International Journal of Applied Earth Observation and Geoinformation 28 (2014) 170–180

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Retrieving canopy height and density of paddy rice from Radarsat-2 images with a canopy scattering model

Yuan Zhang[a,*], Xiaohui Liu[b], Shiliang Su[c], Cuizhen Wang[d]

[a] Key Laboratory of Geographical Information Science, Ministry of Education, East China Normal University, Shanghai 200241, China
[b] Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, CAS, Changchun 130102, China
[c] School of Resource and Environmental Sciences, Wuhan University, Wuhan 430079, China
[d] Department of Geography, University of South Carolina, Columbia, SC 29208, USA

ARTICLE INFO

Article history:
Received 12 September 2013
Accepted 3 December 2013

Keywords:
Radarsat-2
Canopy scattering model
Paddy rice
Canopy height and density

ABSTRACT

Quantification of rice biophysical properties is important not only for rice growth monitoring and cropping management, but for understanding carbon cycle in agricultural ecosystems. In this study, a rice canopy scattering model (RCSM) was firstly utilized to simulate rice backscatter with a root mean square error (RMSE) <1 dB in comparison with the C-band, HH-polarization Radarsat-2 images. And then, by integrating the model with a generic algorithm optimization tools (GOAT), canopy height and density were separately retrieved from Radarsat-2 images acquired in three rice growth stages (elongation stage, heading stage and yellow ripening stage). Accuracy analysis showed that the two parameters could be retrieved with the RMSE of 5.4 cm in height, and 26 (#/m^2) in density. The study demonstrated the potential of Radarsat-2 SAR data for quantitative mapping of biophysical parameters of paddy rice.

1. Introduction

Rice cropping is one of the major agricultural activities in China. Rapid population growth demands higher rice production. In South and Southeast China, agricultural land use has been dramatically replaced by urban build-ups accompanying fast economic development in the past decades (Lin and Ho, 2003; Wu et al., 2009; Su et al., 2011). Croplands for rice cultivation in Northeast China, however, have been increasing since the 1990s (National Bureau Statistics of China, 1990, 2000, 2013; Zhang et al., 2012). Single-season paddy rice is the staple food crop and is widely planted in Northeast China (Frolking et al., 2002). Accounting for 14% of the country's total rice cropping areas, this region has become one of major food providers in China (National Bureau Statistics of China, 2013). Therefore, real-time, reliable rice monitoring in this region has particular significance for steady food provision for the country.

Monitoring rice production with remote sensing technique has been widely carried out in many countries of Southeast Asia (Fang, 1998; Okamoto and Kawashima, 1999; Xiao et al., 2005; Nuarsa et al., 2012). However, frequent cloud cover and rainfall during rice growth season are often challenging to optical remote sensing. Synthetic aperture radar (SAR), due to its all-weather, day-and-night observation capabilities, becomes an important alternative in rice studies (Panigrahy et al., 1999; Oza et al., 2008; Zhang et al., 2011). Many SAR systems have been launched in the past two decades, including ERS-1/2 (launched in 1991/1995), JERS-1 (1992), RADARSAT-1/2 (1995 and 2007), ENVISAT (2002), ALOS-PALSAR (2006), TerraSAR and COSMO-SkyMed (2007). Acquired from these sensors, multi-temporal, multi-polarization SAR images have been widely employed to map rice planting area and to monitor rice growth (Le Toan et al., 1997; Ribbes and Le Toan, 1999; Shao et al., 2001; Li et al., 2003; Chakraborty et al., 2005; Zhang et al., 2009; Bouvet and Le Toan, 2011; Yonezawa et al., 2012; Koppe et al., 2013).

Radar backscatter depends on geometric and physical features of scatterers interacting with SAR signal (Inoue et al., 2002). Previous studies indicate that rice biophysical attributes, e.g. leaf area index (LAI), fresh biomass, and plant height, are closely correlated with backscattering coefficients (Shao et al., 2002; Chen et al., 2006; Wang et al., 2009). Canopy height and density are the two fundamental biophysical attributes of rice development and control factors to estimate biomass. Spatio-temporal variations in rice canopy height and density at different growth stages are closely related to total leaf area of rice paddy that can be reflected by corresponding SAR images. Therefore, modeling the radiative transfer of SAR beam within rice canopy is important to better understanding the rice canopy scattering mechanism.

A limited number of canopy scattering models have been developed to simulate radar backscatter characteristics of paddy rice (Tsang et al., 1995; Wang et al., 2005, 2009). The temporal variation

* Corresponding author. Tel.: +86 2154341231; fax: +86 2154341231.
E-mail address: yuan.zhang75@gmail.com (Y. Zhang).

0303-2434/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jag.2013.12.005

of the radar backscatter for rice was simulated by a first-order solution of the radiative transfer equation. The modeling results were in good agreement with that observed from X-band SAR images of HH and VV polarizations (Le Toan et al., 1989). Also, a coherent scattering model with analytic wave theory was developed for calculating the backscatter from the rice canopy, the simulation results effectively interpreted the C-band Radarsat HH data for incident angles at 23° and 43° (Wang et al., 2005).

However in these above-mentioned models, rice ear was not considered/described in the scattering components of rice canopy, so they were rarely investigated at the heading stages. A rice canopy scattering model (RCSM) were developed based on first-order radiative transfer equation by simulating rice ears and stems as thin dielectric cylinders, and leaf as elliptical disks over a dielectric half-space (Wang et al., 2009). Although the model have a potential to simulate temporal L-band radar signals at various polarization mode (HH, HV and VV) for rice backscatter, the modeled backscatter coefficients (HH and HV) in sample fields did not match so well with that observed from two ALOS/PALSAR data (error of ~3 dB). Therefore, there is a pressing need to modify this microwave scattering model for accurately simulating the scattering characteristics of rice canopy at various rice growth stages.

By taking into account the structural variation of rice plants and rice fields and the coherence or phase interference between vegetative elements, identical possibility distribution function (PDF) was used for describing the leaf orientation at different growth stages was questionable. Furthermore, ground surface should not be constantly treated as a smooth water surface during the whole growth season. There was a large difference in dielectric constants of rice fields between flooding period and after drainage. From the near maturity to harvest, moisture content of rice fields decreased gradually without taking into occasional rainfall events account. This kind of variability would inevitably influence the total canopy scattering. This could explain the large simulation error at rice heading stage that reported in Wang et al. (2009). As a continuing step of Wang et al.'s work, the PDFs of rice leaves of RCSM corresponding to different growth stages would be separately constructed. When rice canopy parameters (height and density) were retrieved, changes in structure parameters and dielectric properties of rice fields would also be adjusted and be assigned in RCSM (see detail in Section 2.3.1). Nowadays, C-band SAR image is the most prevalent and commonly used microwave radar remote sensing data. This study aims to extend the application of RCSM for simulating the interaction of multi-frequency radar signals with rice canopy, and further demonstrate the potential practicability of SAR remote sensing in rice monitoring.

In this present study, three Radarsat-2 SAR images covering a representative production area in Northeast China were acquired in three rice growth stages. The study object is to (1) test the performance of RCSM simulation for C-band backscatter returns and then, (2) quantitatively estimate and map canopy height and density of paddy rice via model inversion.

2. Datasets and methods

2.1. Study area

The study area is located in Dengta City of Liaoning Province, one of the three provinces in the Northeast China (Fig. 1). As a portion of the Liaohe River Plain, it is one of the major rice cropping areas in China. Centered at 123.32° E, 41.42° N, the study area covers a total area of 1.35×10^5 hectare (ha) with a typical temperate monsoon climate. It lies at <50 m geographic elevation above sea level with a gentle and flat topographic relief. Single-season paddy rice is dominant in this area with its growing season from late May to early October. In one growth cycle, five major development stages of rice can be observed: (1) transplanting (late May): seedlings in seedbeds are transplanted into fields; (2) tillering (June): seedlings split up and begin to develop a root system; (3) ear differentiation (early August): ear starts to reproduce; (4) heading (mid August to late September): heads begin to form; and (5) maturing (early October): ears ripen and are ready to harvest. Two major rivers, Hunhe River and Taizihe River, flow through the Plain and feed croplands with abundant water for food production. Unlike the fragmented agricultural lands in southeast China (Wang et al., 2009), total of 2.75×10^4 ha farmlands in Dengta with regular shapes are cultivated as rice plantation. The flat topography and extensive fields make this area favorable for experimental studies of SAR remote sensing in rice monitoring.

2.2. Datasets

2.2.1. Remotely sensed imagery

As shown in Fig. 1, fine beam mode, dual-polarization (HH&HV) Radarsat-2 SAR images were acquired on Jul. 28, Aug. 21, and Sep. 14, 2011. These three dates represent three rice growth stages: elongation, heading and yellow ripening, respectively. The spatial resolution of the images is 10 m with an incidence angle of 34° at the center of the 50 km swath. The SAR imagery processing software, Next ESA SAR Toolbox (NEST) 4B-1.1 (http://nest.array.ca/web/nest) was utilized for reading, pre-processing, and analyzing Radarsat-2 SAR data. A 3 × 3 Gamma-MAP filter (Lopes et al., 1990) was utilized to suppress speckle noises inherent in the SAR images. After radiometric calibration and reprojection, backscattering coefficient (σ°) of each pixel was finally extracted. The output images were resampled to 30 m resolution with the nearest neighbor algorithm using a window size of 3 × 3 to reduce noises in the preprocessing steps above. Three backscattering coefficient maps were separately taken as inputs for retrieving rice parameters at each growth stages.

Two clear scenes of Landsat-7 ETM+ images (Fig. 2A and B) were acquired on Jun. 20 and Sep. 24, 2011 (i.e. transplanting and maturation stage), which were downloaded from the EarthExplorer (http://edcsns17.cr.usgs.gov/EarthExplorer/). Although the ETM+ system has been suffering the malfunction of its scan line corrector (SLC) loss since May 2003, the SLC-off data gaps have less impact on the scene center where the study area is located. The Principal Components Transform (PCT) technique was used to fuse the 30-m multi-spectral bands and the 15-m panchromatic band of these ETM+ images (Welch and Ehlers, 1987). The two ETM+ images were then geographically registered to the Radarsat-2 SAR images with error of <15 m. As shown in Fig. 2, paddy fields in these three dates can be easily identified. Via visual interpretation, the pan-sharpened image was digitized in ArcGIS 9.3 to extract paddy rice fields in the study area.

Most paddy fields were large and in regular shapes, and were extensively distributed over the study area. A few small, fragmented parcels were only observed in the Southwest and the Southeast. The spatial distribution of paddies within this study area in 2011 was digitized by visual interpretation from the two clear ETM+ images (Fig. 2C). Taking the study object into account, the on-screen digitization process was rigorously controlled at the boundary area of rice fields. Mixed pixels on the field boundary were excluded, and only those fields containing "pure" rice pixels were abstracted. Thus the derived rice field map have the highest user's accuracy (100%) although a slight low producer's accuracy. It was observed that total 85 measurement fields in three field campaigns were correctly and precisely delineated. These digitized data then served as a mask map to exclude non-rice lands from Radarsat-2 SAR composition (Fig. 2D).