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Corn Monitoring and Crop Yield Using Optical and Microwave Remote Sensing

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1. Introduction

Remote sensing (RS) is the practice of deriving information about the Earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the Earth surfaces (Campbell, 2006). Using various sensors, we remotely collect data that may be analyzed to obtain information about the object, areas or phenomena being investigated. There are many forms in which the data are acquired, including variations in force distributions, acoustic wave distributions, or electromagnetic energy distributions.

Optical RS makes use of visible, near infrared and short-wave infrared sensors to form images of the Earth's surface by detecting the solar radiation reflected in these wavelengths from targets on the ground. Different materials reflect and absorb energy differently at these visible and infrared wavelengths. Thus, targets can be differentiated by their spectral reflectance signatures captured in the remotely sensed images. Optical RS systems are classified into the following types, depending on the number of spectral bands used in the imaging process: panchromatic imaging systems (i.e. Ikonos pan, Spot HRV-Pan), multispectral imaging systems (i.e. Landsat MSS, Landsat ETM, Spot HRV-XS, Ikonos MS), super spectral imaging systems (i.e. Modis & Meris), hyperspectral imaging systems (i.e. Hyperion on EO1 satellite).

In contrast, radar (Radio Detection and Ranging) sensors operate in the microwave portion of the electromagnetic spectrum beyond the visible and thermal infrared regions (Henderson & Lewis, 1998). Radars have long been exploited for communication and navigation purposes. More recently, Synthetic Aperture Radar (SAR) sensors have become an increasingly important source of information to support agriculture and natural resources monitoring and management. Operating in the microwave region of the electromagnetic spectrum improves signal penetration within vegetation and soil targets. Unlike optical sensors, the longer wavelengths of a radar imaging system are not affected by cloud cover or haze, permitting data acquisition independent of atmospheric conditions. Radar systems transmit microwave signals at specific wavelengths or frequencies according to their design specifications.

SAR sensors transmit microwave energy, illuminating the terrain, and measuring the amount of energy scattered by the target or surface. This response (also known as radar return or backscatter) is recorded by the SAR sensor. The greater the amount of energy scattered back to the sensor, the brighter the response recorded in the radar image. Active microwave sensors provide their own source of electromagnetic energy and are therefore capable of operating independent of sunlight. SARs can therefore acquire data day or night. Radars offer a variety of advantages for geoscientists and agronomists. These sensors are unaffected by adverse atmospheric conditions and because they operate independent of solar illumination, are available to acquire imagery 24 hours a day. Radar data provide a unique perspective of the landscape and many opportunities for quantitative terrain analysis.

Optical RS has been used for monitoring the state of the world's agricultural production, including identifying and differentiating most of the major crop types and conditions. However for agricultural regions under frequent cloud cover, the use of this technology for crop monitoring can be unreliable. In contrast, radar RS data are sensitive to vegetation biomass and structure and as a result these sensors are an attractive option for crop monitoring. Radar data and visible and infra-red wavelengths provide complementary information related to different target properties (Brisco and Brown, 1998). The synergy associated with data acquired by SAR and optical sensors has led to intensive research activities towards the application of RS technologies. Used together, optical and radar data provide a valuable information source for agricultural applications. Results have been very promising for a wide range of specific applications including crop type identification, crop condition, crop monitoring and crop yield.

Since the 1980s optical imagery from sensors such as Landsat and more recently Ikonos and Quickbird, has been used consistently to determine corn cultivated areas in Mexico, where over 7 million hectares of this staple crop are sown every year. Corn yield prediction is an information service provided by the National Institute of Research for Forestry, Agriculture and Livestock (INIFAP) to the Ministry of Agriculture, where it is used as a decision making aid. Techniques to combine information from optical and radar sensors have been proposed to detect and separate vegetation targets. However further development is needed to improve these techniques to increase accuracies for crop condition and crop monitoring. Information with respect to productivity is required as far ahead of harvest time as possible.

Land use, based on intensive and diversified agricultural production, is integral to the economy in many countries. The heterogeneity of corn-growing conditions in developing countries makes accurate data for yield prediction difficult to obtain. Accuracy can be increased for a particular crop by integrating the information provided from optical and radar satellite images.

Government agencies require the best accuracy for production plots in order to relate these statistics to the general agricultural regional or nationwide productivity. More accurate information will support (a) timely responses and better decision making, (b) production risk reduction and (c) increased efficiency in crop management and production.

This chapter will first discuss the interaction of SAR microwaves with agricultural targets by considering the system and target parameters which influence the radar backscattering process. Then, the approaches for crop type identification, the first step in a monitoring program, will be discussed. This will be followed by a review of crop condition, crop monitoring and crop yield estimation using optical and radar data. The chapter ends with comments on present and future research for agricultural applications using optical and microwave remote sensing.

2. Microwave Interaction with Agricultural Targets

Remote sensing observations have been used for identification and monitoring of agricultural targets since the late 19th century when balloons first started carrying photographic cameras and other instruments over the ground. All optical sensors are limited by solar illumination, cloud cover and haze. In spite of this, optical remote sensing has seen many useful if limited applications in agriculture and other areas. The use of radar sensors for agricultural applications has been intensively studied since 1970. The all weather, day or night data acquisition capability of radar systems, provides a more reliable data source. However, the interaction of the radar signal with agricultural targets is affected by a variety of factors. From this perspective, it is convenient to separate the discussion into radar system parameters which affect radar backscatter - such as frequency, polarization and incidence angle - and target parameters which influence the scattering process.

Target parameters can be related to the dielectric and geometrical properties of the material in question. Dielectric properties are very closely associated with the water content of the material while leaf shape and size (with respect to wavelength) are examples of geometrical characteristics (Brisco & Brown, 1998). The brightness of features in a radar image is dependent on the portion of the transmitted energy that is returned back to the radar (hence the term backscatter) from targets on the surface. The magnitude or intensity of this backscattered energy is dependent on how the radar energy interacts with the surface, which is a function of several variables or parameters. These parameters include the particular characteristics of the radar system and the generated image products as well as the characteristics of the incident surface (land cover type, topography, roughness, etc.).

Frequency or wavelength, incidence angle, and polarization are the primary system parameters which define a radar sensor and its data gathering characteristics. Other important system parameters which influence the type of product to use in an application include range and azimuth resolution, swath width, pulse length, transmitter power, and bandwidth.

2.1. The effect of frequency

With respect to the effect of frequency on microwave interaction with an agricultural target, the magnitude of the radar backscatter is dependent upon it (or wavelength) due to: differences in the dielectric constant of water content as a function of frequency; and to the relationship between wavelength and plant part size and/or penetration depth. The degree of moisture content affects the dielectrical properties of an object or medium. Changes in the electrical properties influence the absorption, transmission, and reflection of microwave energy. Thus, the moisture content will influence how targets and surfaces reflect energy from the radar signal and how they will appear on an image. In general, reflectivity (image brightness) increases with increased moisture content.

Since agricultural targets are composed of significant and varying amounts of water this frequency dependence on the dielectric constant is very important in the interaction process. As frequency decreases the signal penetration into crops and/or soil increases and the sizes of the target components (i.e., leaves, stems, etc.) relative to the wavelength are smaller leading to a "smoother" target.

The radar return from each resolution cell of an agricultural target is the vector sum of electromagnetic (EM) fields scattered from the elements of the vegetation canopy, and those scattered from the soil beneath. Individual scattered contributions are determined by the scattered dimensions to wavelength ratio. Radar returns from an ensemble of scatterers are determined by the population of those scatterers, by the scatterer dimension function, and by the EM reflection coefficient of each scatterer. When the scatterer dimension is approximately the size of the wavelength the shape of the scatterer becomes very important in determining the backscattered EM fields and the detailed calculations and interpretations are complex.

Lower frequency radars are better suited for soil moisture estimation, especially when vegetations are present, while the higher frequency systems emphasize the crop component. When large amounts of vegetation are present L-band or lower frequencies are preferred to minimize the crop contribution to the backscatter (Brown *et al.*, 1992). The higher frequencies are generally preferable for crop type mapping, but this can change regionally depending on the crop mix and seasonally as a function of crop development.

When discussing microwave energy propagation and scattering, the polarization of the radiation is an important property. For a plane EM wave, polarization refers to the locus of the electric field vector in the plane perpendicular to the direction of propagation. The length of the vector represents the amplitude of the wave, the rotation rate of the vector represents the frequency of the wave and the polarization refers to the orientation and shape of the pattern traced by the tip of the vector. The linear combination of horizontal (H) and vertical (V) polarization states for the transmitted and received signals (with transmit denoted first) give HH, VV, HV and VH combinations. HV and VH are the cross-polarizations while HH and VV are the like polarizations. With respect to the effect of polarization on microwave interaction with agricultural targets, polarization can be a useful discriminant in SAR image analyses.

Most SAR systems are designed to transmit microwave radiation that is either horizontally polarized (H) or vertically polarized (V). If a SAR transmits and receives two orthogonal polarizations (such as H and V), and records both, and during processing retains the phase between these two polarization, then any transmit-receive polarization can be synthesized. It is the analysis of these transmit and receive polarization combinations that constitute the science of radar polarimetry. Systems that transmit and receive both of these linear polarizations are commonly used.

Radar systems can have one, two or all four of these transmit/receive polarization combinations. Examples include the following types of radar systems:

- HH or VV (or possibly HV or VH) – Single polarization
- HH and HV, VV and VH, or HH and VV – Dual polarization
- HH, VV, HV, and VH with phase information retained – Polarimetric

Quadrature polarization and fully polarimetric can be used as synonyms for "polarimetric". The relative phase between channels is measured in polarimetric radars and is essential for polarization synthesis, for generating a range of polarimetric parameters and for image decomposition.

Ferrazzoli's (2002) work to retrieve crop variables considered three main steps in the process: i) identification of a convenient radar configuration, ii) modeling and iii) solution of the inverse problem. We now discuss aspects relevant to applying these steps to crop monitoring.

SAR systems operate in different wavelength ranges or bands. The choice of wavelength is dependent upon the remote sensing application. L-band radars operate at a wavelength of 15-30 cm and a frequency of 1-2 GHz. S-band operates at a wavelength of 8-15 cm and a frequency of 2-4 GHz. At these wavelengths S-band microwaves are not easily attenuated, making these sensors useful for near and far range weather observation. C-band radars operate at 4-8 cm wavelengths 4-8 GHz frequencies. These frequencies are well suited for many marine applications, in particular ice detection and monitoring. At smaller X band wavelengths (2.5-4 cm and a frequency of 8-12 GHz), microwaves are more sensitive to small scale changes, and these sensors have been used for studies on cloud development and to detect light precipitation. X band microwaves are very easily attenuated making them well suited for very short range weather observation. K band sensors operate at a wavelength of 0.75-1.2 cm or 1.7-2.5 cm and a corresponding frequency of 27-40 GHz or 12-18 GHz.

Microwave scattering from vegetation is dependent upon both the SAR frequency and polarization. Therefore, radar imagery collected using different polarization and wavelength combinations may provide different and complementary information. Multi-polarization combinations permit an image interpreter to infer more information about the agricultural surface characteristics. With polarimetric sensors any linear, circular or elliptical polarization can be synthesized, in addition to other polarimetric information including for example, co-polarization phase statistics or polarization signatures. Polarization signatures are three-dimensional plots which assist in the interpretation of the scattering behavior of the target. The polarization signature of the target provides a convenient way of visualising a target's scattering properties. The signatures are also called "polarization response plots". An incident electromagnetic wave can be selected to have an electric field with ellipticity between -45^o and +45^o, and an orientation between 0 and 180^o. These variables are used as the x- and y-axes of a 3-D plot portraying the polarization signature. For each of these possible incident polarizations, the strength of the backscatter can be computed for the same polarization on transmit and receive (the co-polarized signature) and for orthogonal polarizations on transmit and receive (the cross-polarized signature). The strength is displayed on the z-axis of the signatures.

From experimental airborne SAR systems and the SIR-C (shuttle) mission SAR polarimetry has provided data to researchers who have studied a number of applications. It has been shown that the interpretation of a number of features in a scene is indeed facilitated when the radar is operated in polarimetric mode. The launch of RADARSAT-2 has made polarimetric data available on an operational basis, and uses of such data can be expected to become more routine and more sophisticated. Some agriculture applications for which polarimetric SAR has already proved useful include crop type identification, crop condition monitoring, soil moisture measurement and soil tillage and crop residue identification.

2.2. The effect of the incidence angle

With respect to the effect of incidence angle on microwave interaction with agricultural targets, the relationship between viewing geometry and the geometry of the surface features plays an important role in how the radar energy interacts with targets and affects the corresponding brightness recorded on an image. Variations in viewing geometry will accentuate and enhance topography and relief in different ways, such that varying degrees of foreshortening, layover, and shadow may occur depending on surface slope, orientation, and shape.

The effect of the incident angle (θ) on radar backscatter has proven to be difficult to study with airborne SARs because of the rapid change of θ across the swath and the large dynamic range in backscatter many targets exhibit with varying θ. This challenge is largely overcome on satellite platforms for which the change in θ across the swath is much smaller. Nevertheless, little research has been undertaken to either correct for incidence angle change or to exploit target information as a function of differences in this angle. Mohan and Mehta (1987) used multiple incidence angles in the analysis of SIR-B data. They concluded that microwave radar response at L-Band (HH) at 25.6^0 and 45.2^0 for various land cover features is indeed a function of the incidence angle. For crops differences in radar response are also related to the imaging wavelength as well as to the crop type and its development stage. Shallower incident angles increase the pathlength through the vegetation maximizing response from the crop canopy itself and reducing the contribution from the soil. The radar signal strength decreases exponentially as the canopy depth increases due to both microwave absorption and scattering. Shallower incident angles increase the extinction of the radar signal also due to pathlength. The extinction coefficient is a function of both absorption and multiple scattering losses. At small incidence angles, ($<30^0$) the backscatter is dominated by the direct scattering from the soil while for large incidence angles ($>30^0$), the backscatter is dominated by the direct scattering from the canopy. As a result, small incidence angles are favored for soil moisture applications since roughness effects and vegetation attenuation are minimized at these angles (Daughtry *et al.*, 1991). In general, crop discrimination based on crop-canopy backscatter, is optimal at larger incidence angles.

Much of the information required for crop monitoring can be provided by satellite radar systems operating at L and C band, at linear co- and cross-polarizations and at an intermediate incident angle θ ranges (30^o – 40^o). Retrieval techniques based on multi-temporal data and assimilation of RS information in crop models appears promising. Significant further research and development is required to understand the information provided by polarimetric SARs and to develop the methods and models to extract soil and crop information from these advanced sensors.

Crop type and crop growth stage define the geometry of the canopy and the size, shape and orientation of the canopy constituents which influence microwave attenuation and scattering. The difference in radar backscatter between grain crops and broad-leafed crops is largely explained by the significant difference in the geometry of these canopies, as well as the increased biomass and water content of the broad-leafed crops. A larger backscatter response is associated with broad-leaf crops. In general, for broad-leafed crops like corn C- and L-band backscatter increases rapidly with plant growth, saturating early in the growing season. Little change in backscatter occurs during the rest of the growing season (Bouman, 1988). This saturation effect does not occur for grain crops such as wheat and barley. For these lower biomass crops, very dynamic temporal variations in radar backscatter are observed throughout the growing season. These variations are largely due to changes in crop structure (such as the emergence of grain heads) and canopy moisture changes (as occur during the period of senescence).

Research using C-HH or C-VV configurations has demonstrated that as fields are tilled, the increase in soil surface roughness results in an increase in backscatter (CCRS, 2008). Fields that are covered with significant post-harvest crop residue also experience an increase in backscatter. The increase in multiple scattering associated with rough tilled fields results in the depolarization of the microwave signal and induces a high cross-polarized backscatter. When residue cover is present on the fields, the increase in volume scattering has a similar effect and also results in higher cross-polarized responses (CCRS, 2008).
Plants and soil parameters, also affect microwave interaction with agricultural targets. Several parameters show consistent significant correlations with backscatter. These parameters include plant height, leaf area index (LAI), plant biomass, and plant water content (Brisco & Brown, 1998). Soil type affects the radar backscatter though the soil water holding characteristics and the relative amounts of bound and free water. Organic matter, salinity, sodium content and other soil properties can affect backscatter although these affects are less pronounced relative to the impacts observed from soil roughness and water content.

3. Agricultural Applications Using Optical and Microwave RS

The intensity of vegetation reflectance is commonly greater than from most inorganic materials. Consequently, vegetation appears bright in the near-IR wavelengths due mostly the sensitivity of these wavelengths to internal plant pigmentation. Radar sensors are able to capture plant structure and soil moisture content. As a result, both optical and radar sensors can contribute to measuring and monitoring crop condition at different phenological stages, supporting the estimation of crop yields.
For optical and radar RS, the classification of crops can be challenging as the difference in reflectance or backscatter can be small among crop types. In addition, differences in crop condition among fields of the same crop type, can cause confusion in separating crop by type. Multiple scattering within a canopy can be useful for discrimination of crops using radar RS. Research using multiple dates of radar data has demonstrated that radar RS could play a very important role in agricultural applications (Zhang, 1999). In addition to the sensitivity of radar backscatter to crop canopy characteristics, given their all weather capability, SAR sensors provide a reliable option for crop monitoring. Nevertheless, much research remains in order to advance the use of SAR for operational applications.

3.1. Crop type and crop condition

In order to successfully apply RS technologies for crop classification, refectance and backscatter signatures must be well defined for each crop type. Difficulty arises when signatures among crops are not sufficiently unique or when the variance in the signature within a single crop class is too large. Integration of optical and radar imagery is an attractive option. Both techologies offer complementary information about the crop canopy, and SAR sensors can fill the gap for optical acquisitions during periods of pesistent cloud cover. End of season crop maps are of value, but provision of early season crop area estimates provide additional value as they support in-season crop production and yield forecasting. The heterogeneity of corn-growing conditions in many countries makes accurate data for yield prediction difficult to obtain. Small agricultural plots, irregular shapes, different sowing seasons and variations in crop cultivars are contributing factors to classification errors. Accuracy can be increased for this particular crop through combinations of the information obtained from optical and radar satellite images.

Research studies have demonstrated that timing of image acquisition is very important to the success of crop mapping with optical imagery. Unless optical imagery is available during key stages of crop development and when field data are collected, these images alone will not provide the information necessary for operational field-level crop monitoring. Acquisition of SAR data during key phenological stages is more reliable and consequently, these data are an important information source for crop monitoring system. SAR or SAR-optical solution for crop monitoring have been explored in different regions of the world, and these studies are now reviewed.

Through integration of both optical and SAR imagery, McNairn *et al*. (2008) demonstrated that multi-temporal satellite are successful in the classification of crops for a variety of cropping sytems. McNairn *et al*. (2009) indicate that multitemporal TerraSAR-X data can provide a classification accuracy of 84%; using a post-classification filter to remove noise in the map product final accuracies of 95% were obtained.

Many studies have reported on the use of airborne optical multispectral imagery to estimate crop parameters such as leaf area index, canopy temperature, and plant height. These studies examined the relationship between crop condition and spectral response to determine whether these images could be used to estimate various crop condition parameters. A number of statistically significant correlations exist between the image reflectance and the crop condition parameters and these correlations vary as a function of crop type, time of year, and crop condition. The results suggest that in many cases, multi-spectral optical imagery can be used to monitor variations in crop condition parameters across the growing season for a variety of crop types (Cloutis *et al*,. 1996).

On the other hand and as already explains, SAR investigations have confirmed that microwaves are sensitive to both soil and crop characteristics. Results using multi-temporal RADARSAT-1 imagery have confirmed that C-HH backscatter can detect differences in crop type, crop growth stage and crop indicators like crop height, biomass and leaf area index. Active microwave systems have a significant advantage over optical systems, particularly for crop monitoring, since SAR acquisitions are not impeded by cloud cover. The multi-beam modes associated with RADARSAT-1 also provide significant flexibility related to the timing, spatial resolution and incidence angle of the acquired imagery (McNairn *et al*., 2000)

The availability of multi-polarization data from a number of SAR sensors operating at different frequencies (X-Band from TerraSAR-X, C-Band from ASAR and RADARSAT-2 and L-Band from ALOS PALSAR) has significantly advanced the use of SAR for agriculture and land cover mapping. The multi-polarized configurations provide more information related to crop structure and crop condition. Using simulations of data in preparation for the availability of RADARSAT-2 data, the Canada Centre of Remote Sensing (CCRS) gathered airborne polarimetric imagery over several Canadian sites in 1998 and 1999. These data were used to evaluate the sensitivity of multi-polarized SAR data to characteristics of corn, wheat and soybean crops (McNairn *et al*., 2000). Multiple polarizations provided a significant advantage for crop identification relative to the use of a single or dual polarization. The most important polarization for crop classification was the linear cross polarization (HV or VH). Cross polarization responses are a result of multiple scattering from within a crop canopy. Differences in canopy architecture due to differences in crop type result in unique cross polarization signatures. In a study using C-HH RADARSAT-1 data, multiple dates of

RADARSAT-1 imagery provided information on crop type and condition, with or without the integration of multi-spectral optical imagery. Regression analysis established that some indicators of crop vigor - in particular Leaf Area Index and crop height - were correlated with backscatter. The success of this RADARSAT-1 study was attributed to the acquisition of the SAR data during the critical reproduction and seed development crop growth stages. (McNairn et al., 2002).

3.2 Corn monitoring and crop yield

The prediction of final yield or determination and monitoring of crop condition throughout the growing season has considerable economic value for the agronomic community. Yields vary considerably from year to year. Consequently, considerable effort has been devoted to the estimation of final crop yield using remotely sensed data. Many studies have reported on the use of optical RS for crop monitoring and yield prediction using optical RS (Soria-Ruiz & Fernandez-Ordonez, 2003; Ferencz *et al*., 2004; Soria-Ruiz *et al*., 2004; Calera *et al*., 2004; Fang *et al*., 2008). Although the successful use of optical RS has been demonstrated, implementation of a reliable operational approach dependent upon optical imagery is difficult in regions prone to continuous cloud coverage during the growing seasons. Some results for central Mexico are shown in Figures 1 and 2.

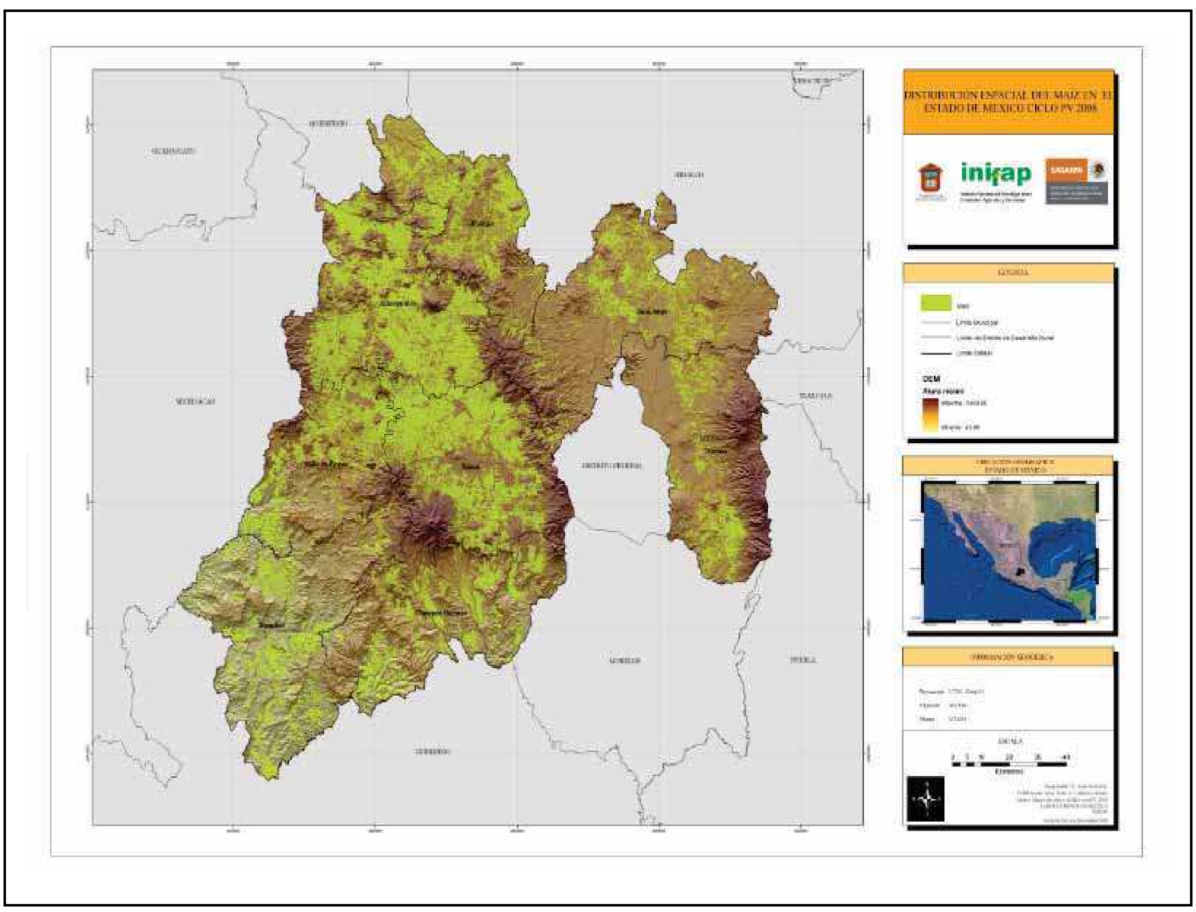

Fig. 1. Corn monitoring in 2008 using Spot Images. State of Mexico. Mexico.

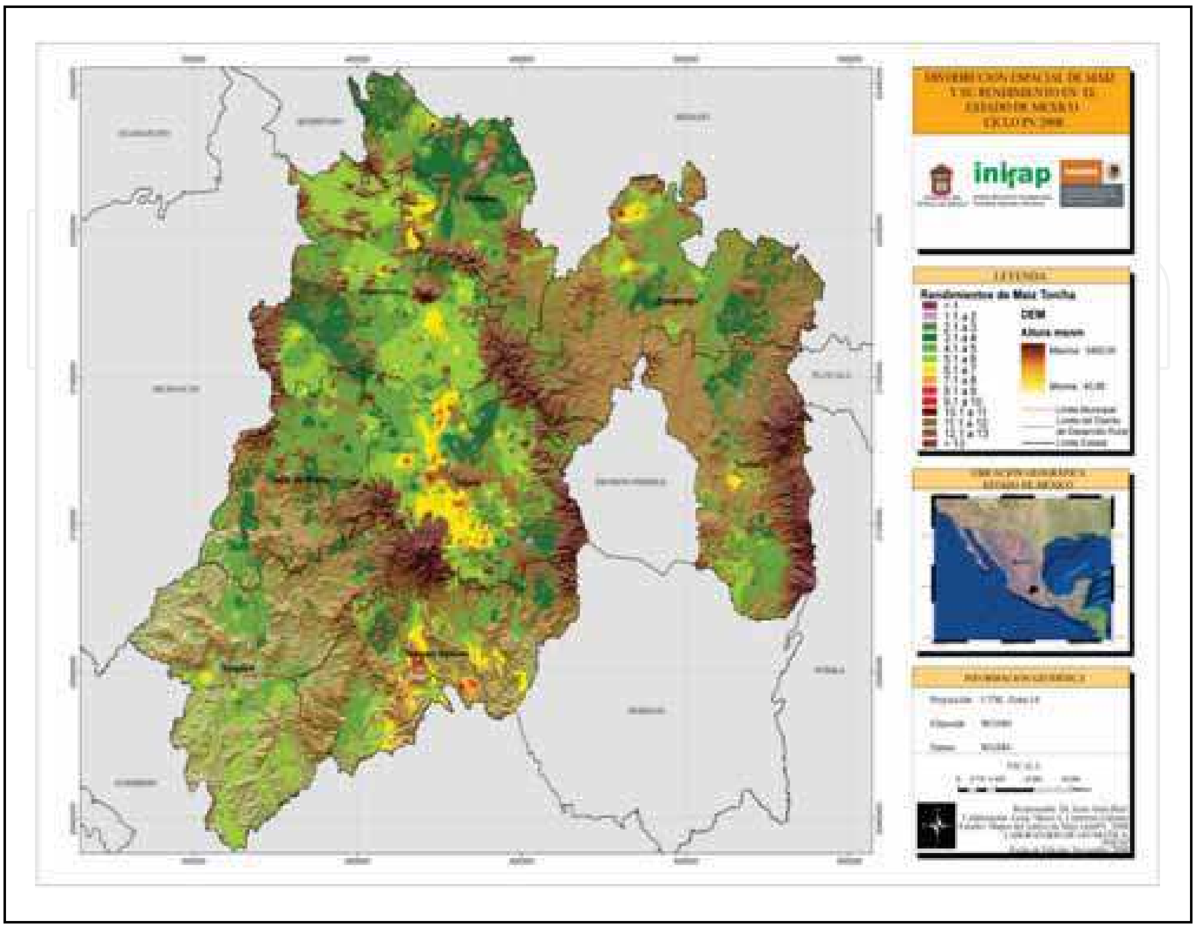

Fig. 2. Corn yield estimation using LAI and Spot images during 2008. State of Mexico, Mexico.

The dielectric constant of water is very large compared to the values of most other materials or targets. Consequently there is a strong dependence of the radar backscatter on the amount of water present in vegetation. However, in order to use the radar backscatter to assess potential crop yield directly (for example using regression analysis) or through a yield model it is necessary to relate the backscatter to vegetation parameters indicative of crop productivity. Leaf area index (LAI) along with the intensity of the solar radiation determines the amount of energy available to the plant for photosynthesis, which in turn drives the plant development and subsequent yield. LAI is related to whole plant biomass, light interception and loss of water through evapotranspiration. From LAI, Major *et al.*, (1986) defined LAI duration which provides a good indication of biomass throughout the season and of the total photosynthetic rate. Consequently, establishing a link between LAI and SAR backscatter would assist with the estimation of crop productivity and yield.
Airborne optical multi-spectral and C-band HH-polarized SAR imagery were acquired in conjunction with ground-based measurements of various crop conditions (Leaf Area Index, canopy temperature, plant height) at a test site in southern Alberta, Canada in July 1994. Data were acquired for a variety of crops (wheat, canola, peas and beans) and irrigation practices. A number of crop condition-imagery relationships were examined to determine whether the imagery could be used to estimate the various crop condition parameters. A

number of statistically significant correlations were found between the imagery and the crop condition parameters, and these correlations varied as a function of crop type, sensor and crop condition parameter. The results suggested that airborne remote sensing is well suited for measuring variations in crop conditions and that C-band SAR and multi-spectral imagery provided complementary information (Cloutis, 1999).

Several methods to estimate crop yield over large hilly areas that include high spatial resolution satellite imagery have been applied. These approaches incorporated QuickBird imagery with a production efficiency model (PEM) to estimate crop yield. The results indicated that QuickBird imagery can improve the accuracy of predicted results relative to the Landsat TM image. The predicted yield approximated well with the data reported by the farmers ($r^2 = 0.86$; $n = 80$). The spatial distributions of crop yield derived also offers valuable information to manage agricultural production and understand ecosystem functioning (Gang *et al.*, 2009). In order to attain better accuracy, Soria-Ruiz *et al.*, (2007) have applied optical and microwave RS data for corn monitoring and crop yield estimation under the heterogeneous corn-growing conditions in Mexico. Fusion of Landsat ETM+ and RADARSAT-1 provided better results than using optical data alone, for identifying crop and other land covers (Soria-Ruiz *et al.*, 2008). These results are summarized in Figure 3.

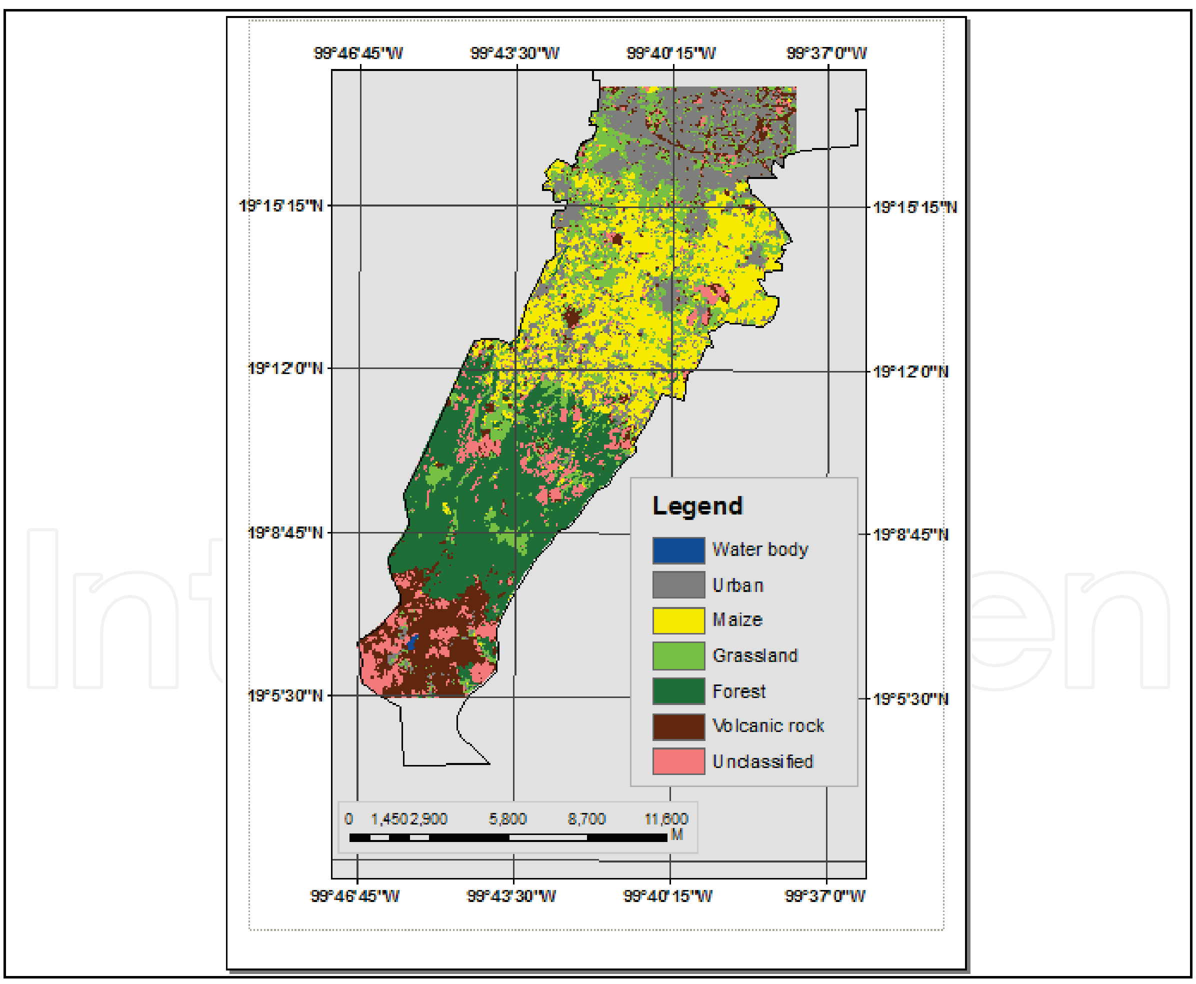

Fig. 3. Land-cover map obtained of data fusion from Landsat ETM and RADARSAT - 1 (Soria-Ruiz *et al.*, 2008).

4. Present and Future Research

Recent research to assess relative classification accuracies of multi-polarized combinations for target crops using airborne data has been reported. In addition to identifying crop type and variety, identifying crop growth stage is valuable. Crop condition, loosely defined as the vigor or health of a crop in a particular growth stage, is related to crop productivity and yield; however, the relationship is complex. Main crop condition indicators include biomass, height, leaf area and contents of plant water, chlorophyll and nitrogen. Crop-type and crop-condition mapping are among the applications that are expected to benefit the most from the technical enhancements embodied by RADARSAT-2. The potential of RADARSAT-1 data for these applications has been rated as "limited", whereas for RADARSAT-2 data this potential is anticipated to be "strong". The Science and Operational Applications Research for RADARSAT-2 Program (SOAR) is promoting the evaluation of SAR capabilities by providing images to our project: N° 2657 RADARSAT-2 for Corn Monitoring and Crop Yield in Mexico (Soria-Ruiz *et al*., 2007).

Within this project, we are researching a) the use of RADARSAT-2 data, SPOT and Ikonos data to determine cultivated areas and monitor crop condition; b) relating polarization signatures from RADARSAT-2 data to corn Leaf Area Index and photosynthetic active radiation (PAR) parameters. The expected benefits of this project are: to obtain knowledge about crop type, crop condition and crop yield with better accuracy than with current methodologies; to support national corn farmers associations; to support the design of agriculture related policies within state agriculture plans; to support the corn product industry and aid government decision making. Relevant results and economical impact will imply operational usage of RADARSAT- 2 data in the agricultural sector in Mexico (Soria-Ruiz *et al*., 2007).

Satellite imagery is an efficient method for mapping crop characteristics over large spatial areas and tracking temporal changes in soil and crop conditions. Some SAR sensors such as RADARSAT-1 acquire imagery with a single transmit-receive polarization, providing a single radar image. Therefore, more than one acquisition date is usually required to estimate meaningful crop information. With RADARSAT-2 several new features are expected to prove beneficial to the agricultural sector. These advancements include the availability of dual-polarization and quad-polarization modes, enabling the simultaneous acquisition of multiple polarizations on transmit and receive. In the quad-polarized mode four polarization channels are acquired. Valuable crop information can be extracted from one RADARSAT-2 image, particularly if these data are integrated with optical or SAR data acquired at complementary (X and L-band) frequencies.

Crop type and crop condition mapping are among the applications together with crop yield that are expected to benefit the most from access to advanced sensors such as RADARSAT-2. The applications potential for RADARSAT-2 data is anticipated to be strong (van der Sanden, 2004). Images acquired in the polarimetric and ultra- fine resolution modes are expected to contain moderately improved information in support of crop-yield mapping. For crop condition mapping, the improved potential of the polarimetric and ultra-fine resolution data products for crop yield mapping can be explained by the increased sensitivity to crop structure and the capacity to obtain within-field zonal information.

5. Conclusion

Crop yield is a key element in rural development and an indicator of national food security. Optical and radar RS have been used separately in most cases for agriculture applications. Increased exploitation of SAR data is expected as these data become more readily accessible and as users become more familiar with the processing and interpretation of these data. In addition significant research is still required to advance methods and models to derive meaningful crop information from SAR data. Recent advances in the integration of optical and SAR data for agriculture applications are shedding more light on the communities understanding of how best to exploit both imagery sources. These advancements will assist in securing more accuracy results to support day-to-day decision making. Optical and radar RS are based on different physical principles. Radar data are sensitive to water content in the vegetation and the large scale structure of the canopy. Optical wavelenghts respond largely to the internal leaf structure and pigmentation. SAR data do not directly measure plant parameters, such as chlorophyll, important for plant photosythnesis. However parameters indicative of plant production, such as leaf area index, influence radar backscatter.

Vegetation type identification has been successful when multi-dimensional approaches have been applied, often with accuracies at or above operationally effective goals of 90% classification accuracy. As with optical imagery, quantification of crop condition is more challenging for SAR data, particularly because radar backscatter also includes scattering contributions for the soil. Nevertheless, the integration of SAR and optical imagery for crop condition and productivity estimation appears promising.

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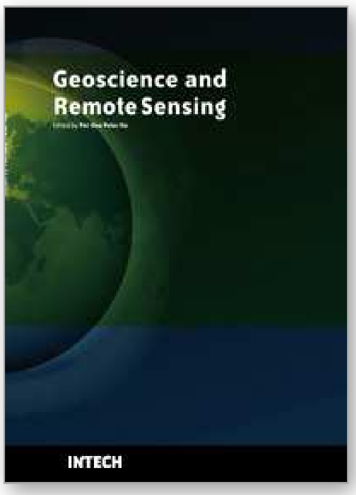
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