affected by various conditions. The stability of the spectrum of the disease is often influenced by the device(s), wheat density in the field, soil types, meteorological conditions and other pests. Therefore, the phenomena of same object with different spectra and different objects with same spectrum are caused easily. That is a difficult problem for remote sensing monitoring. To solve this problem, it is important to obtain the specific spectrum or the diagnostic spectrum via basic studies on spectral properties of the wheat infected by stripe rust under different conditions.

6.2 The Lowest Threshold of Disease Prevalence for Remote Sensing Monitoring

It is an important objective of remote sensing monitoring of wheat stripe rust to realize early monitoring of the disease and even monitoring the disease under its economic injury level or in incubation period. Reflectance spectra of the diseased wheat in incubation period showed different with that of normal wheat and could be used to identify wheat stripe rust [24], [26]. However, could the disease be found out using remote sensing technologies when a small quantity of wheat leaves infected by stripe rust in the field? Is there the lowest threshold of disease prevalence for remote sensing monitoring of wheat stripe rust? If yes and it is determined, it would be very useful for guiding the early control of wheat stripe rust by using the remote sensing information.

6.3 The Spectral Information Distilling Technologies

The distilling of spectral property information is the premise of application of spectral data of wheat stripe rust and *DI* inversion. The common methods to distil spectral property information include the methods based on K-L transform, separability criterion, nonlinear criteria and spectral recomposition [49]. For information distilling from remote sensing images, the technologies such as image enhancement and image classification seem a bit rough and poor because of the affects of sun elevation angle, meteorological conditions and seasonal variation on the remote sensing images at different time. The image processing methods such as Gramm-Schmidt transformation, principal component analysis (PCA), tasseled cap transformation (TCT), spectral mixture analysis and change vector analysis (CVA), and remote sensing image classification methods such as maximum likelihood classification, artificial neural network (ANN) and SVM, could be used to improve information distilling from remote sensing images.

6.4 The Methods to Build Inversion Models Based on Spectral Information

The ultimate goal of remote sensing is the inversion and the use of inversion results for decision-making. For the inversion of wheat stripe rust using remote sensing technologies, it is the key to determine the relationship between disease prevalence and the changes of original spectra, vegetation indexes, derivative spectra and so on, and then to determine sensitive bands and sensitive period for monitoring the disease. In the studies on remote sensing monitoring, generally, spectral reflectance in sensitive bands or the model parameters obtained from its differential transformation are used to build the inversion models of wheat stripe rust by using the methods such as linear regression and nonlinear regression. These methods always have the shortcomings such as the deficiency of sample size and the instability of the errors in application and extension. In order to overcome these shortcomings, it is better to use the methods such as nearest neighbor algorithm, ANN and SVM, to establish the inversion models with minor error, wide application scope and high stability.

7 Future Prospects of Remote Sensing Monitoring of Wheat Stripe Rust

7.1 The Studies on Remote Sensing Monitoring of Multiple Pests of Wheat

There are many kinds of wheat pests, and there are more than eighty wheat diseases in China, of which there are more than twenty diseases causing severe losses [50]. Some different wheat pests cause similar symptoms that make it difficult to distinguish between the pests. Moreover, there are always obvious differences between the symptoms caused by the same wheat pest in different wheat growth stages. So it is very important to carry out the studies on remote sensing identification of multiple pests and the pests in multiple growth stages of wheat. There is still much work to be done in this area. The damages caused by wheat powdery mildew, wheat stripe rust and aphid have been successfully identified by using stepwise discriminate analysis and hierarchical clustering based on the canopy reflectance data [51].

7.2 Further Studies on Monitoring Wheat Stripe Rust by Using Space Remote Sensing Technologies

Now space remote sensing has been widely used in various fields. High resolution remote sensing satellites such as IKNOS, QuickBird, SPOT-5 and ORBVIEW-3, promoted the development of space remote sensing. In China, remote sensing monitoring of many kinds of great natural disasters such as flood disasters, drought disasters, fire disasters of forests and grasslands, sandstorms and red tides, is used to keep abreast of emergency disaster information and make timely decisions. The space remote sensing technologies used in other areas are worth making use for reference in development and exploration of space remote sensing of wheat stripe rust. If the studies on multi-platform, large-scale, multi temporal and multi-band remote sensing are conducted successfully and relationship models between different platforms are built, remote sensing monitoring of wheat stripe rust will come true finally.

7.3 The Integrated Application of 3S Technology in Remote Sensing Monitoring of Wheat Stripe Rust

The term, 3S technology, refers to RS, geographical information system (GIS) and global positioning system (GPS). GIS is a computer decision support system to display, manage and analyze geographic spatial data and to show the processing results in the means of maps, graphics or data. GIS has been widely used in military, agriculture, environmental protection, traffic and transportation, urban planning, and so on. GIS has been well applied in the analysis of spatial dynamics of plant pathogen population, monitoring, forecasting and risk analysis of plant diseases [52]. GPS could be used to realize the localization in the investigations of plant diseases. Thus, the investigations of some plant disease in fixed locations in many consecutive years could be realized. It is very useful for the studies on epidemic dynamics of plant disease during many years and more precise management of plant disease. The integration of RS, GIS and GPS could be implemented in real-time monitoring of plant disease [53], [54], [55], [56]. The localization using GPS is absolutely necessary for the realization of aerial and space remote sensing monitoring of wheat stripe rust. The essential information could be distilled from the remote sensing images more precisely via the localization of target objects. A monitoring and warning information system for remote sensing of wheat stripe rust could be established via the integrated application of 3S technology in future.

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