Precision Agriculture and the Role of Remote Sensing: A Review

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ABSTRACT

Precision agriculture involves the integration of new technologies including Geographic Information Systems (GIS), Global Positioning Systems (GPS) and Remote Sensing (RS) technologies to allow farm producers to manage within field variability to maximize the cost-benefit ratio, rather than using the traditional whole-field approach. Variable Rate Technology (VRT) available with farm implements, such as fertilizer or pesticide applicators and yield monitors, have evolved rapidly and have fostered the growth of precision agriculture. Site specific management allows inputs to be reduced, while optimizing outputs, both of which are attractive to the farm producer. At the same time, by reducing inputs, the run-off of fertilizers and pesticides is reduced, thus improving the environmental condition of the agro-ecosystem. Remote sensing provides input data for many precision agriculture applications including pre-growth soil fertility and moisture analyses, crop growth and growth detractant monitoring (crop scouting), and yield forecasting. This information in turn helps the farm producer in his decision making. Although the acceptance and growth of precision agriculture has been rapid some fundamental requirements are needed to help fully develop and implement this technology. Among these requirements are continued research and development of algorithms for the radiometric and geometric correction of remote sensing data and for information extraction. Also, access to timely, cost-effective remote sensing data, or derived value-added products and the development of decision support making systems or other expert systems integrating GIS, GPS, and RS technologies in a user-friendly fashion are needed. A subsequent training and technology transfer program to accelerate the acceptance and implementation of this technology for the agri-business sector is also a necessity.

Introduction

Producers have routinely observed large variations in crop productivity and final yield within many agricultural fields. Although these variations are often related to differences in soil fertility or localized crop stress, fields have traditionally been treated as one homogeneous unit, with uniform fertilizer or herbicide/pesticide applications. When farming small parcels of land detailed knowledge can assist in the implementation of a sound management strategy. However, during the 20th century the tendency to larger and larger farms in the United States and Canada led to difficulty in implementing this detailed variable land management approach and whole field applications of fertilizers, pesticides, and other farm inputs became the norm.

The development of geomatics technologies in the latter part of the 20th century has aided in the adoption of site specific management strategies. Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing data can be integrated spatially, temporally, and economically to assist the farm producer in managing their land. This approach is called precision agriculture or site specific management (Palmer, 1995; Usery et al., 1995; Forcella, 1993; Pringle et. al., 1993; Carr et al., 1991; Petersen, 1991;). Precision agriculture recognizes the inherent spatial variability associated with soil characteristics and crop growth, and uses this information to prescribe the most appropriate management strategy on a site specific basis. The driving force behind precision agriculture is the economic optimization of crop production. However, coupled with this production goal is the minimization and control of chemical inputs for the management of soil fertility and crop stress. The site specific application of these inputs reduces producer costs and minimizes the environmental impacts associated with chemical use.

This paper describes precision agriculture and provides a brief overview of the literature and background of this technology. The role of remote sensing in precision agriculture is then reviewed followed by a description of the research program being conducted at the Canada Centre for Remote Sensing (CCRS). Some preliminary results from these research activities are presented to augment this section. This is followed by an overview of the economic impact and opportunities of precision agriculture, with a focus on the potential role of remote sensing data and service providers for satisfying this market. The final section outlines some of the research and development issues which need addressing for further development and implementation of this technology.

Overview and Background

Figure 1 illustrates the concept of precision agriculture. In a typical precision agriculture management system, spatially referenced data are collected to quantify site factors which are likely to have an impact upon crop productivity, and thus final yield. Baseline information on site factors often includes elevation and subsurface drainage, as well as measurements to delineate soil zones defined by soil characteristics such as texture and fertility. In addition to this baseline information, data are gathered regularly during the growing season to evaluate the effects of these site factors on crop productivity, as well as to monitor for weed, insect or fungal infestations. Finally, at the time of harvest, site specific yield data are collected.

Data gathered prior to seeding, during crop growth, and at harvest, establish the links between yield and site factors required for longer term site planning. This process allows the producer to adjust future inputs, on a site specific basis, in order to optimize economic yields or, in the case of perpetually poorly producing sites, to reduce costs. However, of immediate concern is the early detection of fertility problems or crop stress during the current growing season. An effective data source must flag problem areas, identify the source of the problem, and delineate its location and spatial extent. In the case of weed infestations, weed type, location and extent need to be mapped early in the infestation. This information is then used to determine the appropriate herbicide application, and to apply the chemical at the correct rate, only to the sites affected.

Variable rate technologies (VRT) and yield monitors are an essential component of site specific management and their use is becoming more prevalent, particularly among producers with large land holdings or high value cash crops. Using the within field variability information collected from site samples or other data inputs, VRTs apply the appropriate chemical inputs to the affected sites in the field. For example, VRTs can mix custom fertilizer blends and apply the correct combination and amount to a site. In the case of weed infestations for example, flow-rate sprayers apply the appropriate type and rate of herbicide, only to those sites affected. Discussions of various aspects of the use of VRT in precision agriculture can be found in Fleischer et al., 1996; Ferguson et al., 1995; Mortensen et al., 1995; Hanson et al., 1995; and Searcy, 1995; Schueller, 1992.

The relationship between plant growth and spectral response in the visible and infra-red wavelengths has been well established using the ratio of red and infra-red reflectance, or some indices based on this ratio (Jackson, 1984; Bauer, 1985). This research has led to the successful development and implementation of an operational crop information system in Canada using NOAA Advanced Very High Resolution Radiometer (AVHRR) data for regional crop condition and yield assessment (Brown et al., 1990). Other work has demonstrated the use of remote sensing data (from various sensors and platforms) for monitoring crop pests and disease, as well as for assessing soil fertility and soil moisture content. Remote sensing also provides the data to convert point measurements into spatial information and to monitor temporally dynamic plant and/or soil conditions. Thus, there is a growing need and capability for using remote sensing data in precision agriculture applications.

With the acceptance and increased use of precision agriculture the need for technical consulting, value-added products and services, geomatics technology software, remote sensing data, etc., as well as VRT implements is increasing. This rapidly growing vertical market is expected to continue to increase as the technology is further developed and brought to the market place (Hough, 1993). To date the development of precision agriculture has mostly relied on the integration of GIS and GPS technology plus the implementation of VRT farm equipment. However, there is an important role for remote sensing in precision agriculture (Moran et al., 1997a; Pearson et al., 1994) and new satellites are being designed for the commercial exploitation of the remote sensing data needs for precision agriculture, as well as other applications (Fritz, 1996).

Role of Remote Sensing in Precision Agriculture

A wide variety of remote sensing devices, ranging from the human eye to earth observation satellites, have been used or evaluated for precision agriculture applications. Indeed, visual observations recorded through a digital notepad geo-referenced to the GIS database may be the most commonly used "remote sensing" device in precision farm management applications. Aerial photography (colour and colour infra-red) and videography are also commonly employed for many different applications in precision agriculture. Although the majority of sensors used have operated in the visible and near infra-red portion of the electro-magnetic spectrum the microwave portion of the spectrum have also proven useful, particularly when data are gathered from aircraft platforms (Moran et al., 1997b). RADARSAT data have also provided useful information about crop and soil parameters, such as weed infestations and soil moisture, but at a coarser spatial resolution (Hirose, 1997). Moran et al., (1997a) provide a recent review of image-based remote sensing for precision crop management.

Remote sensing can be used for precision agriculture in a number of ways by providing input on soil and plant condition and variability to the overall management and decision support system. Remote sensing data provide a very convenient way of converting point observations, for example from a soil test sample, to distributed information within the GIS. Various image classification or geo-statistical approaches, such as kriging, can be implemented in order to achieve this conversion. This spatial information can then be used with other georeferenced overlays within the GIS to identify both seasonally stable and seasonally variable management units, upon which the farmer can base a management strategy. Many of the soil and crop parameters of interest to the farmer are very dynamic with time and thus the timely, repetitive coverage possible with remote sensing platforms, especially satellite platforms, are an attractive source of monitoring information. This information can then be used in conjunction with management units, in order to quickly evaluate potential problems and to provide an effective management solution. This feedback loop can be very effective in precision agriculture applications.

Figure 2 illustrates the relationship between point data, distributed data, and seasonally stable and seasonally variable management units for a typical field. In this figure the soil sample locations (indicated with a cross) are used to develop a series of Nitrogen and Potassium fertility contours, which are then overlayed with the soil type (indicated by different shading). The integration of this information then gives three “management units” for fertilization applications as illustrated in the figure.

Prior to seeding, air photos, multi-spectral scanners, or high resolution satellite imagery can be used to translate results from point soil test samples, acquired using a grid or stratified sampling scheme, to a spatial coverage for the whole field. This is an essential component of the information for managing within field variability as described in the previous section. Surface reflectance from bare soil can be related to a number of physical and chemical properties of the soil including texture, nutrients, calcium carbonate content, organic matter, salinity, and moisture. (Baumgardner et al., 1985) provides a detailed review of the reflectance properties of soil. This information can be used to help determine soil fertilizer applications and for seasonal growth trend analyses. The translation of soil test sample results to a field fertility map using colour photography is illustrated in Figure 3. In this example an inverted regression relationship, developed between the available Nitrogen determined from the point samples and soil colour, can be used to create a spatially detailed nitrogen application map. SAR data can also be used to estimate the near-surface soil moisture content (Dobson and Ulaby, 1986; Pultz et al., 1997). Figure 4a and b shows soil drainage information derived from RADARSAT SAR and SPOT data respectively. Drainage information from the Ontario Soil Survey is provided as an overlay to aid in interpreting the remote sensing data.

Remote sensing techniques can also be used to create highly accurate digital elevation models (DEM) which are useful in many precision agriculture applications, especially irrigated market vegetables. Gagnon et al., 1990 described an approach that can be easily implemented on a personal computer using stereopairs from either airborne or satellite platforms. SAR sensors from airborne and satellite platforms can also be used to generate a DEM (Gray and Farris-Manning, 1993; Vachon et al., 1995).

The most prevalent use of remote sensing in precision agriculture is for monitoring seasonally variable crop condition (Moran et al., 1997a; Pearson et al., 1994). Early research with colour and colour infra-red air photos demonstrated that a number of crop infestations could be detected on the photographs including wheat stem rust, corn leaf blight, and root rot in field beans. A recent review is provided by Hatfield and Pinter (1993). Stress caused by the infestation results in reflectance changes in the vegetation which can then be detected with the remote sensing data. Weeds have different reflectance characteristics than the crops they invade and consequently their location and extent can be mapped and targeted for herbicide application. The early and prompt attention to these growth detractants is important and remote sensing can provide the timely spatial coverage required for effective crop scouting. Figure 5 shows the use of airborne SAR data to identify an outbreak of Bertha Armyworms in a canola field. The darker SAR signature of the area infested by the armyworms is due to the loss of radar backscatter by the damaged crop canopy. The use of *casi* and SPOT-HRV multi-spectral data for identifying weeds using estimates of NDVI is demonstrated in Figure 6. In this case the presence of weeds gives rise to unusual NDVI values, often higher than the surrounding crop, which allows for the spatial mapping of the weed infestation.

Remote sensing data can also be used to create biomass estimates during the growing season using the traditional approach based on vegetation indices (Tucker et al., 1980). The temporal sequence of these biomass maps can then be related to the current management strategy and changes implemented, for example soil fertilization if required, to optimize the final yield. As pointed out by Moran et al., 1997a, remote sensing data can also be used to produce maps of meterological parameters which can be integrated with the biomass maps, or Leaf Area Index (LAI) estimates, in order to predict final yield. Figure 7 shows the use of multi-spectral satellite data for estimating biomass time sequences for management purposes and yield prediction. A final yield map from a VRT yield monitor is also shown for comparison.

The research has repeatedly demonstrated the value of remote sensing for extracting information about soil and crop conditions. Higher resolution satellite data may help adjust the cost per hectare for remote sensing applications in precision agriculture and will thus lead to increased commercial use of remote sensing. Continued algorithm development for sensor calibration including radiometric and geometric corrections, off the shelf software for image processing and GIS integration, and quick data delivery capabilities are also needed to foster the use of remote sensing in precision agriculture.

Precision Farming Research at the Canada Centre for Remote Sensing

The Canada Centre for Remote Sensing (CCRS) in conjunction with other government agencies, universities and value-added industry has been involved in a multi-year experiment to define the role of remote sensing in precision agriculture. For the past five years, CCRS has gathered significant quantities of data over their agricultural super site centered on Altona, Manitoba. The site is quite flat, and has a range of soil textures and crop types, making it well suited for agricultural remote sensing research. Altona was the site of the 1994 SIR-C soil moisture experiment and southern Manitoba has been used extensively to evaluate the information content in RADARSAT for various agricultural applications. Research efforts have demonstrated that both soil moisture (Pultz et al., 1997) and tillage (McNairn et al., 1998) information can be provided by RADARSAT data. Current research initiatives are focusing on the operational crop monitoring capability of RADARSAT.

In 1996, CCRS began the collection of high spatial and high spectral resolution airborne optical data over sites in southern Manitoba. During the 1996 growing season, 27 spatial mode and 14 spectral mode lines of Compact Airborne Spectrographic Imager (*casi*) were collected over four sites, and during two acquisition campaigns (Table 1). The first acquisition occurred just after crop emergence and was designed to evaluate the potential of remote sensing for mapping weed infestations. During the period of peak crop biomass a second set of data was gathered and this data provided information on the sensitivity of visible-infrared reflectances to indicators of crop vigor, crop stress and final yield. The following year, *casi* data were again acquired during peak biomass over a new site centered on Carman, Manitoba. With 9 spatial mode lines and 3 spectral mode lines, approximately 250 km of airborne optical data were acquired during the 1997 campaign.

During both the 1996 and 1997 *casi* image acquisitions, field crews collected GPS-referenced crop samples as well as chlorophyll data and ground spectra (using the GER3700 ground spectrometer) on approximately 30 fields of various crop types (wheat, canola, beans, sugarbeets, potatoes, corn, flax). Crop samples provided data on plant water content, amount of biomass and leaf area index (LAI) estimates. In 1997, ancillary data were available on nitrogen application rates as well as soil NPK (nitrogen-phosphorus-potassium) and organic matter. Variable yield maps and crop scouting information was also provided for some fields.

Statistical analysis of the 1996 *casi* data demonstrated that indicators of canola crop vigor (biomass and leaf area) were significantly related to near-infrared reflectance (Brown et al., 1997). The strong dependence of reflectance on crop condition was further demonstrated on a potato crop from the 1997 data set (Brown et al., 1998). Near infra-red reflectance was then used to map biomass, plant water content and crop height variability across the potato field. Information on crop canopy characteristics derived from high-spatial data is extremely valuable in detecting areas of poorer growth in the field which may require added inputs. Also, this site specific crop information can be used as input into crop growth models for yield forecasting.

CCRS has also been involved in developing techniques to extract quantitative information on crop productivity and crop stress using imaging spectrometry or hyperspectral remote sensing. The objective is to use hyperspectral data to improve the detection of within-field variation and to determine the cause of the spatial differences. Using hyperspectral data from 1996, it was possible to map different target components on a pixel-by-pixel basis using constrained linear unmixing (Adams et al., 1986; Shimabukuru and Smith, 1991). This technique allows one to unmix a pixel spectrum which is usually a mixture of different material into its components (endmembers). The portion of the components of the pixel spectrum are expressed as fractions between 0 and 1. Figure 8 shows the fraction image of the endmember canola and related *casi* RGB image. Within-field variations of this endmember are obvious. The fractions can likely be related to percent cover as preliminary results indicate (Staenz et al., 1997a). Percent ground cover, among other parameters, can then be used to assist in biomass estimation. In general, the unmixing technique provides a powerful tool for site specific mapping to capture the variation within a field for the different target components such as litter, soil, and vegetation. Unlike empirical derivations of crop condition parameters extracted from the high spatial data, spectral unmixing provides a more robust technique for the estimation of such parameters. Within this context, CCRS is exploring the extraction of LAI on a per pixel basis using the crop endmember fraction derived with spectral unmixing (Staenz et al., 1998). The retrieved LAI is more accurate than calculated from vegetation indices such NDVI since the unmixing technique enables the separation of crop from other vegetation types such as weeds on a per pixel basis.

When hyperspectral data are acquired in the 900 to 1250 nm wavelength regions, liquid water content of the vegetation canopy can be estimated on a field basis, utilizing the plant liquid water absorption features at 975 nm or 1180 nm in a combination with physical and empirical models (Staenz et al., 1997b). Liquid water content associated with the crop canopy is an important indicator for crop stress. CCRS is also exploring the possibility of deriving chlorophyll content, another important indicator of crop health and productivity, from hyperspectral data.

In addition to establishing crop productivity and crop stress indicators, an opportunity also exists for mapping weed type and location, during periods or both pre- and post-emergence. From the 1996 spatial data set significant weed patches were visually detected early in the growing season, just after crop emergence, using a colour-infrared combination (533, 620 and 818 nm). By resampling the original *casi* 4 m data it was evident that spatial resolutions of < 10 m were required to visually delineate significant weed patches (Brown et al., 1997). Detection of weed infestations during periods of peak growth is more difficult, but plant fractions derived from spectral unmixing, which indicate areas of non-crop, may be correlated with weed patches. Several sites from both 1996 and 1997 are available to assess this approach.

CCRS is also planning investigations which will focus on the spectral simulation of future sensor data as acquired with proposed multispectral and hyperspectral sensors onboard small satellites (see Tables 2 and 3). This process will give insight on band requirements in terms of position, width, and sampling necessary for the retrieval of specific information. This will help to maximize the extracted information content and, furthermore, to ensure that future satellite programs meet the user requirements.

Commercial Opportunities

The resurgence of interest in precision farming over the last few years has been largely driven by the commercial sector. In the initial stages, a technical team was needed to support the implementation as well as the operation of the equipment. Manufacturer's of niche equipment such as GPS receivers, yield monitors, variable-rate technology, and GIS software offered their hardware and software to the agricultural sector. The systems, however, were not well adapted to the needs of the users and were not easy to integrate into an effective "crop production decision support system".

Many of the systems today, although more user friendly, do not provide a total solution for the users. Therefore, the opportunity to provide a better solution exists and the availability of journals, newsletters, and magazines dedicated to advances in the technology and application is testament to the market potential. In addition to the opportunities for the hardware and software manufacturers, there is equal opportunity for the services industry. Early adopters of the technology are well positioned to provide consulting services to agri-business and to producers. This could include systems integration solutions for businesses, training on the operations and use of the systems, or the processing of data into information.

The rapid introduction and high turnover of the technology, however, has resulted in a gap between the technological capability to measure and apply variable rates of crop inputs, and the scientific understanding of the causal relationships between the inputs and the crop output. Traditionally, producers have looked toward agricultural extension staff and academics for an objective opinion on the merit of the technology. Therefore, there is a need to increase the scientific knowledge and to disseminate it to those working with the producers. Fostering linkages between government, university, and industrial interests would encourage and facilitate the transfer of knowledge and increase the acceptance of the technology by the user community.

Although remote sensing has been around for decades, it's relevance to the applications in the precision farming industry is relatively new. Scientists have demonstrated the potential capability of the technology for specific case studies using ground, airborne, and at times satellite systems. In practice, however, the delivery of a reliable and meaningful product demanded by the users has been more difficult to achieve.

Today, the current satellites carrying optical sensors provide a relatively coarse spatial resolution (20-30 metres, multi-spectral, and 10 metre panchromatic) with a swath coverage between 70-180 km and a re-visit time of 7-16 days. This limits their application to larger fields found in the North American mid-west and is not useful for specialty crops or regions where the field sizes are small. However, the next version of commercial satellites such as Earthwatch's Quickbird series of satellites and Space Imaging-EOSAT's Ikonas satellites will have similar spectral characteristics to today's sensors, but will improve significantly on the spatial resolution (3-10 meter multi-spectral and 1-3 meter panchromatic). Unfortunatley, Earlybird was not successfully launched and is not operable.

These sensors will not only open up other markets within the agricultural sector, but also will improve upon the revisit period. This will be important to an application where a snapshot of the field is required at specific instances in time and within a narrow time window. In addition, the improved revisit will also alleviate some of the problems associated with cloud cover obscuring the target and therefore, a missed opportunity. It will not help, however, if cloud cover is persistent. However, all-weather sensors such as RADARSAT that can image through clouds could be used to complement the optical sensors for this purpose. Further testing, however, is required to demonstrate the reliability of this approach and to fully integrate microwave observations into precision farming applications.

Early detection of problems is one part of the feasibility equation for remote sensing data. The other is a ready access to the data or information product in order that timely remedial measures can be taken to limit the damage or enhance productivity of the crop. This requires an infrastructure to receive and process the satellite imagery or raw data into information and data products, transfer the data or information products to a processor where value-added processing takes place, and then, delivery of the final product to the user. In the past, the infrastructure was not present to turnaround imagery quickly. Past experience has demonstrated that it would nominally take a couple of weeks to obtain the data. Data suppliers recognize the need for faster turnaround and are responding with a more streamlined infrastructure. It is envisioned that all the new commercial satellites coming on-line over the next two years will have a nominal 3 day turnaround with a target for 24 hour delivery of imagery and/or information products.

Issues Affecting the Use of Remote Sensing in Precision Agriculture

Although the research has demonstrated the ability to extract useful information about plant and soil parameters from remote sensing data, the use of this technology in precision farming is secondary to the use of GPS and GIS technologies. This is in part due to the necessity of having these capabilities in place before the producer can start implementing precision farming management strategies. There are other impediments that are being currently addressed through planned high resolution satellites and private sector initiatives. These issues include the spatial resolution of satellite remote sensing products, the area coverage, and the near-real time data delivery requirements. However, there are other barriers which need additional effort before widespread use of remote sensing is realized in precision agriculture.

Most of the current satellite systems do not provide data of sufficient spatial resolution for many of the applications in precision agriculture. Although airborne sensors are being utilized in the development of this application the costs are usually prohibitive for most producers, unless large land holdings or valuable cash crops justify the expense. One solution is the development of private sector value added service companies which could purchase the data, extract the information, and sell it to a number of subscribers, thereby keeping the costs for individual producers lower. Fortunately, there are also a number of high resolution multi-spectral sensors on small satellites being developed which are targeting precision farming as well as other high resolution applications (Fritz, 1996). Tables 2 and 3 provide a description of several of the planned high-resolution and hyper-spectral satellites which will provide a data source for many precision agriculture applications.

Continued research and development is needed on several key areas. Additional work needs to be done on algorithm development for both radiometric and geometric calibration and correction of data products. In some cases, new and improved algorithms are needed for the calibration, correction, and registration of the various remote sensing data products. In other cases, better utilization and documentation of the existing algorithms being used are needed by both the data providers and the data users. Data integration is also a requirement for precision farming and thus better mechanisms for data/information fusion would be very beneficial. Additional research is also needed to develop the feedback loop between the information extracted from the remote sensing data and the farmers management approach. This includes an impact assessment of the value of using the remote sensing data in the management solution for evaluating both short term (seasonally) and long term (year to year) benefits to precision agriculture.

Technical developments alone will not be sufficient to maximize the use of remote sensing technologies in precision farming. A supporting infrastructure is also needed to facilitate data ordering, data processing, timely product delivery, and data storage, including archive information and data accessibility. Progress in distributed data/information networks, such as Canada's CEONet, are planned to help develop this capability. CEONet is an initiative of the Canadian Government to make remotely sensed data and other supporting data sets readily available on the Internet for the development of value-added products and for the subsequent distribution to the end-user.

The development of precision agriculture has been largely market driven but the future growth of this technology needs collaboration between private and public sectors. This is in part due to the resource and fiscal constraints most institutions, both public and private, face in today's economy. The universities and academic institutions need to play a fundamental role in the long-term research issues as well as the training programs for introducing the geomatics technologies to the agricultural community. The private sector has a responsibility for market development, product credibility, and customer satisfaction. The public institutions, at all government levels, need to help by coordinating the various activities involved in developing and implementing precision agriculture and by providing support programs to achieve this objective. All groups should participate in long term needs assessment and strategic planning in order to continue and develop this technology.

In order to gain acceptance for the role of remote sensing in precision farming the advocates must be careful to not over-sell the capabilities and costs of using this source of data for farm producer's information requirements. Furthermore, progress in decision support systems and other "expert systems" for image processing, information extraction, and data integration will help the farm producer integrate remote sensing technology into the precision agriculture market place.

Summary

This paper describes precision agriculture and the role that remote sensing can play in providing a data source for various applications in this emerging technology. Remote sensing data from various platforms ranging from the field level to the satellite perspective can provide useful information about various plant and soil parameters throughout the growing season. This includes early season information related to soil fertility and moisture conditions, mid-season crop monitoring for pest and disease management, and growth trajectory analyses and yield estimation throughout the growth season. Remote sensing data also provides a convenient method for relating point observations to spatial management plans. Precision agriculture is a rapidly expanding vertical market with significant growth opportunities as new data sources like the high-resolution optical satellites, already launched or scheduled for launch in the next few years, become available. Research and development issues are also reviewed including the current research program at CCRS. Although the previous research has demonstrated useful information can be extracted from the remote sensing data, algorithm development for better radiometric and geometric corrections of the data are needed. More effective data integration techniques should also be developed. A supporting infra-structure to provide near real-time, low cost data, including archive, ordering, and delivery capabilities is also required. Finally, an effective technology transfer and training program would help foster the acceptance and implementation of precision agriculture.

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Table 1: casi Spectral Mode and Spatial Mode Sensor Configurations

	Spectral 1996 (1997)	Spatial 1996 (1997)
Spectral Coverage	458-1000 nm (413 – 954 nm)	462-995 nm (454 –940 nm)
Number of Bands	96 (96)	20 (19)
Spectral Sampling Interval	5.7 nm (5.7 nm)	varies
Bandwidth at full width at half maximum (FWHM)	6.8 nm (6.8 nm)	varies
Sensor Altitude Above Sea Level	2745 m (2774 m)	2745 m (2774 m)
Ground Resolution	4 m x 4 m (4 m x 4 m)	3 m x 3 m or 4 m x 4 m (4 m x 4 m)
Swath width (number of pixels)	304 (304)	512 (512)

Table 2. Specifications of Planned High Spatial Resolution Sensors

Sensor	Ground Resolution (m)	Spectral Range (nm)	Photogrammetric Accuracy (m)	Revisit Period at Equator (days)
EarlyBird Panchromatic	3	450-800	40-50	4.75
EarlyBird Multispectral	15	450-890 (3 bands)	-	4.75
QuickBird Panchromatic	1	450-900	< 20	4.75
QuickBird Multispectral	4	450-900(4 bands)	< 20	4.75
OrbView Panchromatic	1	450-900	10-14	3
Resource 21	10	450-900 _ (_4_bands) 1550-1650 (1 band)	-	Twice in 25 min. with 4 satellites
OrbView Multispectral	8	450-900 (4 bands)	-	3
Ikonas (SIS) Panchromatic	1	500-900	10-14	2
Ikonas (SIS) Multispectral	4	450-900 (4 bands)	10-14	2

Table 3. Specifications of Planned Spaceborne Hyperspectral Sensors

Sensor	Agency/Organization	Number of Bands	Wavelength Range (nm)	Bandwidth (nm)	FOV (km)	GIFOV (m)	Launch Date
EO-1: GIS	NASA	~185	400-2500	6 (VNIR) 12 (SWIR)	9.6	30	May 1999
WIS		311	400-2500	6.3-10.3	9.6	30	

NEMO	US Navy	~210	400-2500	~10	30	30/60	2000
Warfighter	Orbimage	200 80	400-2500 3000-5000	9.4-11.3	5	8	2000
ARIES	ARIES	32 3 32	400-1000 SWIR I 2000-2500	20 16 16	15	30	2000

EO = Earth Orbiter: GIS = Grating Imaging Spectrometer; WIS = Wedge Imaging Spectrometer

NEMO = Naval Earth Map Observer

ARIES = Australian Resource Information and Environment Satellite

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