Remote Sensing in Support of Crop Management

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The Canada Centre for Remote Sensing (CCRS) is internationally recognized as a leader in the development of applications of earth-observation data. CCRS also supports an expanding Canadian industry sector that includes world leaders in global ground station, image analysis and radar mapping markets. In conjunction with the private sector, CCRS develops remote sensing technology and applications to address both land and ice/oceans issues. Considering Canada's large land mass and the importance of global agricultural resources, CCRS is actively involved in research specifically related to the application of remote sensing technologies to agriculture.

Agriculture research at CCRS has been driven by end-user requirements. The program has exploited both optical and radar data to address regional and local issues. For more than a decade, Canada has been operationally providing information on the state of its domestic grain crops through a system called the Crop Information System (CIS). This system uses small-scale optical imagery to provide crop information across the Canadian Prairie Region. With Canada's commitment to RADARSAT-1 and RADARSAT-2, CCRS is also developing radar applications related to both soils and crop conditions. In addition, in response to information requirements from the precision agriculture community, CCRS has expanded its hyperspectral program to include research and development of agriculture applications. The purpose of this paper is to provide an overview of CCRS' involvement in agriculture applications research and to describe the domestic and international programs that support both the research and the transfer of this technology.

The Canadian Crop Information System

Canada is the sixth largest producer of wheat in the world although about 80% of its wheat is targeted for export (Reichert *et al*., 1998; Brown *et al*., 1990). As a result of the importance of grain crops to Canadian agri-business, early assessments of crop yield are invaluable to decision makers and analysts within government agencies, grain marketing bodies, agricultural retailers and insurance companies. Consequently in the early 1980s, researchers began exploring the use of Advanced Very High Resolution Radiometer (AVHRR) data for providing information on crop conditions and expected grain yields across the Prairie region of western Canada. The AVHRR sensor is carried on the National Oceanic and Atmospheric Administration (NOAA) satellites and provides images in the visible, near infra-red and thermal infra-red wavelengths. Although the sensor has a course resolution of about one kilometer, the satellite provides daily coverage of earth. This frequent coverage is critical for providing operational crop information at a regional scale.

In 1987, the Canadian Crop Information System (CIS) was initiated as a joint project between the Canada Centre for Remote Sensing, Statistics Canada, the Canadian Wheat Board, and the Manitoba Remote Sensing Centre (Reichert et al., 1998). With the CIS, NOAA AVHRR data are acquired daily throughout the April to October crop growing season over the grain growing regions of western Canada. The data are downloaded to the CCRS satellite receiving station at Prince Alberta, Saskatchewan and then transferred to the Manitoba Remote Sensing Centre (MRSC). The MRSC operates the GEOCOMP system that was designed to perform pre-processing of the AVHRR data. Each AVHRR image is first geometrically registered to a map base and radiometrically calibrated (Brown et al., 1990). A map of the Normalized Difference Vegetation Index (NDVI), the difference between measured radiance values in channel 2 and channel 1 divided by their sum, is then produced. As numerous research studies have demonstrated, NDVI is a measure of crop condition and can be a good indicator of crop stress. Within the CIS, the NDVI values are also used to generate cloud-free composites. The NDVI values are reduced by clouds and atmospheric haze. Hence, by choosing data from the daily image containing the largest NDVI, a weekly, seven-day, cloud-free composite is produced for AVHRR channels 1, 2, 4 and NDVI. Following data pre-processing, Statistics Canada quickly retrieves the composites for channels 1, 2 and 4 from the MRSC using an internet file transfer protocol (FTP) connection (Reichert et al., 1998; Brown et al., 1993).

In conjunction with the development of the CIS, Statistics Canada began implementing the Crop Condition Assessment Program (CCAP) (Reichert et al., 1998; Brown et al., 1993). The CCAP was designed to replace Statistic Canada's supplementary reports to the farm surveys on yield and provided information on crop development throughout the growing season. The CCAP uses the CIS information within a customized GIS interface. Subscribers to CCAP can view several types of image and map products, statistical data and NDVI curves, all of which are updated weekly. These updates are available within two hours of receipt of the CIS composites from MRSC. CCAP deliverables are made available to subscribers via an interactive web site on the Internet. Image products show crop conditions on a pixel by pixel basis for the entire Prairie region of western Canada. Map products illustrate the dominant vegetation condition within Census of Agricultural Regions and Census Consolidated Sub-divisions. Historical data are provided so that subscribers can evaluate current crop conditions with those from previous years or with the normal. The normal is an average of the NDVI channel for the crop years from 1987 to the year prior to the current year.

Statistics Canada uses a linear regression model to explore the correlation between NDVI values during peak growth (early July to mid-August) and reported survey crop yields (Reichert *et al.*, 1998). Spring wheat production is then estimated by multiplying the forecast spring wheat yield from the CIS product by the seeded area from the current season. For the period from 1989 to 1998, the spring wheat yield forecast predicted from the NDVI data had an accuracy ranging from +7.8% to –9.1%. Research is continuing to extend yield predictions to other crops and to incorporate agro-meterological information and remote sensing data into a more robust yield model.

The Poland-Canada Remote Sensing for Agriculture Project was initiated in 1996 to help fulfil the Polish government's requirement for timely information on agricultural productivity and on production-to-market processes in Poland. Under this agreement, the technology developed for the Canadian Crop Information System was transferred to Poland. In 1998, The Polish Crop Condition Assessment System successfully completed its first year of operation. Staff from the Institute of Geodesy and Cartography operated a satellite receiving station, processed the data and input it into a GIS. The Central Statistical Office distributed the 1998 crop condition maps and graphs as part of their regular crop information reports. The information reports provided crop condition assessment and development monitoring, early warnings of production problems, such as drought, geographically referenced reports, and early season yield indicators.

Research and Development of Radar Applications

Since the early 1980s, CCRS has conducted Synthetic Aperture Radar (SAR) research at a number of super-sites across Canada. Within the agriculture program, SAR data have been acquired using several platforms at a range of spatial scales. Prior to the launch of RADARSAT-1, the CCRS Ku/C/ L-band ground-based scatterometer and the X/C-band Convair-580 airborne system were used to conduct lead-in research for applications of C-HH data. These systems have also provided the data necessary to understand incidence angle effects, which are important for many RADARSAT-1 applications. The scatterometer and airborne systems are now being used to assess the information that will be provided by RADARSAT-2's multi-polarized configuration. The primary areas of SAR research explored have included soil moisture and tillage mapping, as well as crop type and crop condition assessment.

Soils Information

Several CCRS research projects have confirmed the significant relationship between near-surface volumetric soil moisture on non-vegetated surfaces and SAR backscatter. Both airborne and ground-based scatterometer data were used to determine the depth of penetration of microwaves and sensitivity to soil moisture. ERS, SIR-C and RADARSAT-1 data sets demonstrated that this relationship held for SARs carried on spaceborne platforms. However agricultualists are generally more interested in the moisture available over a much deeper depth than that penetrated by C-band microwaves. Consequently, scientists at Agriculture and Agri-Food Canada (Li *et al.*, 1997) are investigating the extrapolation of radar derived surface soil moisture to the root zone using models based on the soil profile characteristics. Despite these positive results detection of soil moisture under a vegetation canopy remains difficult. Current soil moisture models are generally designed to predict moisture on bare surfaces. Although total backscatter from a cropped surface often contains contributions from the underlying soil, unravelling the soil and the crop component remains a complex problem.

Ground-based scatterometer as well as airborne and spaceborne SAR systems have also been correlated with tillage of the soil, following crop harvest and before spring planting. Microwave theory dictates that surface roughness significantly affects the intensity of backscatter. The characteristics related to the preparation of the seed bed for planting (type of tillage implement, number of tillage passes) affects the roughness of the surface and several CCRS research projects have demonstrated that C-band SAR can detect these tillage effects. Tillage and soil management practices influence erosion rates and the soil quality. These practices also effect the surface soil physical properties (moisture, temperature) with implications related to seed germination and early crop growth.

Crop Information

General land cover classes (urban, water, wetland, agriculture and forest) are usually easily identified using a single date, single SAR configuration like C-HH. However multi-temporal data sets, or data sets with multiple SAR configurations are required to provide more detailed information on crop type and crop condition. In a CCRS study in western Canada, 3 dates of RADARSAT-1 imagery acquired during the growing season could accurately distinguish one crop from another (McNairn *et al*., 1998). In fact this study demonstrated that multi-temporal SAR data was at least as good, or better than single date satellite optical data for crop mapping. The ability to acquire the RADARSAT-1 data during periods of peak growth, regardless of cloud cover, illustrated the advantages of SAR data for operational crop mapping.

As the crop grows and matures, the changes in crop moisture content and crop structure are also influencing backscatter response. Research based on experimental plots has followed backscatter changes with crop development. However, the RADARSAT-1 work by CCRS has indicated that operational crop type mapping will be complicated by field to field differences that are not only a result of differences in crop type, but also crop growth stage.

Optimal SAR Configurations for Agricultural Mapping

The successful application of SAR data for mapping soils and crop characteristics is often dependent upon the choice in SAR configuration. RADARSAT-1's flexible beam steering capability provides a number of advantages for mapping and monitoring and as well, users of the data can select the incidence angles optimal for any particular application. However, as backscatter responses are dependent upon incidence angle, this effect must be considered when combining multi-beam and multi-mode data sets.

To help users understand the implications of incidence angle on target discrimination, CCRS has examined these incidence angle effects. On non-vegetated surfaces incidence angles can be selected to minimize either soil moisture or surface roughness contributions to the total backscatter. Through scatterometer experiments, the CCRS participation in the 1994 SIR-C/X-SAR campaign and RADARSAT-1 acquisitions, sensitivity of SAR to soil moisture was demonstrated. As well, these studies identified the requirement for small incidence angles (less than 30^o) for soil moisture mapping. Shallower angles, on the order of $40\text{-}50^o$, proved sensitive to surface roughness differences introduced by various tillage implements. Scatterometer results have demonstrated that these shallower angles ($> 40^o$) are also better for crop type discrimination. At these angles, microwaves interact more with the crop volume and less contribution is received from the underlying soil surface.

RADARSAT-1 was designed as an operational satellite and consequently, addressing issues such as optimal time of day for soils and crop mapping is important. Early morning acquisitions can have a number of implications for target discrimination in temperate regions of the globe. In the spring and the fall, soils can freeze overnight and under these conditions the backscatter decreases since the SAR sees these soils as dry, regardless of the soil moisture content (Pultz *et al*., 1997). During the growing season, depending upon the minimum temperature and humidity overnight, dew can form on the crop canopy. RADARSAT-1 descending acquisitions over western Canada demonstrated that dew on the canopy significantly increased backscatter, but did not interfere with crop discrimination (Wood *et al*., 1998). In some regions where dew effects are not a concern, early morning acquisitions can actually minimize the chances of acquiring SAR data after a rain event. Significant rain on the canopy can not only increase backscatter, but can also saturate backscatter recorded on the image making it difficult to discriminate crop types.

RADARSAT-2 will provide not only the multi-beam selections present on RADARSAT-1, but will also provide a choice in polarization. The polarization of the microwave signal dictates which components of the crop and soil contribute to the total amount of energy scattered back to the SAR sensor. Vertically polarized microwaves couple with the predominant vertical structure of most agricultural crops and as a result, the microwave signal is attenuated to a greater extent. This interaction between V-polarized waves and the crop canopy provides good contrast among crop types that have different canopy structures. HH-polarized microwaves are not easily attenuated by vertically structured crops and therefore these microwaves tend to penetrate the crop canopy to a greater extent than VV. As a result, more information is provided about the underlying soil condition when an HH configuration is used. Cross-polarizations respond to significant multiple scattering within the target, as occurs with very rough surfaces, or as a result of significant volume scattering, as occurs within a vegetation canopy. The sensitivity of cross-polarizations to differences in structure and moisture within the crop canopy suggests that this SAR configuration will provide important information related to crop type and crop condition. Results from one scatterometer experiment have indicated that cross-polarizations will be particularly useful for separating crops which have similar canopy geometries.

GlobeSAR 1 and GlobeSAR 2 Programs

GlobeSAR 1, initiated in 1993, was a 3 year program funded by the Canadian Space Agency (CSA), the International Development Research Centre (IDRC) and Natural Resources Canada and delivered by CCRS. The objective of GlobeSAR 1 was to expand the range of applications of radar data and to increase its utility to user countries and regions. The program, as well, transferred the technology developed during GlobeSAR to the participants. As a result, GlobeSAR 1 was able to develop a community of users with the expertise ready to exploit RADARSAT-1 data. Eleven host countries were involved in GlobeSAR 1 involving 63 different institutions and 20 applications areas. During the initial GlobeSAR 1 phase, the airborne CV-580 C-band SAR acquired 100,000 square km of data over 32 sites including many in Southeast Asia. Flights were planned with RADARSAT configurations and were accompanied by an extensive ground data acquisition program. The second phase of the program involved the evaluation of simulated RADARSAT-1 data. Sixty-five simulations were generated from the CV-580 airborne data. GlobeSAR 1 culminated in the analysis of various modes of actual RADARSAT-1 imagery.

The success of GlobeSAR 1 was followed by a second 3 year program – GlobeSAR 2. GlobeSAR 2 was led by CCRS and was designed to develop radar expertise in eleven Latin American countries in order that users could take advantage of RADARSAT-1 imagery. The Canadian International Development Agency (CIDA) funded eight countries and another three countries were supported by funding from IDRC. The project was carried out in co-operation with RADARSAT International Inc., PCI and Atlantis Scientific. Although all participants had a basic capacity in terms of facilities and hardware, they lacked the highly specialized radar processing software and training to effectively use this capacity. Approximately 90 different projects were undertaken in the eleven countries, many of them in agriculture. A list of these projects and current research results can be viewed on the CCRS web site (www.ccrs.nrcan.gc.ca). The GlobeSAR 2 University Program is still ongoing and addresses curriculum development in radar remote sensing and the development of linkages with Canadian universities.

Rice Monitoring

The change in backscatter associated with the growth cycle of paddy rice is significant and this large dynamic range makes SAR well suited for identifying the areas of planted rice and rice growth stage. A number of researchers have demonstrated that SAR imagery can provide useful information about rice type, growth stages and acreages (Takashi *et al*., 1995; Le Toan *et al.*, 1997; Liew *et al*., 1998). Under the GlobeSAR 1 program airborne SAR data were acquired over the Zhaoqing test site in Guangdong Province in the south of China (Shao *et al*., 1999). Multi-date RADARSAT-1 imagery was also acquired from March to December of 1996 and April to July of 1997. This study produced a rice-type distribution map showing 4 types of rice with different life spans.

Crop yield estimation, in general, is still largely in the research arena. Crop development is complex and final yield is driven by numerous factors often tied to key crop phenological stages.

In rice yield estimation, if rice productivity is known SAR data could provide the necessary acreage information for total yield predictions. Satellite SARs also provide the imagery required to monitor drought or flooding events that can severely impact crop productivity.

AGROMA (Agricultural Monitoring Using Remote Sensing and Spatial Analysis), a software tool developed by the Canadian company PCI Geomatics Inc., is helping promote the use of remote sensing for operational crop monitoring (refer to www.pci.on.ca). The rice mapping module uses multi-temporal RADARSAT-1 data to determine areas planted in rice crops. AGROMA also provides an interface to model crop growth and estimate crop yields.

Precision Farming

Across much of North America and Europe, approaches to farming are changing. Pressures to farm in a more environmentally conscious manner and to increase farming profitability have resulted in the development of the site-specific approach to agriculture. The success of precision farming can be at least partially linked to the availability of accurate spatially geo-referenced data. These data can be supplied by a number of different sources, ranging from measurements taken in the field to data collected from space. Information derived from the data can then be used to help assess the current condition of soils as well as crops. If enough data are compiled throughout the growing season, data layers can then be used to monitor changes in the state of these conditions over time and to provide the information required for either near real time mitigation, or for prescribing soil and crop treatments for subsequent years.

CCRS has been looking at the use of hyperspectral and high spatial optical data for a number of applications including precision agriculture. From data acquired in 1996 and 1997, algorithms were developed to extract leaf area index (LAI) and canopy liquid water content from hyperspectral data acquired in the visible and near-infrared spectral regions. As well, using spectral unmixing techniques, several crop indicators including biomass and crop height were correlated with endmember fractions. In the recent Clinton 1999 campaign the Probe-1 sensor was flown over a test site in Ontario. Data were acquired in 96 channels in the region from 400 – 2500 nm. These data will be used to validate bio-physical parameters like LAI and liquid water content derived using existing methods. New semi-empirical models will be developed and tested for estimating chlorophyll and leaf nitrogen content, soil nutrient levels and soil moisture. Spectral unmixing will also be used to derive weed maps.

Research at CCRS into the use of hyperspectral and high spatial data is driven not only by the requirement for data by precision farming, but also by the significant number of proposed satellite launches in the next several years. This research program is helping to prepare Canadian users for sensors like Ikonos-2, Resource 21 and Xstar, and helping to develop the necessary techniques required for users to effectively exploit these new data sources.

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