Estimation of rice biophysical parameters using multi-temporal RADARSAT-2 images

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Abstract. Compared with optical sensors, synthetic aperture radar (SAR) has the capability of acquiring images in all-weather conditions. Thus, SAR images are suitable for using in rice growth regions that are characterized by frequent cloud cover and rain. The objective of this paper was to evaluate the probability of rice biophysical parameters estimation using multi-temporal RADARSAT-2 images, and to develop the estimation models. Three RADARSAT-2 images were acquired during the rice critical growth stages in 2014 near Meishan, Sichuan province, Southwest China. Leaf area index (LAI), the fraction of photosynthetically active radiation (FPAR), height, biomass and canopy water content (WC) were observed at 30 experimental plots over 5 periods. The relationship between RADARSAT-2 backscattering coefficients ($\sigma^0$) or their ratios and rice biophysical parameters were analysed. These biophysical parameters were significantly and consistently correlated with the VV and VH $\sigma^0$ ratio ($\sigma^0_{VV}/\sigma^0_{VH}$) throughout all growth stages. The regression model were developed between biophysical parameters and $\sigma^0_{VV}/\sigma^0_{VH}$. The results suggest that the RADARSAT-2 data has great potential capability for the rice biophysical parameters estimation and the timely rice growth monitoring.

1. Introduction

Rice is an important crop in China, producing approximately one-third of the global rice crop [1,2]. Timely monitoring of rice growth is necessary for precision farming and sustainable agricultural development. Mapping of rice planted area and monitoring of rice growth has been widely studied using remote sensing data at a large scale. Synthetic aperture radar (SAR) has become an important data source for rice studies because of its all weather and day-night observation capabilities [3,4]. Optical remote sensing data acquisitions are challenged in tropical and subtropical areas where rainfall and cloud cover are frequent.

Over the past decades, a number of experiments have been conducted in order to study the correlation of different radar observables to rice biophysical parameters. Inoue et al. (2002) indicated that the C-band $\sigma^0$ may be most useful for estimating the leaf area index (LAI) and biomass by analyzing a comprehensive dataset of backscattering coefficients in five frequency bands (Ka, Ku, X, C, and L), with full polarizations (VV, VH, HV, HH), and four incidence angles (25°, 35°, 45°, 55°)
during a full growing-period of paddy rice [5]. Wang et al. (2009) developed a rice canopy scattering model to examine the L-band radar backscatter in paddy rice fields with PALSAR imagery. Their results showed that L-band HH backscatter was more sensitive to rice structural variation than the VV backscatter and may therefore be more useful in rice mapping and modelling studies [6]. Inoue et al. (2014) examined the consistency of a high-resolution C-band SAR sensor for rice crop monitoring. The results suggested that C-band SAR was suitable for assessing leaf area index (LAI) or fractional photo-synthetically active radiation (FPAR), showing promise for monitoring rice growth with radar alone or in combination with optical sensors [7]. Inoue et al. (2013) explored some unique capabilities of X-band satellite SAR sensors for the assessment of rice growth and yield [8]. Inoue et al. (2014) examined the capabilities and differences of two high-resolution X-band SAR sensors for rice monitoring [9]. Most studies focussed on the rice growth stages and utilized predominantly single polarization SAR data to retrieval biophysical parameters. More research and experimentation is needed to examine the radar response at each growth stage, such as transplanting, tillering, and heading.

The objective of this paper is to validate the capability of estimating rice biophysical parameters using RADARSAT-2 images. LAI, FPAR, plant height, biomass, and canopy water content of rice were measured over the transplanting, tillering, and heading growth stages for a test site near Meishan city in Sichuan Province, China. Three RADARSTA-2 images were acquired during critical rice growth stages. The relationship between RADARSAT-2 $\sigma^0$ or their ratios and rice biophysical parameters were analyzed. The regression models were developed.

2. Data and methods

A study area was selected near Meishan city, Sichuan Province, Southwest China. The area is located within the Chengdu Plain where rice is a major crops. The areas for rice cropping are often fragmented by vegetable plots, by roads, and by human settlements. Under prevailing subtropical weather conditions, more than two-thirds of a year are rainy and cloudy. Most of the rice in the area is transplanted in early May, tillering takes place between late May and early June, and heading occurs in late June; the crop is harvested in the second half of August.

The ground-based measurement were made every 12 days from May 26 to July 13, 2014 at 30 rice fields with a width and a length of at least 50 m, as shown in figure 1. These five observation dates represent three growth stages: transplanting, tillering, and heading growth stages for a test site near Meishan city in Sichuan Province, China. Three RADARSTA-2 images were acquired during critical rice growth stages. The relationship between RADARSAT-2 $\sigma^0$ or their ratios and rice biophysical parameters were analyzed. The regression models were developed.

Rice LAI, FPAR, plant height, biomass, and canopy water content were measured in these experimental plots. The location of each plot was determined by means Global Positioning System (GPS) data collection. The LAI was measured with the LAI2200 plant canopy analyzer. FPAR was measured with the SUNSCAN canopy analysis system. Plant height was measured for each plot. Canopy water content was calculated by the wet and dry weight of rice canopy samples. Biomass was measured by dry weight of rice. In each field plot, three representative positions were chosen, and in every position, two repeated measurements were executed, then the mean value was calculated.

Three fine quad-polarization (SLC mode) RADARSAT-2 SAR images were acquired on May 26, June 19, and July 13 in 2014 with a 24-day repeat cycle. The pixel size of the RADARSAT-2 SLC images is 12 m by 8 m, and the incidence angle range is from 20 degrees to 41 degrees. The swath width of the image is about 25 km. The European Space Agency (ESA) SAR Toolbox (NEST) was used to convert the image data to $\sigma^0$ signatures based on the radiometric parameters provided for each dataset [10]. A $3 \times 3$ enhanced Lee filter was utilized to reduce speckle noise inherent in the SAR images, and all images were geo-referenced using ground control points determined by GPS measurements. In this study, the absolute $\sigma^0$ values of HV and VH were similar for the RADARSAT-2 data, so only $\sigma^0_{VH}$ was used to represent cross-polarization [11].
Figure 1. RADARSAT-2 SAR image of the entire study area, with location of experimental plots indicated. (RADARSAT-2 data © MacDonald Dettwiler and Associates, 2014)

Figure 2. Examples of rice canopies in the study area during the transplanting stage on May 26 (a), on June 7 (b); during the tillering stage on June 19 (c); and during heading on July 1 (d) and July 13 (e)
3. Results

3.1 The relationship between RADARSAT-2 $\sigma^0$ and rice biophysical parameters

The relationship between biophysical measurements and $\sigma^0$ values of HH, VV, VH backscattering polarization and their ratios was determined using the single-date and multi-temporal RADARSAT-2 data. Table 1 shows the Pearson correlation coefficients between rice biophysical parameters, i.e., LAI, FPAR, biomass, height (h) and water content (WC) and the single RADARSAT-2 $\sigma^0$ or their ratios at different stages. The response of each polarization to the rice biophysical parameters was different. At the transplanting stage (May 26), only LAI and FPAR were correlated with the ratio of $\sigma^0_V$ and $\sigma^0_V$, as shown in table 1. At this stage, scattering from the rice canopy was very limited; water is generally the factor that influences the relationship between rice biophysical parameters and $\sigma^0$.

Table 1. The Pearson correlation coefficients between $\sigma^0$ and rice biophysical parameters on May 26

|          | LAI    | FPAR   | Biomass | H      | WC    |
|----------|--------|--------|---------|--------|-------|
| $\sigma^0_{HH}$ | 0.049  | -0.039 | 0.017   | 0.018  | -0.078|
| $\sigma^0_{VV}$ | -0.214 | -0.262 | -0.194  | 0.029  | -0.220|
| $\sigma^0_{VH}$ | 0.010  | 0.000  | -0.031  | 0.146  | -0.155|
| $\sigma^0_{HH}/\sigma^0_{VV}$ | -0.268 | -0.160 | -0.087  | 0.029  | -0.106|
| $\sigma^0_{HH}/\sigma^0_{VH}$ | -0.022 | 0.113  | 0.075   | 0.100  | 0.030 |
| $\sigma^0_{VV}/\sigma^0_{VH}$ | 0.390* | 0.490**| 0.341   | 0.150  | 0.228 |

**p<0.01, *p<0.05, n=30

Table 2. The Pearson correlation coefficients between $\sigma^0$ and rice biophysical parameters on June 19

|          | LAI    | FPAR   | Biomass | H      | WC    |
|----------|--------|--------|---------|--------|-------|
| $\sigma^0_{HH}$ | -0.655**| -0.765**| 0.125   | 0.014  | -0.148|
| $\sigma^0_{VV}$ | -0.421* | -0.485**| 0.219   | -0.005 | -0.165|
| $\sigma^0_{VH}$ | -0.358  | -0.357 | 0.322   | 0.109  | -0.099|
| $\sigma^0_{HH}/\sigma^0_{VV}$ | 0.653**| 0.763**| 0.001   | -0.037 | 0.054 |
| $\sigma^0_{HH}/\sigma^0_{VH}$ | 0.666** | 0.822**| 0.052   | 0.043  | 0.105 |
| $\sigma^0_{VV}/\sigma^0_{VH}$ | 0.197   | 0.308  | 0.095   | 0.152  | 0.124 |

**p<0.01, *p<0.05, n=30

Table 3. The Pearson correlation coefficients between $\sigma^0$ and rice biophysical parameters on July 13

|          | LAI    | FPAR   | Biomass | H      | WC    |
|----------|--------|--------|---------|--------|-------|
| $\sigma^0_{HH}$ | -0.574**| 0.022   | 0.332   | -0.062 | -0.099|
| $\sigma^0_{VV}$ | -0.531**| -0.041  | 0.266   | -0.110 | 0.051 |
| $\sigma^0_{VH}$ | -0.588**| 0.072   | 0.225   | 0.006  | -0.117|
| $\sigma^0_{HH}/\sigma^0_{VV}$ | 0.379* | -0.111 | -0.241  | -0.035 | 0.245 |
| $\sigma^0_{HH}/\sigma^0_{VH}$ | 0.360   | 0.034  | -0.273  | 0.123  | 0.055 |
| $\sigma^0_{VV}/\sigma^0_{VH}$ | 0.017   | 0.150  | -0.102  | 0.201  | -0.237|

**p<0.01, *p<0.05, n=30
Table 4. The Pearson correlation coefficients between $\sigma^0$ and rice biophysical parameters, involving all three stages of rice plant growth.

|               | LAI     | FPAR    | Biomass | H       | WC      |
|---------------|---------|---------|---------|---------|---------|
| $\sigma^0_{HH}$ | 0.036   | 0.138   | 0.167   | 0.136   | 0.061   |
| $\sigma^0_{VV}$ | -0.421**| -0.374**| -0.209* | -0.320**| -0.173  |
| $\sigma^0_{VH}$ | 0.336** | 0.434** | 0.439** | 0.446** | 0.088   |
| $\sigma^0_{HH}/\sigma^0_{VV}$ | -0.398**| -0.490**| -0.396**| -0.455**| -0.230* |
| $\sigma^0_{HH}/\sigma^0_{VH}$ | 0.246*  | 0.185   | 0.132   | 0.177   | -0.001  |
| $\sigma^0_{VV}/\sigma^0_{VH}$ | 0.751** | 0.798** | 0.625** | 0.746** | 0.271** |

**p<0.01, *p<0.05

Figure 3. The relationship between $\sigma^0_{VV}/\sigma^0_{HH}$ and rice biophysical parameters
At the tillering stage (June 19), LAI and FPAR are strongly correlated with $\sigma_{HH}^0$ and $\sigma_{VH}^0$, the ratio of $\sigma_{HH}^0$ and $\sigma_{VH}^0$, and the ratio of $\sigma_{HH}^0$ and $\sigma_{VV}^0$, as shown in table 2. At this stage, rice growth progresses well, and radar backscatter measurements can be obtained for LAI and FPAR retrieval.

At the heading stage (July 13), only LAI was correlated with the $\sigma_0^0$, as shown in table 3. One possible reason for this is that the thick rice leaves, stalk and panicle affect the radar signal. The backscatter measurements $\sigma_0^0$ were often saturated at this growth stage.

The single-date radar image analysis was difficult for rice biophysical parameters estimation. The radar backscatter measurement for rice is largely affected by the different planting dates, rice varieties, and management activities. Multi-temporal satellite image analysis revealed the temporal variation of radar backscatter for rice, which is closely related to biophysical increase along rice growth [6].

Except canopy water content, the other rice biophysical parameters were correlated well with the $\sigma_{VV}^0 / \sigma_{VH}^0$, as shown in table 4. All the rice biophysical parameters were significantly and consistently correlated with the ratio of $\sigma_{VV}^0 / \sigma_{VH}^0$.

3.2 Regression model development

The regression model were developed using rice biophysical parameters and $\sigma_{VV}^0 / \sigma_{VH}^0$ of multi-temporal RADARSAT-2 image. Figure 3 shows the regression model and correlation coefficients, demonstrating that $\sigma_{VV}^0 / \sigma_{VH}^0$ can estimate rice biophysical parameters well. The scatter plots between $\sigma_{VV}^0 / \sigma_{VH}^0$ and LAI, FPAR, biomass and height indicate consistent relationships throughout all growth stages. Data points are plotted along the similar fitted lines for a single stage. These relationships produce exponential curves with high coefficients of determination ($R^2$).

\[
\text{LAI} = 0.0085 \times \exp[9.1481 \times \frac{\sigma_{VV}^0}{\sigma_{VH}^0}] \quad R^2=0.6072
\]

\[
\text{FPAR} = 3.1871 \times \frac{\sigma_{VV}^0}{\sigma_{VH}^0} - 1.3363 \quad R^2=0.6372
\]

\[
\text{Biomass} = 5665.3 \times (\frac{\sigma_{VV}^0}{\sigma_{VH}^0})^{7.0989} \quad R^2=0.5663
\]

\[
h = 0.0174 \times \exp[5.8144 \times \frac{\sigma_{VV}^0}{\sigma_{VH}^0}] \quad R^2=0.5808
\]

Canopy water content did not correlate with $\sigma_{VV}^0 / \sigma_{VH}^0$; rice canopy water status cannot be directly detected by RADARSAT-2 $\sigma_0^0$ or their ratios under flood irrigation conditions.

4. Discussion

The sensitivity of radar backscatter with regard to rice growth at different polarizations is well known [6]. This study demonstrated clear and consistent relationships between RADARSAT-2 $\sigma_0^0$ and rice biophysical parameters, especially in regard to $\sigma_{VV}^0 / \sigma_{VH}^0$ and rice LAI, FPAR, biomass and height. Although the correlation coefficients can be affected by the amount of available radar data, our results suggest that there is a high potential of RADARSAT-2 data for monitoring rice growth in a timely fashion. However, several approaches would be useful to further enhance the potential for operational applications.

Figure 4 shows the temporal and spatial variation of LAI ground measurement. At the beginning of rice growth, the parameters change quickly. The 24-day repeat cycle RADARSAT-2 data cannot satisfy this need. More ground observation and more SAR data are needed to obtain accurate results for rice biophysical parameter retrieval. The radar backscattering signatures of rice fields are determined and influenced by many factors, for example plant biomass, canopy structure, water content and soil moisture. The SAR satellite sensor frequency, polarization, and incidence angle, strongly affect backscattering coefficients [4]. Physical models are useful for backscatter simulation and rice biophysical parameters retrieval. Relatively simple model can support rice crop interpretation, and more sophisticated models can improve predictive capabilities rice biophysical parameters estimation [7].
5. Conclusion

Based on the backscattering coefficients of three RADARSAT-2 images and rice biophysical parameters obtained during the growing season from 30 experimental sites in the Meishan study area, Sichuan Province, China, statistical relationships of RADARSAT-2 backscatter coefficients were analyzed and regression models were developed. The rice LAI, FPAR, biomass and height were significantly and consistently correlated with the VV and VH $\sigma^0$ ratio ($\sigma^0_{VV}/\sigma^0_{VH}$) throughout the main growth stages. The regression models were developed for biophysical parameters and $\sigma^0_{VV}/\sigma^0_{VH}$. The results suggest that the RADARSAT-2 data has high potential for rice biophysical parameters estimation and timely rice growth monitoring.

The preliminary results show that the biophysical parameters can be estimated over the rice growing season using high spatial resolution C-band SAR data. This study further demonstrated the capacity of C-band SAR to estimate biophysical parameters in rice transplanting, tillering for the entire growth season despite some limitations.

6. References

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