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Capability of C-band backscattering coefficients from high-resolution satellite SAR sensors to assess biophysical variables in paddy rice

Yoshio Inoue [a,*], Eiji Sakaiya [b], Cuizhen Wang [c]

[a] National Institute for Agro-Environmental Sciences, Tsukuba, Ibaraki 305-8604, Japan
[b] Aomori-ITC Agricultural Research Institute, Kuroishi 036-0522, Japan
[c] University of Missouri, Columbia, MO 65211, USA

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ABSTRACT

High-resolution (ca. 1 m) synthetic aperture radar (SAR) sensors have great potential for all-weather monitoring of crop biophysical variables in small and mosaic crop fields in Asia. Rice is the most important staple crop in monsoon Asia, and the timely monitoring of rice growth is critical for precision farming and the assessment of productivity. The objective of this study was to determine the potential capability of backscattering coefficients (σ^0) from satellite C-band SAR sensors for the assessment of biophysical variables in rice. SAR images were acquired by a Radarsat-2 sensor in spotlight mode during the critical growth stages over 4 years in one of the major rice-producing areas of Japan. Detailed plant biophysical measurements were made concurrently with the SAR observations. The seasonal consistency of C-band σ^0 was clearly demonstrated. The baseline σ^0 values (minimum σ^0 for zero-biomass paddy fields) were determined to be −28.5 dB in VH and −21.1 dB in HH and VV, respectively. The dynamic change in σ^0 during the full range of rice growth was similar (ca. 12 dB) in all polarizations. A comprehensive analysis revealed the response of C-band σ^0 to biophysical canopy variables. High or moderate sensitivity of σ^0 to canopy height, water content, or chlorophyll content was superficial and was attributable to the change in leaf biomass and structure. Both the leaf area index (LAI) and leaf biomass were significantly and consistently correlated with σ^0 throughout all growth stages. These relationships were expressed by exponential curves with high coefficients of determination, although σ^0 saturates at around a LAI of 3 and a leaf biomass of 180 gDW m^{-2}. The response of σ^0 to total biomass was expressed by an exponential function with a high coefficient of determination, but the sensitivity was clear only within the lower 20% range of the seasonal maximum biomass. The C-band σ^0 had the highest correlation with fAPAR, and the σ^0–fAPAR relationship was linear throughout the growth stages. The results suggest the suitability of C-band σ^0 for the assessment of LAI or fAPAR and show promise for the timely monitoring of rice growth by C-band SAR and/or through its constellation with optical sensors.

1. Introduction

A wide range of satellite sensors are available in the optical, thermal, and microwave spectral domains for the observation of terrestrial ecosystems. However, agricultural applications are highly demanding for advanced specifications in spatial, spectral, and temporal resolutions (Inoue, 2003; Moran, Inoue, & Barnes, 1997). In crop monitoring for precision farming and yield forecasting, the timely observation of plant biophysical and ecophysiological status (e.g., leaf area, biomass, and chlorophyll content) is critical (Doraiswamy et al., 2004; Inoue, 2003; Moran, Inoue, et al., 1997). High spatial resolution is required when observing regions with small and mosaic crop fields, as in many countries in Asia.

Rice (*Oryza sativa* L.) is an important stable crop in monsoon Asia, but rice productivity is strongly affected by water, temperature, and solar radiation. Therefore, timely and high-resolution observation is essential for monitoring rice crops in Asia. Accordingly, SAR sensors have great potential for the timely assessment of biophysical and ecophysiological variables of rice in Asia (e.g., Le Toan et al., 1997; Ribbes & Le Toan, 1999). The extraction of rice fields is relatively robust due to the specular features under flooded surface conditions (e.g., Choudhury, Chakraborty, Santra, & Parihar, 2012; Kurosu, Fujita, & Chiba, 1997; Ribbes & Le Toan, 1999). The combined use of multiple polarizations can effectively classify agricultural fields (e.g., Bouvet, Le Toan, & Lam-Dao, 2009; McNairn, Champagne, Shang, Holmstrom, & Reichert, 2009). Cropping systems or agricultural management practices in rice-growing regions can be identified successfully from SAR observations (e.g., Bouvet & Le Toan 2011; Lopez-Sanchez, Ballester-Berman, & Hajnsek, 2011). However, quantitative assessments of biophysical and ecophysiological plant variables using SAR signatures remain challenging.

* Corresponding author. Tel.: +81 29 838 8220; fax: +81 29 838 8199.
E-mail address: yinoue@affrc.go.jp (Y. Inoue).

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Lopez-Sanchez and Ballester-Berman (2009) highlighted the great potential of microwave remote sensing for monitoring crop biophysical variables by reviewing various experimental studies using ground-based scatterometers (e.g., Bouman, 1991; Inoue et al., 2002; Prévot, Campion, & Guyot, 1993). For example, Inoue et al. (2002) indicated the most suitable combination of frequency band, polarization, and incidence angle for the assessment of each biophysical variable of rice by analyzing a comprehensive dataset of backscattering coefficients in five frequency bands (Ka, Ku, X, C, and L), full polarizations (VV, VH, HV, HH), and four incidence angles (25°, 35°, 45°, 55°) during a full growing-period of paddy rice. Among the major results, the C-band σ^0 was suggested to be the most useful for estimating the leaf area index (LAI) and whole-canopy variables such as biomass.

Most previous studies using satellite C-band SAR sensors have suggested that C-band σ^0 may be able to detect the seasonal changes in crop growth based on the similarity of the seasonal trends in σ^0 and plant height (e.g., Baghdadi, Boyer, Todoroff, El Hajj, & Bégué, 2009; Chakraborty, Manjunath, Panigrahy, Kundu, & Parihar, 2005; Fieuzal, Baup, & Marais-Sicre, 2012; Ribbes & Le Toan, 1999; Shao et al., 2001). However, due to the limited biophysical and ecophysiological data and limited spatial resolutions of SAR sensors, their results remain ambiguous, and the accuracy and consistency seem insufficient for operational applications. Additionally, the apparent similarity of seasonal trends in SAR signatures and plant height does not imply a real relationship but an indirect or superficial relationship, considering that the C-band σ^0 was similar before and after the harvesting of a rice canopy of full height (1 m). More importantly, indications of the similarity of seasonal trends in both σ^0 and plant height are too preliminary to evaluate the potential of SAR sensors for crop diagnostics at critical growth stages and the assessment of crop productivity.

One reason for such uncertainty lies in the insufficient ground-based data relating to canopy biophysical or ecophysiological status. Some sophisticated parameters such as entropy and alpha derived from multi-polarization images have sometimes been used to derive more accurate and/or consistent information on canopy and surface conditions (Lopez-Sanchez, Hajnsek, & Ballester-Berman, 2012, Lopez-Sanchez et al., 2011), but further investigations based on detailed ground-based data are needed for a clear interpretation of the behavior of such parameters. Backscattering process models are useful for the interpretation of measured SAR signatures (e.g., Le Toan et al., 1997; Wang et al., 2009), but their ability is still very limited because of difficulties in the modeling of scattering processes, the determination of key parameters, and the acquisition of various input data (e.g., 3-D canopy structure, plant water content, and soil roughness). Considering the state-of-the-art in these research fields, new investigations need to be based on a detailed sensitivity analysis based on accurate canopy biophysical and ecophysiological measurements.

Another reason for the ambiguity of earlier studies using satellite SAR sensors is the low spatial resolution. Spatial resolution on the order of 1 m has been suggested for advanced investigations to provide more consistent, reliable, and innovative results (Inoue, 2003, Moran, Inoue, et al., 1997). Such high spatial resolution is critical, especially in the small and mosaic crop fields of monsoon Asia, but such spatial resolution has not been available for long. The latest SAR sensors in the C-band (Radarsat-2) and X-band (COSMO-SkyMed and TerraSAR-X) have achieved the required high spatial resolution in spotlight mode, but in-depth studies of the capability of such high-resolution data are still limited (e.g., Fieuzal et al., 2012; Inoue & Sakaiya, 2013; Santi et al., 2012).

Thus, the objectives of this study were to examine the consistency of a high-resolution C-band SAR sensor (i.e., Radarsat-2, spotlight mode) for rice crop monitoring, to investigate the comprehensive relationship of σ^0 with canopy biophysical variables, and to explore the new capabilities of the C-band sensor for assessment of crop growth and yield.

2. Materials and methods

2.1. Test site

One of the major rice-growing regions in northeast Japan (Tsugaru Plain, Aomori Prefecture) was selected as a study area (center: 40°36′20.74″N, 140°33′36.02″E). The land is flat, and rice varieties and crop management practices are relatively uniform in the area. In the region, rice is grown once a year during May–September. The mean air temperature and total precipitation for the period are 18.6 °C and 513 mm, respectively.

In general, paddy fields are flooded and smoothed several days before transplanting, and rice seedlings are transplanted in late May using a rice-planting machine. The normal dates for the panicle initiation stage, heading stage, and maturity stage (harvesting) are mid-July, early August, and mid-September, respectively (Fig. 1). A single rice variety (*O. sativa* L. *japonica*, variety: Tsugaru Roman) is grown in the study area. In general, a bundle of 3–5 seedlings (hill) of about 15 cm long are machine planted at a spacing of 30 × 15 cm under flooded conditions. After transplanting, paddy fields are irrigated continuously until the mid-maturing stage, and the soil surface of the paddy fields is under flooded conditions during most growing periods. Normally, plant growth within each field is highly uniform (coefficient of variance, CV < 10%), but between-field variability in growth and yield is significant because of differences in the soil condition and farming management practices. The majority of paddy fields in the region are 30 × 100 m in size, but the orientation of fields (i.e., row direction) is not identical. The field size is much smaller than that in the United States or European countries but is typical for Japan and most Asian countries.

2.2. Acquisition and processing of C-band SAR images

High-resolution SAR images in the C-band (5.4 GHz) were acquired using the Radarsat-2 sensor in the spotlight mode. As discussed in Section 1, the spotlight mode was considered most suitable for investigating the relationship of SAR signatures with rice biophysical variables because degradation of spatial resolution due to noise-reduction processing is unavoidable. All images were taken in spotlight mode, i.e., at a spatial resolution of 1 × 1 m on the ground.

Seven images were obtained over the vegetative to maturing growth periods in the growing seasons of 2009–2012: on 06 September 2009, 15 July 2010, 16 July 2010, 10 July 2011, 30 September 2011, 27 June 2012, and 24 September 2012. These periods cover the critical growth stages such as panicle initiation, heading, and maturing, when quantitative information on biophysical variables is most useful for growth diagnosis and yield prediction. Stem density, LAI, biomass, fraction of photosynthetically active radiation (fAPAR), and water and chlorophyll contents were the key canopy variables. The time of measurement was around 17:30 LST for all seven images. The size of the observation area was approximately 8 × 20 km.

Measurement configurations such as polarization and incidence angles were carefully selected from the possible configurations during each targeted time window based on the results of our previous study (Inoue et al., 2002). Because only a single-polarization mode was available due to the inherent limitation of the spotlight mode, VH polarization was selected, with some additional polarizations (VV and HH) also used for comparative analysis. Accordingly, intermediate incidence angles (25–35°) were selected from those available.

All image data were converted to σ^0 signatures based on the radiometric parameters provided for each dataset using the Next ESA SAR Toolbox (NEST) 4B (European Space Agency). All images were georeferenced using a high-resolution airborne image (1 m) obtained by the CASI hyperspectral sensor. The boundaries of individual paddy fields accurately matched the GIS polygon data from GIS for the whole region. A 3 × 3 enhanced Lee filter was applied to each image to reduce