INT. J. REMOTE SENSING, 1996, VOL. 17, NO. 13, 2565–2577

Agricultural crop condition monitoring using airborne C-band synthetic aperture radar in southern Alberta

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(Received 13 June 1995; in final form 16 January 1996)

Abstract. Applications of airborne C-band synthetic aperture radar imagery for determining variations in agricultural crop characteristics were investigated at a test site in southern Alberta, Canada. Synthetic aperture radar (SAR) imagery and ground-based crop characteristics data were acquired on 19–20 July 1994 for wheat, canola, beans, peas, and wheat + alfalfa cultivated under a variety of irrigation conditions. The results indicate that the statistically significant relationships that were derived between the ground-based data and SAR imagery are a function of crop type, crop condition parameter, and image processing procedures, and that crop characteristics such as leaf area index and plant height are negatively correlated with radar backscatter.

1. Introduction

In order to investigate the potential applications of airborne C-band synthetic aperture radar (SAR) data to monitoring various agricultural crop characteristics, an airborne remote sensing campaign was undertaken for a number of quarter-section (64·7 ha) test sites in southern Alberta. The goals of the project included investigating whether SAR imagery is capable of detecting variations in a number of crop characteristics (leaf area index (LAI), plant height, canopy temperature), whether these variations vary among different crop types, and how image filtering (speckle reduction) and analytical techniques (tonal versus textural analysis) affect the derived statistical relationships.

The vast majority of previous studies involving SAR applications to agriculture have focused on the effects of different canopy architectures (e.g. Ulaby and Wilson 1985, Bouman and van Kasteren 1990 b), incident angles (e.g., Daughtry *et al.* 1991), radar wavelength (e.g., Thomson *et al.* 1990, Brown *et al.* 1992), soil moisture variations (e.g., Pultz *et al.* 1990, Fischer *et al.* 1992), surface roughness (e.g., Hutton and Brown 1986, Boivin *et al.* 1990, Major *et al.* 1993), and crop types (e.g., Pultz and Brown 1987, Treitz *et al.* 1991, Foody *et al.* 1994) on radar backscatter.

Applications of synthetic aperture radar data to monitoring variations in crop characteristics have been limited. Brisco and Brown (1990) examined the applications of airborne C-HH SAR data to drought stress detection for various crops in southern Saskatchewan. The analysis involved two classes of drought stress (poor/good) for four crop types as well as water and summer fallow classes. It was found that the degree of separability was quite variable and some classes were only poorly

0143-1161/96 $12.00

discriminated. Average backscatter was found to be higher for the healthier crops. Major *et al.* (1991) measured radar backscatter from canola and wheat canopies and found that good statistical relationships existed between radar backscatter and volumetric canopy moisture (positively correlated). Prevot *et al.* (1993) examined the applications of multi-frequency, -polarization, -incident angle SAR data for monitoring wheat canopies. The data were used to develop an algorithm to estimate vegetation water content from SAR data acquired at two different incident angles.

The results of these and other studies strongly suggest that SAR data can be applied to detecting relative variations in crop characteristics within a single field. The project outlined in this study was designed to examine whether relative variations in crop characteristics which may be indicative of incipient or established stress could be detected using SAR data and the most effective means for deriving the radar-crop characteristic relationships. This research program was designed to acquire airborne C-band HH-polarized SAR imagery for a number of agricultural crops in conjunction with ground-based measurements of various crop characteristics such as LAI, plant height and canopy temperatures. The goal was to determine which crop characteristics could most effectively be derived from analysis of SAR imagery and whether these relationships are a function of crop type.

2. Study area

The project involved the acquisition and analysis of ground-based measurements of crop characteristics (LAI, plant height, canopy temperatures) and airborne SAR data. A study area was identified near the town of Lomond, Alberta, Canada, consisting of nine quarter-sections (64·7 ha each) planted with a variety of crops and with variable irrigation practices (figure 1). These fields were subjected to detailed field investigation during 19–20 July 1994. The field characteristics are provided in table 1. Crops which were involved in the study included wheat, wheat underseeded to alfalfa, beans, peas, and canola, irrigated using central pivot and line irrigation as well as dryland farming.

3. Data collection and processing

The study area was overflown on 19 July 1994 by the Canada Centre for Remote Sensing Convair 580 aircraft equipped with a C-band synthetic aperture radar system (Livingstone *et al.* 1987). Data were acquired in the narrow mode (45–76° incidence angle) with three different polarizations (HH, HV, VV); only the HH-polarized data were used in the current analysis in order to provide data most compatible with that available from Radarsat; analysis of the other polarization data sets is ongoing. The study area was overflown at 5800 m ASL, resulting in a spatial resolution of 4·8 m along track and 6·1 m across track. All of the test sites were within 5 km of each other in the across-track direction; consequently backscatter variation was assumed to be indicative of surface variation rather than incidence angle effects.

Both irrigated (central pivot and line irrigated) and unirrigated fields were included in the study (table 1). Sample locations in each field were generally located at the intersection of pivot wheel tracks with diagonal field transects. These locations were also paced off to provide an additional check on repeatability. Sample locations in fields without central pivot irrigation were selected by pacing alone. The repeatability of these locations was on the order of 5 m. Sample locations were generally spaced approximately 50 m apart. Transects were generally oriented from one corner of a quarter section towards the central pivot. Transects in the other fields were based

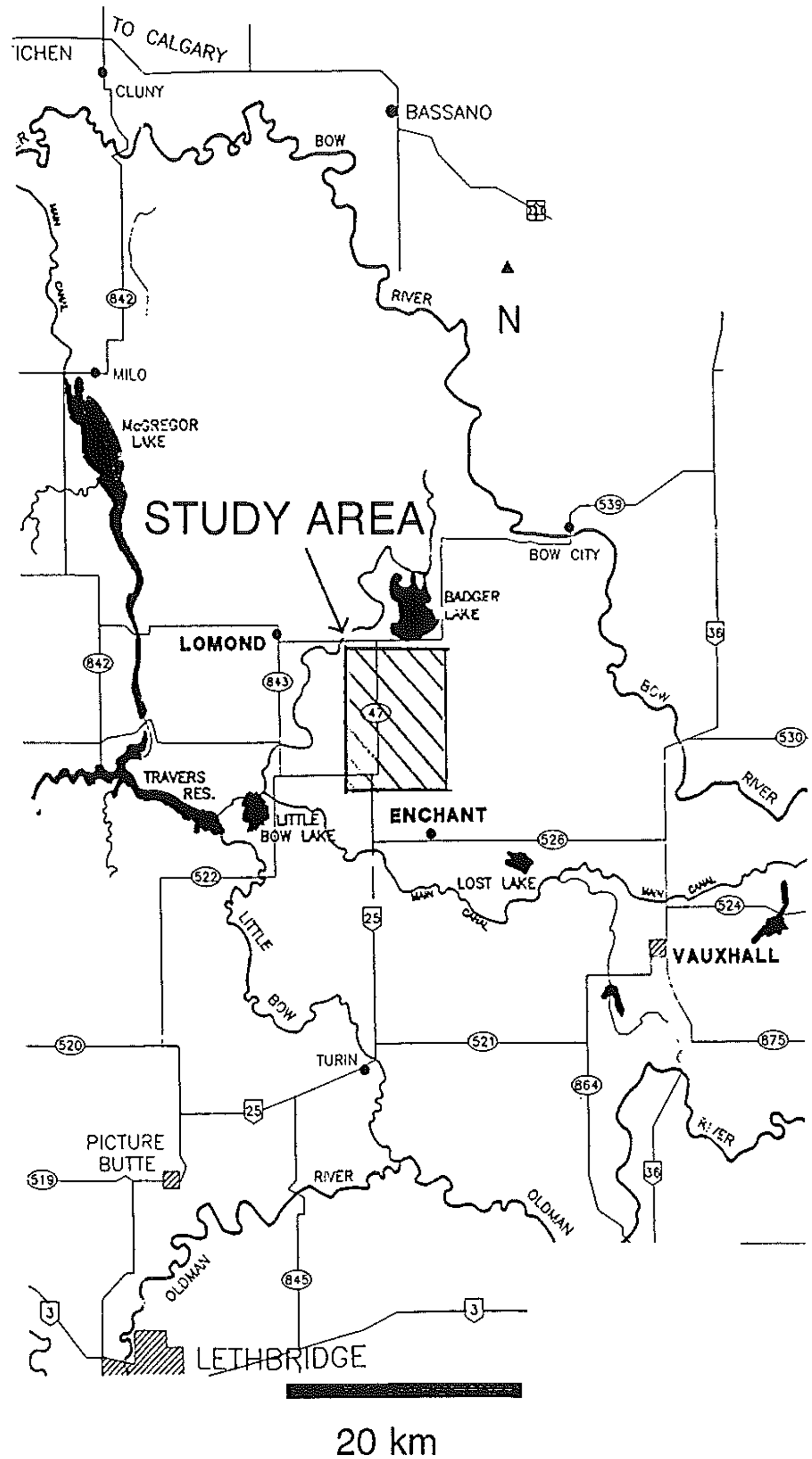

Figure 1. Location of study area near Lomond, Alberta, Canada.

Table 1. Characteristics of the target quarter-sections near Lomond, Alberta, Canada.

Quarter-section	Crop type and extent	Irrigation method
SW 05–15–18	Wheat (40·5 ha—eastern portion and dry corners)	Central pivot
	Peas (24·3 ha—western portion)	
NW 24–15–19	Wheat (64·7 ha)	Central pivot
NE 25–15–19	Canola (52·6 ha—irrigated portion)	Central pivot
	Summer fallow (6·1 ha—northern 2 dry corners)	
	Wheat underseeded to grass 6·1 ha–2 S. dry corners)	
NE 26–15–19	Wheat underseeded to alfalfa (64·7 ha)	Central pivot
NW 26–15–19	Peas (28·3 ha—northern half of irrigated portion)	Central pivot
	Canola (28·3 ha—southern half of irrigated portion)	
	Wheat (8·1 ha—dry corners)	
SE 26–15–19	Wheat (64·7 ha)	Line irrigation
SW 26–15–19	Wheat (32·4 ha)	None
	Summer fallow (32·4 ha)	
NE 27–15–19	Wheat (52·6 ha—irrigated portion and 2 E. dry corners)	Central pivot
	Summer fallow (12·1 ha—2 W. dry corners)	
SE 27–15–19	Beans (52·6 ha—irrigated portion)	Central pivot
	Summer fallow (12·1 ha—dry corners)	

on readily identifiable landmarks, both natural and cultural. Ground-based measurements of crop characteristics were conducted contemporaneously with the overflight and extended into the following day (19–20 July 1994).

The ground-based data consisted of average plant height, canopy temperature minus ambient air temperature, and LAI. Multiple readings were taken at each sample location in the fields and averaged for each station. Data were collected within 5 m of the central sample location. Air temperatures were measured with a sling psychrometer at the beginning and end of each field transect and interpolated for the various sample sites. Given the generally invariant sky conditions during the field transects, this is felt to be a valid assumption. Canopy temperatures were acquired with an Everest Interscience Model 110 infrared thermometer equipped with a 3° field-of-view (FOV). Five measurements were taken at each sample location and averaged. The measurements were taken of sunlit leaves at a 45° zenith angle in the principal plane of the sun. The canopy (T_c) minus ambient air temperature (T_a) were used in the analysis (T_c-T_a) and are referred to simply as canopy temperatures. The LAI measurements were acquired using a LiCor LAI2000 Plant Canopy Analyzer. Twelve LAI readings were acquired at each sample site and averaged. The number of sample locations visited in each field are listed in table 2. No measurements were made within the wheel tracks. The width of the wheel tracks was approximately 30 cm. Given the size of each sample location (~100 m^2), the wheel track covered less than 4 per cent of the sample site. Given that variations in crop characteristics were on the order of a factor of 2 or more, the effect of the wheel track was not deemed to be significant.

4. Data analysis

The spatial resolution of the SAR imagery was such that central pivot irrigation wheel tracks were normally not identifiable in the imagery. In these cases the spacing between pivot tracks as measured during the transects was used to identify the sample locations in the imagery. As the intent was to extract backscatter values from

Table 2. Number of data points used in analysis and range of values.

Crop	Crop characteristic	Number of samples	Range of values in crop characteristic
Wheat	LAI	57	0·6–4·9
	T_c–T_a (°C)	32	−2·7–+2·0
	PH (cm)	43	35–135
Canola	LAI	11	1·2–5·5
	T_c–T_a (°C)	11	−4·0–+2·0
	PH (cm)	11	50–107
Beans	LAI	12	0·9–2·0
	T_c–T_a (°C)	5	−2·4–−0·7
	PH (cm)	22	25–35
Peas	LAI	13	2·8–6·1
	T_c–T_a (°C)	7	−1·7–+0·6
	PH (cm)	7	50–70
Wheat/alfalfa	LAI	17	1·8–3·7
	T_c–T_a (°C)	17	−1·8–+0·3
	PH (cm)	17	60–85

LAI = Leaf area index; T_c–T_a = Canopy minus ambient air temperature; PH = Plant height.

the imagery corresponding to the ground-based sample locations, the locations of the ground-based stations were located on the antenna pattern corrected imagery. In order to ensure that the corresponding backscatter values for each ground-based sample location were properly acquired, and given the uncertainties in precisely locating all of the sample locations in the imagery, it was decided to extract average backscatter values for a 2 pixel × 2 pixel block at each of the sample locations.

Both tonal and textural analysis of the SAR imagery was undertaken. Image rectification was performed by CCRS prior to data delivery. Data preprocessing consisted primarily of applying an antenna pattern correction, which minimizes the effects of intensity variations in the range direction. Antenna pattern correction, image preprocessing and analysis were all performed using the EASI/PACE image analysis package from PCI Ltd (PCI 1992). Backscatter values were extracted from imagery which had been subjected to filtering as well as textural analysis. Tonal images which were examined included the 'raw' antenna pattern corrected image, and images filtered using 3 × 3 and 11 pixel × 11 pixel size Frost adaptive filters (PCI 1992). Frost adaptive filters with intermediate size windows were also examined and it was found that the results were in all cases intermediate between the two extremes. Filter sizes greater than 11 × 11 were not used in the analysis due to the excessive processing time required. Textural 'images' for which values were extracted included textural homogeneity, contrast, and mean. The various SAR 'images' which were used in the analysis are provided in table 3.

The ground-based non-spectral data and extracted SAR backscatter values were subjected to statistical analysis using univariate and multivariate linear regression analysis as a function of crop type. This approach is useful for determining whether potential indicators of incipient stress (canopy temperatures) and established stress (plant height, LAI) can be deduced from the SAR imagery. Correlation coefficients (r) generated for single radar images can vary between −1 and +1; a correlation of +1 indicates a perfect direct linear relationship between two variables (in this case

Table 3. SAR 'images' used in the analysis.

SAR image
Raw image (no filtering)
3 × 3 filtered image
11 × 11 filtered image
Textural homogeneity
Textural contrast
Textural mean
11 × 11 filtered image + textural mean

a radar image and a crop condition parameter); a correlation of −1 indicates that one variable is perfectly inversely correlated with another variable. A correlation coefficient of zero indicates a complete lack of a linear relationship (Davis 1986). Coefficients of multiple correlation (R) were generated for the combinations of two or more radar images. Coefficients of multiple correlation can vary between 0 and +1, with the latter indicating a perfect direct linear relationship, and the former indicating a complete lack of a linear relationship. The number of data points and range of ground-based values available for statistical analysis are provided in table 2.

The statistical significance of the various crop characteristic-SAR image correlations was also assessed. The student t-test was used to determine the level of statistical significance of the derived correlation coefficients. These coefficients were assessed at the 99 per cent level of significance, corresponding to $\sim 2{\cdot}6\sigma$ (Davis 1986). In the ensuing discussion, statistical significance is used to indicate that the correlation coefficients are significant at this level. As statistical significance is a function of the number of degrees of freedom, the correlation coefficients based on combinations of SAR images may be higher than for individual SAR images, but this difference may not be statistically significant. In addition, some crop characteristic data sets contained very few points, yielding high correlation coefficients that are not statistically significant. Correlation coefficients that are statistically significant at the 99 per cent level are highlighted in tables 4–8. As the number of degrees of freedom decreases, either due to a reduction in the number of data points, or an increase in the number of SAR images used in the analysis, progressively higher correlation coefficients are required for a given level of statistical significance.

Table 4. Linear correlation coefficients for wheat fields.

SAR image	LAI[1]	T°[2]	PH (cm)[3]
Raw image	**−0·59**	**0·54**	−0·30
3 × 3 filtered image	**−0·63**	**0·59**	−0·35
11 × 11 filtered image	**−0·59**	**0·61**	**−0·42**
Textural homogeneity	0·05	−0·07	0·06
Textural contrast	**−0·41**	0·23	−0·30
Textural mean	**−0·63**	**0·55**	−0·31
11 × 11 filtered image + textural mean	**0·69**	**0·62**	**0·42**

[1] Leaf Area Index; [2] Canopy minus ambient temperature; [3] Plant height.
Bold values indicate correlation coefficients that are statistically significant at the 99% level.

Table 5. Linear correlation coefficients for canola fields.

SAR image	LAI[1]	T°[2]	PH (cm)[3]
Raw image	0·65	−0·52	0·73
3 × 3 filtered image	0·53	−0·45	0·60
11 × 11 filtered image	0·38	−0·26	0·41
Textural homogeneity	−0·16	−0·55	0·27
Textural contrast	0·38	−0·24	0·35
Textural mean	0·49	−0·40	0·55
11 × 11 filtered image + textural mean	0·50	0·40	0·55

[1] Leaf Area Index; [2] Canopy minus ambient temperature; [3] Plant height.

Table 6. Linear correlation coefficients for bean field.

SAR image	LAI[1]	T°[2]	PH (cm)[3]
Raw image	0·37	−0·92	−0·07
3 × 3 filtered image	0·48	−0·89	−0·18
11 × 11 filtered image	0·65	−0·89	−0·27
Textural homogeneity	−0·21	0·11	−0·11
Textural contrast	0·38	−0·51	0·11
Textural mean	0·43	−0·84	−0·08
11 × 11 filtered image + textural mean	0·66	0·91	0·31

[1] Leaf Area Index; [2] Canopy minus ambient temperature; [3] Plant height.

Table 7. Linear correlation coefficients for pea fields.

SAR image	LAI[1]	T°[2]	PH (cm)[3]
Raw image	**−0·82**	0·39	−0·83
3 × 3 filtered image	**−0·89**	0·33	−0·48
11 × 11 filtered image	**−0·85**	−0·21	0·29
Textural homogeneity	0·11	−0·28	0·41
Textural contrast	**−0·67**	0·65	−0·64
Textural mean	**−0·85**	0·42	−0·73
11 × 11 filtered image + textural mean	**0·89**	0·50	0·82

[1] Leaf Area Index; [2] Canopy minus ambient temperature; [3] Plant height.
Bold values indicate correlation coefficients that are statistically significant at the 99% level.

Table 8. Linear correlation coefficients for wheat underseeded to alfalfa field.

SAR image	LAI[1]	T°[2]	PH (cm)[3]
Raw image	0·17	−0·08	−0·06
3 × 3 filtered image	0·15	−0·02	0·09
11 × 11 filtered image	0·20	0·02	0·34
Textural homogeneity	0·38	−0·01	−0·33
Textural contrast	−0·25	−0·42	0·28
Textural mean	0·24	0·11	0·03
11 × 11 filtered image + textural mean	0·24	0·16	0·51

[1] Leaf Area Index; [2] Canopy minus ambient temperature; [3] Plant height.

useful results than textural analysis. Textural mean was the most highly correlated textural image for LAI and plant height as well as exhibiting the highest average correlation of the textural images.

Unlike the wheat crop, increasing the size of the Frost adaptive filter results in decreases in correlation coefficients for all three crop condition parameters. This implies that variations in crop conditions exist at a smaller scale than for the wheat crops, although given the operational project constraints, this hypothesis could not be rigorously examined prior to crop harvesting. Nevertheless the heterogeneity of the canola crop relative to the wheat crop was noted during the field campaign.

Given the generally low correlation coefficients for the 11×11 filtered image, inclusion of the textural mean in the analysis (the most highly correlated textural image, on average) resulted in significant improvements in correlation coefficients over the 11×11 filtered image alone for all three crop characteristics. The correlation coefficients matched or slightly exceeded the results for the textural mean alone. These results can be interpreted in two ways: inclusion of textural imagery in the analysis can improve correlation coefficients for poorly or moderately correlated tonal imagery, or inclusion of tonal imagery in the analysis will have little effect on moderately correlated textural imagery.

5.3. *Beans*

As the area under bean cultivation was fully irrigated, dryland data were not available and hence the range in crop characteristic values was not as extensive as for the other crops (table 2). As with the canola, none of the derived correlation coefficients are statistically significant at the 99 per cent level. The correlation coefficients for the bean field are presented in table 6. No single radar image or combination was most highly correlated with all three crop condition parameters. The tonal images were generally more highly correlated than the textural images. Textural mean was the most highly correlated of the textural images for LAI and canopy temperatures as well as on average.

The effect of filtering on the correlation coefficients generally followed the trends exhibited by the wheat crop: increasing correlation with increasing filter size. This suggests that variations in crop conditions may exist predominantly at a scale larger than the average pixel size. The combination of the 11×11 filtered image with the textural mean yielded correlation coefficients equivalent to or slightly higher than the 11×11 filtered image alone, suggesting that the inclusion of textural imagery in the analysis will result in only marginal improvements in correlation coefficients. Once again it should be noted that these results are not significant at the 99 per cent level but many are significant at lower levels.

5.4. *Peas*

Two pea fields were sampled during the course of the campaign, allowing a more robust comparison than for a single field. In the course of the field transects it was noted that the pea crop exhibited wide variability in terms of visual appearance, in spite of the fact that the pea crops in both fields were fully irrigated. The correlation coefficients for the pea fields are presented in table 7. Leaf area index is the most highly correlated crop condition parameter ($-0{\cdot}89$), followed by plant height ($-0{\cdot}83$), and canopy temperatures ($0{\cdot}65$). In spite of the limited number of ground-based measurements, statistically significant correlations were found for most of the SAR images with LAI.

The effects of filtering on tonal image correlation coefficients are variable. In some cases filtering provides improvements in correlation coefficients (wheat, bean), in other cases correlation coefficients decline (canola, peas), and in some cases the results are mixed (wheat underseeded to alfalfa). This effect appears to be a function of filter size: increasing the size of the filter magnifies the increases or decreases. This study was focused on a total of five crops, at a single site and for a single overflight, consequently it is difficult to draw generalizations from the data; in addition, no comparable studies have been located in the literature.

The lack of systematic relationships extends to the detailed results. No one crop characteristic is most highly correlated for all crop types. Similarly no single crop was the most highly correlated for all three crop characteristics and no single radar image or combination was best suited for any one crop or crop characteristic.

Given that the highest number of ground-based measurements were made for the wheat crop and that this crop yielded the highest number of statistically significant correlations, these data can be considered indicative of the applicability of SAR to crop characteristic monitoring. The ground-based measurements yielded the following correlation coefficients: $-0{\cdot}75$ for LAI to canopy temperature, $0{\cdot}79$ for LAI to plant height, and $-0{\cdot}54$ for plant height to canopy temperature. All of these values are statistically significant at the 99 per cent level.

The inverse correlation between LAI and plant height with canopy temperature is expected given that healthy crops should possess high LAIs, be taller and exhibit lower canopy temperatures due to more efficient evapotranspiration than stressed crops. As expected LAI and plant height exhibit a positive correlation.

The inverse correlation between LAI and plant height with radar backscatter is at odds with simplified models of vegetation backscatter which suggest that backscatter should be positively correlated with biomass, and by extension LAI and plant height (Brakke *et al.* 1981, Ulaby *et al.* 1984, Brisco and Brown 1990). It should be noted that the pea fields also exhibit statistically significant negative correlations between LAI and radar backscatter. A number of possible explanations can be invoked to explain the results. It is known that microwave backscatter is affected by a number of factors in addition to above-ground biomass, including soil moisture, row/field/ditch orientation and spacing, soil roughness, and crop phenology (e.g., Wu *et al.* 1985, Hutton and Brown 1986, Boivin *et al.* 1990, Bouman and van Kasteren 1990 a, 1990 b). It therefore seems conceivable that some combination of these factors may account for the observed negative correlation. Similarly the positive correlation between canopy temperatures and radar backscatter may be attributable to a combination of the aforementioned factors. During the field transects it was noted that both row orientation and soil moisture were quite variable within a single field.

The results suggest that the applications of SAR imagery to monitoring variations in crop characteristics may be somewhat limited, and that backscatter, at least under the conditions prevalent in this study, may be strongly affected by factors other than above-ground biomass.

A number of issues require further resolution. Filtering may improve or degrade the correlations, and the data are insufficient to determine which factors must be considered prior to filtering and the optimum size and characteristics of the filter. In addition, no one image or combination will yield the highest correlations for any one crop or crop characteristic and it appears difficult, if not impossible, to predict which image(s) will provide the highest correlation in all cases. In general, it appears that the best results are obtainable from a combination of both tonal and textural images; at the very least the inclusion of textural imagery (at least for textural mean) in the analysis will probably not appreciably degrade the results. The results also suggest that tonal images will generally yield higher correlations than textural images.

For SAR monitoring of agricultural crop conditions to become a viable enterprise, additional studies are required to determine the ground-based factors which affect the correlation coefficients and their relative importance. As an example, it is suspected that the scale of intra-field variations may be the cause of changes in correlation coefficients (both positive and negative) with increasing filter size. However, it is not known whether these variations are associated with soil and/or crop quality, surface roughness, soil moisture, or the magnitude and scale at which these variations become important.

The results of this study indicate that while statistically significant correlations exist between various crop characteristics and backscatter, the sense of the relationships is at odds with simplified canopy models. This suggests that non-canopy factors may be important contributors to SAR backscatter.

Acknowledgments

This work was undertaken under the aegis of the National Research Council Industrial Research Assistance Program. The authors wish to thank Agriculture and Agri-food Canada for their technical assistance in the project and the Canada Centre for Remote Sensing, and in particular Dr Ron Brown, for acquisition of the airborne synthetic aperture radar data. Thanks also to Mr Ed Nikkel for generously providing access to his lands, and to Ian Major and Darren Nikkel for assisting with the ground campaigns. Thanks also to the two anonymous reviewers for their cogent comments.

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