IMAGE-BASED REMOTE SENSING FOR AGRICULTURAL MANAGEMENT - PERSPECTIVES OF IMAGE PROVIDERS, RESEARCH SCIENTISTS AND USERS*

M. Susan Moran
USDA ARS U.S. Water Conservation Laboratory
Tucson, Arizona, USA

ABSTRACT

The objective of this paper was to assess remote sensing (RS) technology for precision farm management (PCM). The primary limitations were found to be the lack of an image-based remote sensing system dedicated to providing PCM-scale information, the gap between user needs and available products, and the failure of research scientists to involve users in their research and to promote technology transfer. These limitations may soon be remedied due to 1) the recent launch of the first commercial, high-resolution satellite-based sensor which will meet many PCM information requirements (as listed herein) and the pending launches of several more suitable commercial sensors; 2) image providers are responding to user requests for quantitative, validated products and personal help with image product interpretation; and 3) universities and government research laboratories are starting to reward research scientists for technology transfer and for involving users in research program development.

1.0 INTRODUCTION

Precision crop management (PCM) is an emerging agricultural management system using information and technology to identify, analyze and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability and protection of the environment (Robert et al., 1994). Many experts agree that there is a good match between the information needs of PCM and the offerings of spatially-distributed information about crop and soil conditions provided by image-based remote sensing (RS) (e.g., Johannsen et al., 1998). The question remains: *"Can current RS technology meet the very stringent information requirements of PCM?"*.

Robert et al. (1996) stated that new technologies go through three phases: excitement, chaos and rebirth, and that PCM was still in the first development phase of excitement. Remote sensing for farm management appears to be in the third developmental phase of rebirth. The phase of excitement for RS was in the late 1970s and early 1980s, when a great research effort was focused on the use of multi-spectral images for crop inventory and production. The Large Area Crop Inventory Experiment (LACIE) and AgRISTARS programs were conducted by USDA, NASA and NOAA producing robust methods for regional crop assessment, and defining the physics of relations between spectral measurements and biophysical properties of crops and soils (MacDonald and Hall, 1980). This was also the era of cheap and voluminous imagery provided by NASA and NOAA through the Landsat program and NASA's airborne sensors.

This was followed by a period of chaos as numerous small and large companies in the late 1980s and early 1990s were formed to provide image products for farm management. In the throes of sensor and product development within the highly competitive commercial and academic environments, instruments failed, pilots quit, planes broke down, products were overrated and inadequate, companies went bankrupt, and as one user stated, "We got burned". Also, during the late 1980s and early 1990s, the Landsat program was moved from NASA to NOAA, and the Landsat system was eventually operated by a commercial venture, EOSAT. This resulted in an increase in data pricing as well as severely restricted copyright protection, and thus, the steady stream of Landsat data dried up as a source for remote sensing research (Goward et al., 1999).

The late 1990s have been a time of rebirth for remote sensing for farm management. The recent convergence of technological advances in geographic information systems (GIS), global positioning systems (GPS), and automatic

---

* Presented at the Second International on Geospatial information in Agriculture and Forestry Conference, Lake Buena Vista, Florida, 10-12 January 2000.

control of farm machinery through variable rate technology (VRT) within the PCM system have provided an ideal framework for utilizing RS for farm management. Furthermore, in April 1999, the Landsat-7 ETM+ sensor was launched with increased spatial resolution in the thermal band, a new panchromatic band, and improved radiometric accuracy, at a cost-of-reproduction without copyright restrictions. In September 1999, the first of several proposed commercial satellite-based sensors, the IKONOS II system, was launched by Space Imaging Corp. to provide multi-spectral data in visible and near-infrared wavelengths, at 4 m resolution with the possibility of 1-3 day repeat coverage and 24 hour turnaround. These launches, along with the substructure provided by PCM, should revitalize the scientific and commercial communities to help RS achieve its potential as an information source for PCM.

To better answer the posed question about RS technology, I conducted a limited survey of three groups (with number of contacts in parentheses): image providers (5), research scientists (5), and users (13). By my definitions, *image providers* are companies trying to make a profit from selling remote sensing image products for farm management; *research scientists* are people at universities or government research laboratories studying remote sensing science with the goal of providing algorithms and models for farm management; and *users* are people or corporations who have already purchased remote sensing image products for PCM. Representatives from each of the three groups were contacted by telephone, and asked a series of questions related to remote sensing for PCM. The results of this limited survey provided an insight into their experiences, attitudes, and expectations, and provided the foundation to answer the posed question.

The limitations of RS technology for PCM lie primarily in the lack of an image-based remote sensing system dedicated to PCM information requirements. Secondly, there has been a discrepancy between the information the user wants, and what can be provided within the technical and economic constraints of the image provider. Finally, most research scientists working with remote sensing are designing their studies without the input of the users, and with no plan for technology transfer. These three issues are the topics of Sections 3-5 in this manuscript. As a prelude to those discussions, Section 2 presents a short comparison between the conventional sources of information for farm managers (obtained through sampling) and the relatively new technology of remote sensing.

2.0 SAMPLING VERSUS SENSING

In this survey, most users viewed remote sensing as simply another source of information that differed in accuracy, sampling density and turnaround time from the available, conventional sources of information, such as neutron probes for measuring soil moisture, soil pits for finding claypan, and petiole samples for determining plant nitrogen status. That is, remote sensing was seen as part of a continuum of available tools rather than a discrete departure from conventional information sources. This assertion is well-supported by a conceptual model of sampling versus sensing presented by Swinton and Jones (1998), and the following discussion is taken largely from their work. By Swinton and Jones' definition, sampling refers to collecting individual observations from the population of interest, and using them to make inferences about the population as a whole. Sampling entails direct measurement of the attribute(s) of interest (e.g. soil nitrogen) for making management inferences. Approaches for PCM generally use sampling on a grid to provide a denser sampling approach to make inferences about smaller areas within a field. Sensing refers to automated data collection using intensive sampling (a raster image in remote sensing parlance). In contrast with sampling, sensing frequently relies on a proxy variable that is correlated with the attribute of management interest.

According to the Swinton and Jones' conceptual model, conventional sampling which measures the attribute rather than a proxy has a higher level of measurement accuracy than sensing. However, grid sampling has a lower spatial and temporal accuracy than sensing because the sampled values represent a larger area, and the elapsed time between the sample and the management decision is relatively long due to time-consuming laboratory processing. Ideally, the farm manager wants accurate location, accurate measurement and quick turnaround. Whether the farm manager chooses sampling or sensing depends on the relative importance of location, measurement error and timing, as well as the cost of information acquisition and the ease of use and clarity of interpretation. By contrast, payoffs of sampling methods are highest when sensor equipment is not reliable, timeliness does not matter (e.g., phosphorus application), and spatial variability occurs on a larger scale.

When remote sensing information is considered in terms of the accuracy, resolution and timeliness required for PCM applications, it becomes a straight-forward exercise to determine the sensor and platform characteristics most suitable for PCM. This is the topic of the next section.

3.0 SPECIFICATIONS FOR AN IMAGING SYSTEM FOR PCM

According to the model of Swinton and Jones (1998), a sensor system suitable for PCM would provide fairly accurate measurements of crop and soil conditions, quick and reliable information turnaround, highly accurate geo-registration, frequent repeat, and fine spatial resolution. These five information requirements will be addressed in the following subsection, followed by proposed system specifications that could meet those requirements.

3.1 USER INFORMATION REQUIREMENTS

3.1.1. Measurement Accuracy Users agreed that an accuracy of 70-75% in the measurement of most crop or soil conditions was sufficient to implement PCM and improve farm profitability. This is in contrast with the goal of many research scientists to provide algorithms and models with 90-95% accuracy. Measurement accuracies of 70-75% correspond well with many assessments of PCM profitability. For example, Lowenberg-DeBoer (1998) found that a farm with only 10% low yield potential soil could show positive returns to variable rate planting. In another example in Minnesota, Malzer et al. (1996) reported that current nitrogen recommendations over-fertilized one field by ~45% and under-fertilized a second by ~30%; the potential profit from precision N rate management was ~20% of the current N profitability estimates. With profitability reported for such small management areas and with the potential for such large over- and under-applications of chemicals, there is potential for improving farm profits with even moderately accurate (75%) information.

Furthermore, users were in agreement that the accuracy of the image product must be quantified through a series of documented experiments, and further testing on their own farm. In all cases, users were willing to provide their own test plots and pay for the image data in return for interpretation and analysis by a scientist working with the image provider. For progressive managers of large farms, this is the conventional method for testing new farming technologies. Generally, if the first year's yield test is encouraging, the farm manager will repeat the test during the second year; if the first year's yield test is phenomenal, the farm manager will conduct a larger test the second year; and if the first year's yield test is discouraging, they will not repeat the test and will discard the new technology. All users in the survey were already testing other new technologies at their own expense.

3.1.2 Product Delivery The highest priority for all users and image providers was quick turnaround. Unlike measurement accuracy for which users were willing to accept 70% accuracy, the users expected 100% reliability in image delivery. The consensus of all users and image providers was that images must be delivered within 24 hours, preferably within 12 hours. That is, image data that was acquired on the afternoon of day 1 should be processed and delivered to the farm manager by the morning of day 2. Moran et al. (1997) found that a 12-hour turnaround time was sufficient for all PCM applications except some time-critical crop management (TCCM) operations which require a quick assessment of the extent of the damage and immediate management. They reported that a 24-hour turnaround time was still sufficient for the majority of the management operations, but a 1-week turnaround would only be useful for providing GIS data layers (e.g., elevation, soil management units) for the next year's cropping cycle.

3.1.3 Location Accuracy The second highest priority for all users and image providers was highly accurate georegistration. For PCM, it is necessary to pinpoint the location of the anomalous crop or soil condition for proper precision management and inclusion in a GIS. This was one issue for which users and image providers had largely different expectations. As an example of the precision possible with variable rate technology, one user reported that he could vary cultivation practices (seeding, planting) to within 5 *cm*. This relates well to the levels of location accuracy for PCM cited by Palmer (1994) ranging from the finest at 1 *cm* ("plant specific" accuracy) to the coarsest at several meters (to match the gradients of soil parameters). Another consideration is the positional accuracy of tractor-mounted variable rate granular spreaders, which has been estimated to be 10-30% of a 7-*m* swath width

(Chaplin et al., 1994) resulting in approximately 2-*m* accuracy. These user accuracy requirements of approximately 2 *m* are in contrast with the positional accuracies offered by some image providers. Users reported receiving geo-registered remotely sensed information from airborne sensors with 2-5 *m* spatial resolution with location errors from 20-500 *m*. In one case, the cropped field of interest was not even included in the image. On the other hand, image providers were aware of the importance of accurate geo-registration and were striving for 1-pixel accuracy in automated or semi-automated procedures. One-pixel accuracy is feasible with sensors on stable satellite platforms, but may be difficult to obtain with aircraft-mounted sensors due to turbulence, the skills of the pilot, and the necessity of mosaicing image frames to obtain whole-farm coverage.

3.1.4 Revisit Period Unlike the very restrictive requirements for turnaround time (12-24 hours with 100% reliability), users had more relaxed expectations for repeat coverage. The requirements ranged from twice per week for irrigation scheduling to biweekly for general damage detection. The users were hesitant to receive more frequent information because it was a time consuming task to browse the images, identify the anomalies, scout the fields to determine the cause of the anomaly, make a management decision, and amass the personnel and materials to accomplish the management task. All users agreed that when the image products are more quantitative (that is, offering an accurate assessment of the cause of the anomaly and suggesting a management activity), then the users would request more frequent repeat coverage. Image providers working with aircraft-based sensors reported that they were stretching their personnel and equipment limits to provide repeat passes on a weekly basis. Image providers working with satellite-based sensors are confined by the orbital constraints and numbers of satellites, and are often limited to repeat passes every two weeks.

3.1.5 Management Unit Like positional accuracy, the spatial resolution required for PCM depends upon the management operation. For example, Cahn and Hummel (1994) reported that fertilizer rates may need to change every 10-20 *m* for nutrients such as nitrogen that vary across short distances. Spatial resolution will also be constrained by the limitations of the tractor-mounted field equipment used for variable rate application. The cutting width of commonly-used corn and soybean combines are on the order of 6 *m* (Bashford et al., 1994) and the width of common granular spreaders is nearly 7 *m* (Chaplin et al., 1994). There was a user consensus that it was economical to manage crop and soil units with a nominal size of 10 *m*.

3.2 SYSTEM SPECIFICATIONS

The user requirements for remotely sensed information in PCM based on this limited survey of users, image providers, research scientists, and the literature are summarized in Table 1. The first three user requirements translate directly to sensor and algorithm specifications, where the value-added product accuracy should be on the order of 75%, the turnaround time should be within 24 hours of acquisition, and the geo-registration should be as accurate as possible (within 1 pixel).

To translate the latter two user requirements (revisit period and management unit) into sensor specifications, one needs to account for basic sensor limitations and site-specific atmospheric conditions. Regarding revisit period, aircraft-based sensors have the scheduling flexibility to provide the cloud-free conditions required by optical sensors on a near-weekly basis. This can become complicated when weather conditions are particularly bad; one image provider recounted an experience when cloudy conditions persisted for 11 days and they spent the next few weeks trying to meet past and current imaging commitments. 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 et al., 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

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

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.

The management unit resolution was estimated to be 10-20 *m* based on user interviews and VRT equipment limitations; note, this 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 pixel size must necessarily be less than 10 *m*. Moran et al. (1997) suggested that the pixel size (PS, *m*) needed to resolve the PCM management unit (MU, *m*) is a function of the sensor signal-to-noise ($f_{S/N}$) and the geometric registration accuracy (f_{RA}), where

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

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 $f_{RA} = 1$, pixel size 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.

Thus, the user requirements discussed in the previous subsection translate conservatively to system and processing specifications as listed in Table 1. Note that these specifications are for PCM which is characterized by management of crop and soil variability at the "within-field" scale. The specifications for a RS system dedicated to farm management at the field or local scale would be different, in particular pixel size would be larger. Furthermore, this assessment does not address the crucial and difficult issue of selection of spectral band widths and wavelengths, nor the economic and technical constraints in building and operating such a system.

Table 1. Summary of PCM user information requirements translated to specifications for a RS system.

User Information Requirements		System Specifications	
Measurement Accuracy	70-75%	Algorithm Accuracy	70-75%
Product Delivery	< 24 hours	Turnaround Time	< 24 hours
Location Accuracy	2 *m*	Geo-registration Accuracy	1 pixel
Revisit Period	1 week	Repeat Cycle	3 days
Management Unit	10-20 *m*	Pixel Size	2-5 *m*

4.0 REMOTELY SENSED PRODUCTS FOR PRECISION CROP MANAGEMENT

The users contacted in this survey were confident and unanimous in their description of the preferred image product:

1) Users expected a color map product (hardcopy, or preferably digital) with "quantitative" information that could be used to make decisions, not simply identify anomalies. They wanted to know where the anomaly was located, how large it was, and *what had caused it.*

2) Users wanted personal help with image interpretation, in the form of person-to-person contact, a reliable help line, or user-friendly software. Person-to-person contact was the preferred information delivery method. During the crop growing season, users reported working under extreme time constraints and not having the time or patience to interpret a complex product in a format that was inappropriate for making management decisions.

3) Users expected the image provider (or research scientists) to do the product validation first, before presenting it to the user for purchase. Users were all willing to conduct additional yield tests on their own farm, but they were not interested in high-risk ventures.

4) Users wanted honest, reasonable marketing of the image product. All users felt that RS products had been oversold, and that users had been promised much more than had ever been delivered. As a result, users described themselves as skeptical, reluctant and distrustful.

The image providers interviewed were aware of the users' expectations. Four of five image providers were offering "high end" products including maps of weeds, insect infestations, nutrient deficiency, water deficiency and/or yield. The fifth image provider was providing only maps of anomalies and hoped that buyers, such as crop consultants or chemical dealers, would process the high quality image to sell value-added products to farm managers. All image providers were conducting product validation studies to some extent. Several companies had hired or contracted with research scientists to provide an independent and more extensive validation of results.

All image providers were struggling to provide help in image interpretation to the users. Some companies were providing face-to-face on-farm interpretation at a great deal of expense, but with good success. Other companies were putting similar expense into providing a useful and simple software interface that could improve users' image interpretation. Finally, one company had a 24-hour help line to allow users to get personal information at any time.

When users were asked what caused them to continue purchasing RS images for a second (or third, fourth, etc.) season, they all responded that it was profitability; that is, the imagery either improved yields or reduced costs. Secondarily, it was because they had a personal interest in the technology, and thought they might benefit economically in the future. The factors cited by users who did not continue to purchase images were lack of profitability, lack of time and labor, and inability to use VRT in response to image information. The image providers described the same story from a different perspective. They stated that they lost customers primarily due to weather and the economy, and secondarily due to instrument failures that prevented them from offering further overflights. Weather-related problems included a very wet Spring in which customers could not plant their crops and thus did not need imagery, and a very good growing season in which customers had exceptional crops and did not see the profit from investment in remotely sensed images (see also study by Braga et al., 1998). The economy has a very important impact on repeat business in agricultural production; due to the low profit margin on many crops, when the price of a crop drops, it is more economical to leave fields fallow for a season than to plant a crop.

5.0 ROLE OF RESEARCH SCIENTISTS

Both users and image providers appreciated the studies of research scientists working at universities and government laboratories. On the other hand, users would like to see more research scientists working hand-in-hand with image providers because they felt it provided more credence to the company's agricultural products. Image providers suggested that research scientists should put more effort into technology transfer to prove that their algorithms and models were robust and operational. The research scientists interviewed for this review were already working with commercial companies. In their view, the role of research scientists in promoting remote sensing for PCM was to "be practical", understand the accuracy requirements in algorithm and model development, and keep in mind that the users and image providers are interested primarily in profitability.

With these issues in mind, the role of research scientists in promoting RS for PCM could be improved through greater interaction with the client (either the user or the image provider), including

- definition of the research program based on client needs (identified by the client) and participation of clients in the program operation;
- ownership of the system by the client (clients need to help assembling information and applying it);
- education of clients on the capabilities of remote sensing, and gradual implementation of the new program (to allow the client to maintain an understanding of the new technology); and
- economic analysis to show clients the economic benefit of using RS over traditional approaches.

Furthermore, research scientists reported that universities and government laboratories were changing to reward research scientists for technology transfer and encourage them to use a team approach and involve clients in program development.

6.0 CONCLUDING PERSPECTIVE

Nearly 9% of the one-half million farmers growing corn in the U.S. used some aspect of PCM for corn production in 1996 (representing nearly one-fifth of 1996 harvested corn acreage), and of these PCM users, 54% used tractor-mounted yield monitors to map field variability (Daberkow and McBride, 1998). These numbers illustrate the large potential market for remotely sensed agricultural information and the capacity of farm managers to adopt new technology. Whether image-based RS technology is included in emerging PCM systems will depend on the ability of commercial image providers, engineers and research scientists to meet the stringent PCM requirements for quantitative, validated information products. This will mean improvements in product turnaround and image registration, as well as successful launches of upcoming commercial satellite-based sensors with spatial resolutions of 2-5 *m* and/or further advances in aircraft-based mounts and sensors. A strategy will have to be developed for independent validation of algorithms produced by research scientists and proprietary products produced by for-profit commercial companies to satisfy the requirements of risk-adverse farm managers. The economics of RS for PCM will have to be determined through well-designed experiments comparing profits obtained through conventional and high-technology management systems. Finally, an effort will have to be made to encourage a systematic, triangular education of image providers, research scientists and users through inclusion of all clients in program development and implementation.

7.0 ACKNOWLEDGMENTS

This work would not have been possible without the honest insights provided by the image providers, research scientists and users contacted in this limited survey. I would also like to thank the three knowledgeable reviewers who offered their comments on and corrections to the first draft.

8.0 REFERENCES

Bashford, L.L., S. Al-Hamed, M. Schroeder and M. Ismail (1994) Mapping soybean and corn yields using a yield monitor and GPS, Proc. Site-Specific Mgmt. for Agric. Sys., 27-30 March 1994, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p. 691-708.

Braga, R.P., J.W. Jones and B. Basso (1998) Weather induced variability in site-specific management profitability: a case study, Proc. 4th Intl. Conf. on.Prec. Agric., 19-22 July 1998, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p.1853-1863.

Cahn, M.D. and J.W. Hummel (1994) Variable rate system for side-dressing liquid N fertilizer, Proc. Site-Specific Mgmt. for Agric. Sys., 27-30 March 1994, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p. 683-689.

Chaplin, J., E. Roytburg and J. Kaplan (1994) Measuring the spatial performance of chemical applicators, Proc. Site-Specific Mgmt. for Agric. Sys., 27-30 March 1994, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p. 651-670.

Daberkow, S.G. and W.D. McBride (1998) Adoption of precision agriculture technologies by U.S. corn producers, Proc. 4th Intl. Conf. on Prec. Agric., 19-22 July 1998, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p. 1821-1832.

Goward, S.N., J.G. Masek, D.L. Williams and J.R. Irons (1999) The Landsat science mission: today and tomorrow, ASPRS'99 Annual Conference Proceedings, ASPRS.

Johannsen, C.J., P.G. Carter, P.R. Willis, E. Owubah, B. Erikson, K. Ross and N. Targulian (1998) Applying remote sensing technology to precision farming, Proc. 4th Intl. Conf. on Prec. Agric., 19-22 July 1998, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p.1413-1422.

Lowenberg-DeBoer, J. (1998) Economics of variable rate planting for corn, Proc. 4th Intl. Conf. on Prec. Agric., 19-22 July 1998, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p.1643-1652.

MacDonald, R.B. and F.G. Hall (1980) Global crop forecasting, Science 208:670-679.

Malzer, G.L., P.J. Copeland, J.G. Davis, J.A. Lamb, P.C. Robert and T.W. Brulsema (1996) Spatial variability of profitability in site-specific N management, Proc. 3rd Intl. Conf. on Prec. Agric., 23-26 June 1996, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p.967-976.

Marshall, G.J., J.A. Dowdeswell and W.G. Rees (1994) The spatial and temporal effect of cloud cover on the acquisition of high quality Landsat imagery in the European arctic sector, Rem. Sens. Env. 50:149-160.

Moran, M.S., Y. Inoue and E.M. Barnes (1997) Opportunities and limitations for image-based remote sensing in precision crop management, Rem. Sens. Env. 61:319-346.

Palmer, R.J. (1994) Positioning aspects of site-specific applications, Proc. Site-Specific Mgmt. for Agric. Sys., 27-30 March 1994, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p. 613-618.

Qi, J., A.R. Huete, M.S. Moran, A. Chehbouni and R.D. Jackson (1993) Interpretation of vegetation indices derived from multi-temporal SPOT images, Rem. Sens. Env. 44:89-101.

Robert, P.C., R.H. Rust and W.E Larson (1994) Preface, Proc. Site-Specific Mgmt. for Agric. Sys., 27-30 March 1994, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p.xiii-xiv.

Robert, P.C., R.H. Rust and W.E. Larson (1996) Preface, Proc. 3rd Intl. Conf. on Prec. Agric., 23-26 June 1996, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p.xvii.

Slater, P.N. (1980) Remote sensing - Optics and optical systems, Addison-Wesley, Reading, MA, 575 pp.

Swinton, S.M. and K.Q. Jones (1998) From data to information: adding value to site-specific data, Proc. 4th Intl. Conf. on Prec. Agric., 19-22 July 1998, Minneapolis, Minn., ASA-CSSA-SSSA, Madison, Wis., p. 1681-1692.