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Remote sensing in agriculture

New imaging sensor technologies suitable for agricultural management

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Summary

Studies over the last 25 years have shown that spectral measurements in visible, near-infrared, thermal infrared, and microwave wavelengths can be related to crop water stress, nitrogen deficiency, stand density, soil moisture, weed and insect infestations, and many more crop conditions. The main reason that few of these algorithms and models have become operational and commercially available is the lack of an orbiting system dedicated to providing images in the spectral, spatial, and temporal resolutions required for agricultural management. The objective of this work was to define the general specifications of a satellite-based imaging sensor system for agricultural management based on 1) known user information requirements and 2) the state of the science of agricultural remote sensing. This was followed by a review of the technological developments in sensor and spacecraft design to determine the feasibility of building and launching such a system this decade.

Key words: Remote sensing, agricultural management, sensor technology

Introduction

In recent reviews of image-based remote sensing for agricultural management, the single greatest limitation was found to be the lack of an orbiting remote sensing system dedicated to providing field-scale information (Moran, Inoue & Barnes, 1997). To resolve this, it is necessary to define the sensor specification most suitable for agricultural management, and then, to assess the ability of current sensor technology to meet these specifications. A four-step process is proposed herein in which 1) information requirements for agricultural management are prioritized; 2) an assessment is made of the ability of remote sensing science to meet such requirements ; 3) the list of information requirements is translated into system specifications; and 4) an assessment is made of the ability of technology to fulfill system specifications. A preliminary demonstration of this logical progression is given in the following four sections based on user surveys, published reviews of remote sensing science, and technologies of recently launched government and commercial satellite sensors. This is not a final recommendation for the ideal remote sensing system for agricultural management, but rather a template for determining priorities in system design and technology development. Readers unfamiliar with remote sensing science and sensor technology are encouraged to refer to the general references by Henderson & Lewis (1998) and Schott (1997). Readers unfamiliar with the latest technologies in agricultural management should review the proceedings of a series of international conferences on precision agriculture (Robert, Rust & Larson, 1994; 1996; 1998).

User Requirements

The first step in system design should be to define the user requirements for the system. This section provides a summary of two efforts that were made to compile user information requirements for agricultural management in the United States.

Ag20/20 is a joint program among NASA, USDA and commodity organizations (corn, cotton, soybean and wheat) with a goal to increase production efficiency, reduce production risk by improving information availability with regard to production limiting factors, and reduce potential environmental impacts of agricultural practices through better management decisions. The above-mentioned organizations have met several times to identify the baseline grower information needs that could be addressed with remote sensing and other geo-spatial technologies. The priority information needs identified by the corn, cotton, soybean and wheat commodity groups were

A1) fertilizer application,

A2) weed scouting/herbicide application,

A3) insect scouting/insecticide application, and

A4) irrigation/soil moisture information.

In a more limited effort, Moran (2000) surveyed a group of users to determine the information accuracy delivery requirements, where "users" were people or corporations who had already purchased remote sensing image products for agricultural management. The surveyed users were nearly unanimous on the following issues:

Information turnaround:

B1) The users' highest priority was quick information turnaround (within 24 hours) with 100% reliability in image delivery;

Information locational accuracy:

B2) The users' second highest priority was highly accurate geolocation (to within one pixel) to pinpoint anomalous crop or soil conditions for proper precision management;

Information accuracy:

B3) 70-75% accuracy in the measurement of most crop or soil conditions was considered sufficient for crop management to improve farm profitability;

B4) Users expected that the accuracy of remote sensing products must be quantified through a series of documented experiments *before* the product is offered to users for purchase;

Repeat Coverage:

B5) Requirements for repeat coverage depended upon the application, ranging from twice per week (for irrigation scheduling) to biweekly (for general damage detection);

Management Unit Size:

B6) The spatial resolution of information depended upon the management application, but there was some consensus that manageable units were on the order of 10-20 m;

Role of Research Scientists:

B7) Studies by research scientists at universities/government laboratories were appreciated;

B8) Users would like to see research scientists a) working hand-in-hand with commercial companies to add credence to the company's agricultural products and b) putting more effort into technology transfer to prove their algorithms are robust and operational;

Commercial Products:

B9) Users expected a color map product (preferably digital) with "quantitative" information that could be used to make decisions, not simply identify anomalies;

B10) Users wanted personal help with image interpretation, in the form of (in order of preference) person-to-person contact, a reliable help line, or user-friendly software; and

B11) Users asked for honest, reasonable marketing of the image product.

State of the Science

Before translating user requirements into system specifications, it is necessary to assess the ability of current remote sensing algorithms and models to meet users' crop and soil information requirements. The Ag20/20 group identified four basic information needs for crops and soils related to nutrient, weed, insect and water management (A1-A4). In a review by Moran, Inoue & Barnes (1997), hundreds of examples were given showing that remote sensing could be used for monitoring crop transpiration rates (related to stress), soil moisture content, crop nutrient deficiency, crop disease, and weed and insect infestations. Most of the studies cited were based on measurements in the visible and NIR spectrum (wide and narrow wavelength-bands) and the thermal infrared spectrum. Moran *et al.* (1997) concluded that there was considerable evidence that multispectral images could be used for identifying and monitoring such seasonally-variable soil and crop conditions. Similar conclusions were drawn in earlier reviews by Jackson (1984), Bauer (1985) and Hatfield & Pinter (1993). Thus, evidence suggests that it is *theoretically* possible to use remote sensing to meet the four most important information needs identified by the Ag20/20 cotton, corn, soybean and wheat growers.

Such reviews of the science present an optimistic view of remote sensing for agricultural management, but do not address the basic question: Can such algorithms be implemented operationally with *satellite-based* sensors? This question raises the issues of sensor calibration, image corrections for atmospheric and geometric effects, and product scaling. An insight into the products that are currently feasible can be obtained by looking at the product list for the currently orbiting Terra moderate resolution imaging spectrometer (MODIS; see web site at http://terra.nasa.gov/). MODIS includes an on-board calibration system that allows conversion of sensor digital count (*dc*) to the sensor-independent value of radiance. MODIS atmospheric products (aerosols, vapor profiles and cloud maps) are then used to convert MODIS-measured radiance to images of surface reflectance, temperature and emittance. The geo-located MODIS reflectance, temperature and emittance products are the basic inputs to a series of MODIS algorithms and models that produce information directly related to agricultural management at resolutions of 0.25 to 1 km. These include leaf area index (LAI), evapotranspiration (ET), fractional absorbed photosynthetically active radiation (*fAPAR)*, vegetation production, net primary production (NPP), plant pigment concentration, surface albedo (α), and vegetation cover. Accuracies for most products have been estimated and are available at the web site http://modarch.gsfc.nasa.gov/MODIS/.

The suite of MODIS products offers a reasonable assessment of what information can be derived directly from remotely sensed measurements of surface reflectance and temperature, and perhaps more importantly, what information cannot. The users surveyed by Moran (2000) wanted to know "where an anomaly was located, how large it was, and *what had caused it*". MODIS-like products can offer information on the location and size of an anomalous unit, but cannot be used to determine best management practices related to chemical and water applications or other field operations. On the other hand, products such as LAI, *fPAR*, ET, NPP, and α encompass the primary inputs into agricultural process models that are commonly used with meteorological measurements to predict yield and drive crop management decisions (e.g., Nouvellon *et al.*, 2000). A multitude of studies have reported that a combined modeling/remote sensing approach can provide hourly or daily information about local crop and soil conditions to allow integrated farm management strategies (Bouman, 1992; Clevers, Büker, Van Leeuwen & Bouman, 1994; and Moulin, Bondeau & Delécolle, 1998).

A product specifically requested by users (A4) but missing from the MODIS suite of products is soil moisture. Most remote sensing algorithms developed to map soil moisture content of agricultural fields are based on measurements of radar backscatter (generally synthetic aperture radar (SAR) at wavelengths of ~3 to 70 cm), not the optical wavelengths, due to the sensitivity of SAR backscatter to surface soil moisture conditions. Best results in determining surface soil moisture have been obtained with multi-wavelength, multi-polarization, multi-temporal, or multi-view SAR sensors (e.g., Dobson & Ulaby, 1998; Moran, Hymer, Qi & Sano, 2000). Due to SAR sensitivities to variations in surface roughness, topography and vegetation density, there is still little confidence in SAR-derived soil moisture products. On the other hand, the ability of the SAR signal to provide information regardless of cloud conditions has made this technology very appealing for agricultural management.

System Specifications

The user requirements for remotely sensed information for agricultural management based on user surveys (A1-A4 and B1-B11) and the state of science are translated to system specifications in Table 1. As cited in the previous section, the user requirements for information about fertilizer, herbicide, insecticide and water application (A1-A4) can be met by algorithms and models designed to interpret the sensor signals in the visible, NIR, thermal and microwave spectrum. The user requirements for product delivery (B1), location accuracy (B2), and measurement accuracy (B3) translate directly to sensor and algorithm specifications, where the turnaround time should be within 24 hours of acquisition, the image geo-location should be as accurate as possible (within 1 pixel), and the derived product accuracy should be on the order of 75%.

To translate user requirements for revisit period (B5) and management unit (B6) into sensor specifications, one needs to account for basic sensor limitations and site-specific atmospheric conditions. Regarding revisit period, satellite-based sensors are restricted to an orbit schedule that oftentimes doesn't allow repeat coverage more often than every two weeks. When cloudy conditions are considered, the repeat coverage could be as infrequent as every fourth overpass, meaning every two months (Marshall, Dowdeswell & Rees, 1994). Pointable satellite-based sensors allow a greater chance of acquiring cloud-free images, but there is increased difficulty in image interpretation due to the complex bidirectional reflectance distribution function (BRDF, Qi *et al.*, 1993). Moran *et al.* (1997) suggested that the repeat cycle (RC) of the sensor could be computed as a function of the revisit period (RP) requirement and the probability (0-1) of cloud interference at the location (f_c), and of scheduling conflicts with other users (f_s) for pointable sensors, where

$$RC = RP[1-(f_c+f_s-f_cf_s)]. \tag{1}$$

For f_c = 0.5 (1 of 2 images are cloudy) and f_s = 0 (no conflicts with other programming requests), the repeat cycle of the sensor will be approximately 3 days to ensure a weekly revisit period.

Table 1. *Summary of user information requirements translated to specifications for a remote sensing system for agricultural management*

User Information Requirements		***System Specifications***	
Information Needs:	A1) fertilizer A2) herbicide A3) insecticide A4) irrigation	Spectral Wavelengths:	Wide-band Visible/ NIR, Narrow-band Visible/NIR, Hyperspectral, Thermal, Radar
Product Delivery:	B1) <24 hours	Turnaround Time:	< 24 hours
Location Accuracy:	B2) within one resolution cell	Image Geolocation Accuracy:	1 pixel
Measurement Accuracy:	B3) 70-75%	Algorithm Accuracy:	70-75%
Revisit Period:	B5) 1 week	Repeat Cycle:	3 days
Management Unit:	B6) 10-20 *m*	Spatial Resolution:	2-5 *m*
Commercial Product:	B9) quantitative information	Product Level:	Optical: Surface reflectance and/or temperature Radar: topography-corrected backscatter

The management unit resolution, estimated to be 10-20 m, is a user requirement, not a system specification. For a remote sensing system to provide information on crop and soil anomalies at 10 m resolution, the sensor spatial resolution must necessarily be less than 10 m. Moran *et al.* (1997) suggested that the spatial resolution (SR, m) needed to resolve the agricultural management unit (MU, m) is a function of the sensor signal-to-noise ($f_{S/N}$) and the geometric registration accuracy (f_{RA}), where

$$SR = MU/(1 + f_{S/N} + f_{RA}), \tag{2}$$

and $f_{S/N}$ could range from 5-10 (number of contaminated edge pixels) due to the atmospheric adjacency effect and sensor modulation transfer function (Slater, 1980). Assuming that registration accuracy is within one pixel, then f_{RA} would be 1.0. For $f_{S/N}$ =5 and f_{RA} =1, spatial resolution must be approximately 2 m to manage a field unit of 10 m. This estimate of $f_{S/N}$ does not account for image post-processing that could minimize MTF or atmospheric effects, nor does it account for the permissive requirement for measurement accuracy (70-75%) which may allow less stringent requirements for sensor signal-to-noise ratio.

The user requirement for quantitative information about crop and soil conditions can be translated into a sensor calibration requirement and a sensor product level. That is, for optical sensors, the most basic product should be surface reflectance in the visible and NIR spectrum, and temperature in the thermal spectrum. For SAR sensors, the most basic product should be backscatter derived from a calibrated sensor and corrected for topographic effects with a digital elevation model (DEM).

State of the Technology

The final step in this analysis is to assess the state of sensor and spacecraft technology to meet the sensor specifications listed in Table 1. It was not within the realm of this work to conduct a technical review of current engineering and optics development; instead, an insight into the state of technology was obtained from the sensor characteristics of the most recently launched (and to be launched) commercial and non-classified government satellites. Of particular interest were two satellite systems developed through technology verification projects [the Dept. of Energy Multispectral Thermal Imager (MTI) and NASA Earth Observing-1 (EO-1)] and one commercial sensor [the Space Imaging Corp. IKONOS] (see specifications and references in Table 2). The MTI and EO-1 sensor systems offer advanced technologies in multispectral and thermal imaging, radiometric calibration, atmospheric characterization, geometric registration and spacecraft technologies to reduce cost, mass and complexity. The IKONOS sensor represents a commercial venture to provide frequent (every 3 days), high-resolution (1-4 m), multispectral imagery for land monitoring and management. The technology driven characteristics of MTI and EO-1 and the commercially driven characteristics of IKONOS offer a good view of the state of technology related to development of an agricultural remote sensing system. The objective of the following discussion is not to identify currently orbiting sensors that could be used for agricultural management, but to illustrate the current technology that could used to meet the specifications listed in Column 4 of Table 1.

Spectral Wavelengths

With a design goal of low cost and low mass, the EO-1 system provides a 10-channel sensor with wide spectral bands, a hyperspectral sensor with 220 narrow spectral bands in the wavelength range 0.4-2.5 μm, and an atmospheric corrector. The MTI system offers multiple reflective and thermal wavelength bands similar those of the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; see web site at http://asterweb.jpl.nasa.gov/). The Canadian RADARSAT mission (see web site at http://www.ccrs.nrcan.gc.ca/ccrs/tekrd/radarsat/specs/) offers the first multi-view SAR system, though multi-frequency and multi-polarization systems are still unavailable.

Turnaround Time

Despite the fact that quick and reliable turnaround time was the highest priority identified by users (B1), it is the only system specification that has not been met with current and planned orbiting systems. Though the IKONOS was launched to serve (among others) the agricultural market, the turnaround time is still estimated to be 30 days for georeferenced products. The SPOT Imaging Corp. High Resolution Visible (HRV) sensor also offers products for agricultural applications and has a similar turnaround time of 2 weeks to 1 month (see web site at http://www.spot.com). On the other hand, EO-1 is testing a wide-band advanced recorder processor (WARP) offering high speed image data recording with ingest rates of 40 Gbps, thus improving one aspect of image turnaround time.

Image Geolocation Accuracy

Both SPOT HRV and Space Imaging IKONOS offer an orthorectified image product that would be ideal for agricultural management. The NASA EO-1 is testing a low mass pulsed plasma thruster (PPT) propulsion unit for precision attitude control that will both improve sensor pointing and enable more instrumentation to be included on a single mission without sacrificing geometric integrity.

Algorithm Accuracy

Algorithm accuracy is directly related to radiometric quality and calibration of the orbiting sensor. Both DOE and NASA have made radiometric accuracy a critical goal of the MTI and EO-1 missions, respectively. Both systems use the strategy of accurately calibrating the sensor prior to launch and then maintaining calibration in orbit with a built-in calibration system and source. For example, the EO-1 ALI has an in-flight calibration plan that includes a twelve level solar calibration, three level internal source, lunar calibration and vicarious ground calibration to achieve 5% absolute and 2% relative radiometric calibration accuracy.

Repeat Cycle

The EO-1 system offers the enhanced formation flying (EFF) technology for onboard constellation and formation control that will enable a large number of spacecraft to be managed with a minimum of ground support. EFF technology allows many small, inexpensive spacecraft to fly in formation and gather concurrent science data in a virtual platform, thus increasing data collection and frequency. In another approach, the IKONOS system uses a pointable sensor to offer a 3-day repeat cycle that meets the requirements listed in Table 1. The use of pointable sensors offers more frequent revisits, but results in increased complexity of image interpretation for non-lambertian agricultural targets.

Spatial Resolution

The IKONOS spatial resolutions of 1 m panchromatic and 4 m multispectral meet the stringent requirement of 2-5 m for agricultural management. The 20 m spatial resolution of the MTI thermal bands is a testament to recent technological developments in thermal remote sensing. Though the MTI thermal resolution does not meet the user request for 5 m pixels, it is a substantial improvement over the resolution of other recently launched satellite systems such as the Terra ASTER (90 m) and the Landsat 7 ETM+ (60 m) (see web site http://landsat7.usgs.gov). Using "ultra-fine" beam modes, the RADARSAT system can offer SAR data with resolution of 3 m and a swath width of 20 km, though in practice the SAR resolution will be coarser due to post-processing to remove SAR "speckle".

Product Level

The EO-1, MTI and Terra systems have included new technology to measure atmospheric conditions during overpass to allow image post-processing for surface reflectance and temperature retrieval from sensor digital number. The EO-1 LAC and Terra Multi-angle Imaging Spectro-Radiometer (MISR; see web site http://www.misr.jpl.nasa.gov) will measure atmospheric absorption due to water vapor or aerosols to provide significant improvements in retrieval of surface reflectance. The MTI and Terra MODIS sensors use image post-processing to interpret the signal in selective wavelengths to infer atmospheric conditions that can be used for surface reflectance and temperature retrieval.

Table 2. *Specifications of two technology verification projects (EO-1 and MTI) and one commercial venture (IKONOS) with relevance to agricultural management information requirements (where NA means the sensor characteristic is not applicable to this technology assessment)*						
Sensor	***Advanced Technologies***	***Spectral Wavelengths***	***Turn-around Time***	***Repeat Cycle***	***Spatial Resolution***	***Further Reference***
Dept. of Energy Multispectral Thermal Imager (MTI); launched March 2000	Multispectral and thermal imaging; Advanced radiometric calibration; Atmospheric characterization; Modeling and analysis	15 bands: Visible, shortwave IR (SWIR), midwave IR (MWIR), thermal IR (TIR)	NA	7 days at 1300 or 0100 hours ± 1 hour	5 m for Visible bands; 20 m for other bands Swath width: 12 km	Kay *et al.* (1999)
NASA Earth Observing -1 (EO-1) sensors: Advanced Land Imager (ALI), Hyperion and LEISA Atmospheric Corrector (LAC); to be launched September 2000	Revolutionary land imaging technologies to improve radiometric and geometric image quality; Spacecraft technologies to reduce cost, mass, and complexity	ALI: 10 bands (0.4 - 2.4 μm); Hyperion: 220 bands (0.4 - 2.5 μm); LAC: 256 bands (0.9 - 1.6 μm)	NA	16 days, acquisition on days 1, 2, 9, and 16	ALI: 30 m Hyperion: 30 m LAC: 250 m Swath width: ALI: 37 km Hyperion: 7.5 km LAC: 185 km	http://eo1.gsfc.nasa.gov
Space Imaging IKONOS; launched September 1999	Agile spacecraft for in-track and cross-track pointing; Rapid ground processing	Panchromatic (0.45-0.90 μm); Multispectral (blue, green, red, NIR)	30 days for georeference product; 90 days for orthorectify product	2.9 days at 1 m resolution; 1.5 days at 1.5 m resolution (at 40° latitude)	1 m Panchromatic; 4 m multispectral Swath width: 13 km	http://spaceimaging.com

Summary and Conclusions

A survey of user needs for agricultural management revealed that information about nutrients, weeds, insects and water was crucial to best management of agricultural resources. An assessment of the state of remote sensing science indicated that it is possible to obtain such information from remotely sensed imagery in the visible, near-infrared, thermal and radar wavelengths. Users also indicated that the information was needed weekly within 24 hours of measurement with highly accurate geo-location and fine resolution. These user requirements were translated into a restrictive set of sensor specifications that is not being met by any currently orbiting sensor (Table 1). Despite the restrictive specifications, there is evidence that currently available technology can meet most user requirements for a remote sensing system dedicated to agricultural management (Table 2). The only system specification that is not being met by currently orbiting commercial and non-classified government sensors on a regular basis is a turnaround time of 24 hours from image acquisition to delivery. This is an unfortunate failing since a quick turnaround with 100% reliability was identified by users as their highest priority requirement.

This exercise in translating user information requirements into sensor specifications offers a preliminary design for a remote sensing system dedicated to agricultural management. The next steps in technology development should be an analysis of the mass, power consumption and economic cost of such an idealistic system. It has been over 30 years since USDA scientists first suggested a resource management system based on daily interpretation of high-resolution satellite images (Park, Colwell & Meyers, 1968). Since then, there have been rapid developments in remote sensing technology, as well as global positioning systems (GPS), geographic information systems (GIS) and variable rate technology (VRT) for agricultural applications. As a result, GPS, GIS and VRT are becoming an integral part of many operational farm management systems, and yet remote sensing is still considered primarily a research tool. It is time to identify and resolve the technologic issues associated with a dedicated agricultural remote sensing system and fulfill the dream of an information- and technology-based agricultural management system.

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