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Image-Based Remote Sensing for Precision Crop Management - A Status Report

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Abstract

This status report offers an assessment of progress made in image-based remote sensing in relation to the information needs of precision crop management (PCM). The assessment includes discussion of 1) image geometric, radiometric, and atmospheric correction, 2) retrieval of crop and soil information from image data, and 3) transformation of such information into management advice that could be implemented with PCM technology. The report is presented through examples of case studies conducted on Arizona farms by scientists with the USDA Agricultural Research Service.

Introduction

Precision crop management (PCM) is an emerging agricultural management system designed to link management actions to site-specific soil and crop conditions, and place inputs where they are most needed to maximize farm efficiency. Though technology is largely in place to implement PCM operations, there is still a great need for information on crop and soil conditions at the temporal frequency and spatial resolution required for making crop management decisions. Remote sensing could play a pivotal role in PCM by providing such information from multi-spectral images acquired with aircraft- and satellite-based sensors. A great deal of progress has been made in the science of remote sensing and in the fields of image processing and sensor design and deployment. This status report offers an assessment of such progress in relation to PCM information needs.

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The remote sensing products available for PCM have been classified into five levels, where products at each increasing level are more sophisticated and are dependent upon the accuracy of the product at the previous level, and the product at the top level is potentially the most useful for farm management (illustrated as a pyramid in Figure 1). The product **at the lowest level**, an image of at-sensor radiance, is useful for farm reconnaissance, but not for temporal crop and soil assessment because it retains the unwanted effects of variations in solar angle and atmospheric conditions. **At the second level**, information of surface reflectance and temperature have been retrieved from the image and the effects of atmosphere and solar angle have been minimized. These images of surface reflectance and temperature are the basic inputs to algorithms for determining crop and soil conditions at the third level. **At the third level**, spectral images have been converted through empirical or theoretical algorithms to maps of water deficit, crop stress and green vegetation density. **At the fourth level**, physical models are introduced to combine the spatial information of level-three images with the temporal frequency of the model, and provide daily or hourly information on local crop and soil conditions. **Finally, at the fifth level**, the results of level-four modeling are incorporated into a decision support system (DSS) to derive integrated farm management strategies based on information from on-site measurements and remotely sensed images.

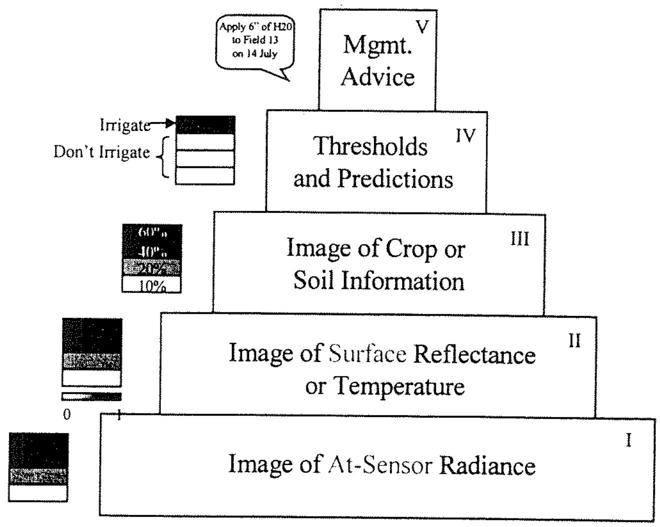


Figure 1. Five levels of RS products for precision crop management, illustrated with figures to the left that show the type of information provided at each level.

Examples of products at each of the five levels are included in the next sections. These examples were taken from work conducted by scientists at the U.S. Water Conservation Laboratory (USWCL), Phoenix, Arizona, who have been working for over 20 years to develop remote sensing products for farm management. Though these examples represent only the work at USWCL, they reflect the general trends and achievements of the remote sensing community as a whole.

Product Level I: Images of At-satellite Radiance

USWCL has conducted in-flight calibrations of airplane and satellite-based sensors in cooperation with scientists from the Univ. of Ariz. Optical Sciences Center (Figure 2). The results of over ten years of work have shown that

1) over time, sensor sensitivity degrades up to 27%;
2) sensor degradation depends on type and filter;
3) in-flight sensor calibration uncertainty is less than 5%; and
4) regular calibrations result in high-quality images (Slater et al., 1987).

These results show that in-flight sensor calibration is both accurate and essential for proper interpretation of remote sensing images for monitoring temporal changes in crop and soil conditions.

Product Level II: Images of Surface Reflectance or Temperature

Retrieval of surface reflectance from image radiance can be accomplished through complicated and expensive measurements of atmospheric conditions, and modeling of atmospheric radiative transfer (an inversion of the approach illustrated in Figure 2). This approach is generally unsuitable for agricultural applications due to complexity and expense. Instead, USWCL scientists have explored the use of canvas reference tarps that could be deployed during each overpass (Figure 3) and on-farm invariant targets (such as landing strips or dirt roads) that could be used to normalize the images to a common reference. These operational approaches have resulted in retrieved reflectance factors of accuracy to within 0.01 reflectance in the visible and NIR-infrared wavelengths, and retrieved surface temperatures to within 1 °C of ground-based measurements (Moran et al., 1997; Moran et al., 2000a).

Product Level III: Maps of Crop or Soil Information

Examples of three image products developed in collaboration with USWCL scientists are the soil-adjusted vegetation index (SAVI), water deficit index (WDI), and crop water stress index (CWSI). The SAVI is derived from surface reflectances in the near-infrared and red spectrum. SAVI has been found to be sensitive to such vegetation parameters as

1) green leaf area index,
2) fraction absorbed photosynthetically active radiation, and

3) percent of the ground surface covered by vegetation (Huete, 1988).

The WDI and CWSI are derived from measurements of surface temperature and spectral vegetation index, combined with meteorological data. For WDI, this is illustrated graphically by the small inset associated with the WDI image in Figure 4. WDI indicates the rate of evaporative water loss from cropped fields and can be used to

1) monitor efficacy of irrigations, and

2) identify fields where evaporative water loss is greatest (Moran et al., 1994).

CWSI provides information on crop health and vigor, and can be used to

1) determine when to irrigate and how much water to apply, and

2) identify fields with insect or other health-related problems (Jackson et al., 1981).

CWSI, which is the basis for WDI, is perhaps the most universally accepted remote sensing algorithm developed by USWCL scientists.

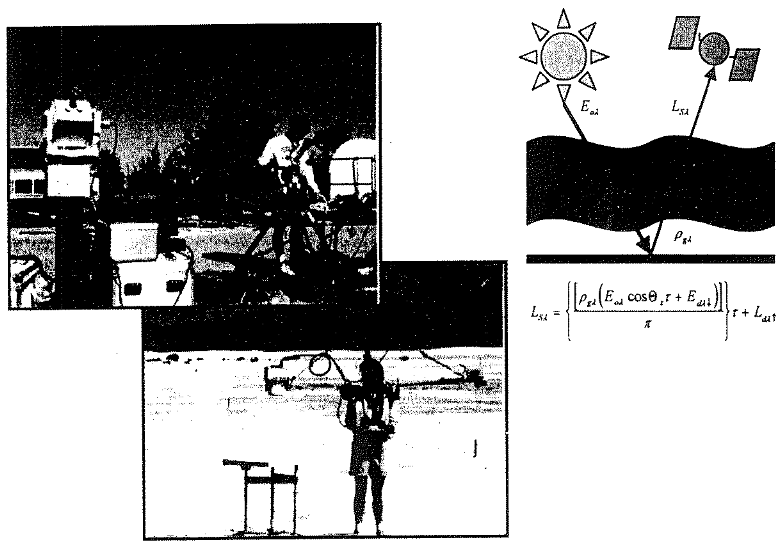


Figure 2. An illustration of the approach and measurements used by Arizona scientists for in-flight sensor absolute calibration, where the figure in the upper right illustrates the radiative transfer of the solar beam to the orbiting sensor, the photo in the upper left shows the solar radiometer used to measure atmospheric conditions, and the photo at lower center shows the yoke-based radiometer used to measure surface reflectance.

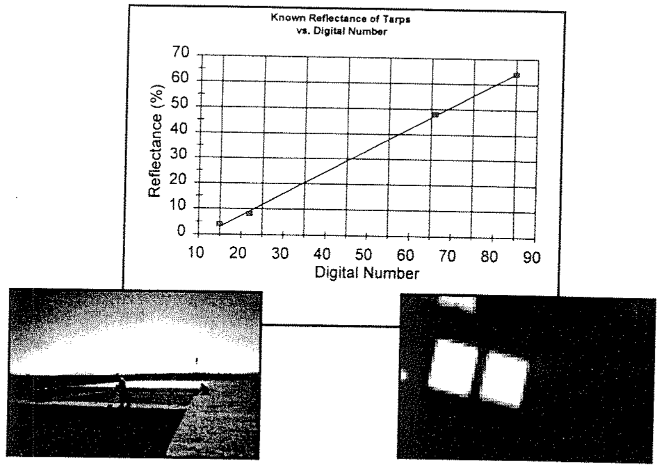


Figure 3. Use of calibrated canvas tarps to compute the relation between digital number (dn) measured by the airborne sensor and surface reflectance, where the figure on top center represents results from the deployment of four tarps (illustrated by photo at lower left and digital image at lower right) within the image footprint of the sensor.

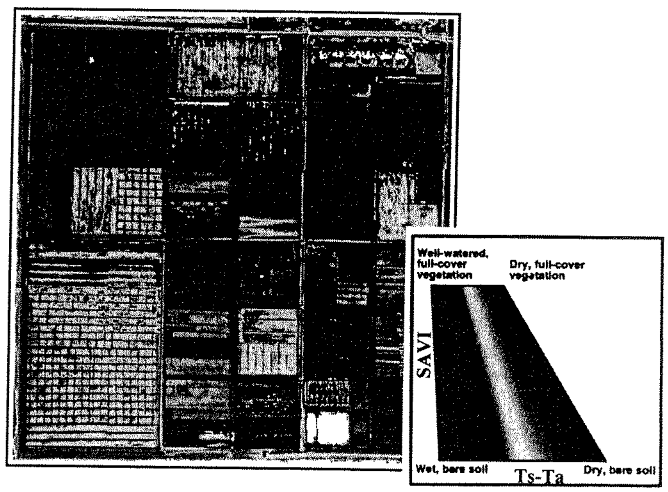


Figure 4. An image of the water deficit index (WDI) for the Maricopa Agricultural Center near Phoenix Arizona, where the inset shows the relation between SAVI and surface-air temperature that was used to discriminate fields in which evaporative water loss was greatest (color image available at http://www.uswcl.ars.ag.gov).

Product Level IV: Incorporation of Remotely Sensed Data into Process Models

At level IV, a combination approach is used to supplement the accurate but infrequent measurements of remotely sensed surface parameters (such as vegetation cover, evaporation rate and plant vigor) with daily simulated estimates of such parameters based on physical models and meteorological information (Figure 5). Results from a synthesis of remote sensing with a cotton growth model (Maas, 1993) in Arizona are illustrated in Figure 6; the predicted green leaf area index (GLAI) and daily evaporation rates were within 0.55 GLAI and 1.6 mm/day of measured values of GLAI and evaporation, respectively (Moran et al., 1995). Thus, the *high temporal frequency* of the simulation model was combined with the *high spatial resolution and high accuracy* of the remotely-sensed data to provide daily, accurate estimates of some surface parameters for effective resource management.

To support this modeling work, scientists at USWCL have compiled all the images and supporting ground data acquired in USWCL experiments since 1984 into the Water Conservation Laboratory Image and Ground Data Archive (WIGDA99). WIGDA99 contains 315 entries for spectral images and 709 entries for associated ground data files, with each entry documented with metadata to allow the user to locate data according to user-specified criteria and to easily determine which images are related to which ground data files, and *vice-versa* (Moran et al., 2000b).

Product Level V: Remotely Sensed Data in Decision Support Systems

To optimize the usefulness of remotely-sensed information for such farm management decisions as irrigation scheduling and chemical applications, it will be necessary to incorporate this information in a decision support system (DSS). A good example of such an approach is the Linear Move Irrigation Experiment (LiMIE) conducted by scientists at USWCL (Figure 7). In LiMIE, a cart-based sensor has been installed on a linear move irrigation system to make daily measurements of surface reflectance and temperature for input to a physical crop growth model. Preliminary results have shown that crop models and DSS are useful tools for interpreting remotely sensed data to properly manage within-field variations in nitrogen and water (Ed Barnes, USWCL, Personal Communication; http://www.uswcl.ars.ag.gov).

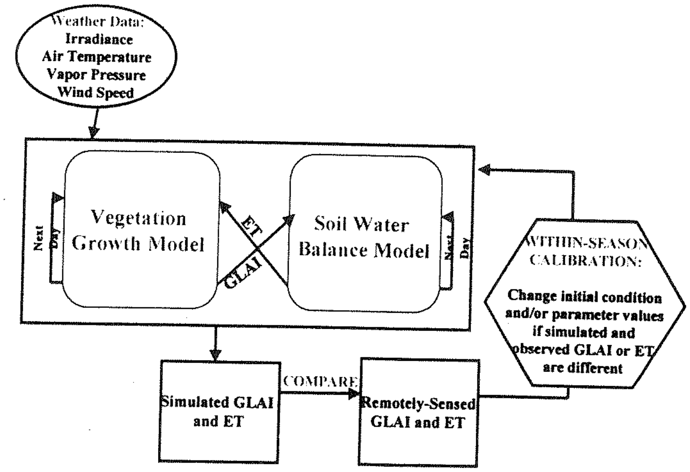


Figure 5. A combined remote sensing/modeling approach in which remotely-sensed estimates of surface conditions are used to calibrate the model inputs to provide accurate, spatially-distributed, daily information for resource management.

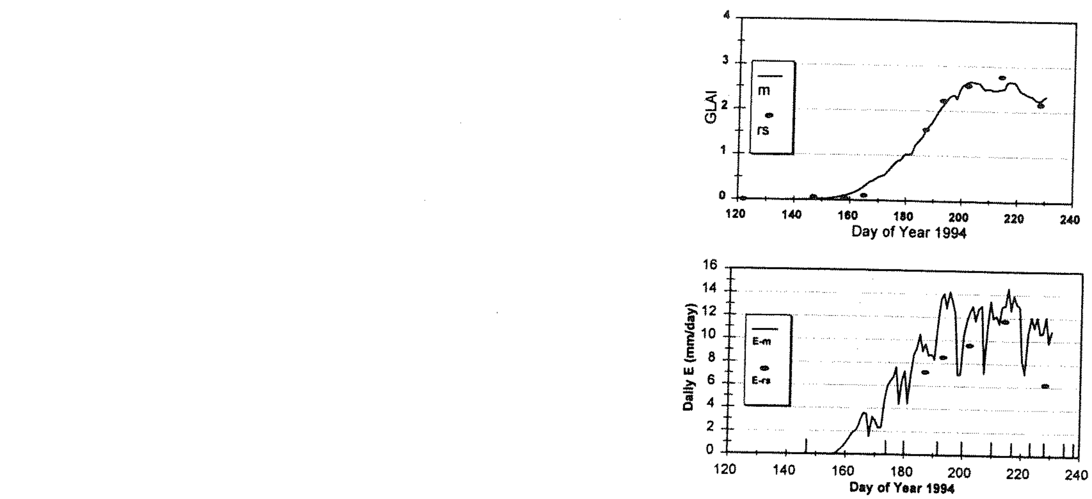
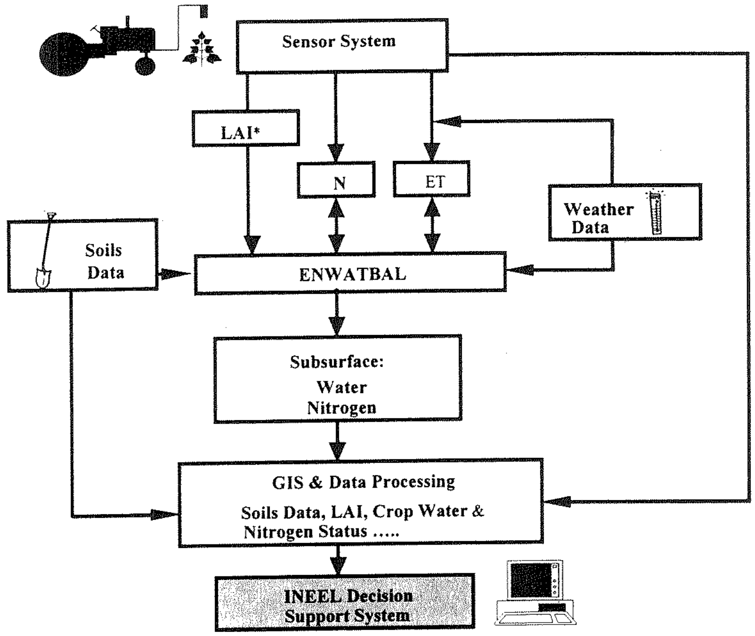


Figure 6. Results from a synthesis of remotely sensed measurements (solid circles) with a cotton growth model (output represented by a solid line) in Arizona to model crop green leaf area index (GLAI) and daily evaporation (E) rates.



***Notation: LAI = Leaf Area Index; N = Crop nitrogen status; ET = Evapotranspiration**

Figure 7. The experimental design of the Linear Move Irrigation Experiment (LiMIE) in which remotely sensed measurements of surface reflectance and temperature were used as inputs to a physical crop growth model (ENWATBAL), and model outputs (soils data, LAI, crop water and nitrogen status) were assimilated into a decision support system (DSS) to develop field-scale management strategies.

Summary

This report concludes with an assessment of the state-of-the-art of remote sensing for precision crop management. In relation to the five levels of the pyramid (Figure 1), **at the lowest level**, it is now the norm for sensors to be calibrated to units of radiance and most sensors launched in the 1990s have a protocol for continuing in-flight calibration. **At the second level,** there are a multitude of approaches that work well for retrieval of reflectance and temperature from image radiance, but there is as yet no universally accepted method for this procedure. A measure of our success **at the third level** is the incorporation of several remote sensing algorithms and models into the products being sold by commercial companies. There has been far less progress made **at the fourth and fifth levels.** There are several physical models that have been refined to assimilate remotely sensed information, and these are in the process of being validated and distributed. Regarding DSS, there are several robust DSS available, but none have been designed specifically to accept remote sensing input and there has been little progress toward this goal. **In summary**, great strides have been made in the first three levels; there is currently much research activity devoted to assimilating remotely sensed images into physical models (fourth level); and there are few examples of remote sensing information being used in a DSS to provide farm management advice. The work of scientists and engineers should continue toward the goal of someday providing sound management advice to farmers based in part on spectral measurements made by sensors aboard aircraft or orbiting satellites.

Acknowledgments

Thanks to the scientists and technicians at USWCL who made this work possible.

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