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Estimation of rice grain yield from dual-polarization Radarsat-2 SAR data by integrating a rice canopy scattering model and a genetic algorithm

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ABSTRACT

Fast and accurate estimation of rice yield plays a role in forecasting rice productivity for ensuring regional or national food security. Microwave synthetic aperture radar (SAR) data has been proved to have a great potential for rice monitoring and parameters retrieval. In this study, a rice canopy scattering model (RCSM) was revised and then was applied to simulate the backscatter of rice canopy. The combination of RCSM and genetic algorithm (GA) was proposed for retrieving two important rice parameters relating to grain yield, ear length and ear number density, from a C-band, dual-polarization (HH and HV) Radarsat-2 SAR data. The stability of retrieved results of GA inversion was also evaluated by changing various parameter configurations.

Results show that RCSM can effectively simulate backscattering coefficients of rice canopy at HH and HV mode with an error of <1 dB. Reasonable selection of GA's parameters is essential for stability and efficiency of rice parameter retrieval. Two rice parameters are retrieved by the proposed RCSM-GA technology with better accuracy. The rice ear length are estimated with error of <1.5 cm, and ear number density with error of <23 #/m^2. Rice grain yields are effectively estimated and mapped by the retrieved ear length and number density via a simple yield regression equation. This study further illustrates the capability of C-band Radarsat-2 SAR data on retrieval of rice ear parameters and the practicability of radar remote sensing technology for operational yield estimation.

1. Introduction

Rice, as one of staple food crops, is feeding about half the world's population (Khush, 2005). Especially in China, rice has been extensively cultivated to provide food for the growing population. Until 2014, rice grain yield has been harvested over 600 million tons, which accounts for 34% of all main crops in this country (China State Administration of Grain, 2015). Timely and reliable forecast of rice yield prior to harvest plays a role in making decision for rice production, predicting market price of rice grain and ensuring food security (Mosleh et al., 2015).

Fast development of remote sensing (RS) technology provides an alternative for local rice-cropping monitoring, as well as rice yield estimation at regional or national scale (Shibayama and Akiyama, 1991; Tennakoon et al., 1992; Fang, 1998; Xiao et al., 2005; Wang et al., 2010a; Kuenzer and Knauer, 2013; Son et al., 2013; Manjunath et al., 2015; Zhou et al., 2016). However, the availability of optical RS data is often limited to cloud-free weather conditions. In contrast, the all-weather day-and-night observation capability of microwave radar makes synthetic aperture radar (SAR) data more applicable in rice mapping (Chen et al., 2006; Panigrahy et al., 1999; Bouvet and Le Toan, 2011; Zhang et al., 2009, 2011; Li et al., 2012; Jiao et al., 2014), growth monitoring (Kurosu et al., 1995; Le Toan et al., 1997; Bouvet et al., 2009; Shao et al., 2001; Yang et al., 2014; Inoue et al., 2014a; Rossi and Erten, 2015) and phenology retrieval (Lopez-Sanchez et al., 2012, 2014) owing to unique temporal scattering characteristics of rice paddies. Moreover, the penetrability of microwave signals makes radar backscatter highly sensitive to the rice biomass (Le Toan et al., 1997; Ribbes and Le Toan, 1999; Inoue et al., 2002). Among a large number of SAR data (ERS-1/2 SAR, ENVISAT ASAR, ALOS-1/2 PALSAR, Radarsat-1/2 SAR,

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TerraSAR, COSMO-SkyMed, Sentinel-1, etc.), the C-band Radarsat SAR has been proved to be an fairly favorable data for retrieving rice canopy parameters and estimating biomass/yield (Chakraborty and Panigrahy, 2000; Chakraborty et al., 2005; Chen et al., 2011; Li et al., 2003; Jia et al., 2013; Zhang et al., 2014; Inoue et al., 2014b Chakraborty et al., 2005; Chen et al., 2011; Li et al., 2003; Jia et al., 2013; Zhang et al., 2014; Inoue et al., 2014b).

However, there is a huge challenge for the SAR data to estimate rice yield with empirical models. It is difficult to achieve an effective regression equation that directly relates the yield information to radar backscattering coefficients (σ°) of rice. This was probably attributed to the complex microwave scattering mechanism of rice canopy. The physical interaction of radar signals with rice canopy constituents cannot be explicitly described with simple mathematical formula. In order to accurately estimate rice yield from SAR image, the investigation of the nonlinear relation between physical properties of rice canopy constituents (mainly rice ears) and radar returns back to SAR sensor is necessary.

In general, the total backscatter of rice paddies recorded by SAR image contains (1) volume scattering in rice canopy itself (ears, leaves and stems), (2) multiple scattering between the canopy layer and underlying ground surfaces, and (3) surface scattering by the ground surfaces (soil or water). At relatively mature stage, scattering intensity of rice canopy largely depends on the scattering of rice ears besides the dominant leaves. In past studies, SAR polarimetry has been used for analyzing the three scattering contributions by three-components decomposition approach or the target decomposition theorems (Cloude and Pottier, 1996; Freeman and Durden, 1998; Touzi, 2007; Li et al., 2012). However, there is not yet a practicable technique which can separates ear scattering components from the total backscatter of rice canopy. Therefore, it is impracticable to directly relate the rice grain yield (ear weight) to ear scattering of radar image by statistical analysis.

As far as a field parcel is concerned, more rice ears produce more grain, so does the longer ear for a single rice plant. Therefore two parameters, ear density (ears number per square meter) and ear length, are directly related to the grain yield. For the scattering mechanics of rice canopy, the two parameters are also key factors determining the total scattering of rice canopy. How to quantify the contributions of these parameters to total scattering of rice canopy is crucial for rice yield estimation with microwave SAR data. As such, some physical models have been constructed to simulate backscatter signatures based on specific characteristics of radar system (frequency, incidence angle and polarization mode) and various structural characters (size, number, shape, orientation, water content, etc.) of rice constituents. These models are helpful for characterizing scattering characteristics and modeling contributions of rice scatterers (ears, leaves and stems) to total canopy backscatter at different rice developing stages (Le Toan et al., 1989; Tsang et al., 1995; Shao et al., 2002; Wang et al., 2005, 2009).

Microwave scattering models are often used to predict backscatter from a number of ground-based measurements of observed objects (Attema and Ulaby, 1978; Ulaby et al., 1990; Karam et al., 1995). For a scattering simulation of rice canopy, the number of inputs (rice parameters) is often much larger than that of outputs in the "forward model" (Le Toan et al., 1997; Wang et al., 2009; Zhang et al., 2014). Consequently, it is difficult, even impossible, to find a unique solution when they are inversed by conventional inversion methods such as linear inversion, iterative algorithm. This "ill-posed" inverse problem remains unsolved as a pressing issue in existing retrieval application of various RS data (Wang et al., 2010b). Therefore, the selection of an efficient inversion algorithm is pivotal for obtaining an optimal result for retrieving parameters.

Remote sensing inversion is in nature to resolve a nonlinear problem. In many past studies, optimization algorithms have been used for estimation of geo-/bio-physical parameters such as downhill simplex method, conjugate direction set method, quasi-Newton method, support vector regression, etc. (Antyufeev and Marshak, 1990; Kuusk, 1991; Privette et al., 1994; Liang and Strahler, 1994; Pinty et al., 1990; Durbha et al., 2007). However, these algorithms often generate multiple solutions at local minima, which will lead to a large uncertainty and inaccuracy in retrieved results. Artificial neural network (ANN) algorithms have been popularly applied for retrieval of vegetation or soil parameters from various RS data (Jin and Liu, 1997; Chang and Islam, 2000; Baghdadi et al., 2002, 2012; Del Frate and Solimini, 2004; Del Frate et al., 2004; Chen and McNairn, 2006; Jia et al., 2013). However, the training/testing of networks need a large number of sample pairs of inputs and outputs. A limited in situ data is often a challenge for producing an optimal network. Additionally, the "optimal" neural network trained on specific experimental data is strongly constrained by the input data thus the applicability on other data set is questionable. These limitations inevitably reduce the applicability of ANN to obtain reliable retrieved results.

The genetic algorithm (GA) is a variable screening procedure based on the principle of evolutionary genetics (Holland, 1975). GA is not only able to identify a "global" optimal solution, but also can avoid high sensitivity to the selection of initial guess (De Castro and Cavalca, 2003). It provides a systematic scanning within a population avoiding being stuck on a "local" maxima or minima. Many studies have demonstrated the potential of GA to a variety of optimization problems such as classification of RS imagery, retrieval of vegetation parameters, retrieval of roughness and moisture of soil surfaces, spilled oil detection on sea surface, just to name a few. (Tso and Mather, 1999; Lin and Sarabandi, 1999; Jin and Wang, 2001; Fang et al., 2003; Garzelli and Nencini, 2006; Jubai et al., 2006; Van Coillie et al., 2007; Zhang et al., 2014; Li et al., 2015). Generally, GA is more efficient and robust method than gradient search methods given that many local optima within a search space, although relatively expensive computational cost.

In this study, we proposed an operational and practicable scheme to estimate rice yield distribution from Radarsat-2 SAR data. A rice canopy scattering model (RCSM) developed in our previous study (Zhang et al., 2014) was revised to simulate the backscattering coefficients according to various parameter sets of rice canopy measured at field in mature stage. A genetic algorithm optimization tool was performed to retrieve key biophysical parameters with respect to rice ear weight, i.e. grain yield. The objective of this study is to evaluate the potential of a combined technique (RCSM-GA) for estimating the rice yield with dual-polarized Radarsat-2 SAR data.

2. Dataset and methodology

2.1. Study area

The study area is located between the Hunhe River and the Shahe River within Liaoyang City of Liaoning Province, Northeast China (Centered at 123.14°E, 41.47°N) (Fig. 1). As a portion of the Liaohe River Plain, Single-season paddy rice is cultivated in this region with its growing season from late May to early October (Zhang et al., 2014). Typical temperate monsoon climate, gentle and flat topographic relief, and abundant water resources provide a favorable circumstance for rice production. Such area is thus particularly suitable for conducting scientific research on rice remote sensing application.

2.2. Remote sensing data sets

A fine beam mode, C-band, dual-polarized (HH + HV) Radarsat-2 SAR single-look complex (SLC) data was acquired on September