Wheat lodging monitoring using polarimetric index from RADARSAT-2 data

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ABSTRACT: The feasibility of monitoring lodging of wheat fields by exploiting fully polarimetric C-band radar images acquired by the Radarsat-2 sensor has been investigated in this paper. A set of polarimetric observables that can be derived from this data type has been studied by employing a time series of images gathered during the whole cultivation period of wheat. Among the analyzed parameters, besides backscattering coefficients and ratios, clear signatures were observed in their evolutions as a function of phonological stages of typical lodging fields when comparing to the ones of typical normal fields, as well as in parameters provided by target decomposition techniques. Then a method called polarimetric index, availing the advantage of the sensitivity of polarimetry to the structure, was put forward to monitor wheat lodging. The method was validated by two sets of in-situ data collected in Shangkuli Farmland area, Inner Mongolia, China, at heading and ripe stages of spring wheat. Almost all the lodging fields were successfully distinguished from normal fields. Furthermore, the result revealed that the polarimetric index can reflect the intrinsic feature of lodging wheat with good anti-inference ability such as wheat growth difference. While optical sensors relied on its spectral features to monitor crop lodging, the proposed method based on radar data utilized polarimetric features to monitor crop lodging.

Keywords—Lodging, Radarsat-2, Polarimetric feature, Multi-temporal, Wheat, Monitoring, Crop growth, Disaster

1. Introduction

As one of the most widespread disasters in agriculture production, wheat lodging is an important constraint limiting its yields and quality (Berry, *et al.*, 2003, 2004; Peake, *et al.*, 2014). After the occurrence of lodging, the circulation of its plant water and nutrient content will be impeded and its vegetation photosynthesis will also be suppressed due to physiological disruptions, and subsequently its grain-filling and yield formation will be affected(Kong, *et al.*, 2003). Significant economic losses will be caused every year (e.g. yield losses will reach up to 27% when severe lodging occurs) (Berry, *et al.*, 2012; Peng, *et al.*, 2014). It becomes worse while taking into account the difficulty it brings to harvesting machinery (Peake, *et al.*, 2014). Therefore, lodging monitoring in large area will contribute great to agricultural disaster prevention, damage reduction, yield prediction and loss evaluation etc.

Remote sensing technology provides a promising tool to grasp timely, synoptic and repetitive information about the status of agricultural crops. It has been used to attempt to monitor crop lodging in recent years. The feasibility was demonstrated in winter wheat lodging monitoring with

Landsat imagery (Liu *et al*., 2005), it was found that canopy spectral reflectance (in Visible and Near-Infrared band) will increase with lodging angle while the normalized difference vegetation index (NDVI) will decrease with lodging angle. The reasons and characteristics of canopy spectral variation in wheat filling stage were further analyzed (Hu *et al*., 2011). The lodging of paddy rice was identified by support vector machine method based on ground-mounted Visible/Near-Infrared Spectrometer data (Liu *et al*., 2009). The hemispherical directional reflectance factor (HDRF) and polarized reflection of lodging maize were measured, it was found that its spectral reflectance was affected by viewing angle and its reflected light was highly polarized (Bao *et al*., 2013). In addition, the lodging influence on maize grain quality has been evaluated based on field hyperspectral data and continuous wavelet technique (Zhang *et al*., 2012). Wu *et al*., (2013) assessed the lodging's impact on winter wheat yield through images processing and spectral analysis.

It could be found that previous methods are mainly based on the variation of spectral reflectance, the spectral features change when vegetation lodging occurs. However, the spectrum technology of optical sensors has its limitations. The spectral change due to lodging is relatively weak, and it is often drowned out amid complex mixed spectrum. Actually, the change of spectral features may be caused by many other sources, such as soil background or other crop stresses including water, fertilizer and pesticide stress, etc. (Schaepman, *et.al*, 2009; Sankarana, *et.al*., 2010). Therefore it is difficult to separate and extract 'weak information' of lodging from a variety of disturbing factors. In addition, vegetation lodging is often accompanied by bad weather, there is no guarantee to get available images timely due to optical system's limited capacity in bad weather. In comparison to optical sensors, spaceborne synthetic aperture radar (SAR) instruments can overcome inherent limitations of optical sensors owing to its all-weather, day and night acquisition capabilities (Kugler *et al*., 2010). More importantly, SAR observation is instinctively sensitive to the structure changes of ground target (Ulaby *et al*., 1986). Since vegetation structure changes obviously after lodging, SAR data have more advantages to monitor crop lodging theoretically. Nevertheless no study about monitoring lodging using SAR data has been reported to date.

This study therefore is centered on exploring the potential capability of radar remote sensing for monitoring wheat lodging. Firstly, dynamic response pattern of backscattering coefficient intensity observables and polarimetric decomposition parameters of lodging wheat fields were analyzed to identify sensitive features for lodging wheat fields. Then a simple method for monitoring wheat lodging was proposed. Finally, the method was validated by two in-situ data sets collected in Shangkuli Farmland area, Inner Mongolia, China, in 2013.

2. **Materials and methods**

2.1 Study area

The study zone is the Shangkuli Farm in Inner Mongolia, China(50.28°-50.39°N;120.76°-120.89°E), located in the northwest of Greater Khingan Mountains and the north of Hulunbuir steppe, as shown in Fig. 1. It is a cold temperate continental monsoon climate, cold and dry in the long winter, warm and wet in the short summer, supporting one harvest per year. Leached chernozem soil dominates this region and topographic variations are minimal with slopes generally less than 1% in this farm. It lies on the transition zone of forest and prairie, is typical of agricultural land use within Northeast China. The farm extends over 3000 hectares, with simple plant structure and homogeneous field parcels. Approximately 90% of farmland is used for annual crop cultivation, principally spring wheat and canola, with minor acreages planted to spring barley. They are usually planted from May to June, reach maturity in middle August, and harvested in early September. The wind is often strong, and the crops are vulnerable, especially when the plants are high. Fields in this region are larger than most fragmented fields in China, typically nearly 20 hectares.

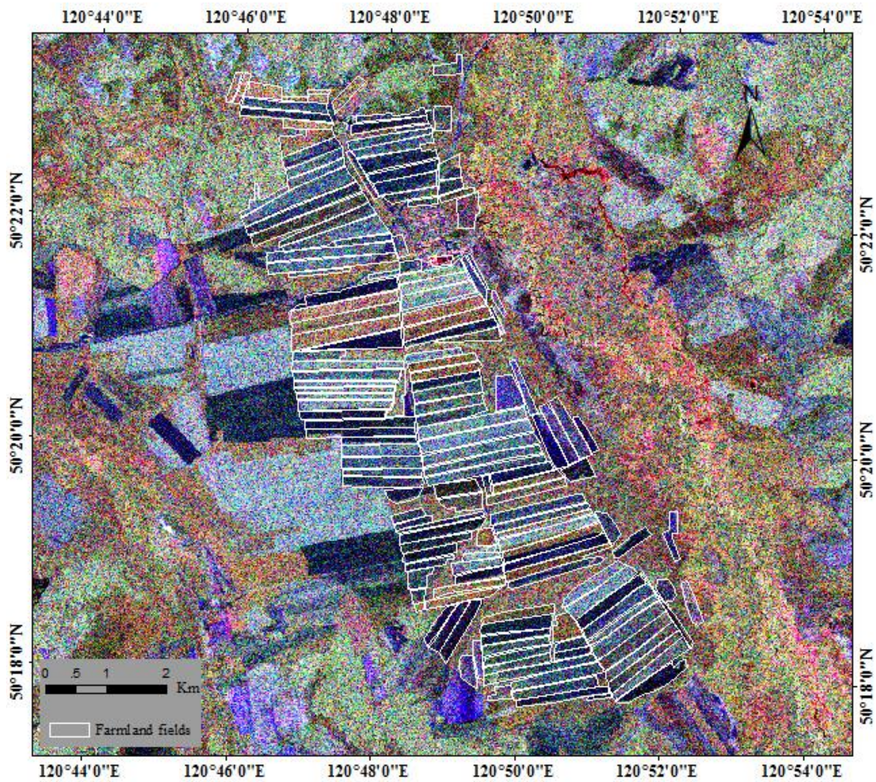


Fig.1 Location map of the study area in Inner Mongolia, China; Background: Pauli-basis RGB image of Radarsat-2, acquired on June 16, 2013, as a color composite of $|S_{hh}\text{-}S_{vv}|^2$ (red), $|S_{hh}+S_{vv}|^2$ (blue), and $|S_{hv}|^2$ (green).

2.2 SAR data and ground truth data

A time series of fully polarimetric C-band Radarsat-2 images were acquired during the growing season in 2013, with a spatial resolution of 8×8 m in Fine Quad mode. Five Radarsat-2 scenes were obtained in repeat pass with 24-day intervals in order to obtain a multi-temporal data stack with similar acquisition parameters (see Table 1). It should be mentioned that similar acquisition parameters will help to reduce the backscattering effect due to satellite observation configurations such as incidence angle. Their periods cover the critical growth stages of spring wheat from its sowing to its harvest, as listed in Table 2. Radarsat-2 data in Single Look Complex (SLC) format was utilized in this study.

Synchronous field measurement campaigns were carried out for every satellite overpass. Crop growth status was surveyed including corresponding vegetation and soil biophysical parameters, such as plant height, leaf area index, vegetation water content, and soil moisture, etc. The geographical position was recorded with a Trimble Pathfinder® DGPS with a 50cm-precision. It was found several wheat fields were lodged on August, due to windy and rainy weather. So specifically, the lodging situation was surveyed in its heading (August 3) and ripe (August 27) periods. On August 3, 31 wheat fields were investigated, among which 18 fields grew normally while 13 fields were in different lodging situation. On August 27, 29 wheat fields were surveyed, among which 12 fields have just been harvested, 9 fields were in different status, and the rest 8 fields were normal.

In addition, farmland management data were collected, such as crop planting distribution, sowing dates, crop variety, plant direction, and irrigation data etc. And one automatic meteorological station was installed for collecting meteorology data. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) with 30m resolution was downloaded from http://www.gdem.aster.ersdac.or.jp.

Table 1 Corresponding phonological stages of wheat fields of 5 Radarsat-2 images

Acquisition dates	Phenology stages
2013-05-23	Sowing
2013-06-16	Jointing
2013-07-10	Heading
2013-08-03	Filling
2013-08-27	Ripe

Table 2 Main parameters of 5 Radarsat-2 images

Parameter	Values
Imaging Mode	Fine Quad Polarization
Center frequency	5.405GHz
Incidence angle	37.4 °-38.8 °
Resolution	8m
Orbit direction	Ascending
Beam mode	FQ18
Acquired Time	UTC 09:47:33

2.3 Preprocessing of SAR Image

The five polarimetric Radarsat-2 imagery were processed and analyzed in PolSARPro version 4.2 (from the European Space Agency), Nest version 4A (from the European Space Agency) and Mapready version 3.1 (from the Alaska Satellite Facility), using the procedures show in Fig.2. Radarsat-2 fine quad-pol SLC data were provided as a Stokes matrix for each slant range pixel. Firstly, radiometric calibration were carried out using a look-up table in product file, to transform the digital number of each pixel(amplitude of the backscattered signal for pixel *i*, DN_i) into backscattering coefficient (σ_i^0) (Koppe, *et al.*, 2013). The data were then multi-looked and filtered using a 5×5 boxcar filter to suppress speckle. The filtered SAR images is ingested to form scattering matrix (*S2*), and then converted to a symmetrized 3×3 covariance matrix (*C3*) and coherent matrix (*T3*) which averages the cross-pol backscatter to a single cross-pol value (Lee&Pottier, 2009). Then the dataset were ortho-rectified by DEM-simulation and registration. The 30m ASTER GDEM was used to simulate the SAR image according to its imaging geometry and available orbit information in the metadata, and the real SAR image is matched to the simulated image, warping to the DEM coordinate system (Sheng, *et al.*, 2005; Gens, *et al.*, 2013). After the terrain correction, the dataset were geocoded into Universal Transverse Mercator (UTM) map projection. Finally all the orthorectified dataset reached one pixel accuracy in geographic position. For mathematical details of these procedures, the reader is referred to Boerner *et al.* (1998).

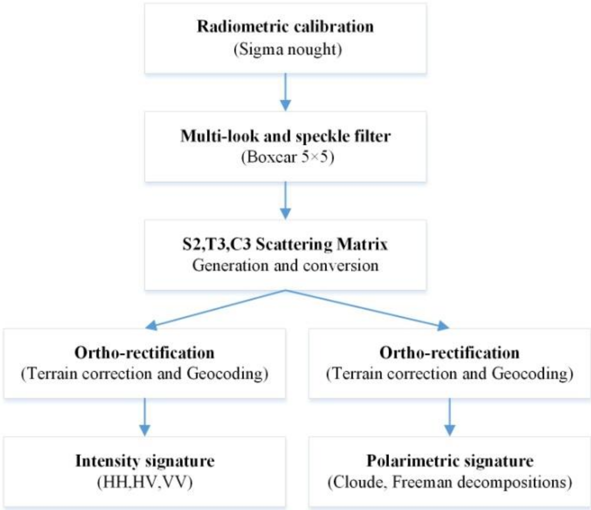


Fig.2 The flowchart of preprocessing of Radarsat-2 data

2.4 Polarization target decomposition techniques

Polarization target decomposition, applied to fully polarimetric SAR data, is an efficient tool for extracting polarimetric features and physical information from the observed scattering of microwaves (Cloude, 2009). Two incoherent polarimetric decompositions were used in this study: the model-based decompositions of Freeman-Durden (Freeman and Durden, 1998), and the eigenvalue decomposition developed by Cloude-Pottier (Cloude and Pottier, 1997).

Freeman-Durden method, as a physical scattering model-based decomposition, decomposes the backscatter response into three categories of volume scattering (noted as Vol) modeled as a set of randomly oriented dipoles, the double-bounce scattering (noted as Dbl) modeled by a dihedral corner reflector, and surface or single-bounce scattering (noted as Odd) modeled by a first-order Bragg surface scatter (Freeman and Durden, 1998). The parameter *span* means the total scattering power in four polarizations.

By contrast, the eigenvalue-based Cloude-Pottier decomposition does not partition the energy into these three processes, but does predict the dominant scattering type and its relevance (Cloude and Pottier, 1997). It decomposes the coherency matrix into different eigenvectors and eigenvalues, which classify and describe the primary scattering mechanisms. Physical information provided by the decomposition is characterized with four variables: entropy (H), alpha ($\overline{\alpha}$), anisotropy (A), and lamda ($\overline{\lambda}$). The entropy, ranging from 0 to 1, represents the randomness of the scattering process from isotropic scattering (H=0) to totally random scattering (H=1), and is theoretically associated with depolarization effects of target features. The alpha angle can be used to discriminate between the three dominant scattering mechanisms. The anisotropy is used to identify the importance of eigenvalues when used complementary to entropy, and independently, they can be used to assess structural and spatial homogeneity of a target. The parameter lamda corresponds to the mean target power (Cloude, 2009).

*2.5 **Feature identification of lodging wheat from time-series SAR data***

Features differences were investigated through the comparison of typical lodging wheat and typical normal wheat, and sensitive features implicit in SAR data for lodging wheat were identified by the comparison of instant fluctuation and time-series trends, in the context of its dynamic change during the whole growth cycle.

Two SAR observables sets were used as potential indicator of lodging wheat: i) backscattering coefficients and their intensity ratio signatures from different polarization channel and ii) polarimetric signatures acquired by polarimetric decompositions. To better overcome the intrinsic speckle effect, backscatter coefficients and other derived parameters were averaged at the wheat parcel level. The average value of image pixel inside a plot will represent the status of this parcel. Two pair, three typical wheat parcels were analyzed, including one normal one (XM10) and two lodging ones (XM04 and XM07, as in Fig.3). According to our field surveys, XM04 and XM07 grew normally from May 23 to July 10, but lodged during July 10 to August 3, while XM10 grew normally in the whole growth stages. The dynamic response behavior of lodging wheat and normal wheat were compared in different features. It should be noted that 3 parcels have similar growing conditions, with the same variety, sowing date, row direction and similar growth conditions such as soil, rainfall, and temperature etc.

*2.6 **Polarimetric index method for lodging monitoring and its validation***

Since the sensitive features of lodging wheat were found in section 2.5, a method called polarimetric index was put forward to monitor lodging wheat. Then the method was validated by two group rest in-situ data, one collected in heading stage, and the other in ripe stage, in Shangkuli Farmland Area.

Fig. 3 Typical lodging wheat fields

3. Results and analysis

*3.1 **Feature identification of lodging wheat from time-series SAR data***

Based on consecutive time-series Radarsat-2 observations, discriminative features of lodging wheat were examined by dynamic contrast analysis between typical lodging wheat field and normal one in the same growth conditions.

Firstly, the backscattering coefficient signature in different polarization was investigated. Fig. 4 presented two group contrast results: XM04 and XM10, XM07 and XM10. In Fig.3, curve lines illustrated the temporal evolution of the backscattering coefficient sigma nought of the wheat fields as a function of days after sowing at HH, HV and VV polarization. And the dash lines indicated XM04 and XM07, which lodged between July 10 and August 3; the solid lines indicated

XM10, which grew normally from beginning to end.

As shown in Fig. 3, before lodging occurred, such as in May 23, June 16 and July 10, there are no distinct difference between lodging ones and normal ones in each polarization; Nevertheless, after lodging occurred, striking difference could be found, especially on August 3 (heading-filling periods), there were remarkable differences between lodging and normal ones in all polarization channels. Specially, for lodging ones, σ^0_{hh} decreased remarkably, while σ^0_{vv} increased (approach to σ^0_{hh}), and σ^0_{hv} increased slightly, compared to normal ones.

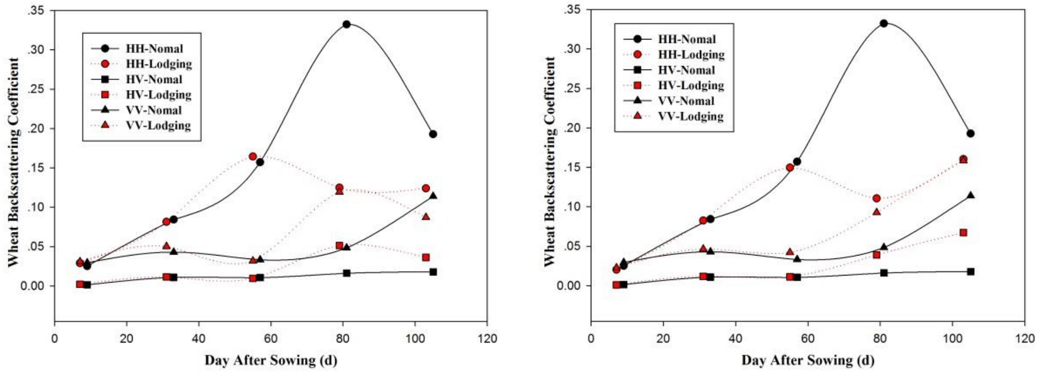


Fig.4 The σ^0 comparison of field XM07 and XM10; the solid lines stand for σ^0change of lodging parcel XM07 over time in different polarization, the dashed lines stand for σ^0change of normal parcel XM10 over time in different polarization.

Secondly, polarimetric signature based on dual-polarization channel was investigated. In this study, we used the ratio of backscattering coefficient in different polarization. Fig. 4demonstratedthe dynamic response behavior of two polarimetric ratios: $\sigma^0_{hh}/\sigma^0_{vv}$ and $\sigma^0_{hh}/\sigma^0_{hv}$. From Fig.5, when the lodging wheat fields (XM04 and XM07) were compared with normal one (XM10), it showed consistent performance in May 23, June 16 and July 10; but after lodging occurred, especially in August 3, it revealed distinct gap between lodging field and normal one.

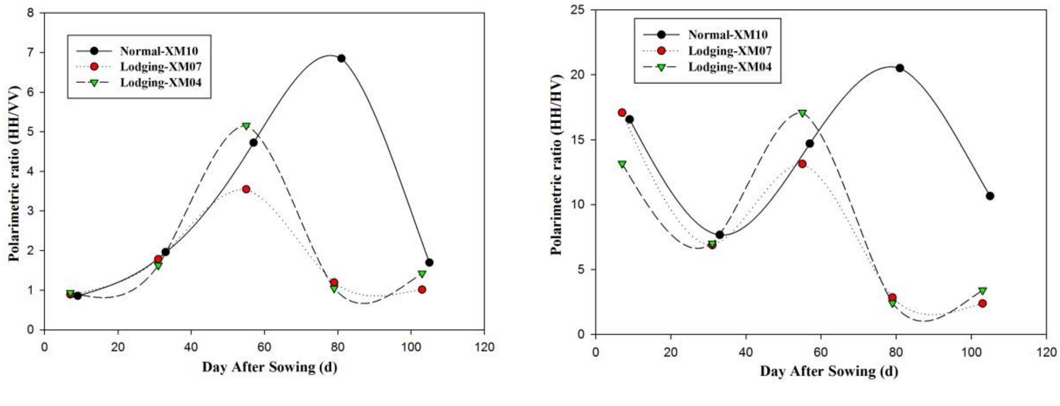


Fig.5 The σ^0 comparison of field XM07 and XM10; the solid lines stand for σ^0change of lodging parcel XM07 over time in different polarization, the dashed lines stand for σ^0change of normal parcel XM10 over time in different polarization.

Moreover, for a more thoroughly understanding of SAR response to lodging wheat, other polarimetric signatures of lodging wheat were examined based on fully polarization SAR data. The Freeman-Durden decomposition and the Cloude-Pottier decomposition techniques were utilized respectively. Firstly, odd scattering, double-bounce scattering, and volume scattering component of wheat fields were obtained relying on Freeman-Durden decomposition method. As an example, Fig.6 (left) illustrated the dynamic evolution of double-bounce scattering over different growth stages. As shown in Fig.6 (left), since lodging occurred in August 3, a great divergence between normal field and lodging field started to appear. Further, we analyzed the contribution ratio of double-bounce scattering in total power, and its dynamic response behavior was presented in Fig.6 (right).With the same pattern as previous, it revealed distinct gap between normal field and lodging field on August 3.

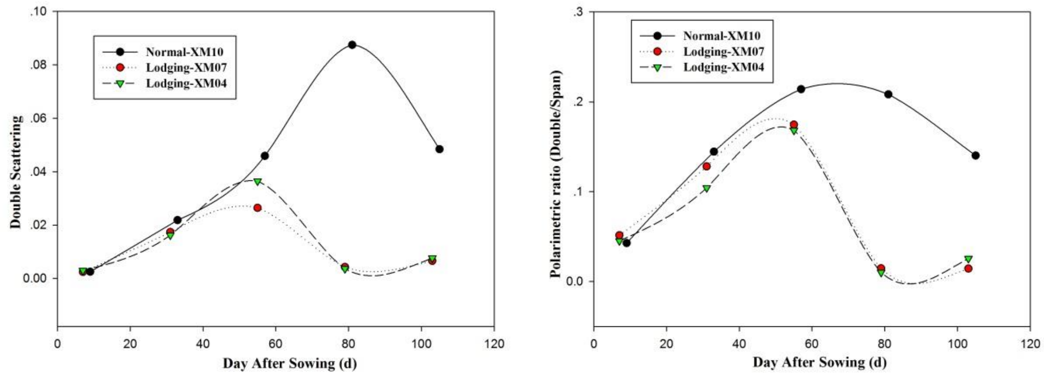


Fig.6 The σ^0 comparison of field XM07 and XM10; the solid lines stand for σ^0change of lodging parcel XM07 over time in different polarization, the dashed lines stand for σ^0change of normal parcel XM10 over time in different polarization.

In addition, we can get polarimetric parameters such as entropy, alpha, lamda, and anisotropy with the Cloude-Pottier decomposition method. Fig. 7 presented the results of entropy and alpha. In Fig. 7, it revealed distinct difference for entropy, but little difference for alpha on August 3 between normal and lodging wheat. As we known, values within 40.0 to 52.5 indicatevolume scattering was the dominant scattering mechanisms (Lee and Pottier, 2009)

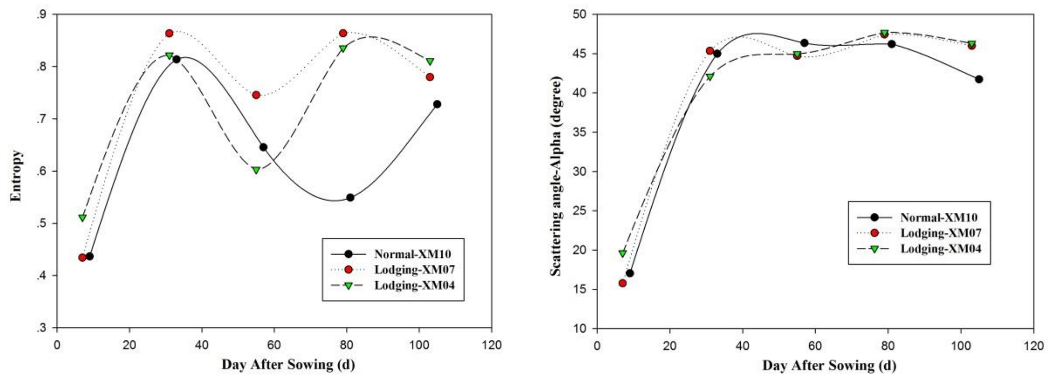


Fig.7 The σ^0 comparison of field XM07 and XM10; the solid lines stand for σ^0change of lodging parcel XM07 over time in different polarization, the dashed lines stand for σ^0change of normal parcel XM10 over time in different polarization.

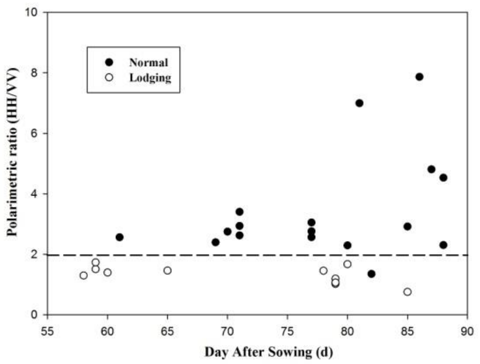
Since the 3 wheat field parcels have the same growth conditions, and the influence from other main factors was eliminated, we can deduce that the difference of lodging fields compared to normal one would be caused by lodging behavior, and the lodging would be the dominant reason for distinct SAR features difference. Therefore, as previous results, polarimetric features are very sensitive to wheat lodging.

*3.2 **Polarimetric index method for lodging monitoring and its validation***

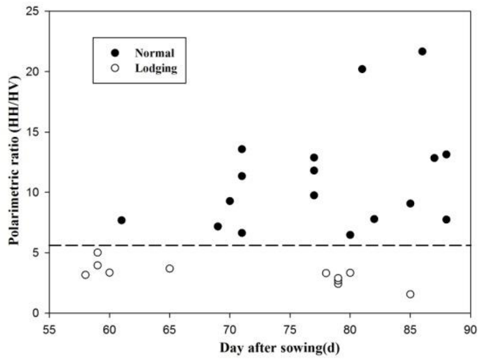
Based on the sensibility of polarimetric features to lodging wheat, a method called polarimetric index was put forward to monitor lodging wheat: the polarimetric index will be used as an indicator, and the situation of lodging field will be determined by the polarimetric index difference when compared with normal wheat field. The polarimetric index in this study is defined as the backscattering ratio in HH and VV polarization ($\sigma^0_{hh}/\sigma^0_{vv}$), or the backscattering ratio in HH and HV polarization ($\sigma^0_{hh}/\sigma^0_{hv}$), or the odd scattering contribution ratio in total scattering (Odd/Span), or the double-bounce scattering ratio in total scattering (Dbl/Span). Polarimetric index is a normalized index, it will not only lessen the influence of environment, crop growth variation, and system bias, but also it will enhance the sensibility to lodging wheat.

The polarimetric index method was validated by two group in-situ data. The first group validation data, including 28 parcels, was collected on August 3. At that time, 17 parcels grew normally, 11 parcels were in different lodging situation. The results of four polarimetric index are shown in Fig. 8. Solid circles indicate normal parcels, while hollow circles indicate parcels in lodging situation on August 3. Fig. 8 indicates the results when polarimetric index is $\sigma^0_{hh}/\sigma^0_{vv}$, $\sigma^0_{hh}/\sigma^0_{hv}$, Double/Span, and Odd/Span, respectively.

As in Fig. 8, almost all the lodging wheat parcels is detected effectively from normal parcels. Circles above the dash line are normal wheat fields, while all the lodging parcels are under the dash line. There are only two exceptional parcels. One normal parcel was under the dash line in Fig. 8(a), however, after the recheck, the wheat vegetation in the parcel turn yellow, and the stalks are thin, the vegetation water content is low, so we deduced that the declination of $\sigma^0_{hh}/\sigma^0_{vv}$ is caused by the enhanced penetrability of SAR signal. Another lodging parcel was above the dash line in Fig.8(c), however, after the recheck, the ratio of lodging region area in the whole parcel was very small.



(a)



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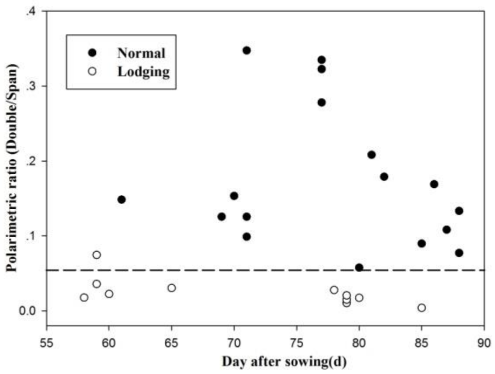
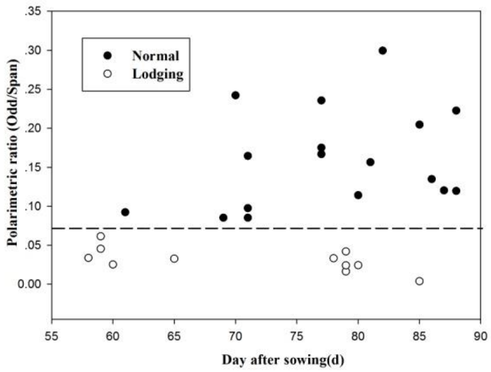


(c)



(d)

Fig. 8 Discrimination results of different polarimetric index on August 3

The second group validation data include 26 parcels on August 27. At that time, 12 parcels have just been harvested, 7 parcels were in different lodging status, and the rest 7 parcels were normal and have not been harvested. The results are shown in Fig. 9. Solid circles represent normal parcels, while hollow circles represent parcels in lodging situation, and triangles represent harvested parcels on August 27. Fig 9 indicates the results when polarimetric index is $\sigma_{hh}^0/\sigma_{vv}^0$, $\sigma_{hh}^0/\sigma_{hv}^0$, Double/Span, and Odd/Span, respectively.

From Fig.9 (a)(b), although all the lodging parcels are separated from normal parcels, the lodging parcels are liable to confuse with harvested parcels. However, from Fig.9(c)(d), not only the Odd/Span, and Dbl/Span polarimetric index can detect lodging parcels from normal parcels, but also it can distinguish lodging parcels and harvested parcels.

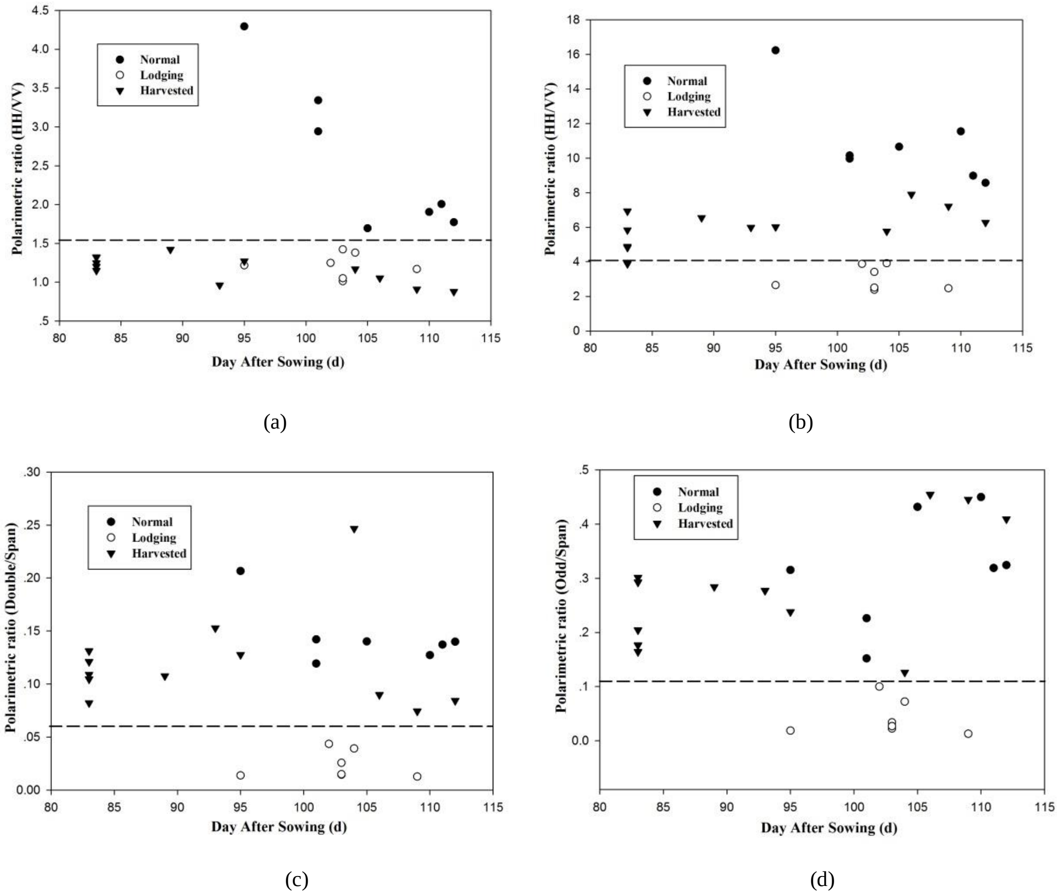


Fig. 9 Discrimination results of different polarimetric index on August 27

By contrast, Fig.10 presented the result only by single channel backscattering coefficient, such as σ_{hh}^0, σ_{hv}^0 and σ_{vv}^0. Although single backscattering coefficient is sensitive to wheat lodging, it doesn't show good ability of identify lodging parcels from normal parcels. That is because σ_{vv}^0 is also influenced by wheat growth, the sensibility of single channel backscattering coefficient is drowned amid the influence of the growth difference. However, the proposed polarimetric index method used ratio instead of absolute power, which reflect the relationship of different polarization channels.

Therefore, our polarimetric index method, especially based on Odd/Span and Dbl/Span, can reflect the intrinsic feature of lodging with good anti-inference ability such as resisting influence of growth difference, vegetation water content and harvest situation, etc.

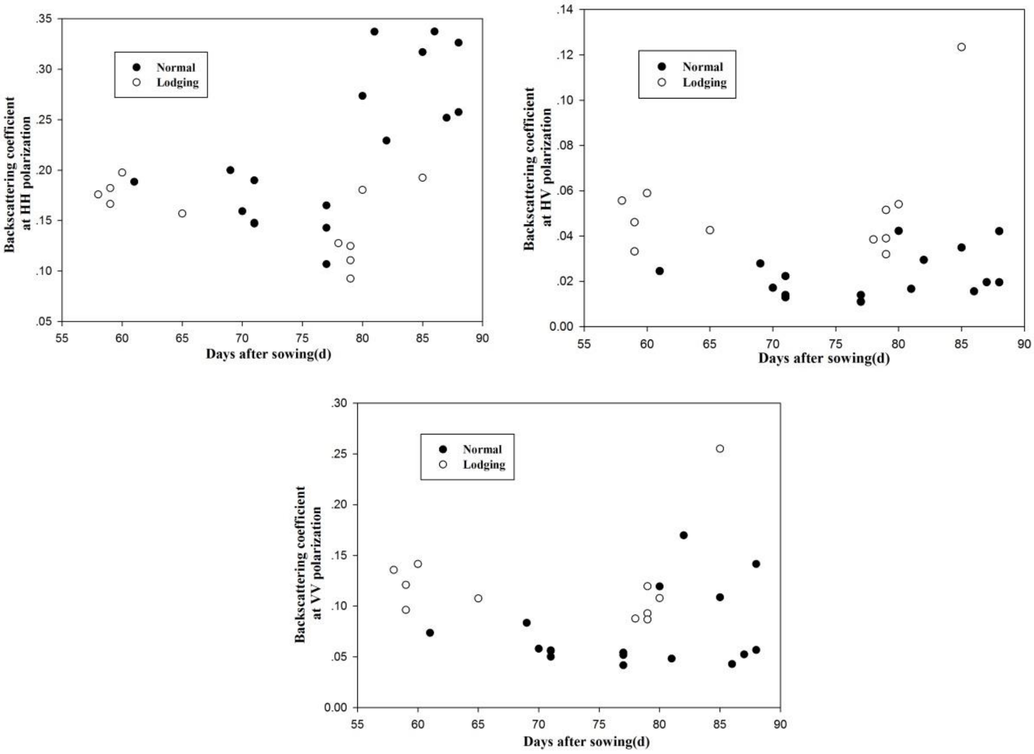


Fig. 10 Discrimination results by single polaration backscattering coefficient on August 3

4. Discussions

4.1 The mechanism and explain for our method

The polarimetric index method proposed takes the full advantage of the sensibility of SAR polarimetric features to structure change of lodging wheat. The sensibility comes from structural characteristics of wheat and polarization characteristics of SAR.

In fact, crop lodging behavior is mainly reflected in structure change of its vegetation. For normal wheat vegetation, one obvious vegetation structure feature can be found that it's vertical-oriented. Wheat stalks grow uprightly, and the leaves lean slightly and are slender, especially in the later stages. However, once wheat lodging occurs, this vertical-oriented structure feature is destroyed immediately.

Since its particular structure, it brings backscattering difference at different polarization. When the electromagnetic wave diffuses to the normal wheat vegetation, the electric field with vertical-orientated vibration will enter the vertical-orientated wheat and induce inner particles into polarization which will produce electric current. Then the electric current will be attenuated because a transmission path appears in the vertical structure wheat. It will lead to the energy loss of electromagnetic waves within wheat vegetation, so the backscattering energy in VV polarization (σ_{vv}^0) would be smaller than the one in HH polarization (σ_{hh}^0). Similar phenomenon was observed in other researches (Bouvet, *et al.*, 2009; Larranaga, *et al.*, 2013; Zhang, *et. al.* 2014).

When wheat lodging occurs, the situation changes to opposite side. The σ_{hh}^0 will decline due to attenuation and σ_{vv}^0 will increase. Moreover, for cross polarization, σ_{hv}^0 will increase due to the enhancement of multiple scattering. Therefore the polarimetric index based on backscattering intensities ratio presents the sensibility to lodging wheat.

Furthermore, the lodging procedure is accompanied by scattering mechanism changes. The volume scattering will increase since lodging brings more multiple scattering. The double-bounce scattering, which is modeled by a dihedral corner reflector, mainly comes from the dihedral scattering by wheat stalks and ground surface. Once the wheat lodging occurs, the dihedral corner disappeared, and the double-bounce scattering will decline. Meanwhile lodging results in more rough surface for SAR observation, the surface component from Bragg scattering will decrease. Therefore, the polarimetric index based on Freeman-Durden decomposition also presents the sensibility to lodging wheat.

In addition, the proposed polarimetric index is a normalization ratio index, it will enhance the sensibility and reduce the effect by absolute total power. It will eliminate the influence the growth.

4.2 Comparison with optical remote sensing method

Optical sensors have advantage in detecting the biochemical change of lodging vegetation such as pigment variation(Liu, *et al.*, 2005), while radar instruments own advantage in reflecting the structural change of lodging vegetation. Structural change is one of the most obvious features for lodging wheat. When optical remote sensing relies on its spectral feature to monitor lodging, the proposed method based on radar data uses its polarimetric features to monitor lodging. Polarimetric feature is unique in radar remote sensing when compared to optical remote sensing. Although optical remote sensing owns polarization attributes theoretically, it is difficult to demonstrate polarization phenomenon due to the chaotic and passive nature light source (Vanderbilt, *et al.*, 1985). However, radar imaging comes from active light source, polarimetric observation can be generated by controlling polarization direction autonomously when emitted and received (Ulaby et *al.*, 1986).

4.3 The existing issues and future development

The preliminary result presented in this paper showed great potential in monitoring wheat lodging by SAR data. However, the study area is relatively simple with large and homogeneous fields. There are still several issues towards operational application in complex and fragmented agricultural areas. The monitor result may be affected by harvest status, vegetation water content, topography, and soil moisture etc. And more importantly, some scientific question is in urgent need for further study:

1) It is necessary to establish quantitative models to monitor quantitatively its severity level of lodging, such as the lodging angle and lodging extent. It will help to understand the effect of wheat lodging to crop production;
2) It will encounter classical mixed pixel problem in the case that the lodging area is smaller than the area of one pixel, in consideration of heterogeneous lodging;
3) We should explore further other more efficient features, which is only sensitive to crop lodging but not affected by crop growth condition and SAR observation configuration.

5. Conclusions

The potential capability of radar remote sensing for monitoring wheat lodging was explored in this study. The response behavior of different SAR observables from time-series Radarsat-2 observation data for lodging wheat was examined as a function of days after sowing. The discriminative features were identified through the comparison of normal and lodging fields. It was found that polarimetric features, such as the backscattering intensities and scattering components from polarimetric decompositions, were very sensitive to the lodging of wheat. The sensitivity was caused by unique structure characteristics of vertical-oriented wheat and instinctive polarization characteristics of SAR. Then a polarimetric index method for monitoring wheat lodging was proposed based on the sensitivity. The method was validated by two sets of in-situ data collected in wheat heading and ripe periods in Shangkuli Farmland area, Inner Mongolia, China. The results revealed that it has excellent separate ability for lodging wheat and normal wheat. In addition, in contrast to other methods, it showed that this method own anti-interference ability especially for growth difference, and can describe the intrinsic feature of lodging.

Although some other aspects should be considered in a final application, it has been proven that radar remote sensing has great potential for crops lodging monitoring. Considering that available means for monitoring crops lodging in large area is very limited, this study provides a new method for monitoring wheat lodging spatially. The method will have a promising application in the future since its simplicity and effectiveness.

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