Radar Vegetation Index for Estimating the Vegetation Water Content of Rice and Soybean

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***Abstract*—Vegetation water content (VWC) is an important biophysical parameter and has a significant role in the retrieval of soil moisture using microwave remote sensing. Here, the radar vegetation index (RVI) was evaluated for estimating VWC. Analysis utilized a data set obtained by a ground-based multifrequency polarimetric scatterometer system, with a single incidence angle of 40°, during an entire growth period of rice and soybean. Temporal variations of the backscattering coefficients for the L-, C-, and X-bands, RVI, VWC, leaf area index, and normalized difference vegetation index were analyzed. The L-band RVI was found to be correlated to the different vegetation indices. Prediction equations for the estimation of VWC from the RVI were developed. The results indicated that it was possible to estimate VWC with an accuracy of 0.21 $kg \cdot m^{-2}$ using L-band RVI observations. These results demonstrate that valuable new information can be extracted from current and future radar satellite systems on the vegetation condition of two globally important crop types. The results are directly applicable to systems such as the proposed NASA Soil Moisture Active Passive satellite.**

***Index Terms*—Leaf area index (LAI), microwave remote sensing, normalized difference vegetation index (NDVI), polarimetric scatterometer, radar vegetation index (RVI), vegetation water content (VWC).**

I. Introduction

MICROWAVE remote sensing, in particular radar, has a great potential to complement traditional remote sensing techniques in the monitoring and assessment of crop growth. The primary advantages of radar are that it can penetrate through clouds and acquire day or night time data. In addition, at the appropriate frequencies, it provides information on the entire canopy and not just the first layer of leaves. Characterizing vegetation (crop growth) and obtaining radar observations for a range of system configurations are challenging problems. Although numerous experiments have been carried out to investigate the response of microwave sensors to crop growth parameters [1]–[4], additional comprehensive studies for a variety of crops are needed to develop robust retrieval methods. One approach to providing these data sets is to use a multifrequency ground-based polarimetric scatterometer. This approach facilitates better control of the target (field) conditions and, as implemented here, facilitates the continuous monitoring of a field. Several previous investigations have utilized this approach [5], [6].

The vegetation canopy can be characterized using several different (but related) biophysical variables (i.e., vegetation water content (VWC) and biomass) as well as traditional remote sensing indices [i.e., normalized difference vegetation index (NDVI) and leaf area index (LAI)]. VWC is an important parameter in agricultural and forest studies and has been used for drought assessment and yield estimation [7], [8]. VWC is also of particular importance in retrieving soil moisture from remotely sensed microwave data [9], [10]. Previous studies have analyzed the relationship between NDVI (as well as other indices) and VWC and developed techniques to estimate VWC and other biophysical variables [9], [11].

In this investigation, we examine the relationship between polarimetric radar data, VWC, and several vegetation indices. The major focus is on the use of the proposed radar vegetation index (RVI) [12]. The data utilized were obtained with a ground-based multifrequency polarimetric radar system that provided measurements every 10 min over the crop growing season. Two different crop types (rice and soybean) were investigated. These observations were analyzed to determine what new information can be extracted from current and future radar satellite systems on the vegetation condition, specifically the VWC, of two globally important crop types. It should be noted that the radar system used operated at a single incidence angle of 40°, and therefore, the results are directly applicable to systems such as the proposed National Aeronautics and Space Administration Soil Moisture Active Passive (SMAP) satellite.

II. Radar Variables Related to Vegetation

Radar-based variables that may be related to vegetation condition include the polarimetric measurements (radar backscatter for a specific horizontal and/or vertical configuration), eigenvalues based upon the set of observations, derived parameters such as the correlation between polarimetric channels, and the RVI [12], which will be described hereinafter.

The value of the remotely sensed variable or parameter depends upon the intended application. In this case, we are

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TABLE I
SCATTEROMETER SYSTEM SPECIFICATIONS

Parameter		X-Band	C-Band	L-Band
Frequency (GHz)		9.65±0.5	5.3±0.3	1.27±0.06
Beam width	E-Plane (°)	12	15	25
	H-Plane (°)	12	15	25
Number of Frequency Points		1601	801	201
Antenna Type		Dual polarimetric square horn		
Antenna Gain (dB)		22.4	20.1	12.4
Slant Range Resolution (m)		0.15	0.25	1.25
Band Width (MHz)		1000	600	120
Polarization		HH, HV, VH, VV		
Incidence Angle (°)		40		
Platform Height (m)		4.16		
Measurement interval		10 minutes		

seeking a robust way to characterize VWC using radar observations. The technique should attempt to minimize the impact of crop structure, incidence angle, and environmental conditions (i.e., soil moisture). One of the most promising approaches is the RVI, which has been shown to have low sensitivity to environmental condition effects [12]. RVI is a function of incidence angle since the path length through the vegetation canopy will increase as the incidence angle increases. However, the current analysis focuses on a single incidence angle.

The RVI has been proposed as a method for monitoring the level of vegetation growth, particularly when time series data are available. However, few studies have attempted to establish a relationship between RVI and biophysical variables [12]. In this letter, we analyze the relationships between the RVI for a variety of relevant configurations (L-, C-, and X-bands) and crop growth parameters (VWC, LAI, and NDVI) over an entire rice and soybean growth cycle. The RVI is given by

$$\mathrm{RVI} = \frac{8\sigma_{\mathrm{HV}}}{\sigma_{\mathrm{HH}} + \sigma_{\mathrm{VV}} + 2\sigma_{\mathrm{HV}}} \quad (1)$$

where σ_{HV} is the cross-polarization backscattering cross section and σ_{HH} and σ_{VV} are the copolarization backscattering cross sections represented in power units. RVI generally ranges between 0 and 1 and is a measure of the randomness of the scattering. RVI is near zero for a smooth bare surface and increases as a crop grows (up to a point in the growth cycle).

There have been a number of investigations that have examined the relationships between biophysical variables and radar parameters [13]–[17]. We used many of these in assessing the levels and patterns of response of the backscattering coefficient in the current investigation. However, it should be noted that high-resolution radar observations are very sensitive to the specifics of a particular study and that, in some cases, the published results do not agree.

III. MICROWAVE SCATTEROMETER SYSTEM

A multifrequency polarimetric scatterometer was used to provide the data for this investigation. This system provides data at the L-, C-, and X-bands. Details of the system are summarized in Table I. The system consists of three dual square horn antennas with collection and processing hardware (see Table I). The sizes of the footprints are 1.50 × 1.14 m (X-band), 1.89 × 1.42 m (C-band), and 3.40 × 2.44 m (L-band).

The center frequency of each of the antennas was selected to replicate existing and planned radar satellites. The system components were installed inside an air-conditioned shelter to maintain constant temperature and humidity during the data acquisition period. Backscattering coefficients were calculated by applying the radar equation [18]. The system was calibrated using a triangular trihedral corner reflector with a backscattering coefficient of 0.7 dB. The overall performance of the system was also verified by comparing the observations to those obtained by other investigators using similar systems and study conditions [5], [6].

Measurements were made automatically every 10 min. A daily average backscattering coefficient was computed from the 144 measurements obtained over the course of each day. Note that only L- and C-band observations were available during the rice experiment in 2007.

IV. FIELD EXPERIMENT DESCRIPTIONS

A. 2007 Rice Experiment

A rice field located near the National Academy of Agricultural Science experimental field (Latitude 37.2578, Longitude 126.9893) was studied in 2007. The paddy field was first flooded, and then, the rice seedlings were transplanted on May 18. The size of the rice paddy field was 22 × 31 m, and rice seedlings were about 15 cm tall and were spaced 30 cm × 15 cm apart at the time of transplanting. The peak biomass occurred on August 16 (heading stage), and the plants were harvested on October 11 (146 days after transplanting). It should be noted that the field was flooded during the entire experiment except during harvest. Photographs illustrating plant conditions are included in Fig. 1.

Biophysical observations, including fresh and dry biomass and plant height, were acquired once every week by destructive sampling. VWC was derived by computing the difference between the fresh and dry biomass. Total LAI was measured using a LAI-2000 (LI-COR, Lincoln, NE), which is an indirect method for estimating total LAI [19]. NDVI of the rice canopy was derived using measurements provided by an active optical sensor (Greenseeker, RT 100 model # 505, NTech Inc.). This sensor uses light-emitting diodes to generate red (wavelength of 656 nm) and near-infrared (wavelength of 774 nm) light. The reflected light from the crop is measured by a photodiode located at the front of the sensor head. The NDVI sensor was hand carried through the field. Measurements were made at nadir position (~0.8 m) directly above the rice canopy for nine points in the field.

B. 2010 Soybean Experiment

The soybean study was conducted at the National Institute of Crop Science experimental field (Latitude 37.2597, Longitude 126.9757). The size of the soybean field was 25 × 32 m, and the sowing date was June 4. The plants reached peak biomass on September 28 and were harvested on October 20 (139 days after sowing). Photographs illustrating plant conditions are included

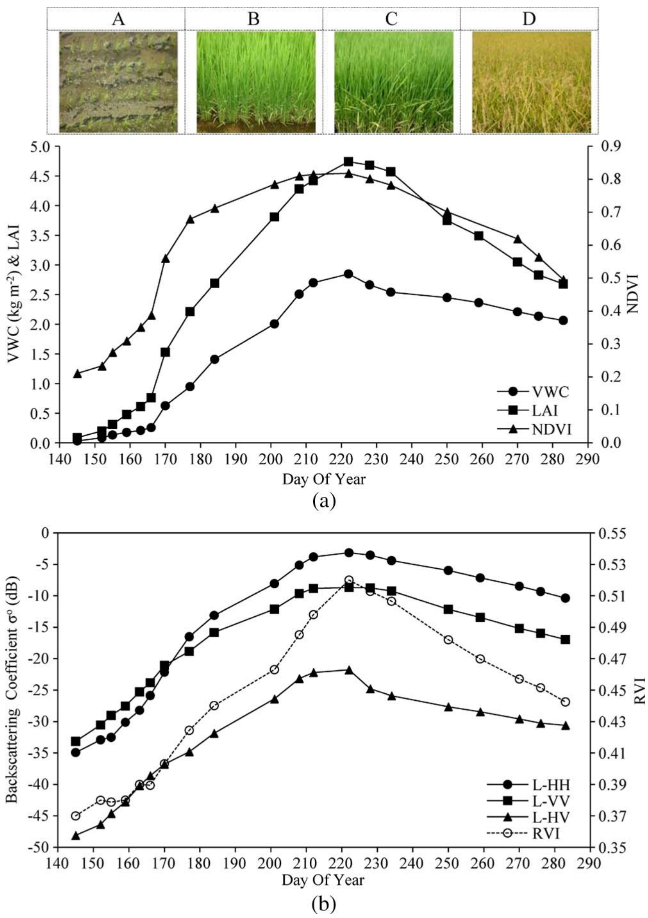

Fig. 1. Temporal variation of σ° in L-band, RVI, VWC, LAI, and NDVI during the rice growth period: (a) VWC, LAI, and NDVI and (b) σ° and RVI for L-band. Field photographs of rice in different growth stages: (A) Transplanting (DOY 140), (B) panicle formation (DOY 206), (C) heading (DOY 222), and (D) harvesting (DOY 283).

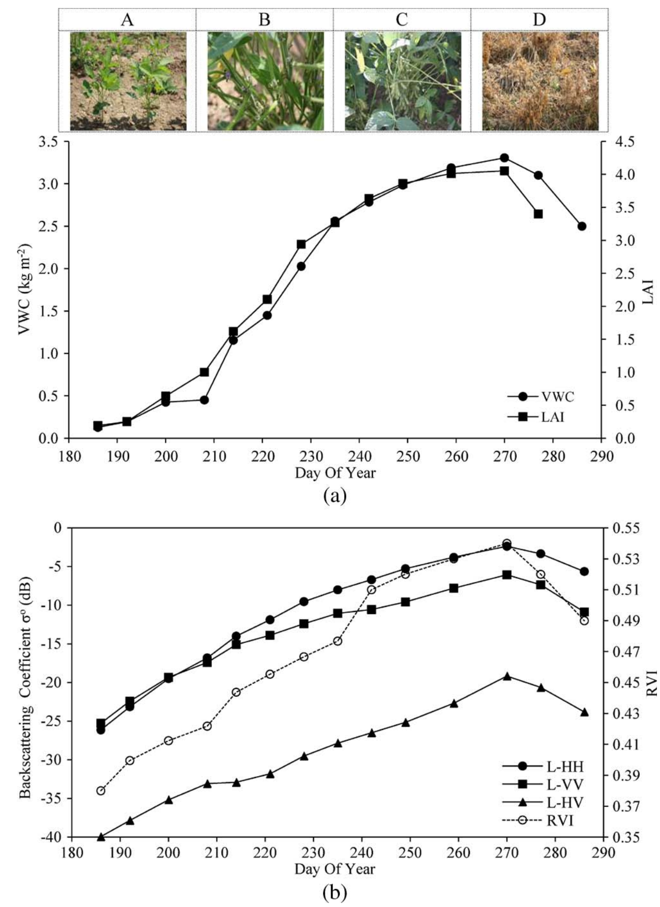

Fig. 2. Temporal variation of σ° in L-band, RVI, VWC, and LAI during the soybean growth period: (a) Vegetation biophysical parameters (VWC and LAI) and (b) σ° and RVI for L-band. Field photographs of soybean in different growth stages: (A) Forth trifoliolate (V4, DOY 186), (B) beginning pod (DOY 228), (C) full seed (DOY 271), and (D) harvesting (DOY 286).

in Fig. 2. Biophysical measurements (including fresh and dry biomass, plant height, and LAI) were observed weekly.

The biomass and VWC were measured as the sum of leaves, stem, and pods by destructive sampling. Total LAI was measured using a LAI-3100 (LI-COR, Lincoln, NE), which is a direct method for estimating total LAI. This instrument operates differently than the device used with rice in 2007. However, an earlier study by Welles [20] showed that observations made by the direct (LAI-3100) and indirect (LAI-2000) methods compared well with each other. Measurement of the soil moisture within the top 0.05 m was performed using a portable probe (Echo-5 TE probe, Decagon Device, Inc.). NDVI data were not available for the soybean experiment. Crop row orientation was parallel to the azimuth angle of the antenna.

V. Analysis

A. Time Series Plot of L-Band Backscattering Coefficients, RVI, VWC, LAI, and NDVI

Fig. 1 shows the observed L-band σ° for all polarizations over the rice field. It also includes the RVI, VWC, LAI, and NDVI for the entire rice experiment. VWC, LAI, and NDVI all increased until Day of Year (DOY) 222 (rice heading stage: 50% of the heads were totally emerged from their leaf sheath) and then declined until the harvesting stage (DOY 283). L-band backscattering coefficients increased, as did the RVI, until DOY 222 and then decreased along with VWC, LAI, and NDVI. The pattern of temporal change was smooth for all variables. We also observed that the change in the backscattering coefficient over the growing season was quite large for all polarimetric channels ($\sim$25 dB).

Fig. 2 shows that the L-band backscattering coefficients for all polarizations gradually increased until DOY 271 (R6, full seed stage: pod containing a green seed that fills the pod capacity at one of the four uppermost nodes on the main stem) and then decreased until the harvesting stage (DOY 288) for the soybean study. On DOY 271, the soybean fresh and dry biomass and plant height reached their maximum. RVI, VWC, and LAI also reached their maximum on the same DOY and then decreased thereafter. The change in the backscatter coefficients over the season was slightly smaller than that observed for rice ($\sim$20 dB). The results described earlier established the correlation in temporal trends for both crops and a basis for a relationship between RVI and VWC.

B. Estimation of Crop Biophysical Variables Using RVI

Fig. 3 shows comparisons between L- and C-band RVIs and growth data for rice (VWC). L-band RVI and VWC were highly

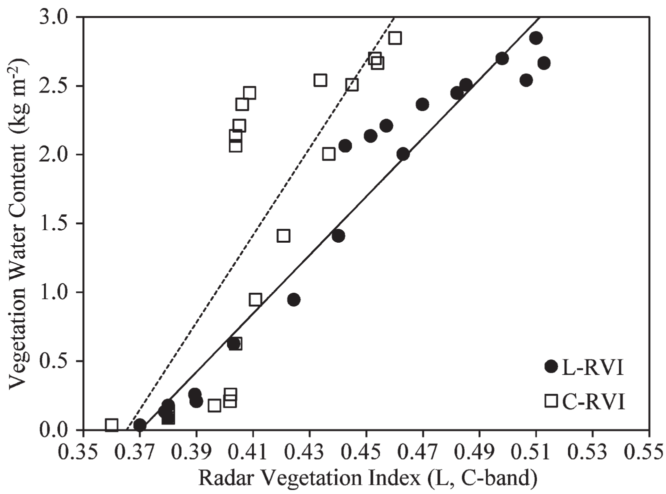

Fig. 3. Relationship between VWC and L-, C-band RVIs for rice.

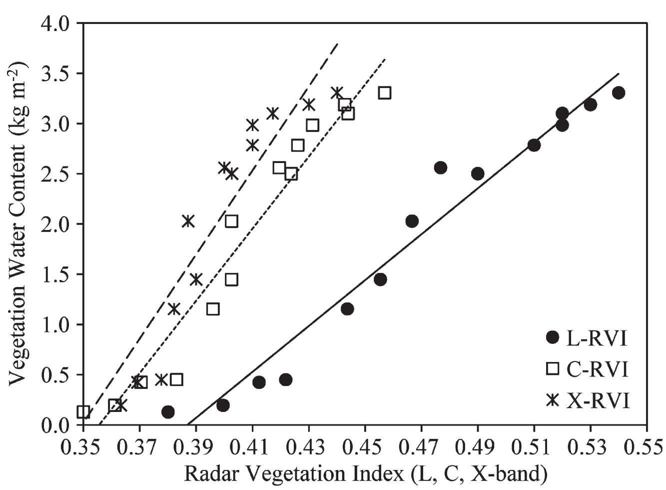

Fig. 4. Relationship between VWC and L-, C-, and X-band RVIs for soybean.

correlated ($r = 0.96$). In comparing the correlation coefficient of L-band RVI and C-band RVI, it was observed that L-band RVI had a higher correlation with VWC than C-band, which indicates that the L-band RVI may be better than C-band RVI for the retrieval of rice growth parameters (see Table III).

Fig. 4 presents a comparison between the L-, C-, and X-band RVIs and VWC over the soybean growth cycle. The correlation between the L-band RVI and VWC is very good ($r = 0.98$).

Prediction equations were developed using the RVI based on the observed linear relationships between RVI and VWC. Root-mean-square error (rmse) was used as the primary metric for assessing retrieval performance. As a first step, prediction equations for VWC using the LAI and NDVI (rice only) were developed to establish a baseline (how well we might estimate VWC using visible–near-infrared observations) for intercomparison. Table II includes the results of this analysis and shows that both LAI and NDVI had good linear correlation with VWC ($r \geq 0.89$) and as a result the retrieval equations performed well.

Table III summarizes the statistical performance in estimating VWC using RVI for each available radar band. The slope of the regression equation decreases with frequency (L-band RVI has the lowest slope). These results indicate that the L-band RVI has the largest range of RVI observations over the crop growing cycle. The accuracy (lower rmse) of the retrieved VWC for rice using RVI increases as frequency decreases. There was a slight improvement in estimating VWC using RVI as compared to using NDVI and a significant improvement over using LAI (see Table II).

For soybeans, the same trend of increasing rmse with frequency was found. In this case, no NDVI measurements were available; however, the improvement in using RVI over using LAI was significant.

In order to explore how robust the RVI approach might be regardless of crop type, both data sets were combined (see Fig. 5). The correlation coefficient and the retrieval accuracy decreased over those obtained for the individual crops. Results in Table III indicate that, for L-band, a very good relationship between RVI and VWC with an overall rmse of 0.21 kg $\cdot$ m^{-2} could be established.

As a qualification, we recognize that the radar signal is affected by a number of target and system configuration parameters that include the following: leaf size, orientation, canopy structure, vegetation biomass, surface roughness, soil moisture, and sensor characteristics. Although we did not consider the soil moisture information as a significant component of the current analysis, for the soybean study, the RVI did not correlate well with observed soil moisture ($r = 0.41$ and 0.34 for the L- and C-bands, respectively). Since there was no tillage during the study, the surface roughness did not change significantly during the experiment.

The objective of this study was to examine a proposed vegetation parameterization scheme using radar observations that could be used to estimate vegetation water content as part of the SMAP mission. VWC is a critical variable in the estimation of soil moisture from passive microwave observations. Currently, visible and infrared sensors are used to estimate VWC; however, these are not available on the same satellite platform, and they have known limitations. Development of this radar-based parameterization using data available from SMAP may be more robust and accurate.

VI. Summary

Backscattering coefficients for the L-, C-, and X-bands, vegetation indices (RVI, NDVI, and LAI), and crop growth data (VWC) were observed over rice and soybean growth cycles. RVI for all frequency bands gradually increased in accordance with crop growth and decreased with a reduction of VWC. RVI for L-, C-, and X-bands was compared to VWC, LAI, and NDVI. It was found that L-band RVI was well correlated with VWC, LAI, and NDVI. Retrieval equations were developed for estimating VWC using the RVI in both crops. The most accurate VWC retrievals were achieved using the L-band RVI, and these were better than the C- and X-band RVIs. Combining both crops using L-band RVI resulted in a robust VWC relationship. This investigation focused on a 40° single incidence angle observing system, as will be employed with SMAP. It is expected that the effects of the incidence and the azimuth angle could affect the results. These results demonstrate the potential of using L-band radar observations

TABLE II
LINEAR REGRESSION OF VWC AND OPTICAL VEGETATION INDICES

	Crop							
	Rice				Soybean			
	m	c	r	RMSE	m	c	r	RMSE
LAI	1.3362	0.2883	0.98	1.1678	1.1796	0.2274	0.99	0.7033
NDVI	0.1788	0.3107	0.89	0.2416	-	-	-	-

m: Slope, c: Intercept, r: Correlation coefficient, RMSE: Root Mean Square Error (kg m^{-2})

TABLE III
LINEAR REGRESSION OF VWC AND RVI OF EACH BAND

		Crop											
		Rice				Soybean				Rice + Soybean			
		m	c	r	RMSE	m	c	r	RMSE	m	c	r	RMSE
VWC	L	21.247	-7.8666	0.96	**0.2308**	22.799	-8.818	0.98	**0.1774**	21.297	-7.9811	0.97	**0.2103**
	C	31.65	-11.562	0.79	0.6465	35.879	-12.758	0.97	0.2638	32.922	-11.867	0.85	0.5913
	X	-	-	-	-	41.786	-14.598	0.94	0.3897	-	-	-	-

Rice: No X-band observation during in 2007, Soybean: No NDVI measurement in 2010

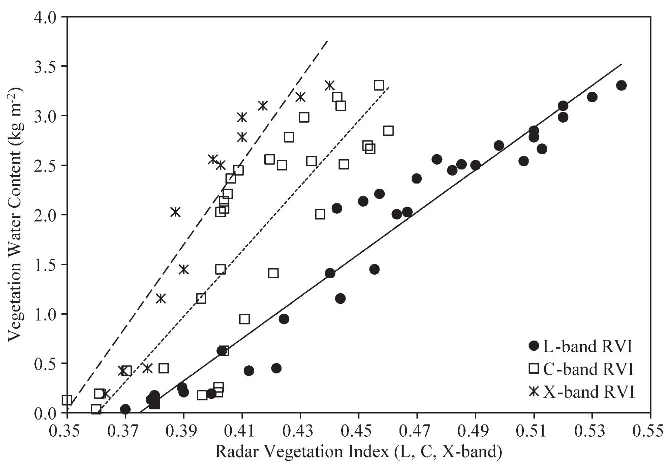

Fig. 5. Relationship between VWC and L-, C-, and X-band RVIs for rice and soybean.

from upcoming satellite missions that include Aquarius (2011) and SMAP (2014) to retrieve VWC information and contribute to crop growth monitoring.

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