Practical Applications of Remote Sensing Technology—An Industry Perspective

John LeBoeuf

ADDITIONAL INDEX WORDS. aerial imaging, satellite imagery, green vegetation index

---

SUMMARY. The initial surge of interest in precision agriculture technologies exhibited by innovators and early adopters involved in crop production appears to have crossed over an important threshold. As valuable field experience increases and learning by doing advances, successful applications of management practices are being identified even though few are adequately documented with economic benefits. Access to accurate information pertaining to applications of site-specific management would be expected to motivate more producers to incorporate technology uses with crop production. This next group of producers has been watching technology developments as they preferred to avoid risk and wait for identifiable benefits. Waiting for detailed case studies involving high value fruits and vegetables may be the wrong approach to take. Fierce competition and strict confidentiality are expected in the fresh market industry. Thus, personal experience with technology becomes more relevant to innovative producers than published literature. This is especially true in California where 350 different crops are produced. High resolution imagery from digital aerial and satellite sensors has been used in crop production in California to identify plant stress, direct plant tissue and soil sampling efforts, and provide information for analysis and interpretation of crop growth. Examples of remote sensing imagery that have provided valuable in-season progress reports will be identified. The focus will be on practice, not theory, as seen from an industry perspective.

The initial surge of interest in new and emerging technologies exhibited by innovators and early adopters involved in farming appeared to be a revolution coming to production agriculture due to considerable media coverage. The word revolution implies a sudden or complete change. There has been a somewhat slow evolution of information technologies in horticultural crop production as innovators combined their prior field experience with an attitude of learning by doing while looking for practical applications for farm management. As a suite of technologies became available for use in production agriculture, a new management strategy that combined information with decision making became known as precision agriculture (National Research Council, 1997). This management concept is also referred to as site-specific crop management. Its use in horticultural crop production has shown numerous potential benefits. Many of the precision technologies are scale neutral and thus can be used by growers involved in various sized farming operations.

Visual Information Network Partner for Space Imaging, AgriDataSensing, Inc., 8398 North Ninth Street, Fresno, CA 93720-2217; e-mail: AgriDataSensing1@aol.com.

The use of new technologies involves monitoring activities, diagnosis of problems, and a management response (Zilberman, 1996). Practical applications are being identified with remote sensing being the main focus of this discussion.

The Land Remote Sensing Policy Act of 1992 set things into motion as applicants were allowed to obtain licenses to operate in satellite technology (KMPG Peat Marwick LLP, 1998). Interest was shifted from the public sector into the private sector. Activities were initially centered around aerial imaging as new sensors were being tested for possible use in satellites. This action prompted a quick surge of interest in 1993 to bring remote sensing technology into several major agricultural production regions, including the San Joaquin Valley in California. It was also in 1993 that the global positioning system (GPS) became fully operational with 24 h a day coverage providing latitude, longitude, elevation, and time of day information (National Research Council, 1995). While interest was quickly generated in agronomic crops such as corn (*Zea mays* L.) and soybean (*Glycine max* L.), attempts to bring information technologies into horticultural crop production were much slower and strategically geared toward high value fruits and vegetables which typically are produced in much smaller plantings. Efforts were made to look for examples of horticultural crops that could benefit from the use of timely information as an aid in the decision making process in the field and on the farm with the additional long term vision to search for beneficial uses applicable on both regional and global scales. Efforts were also made to look for opportunities for remote sensing and the limitations for use in precision agriculture (Moran and Barnes, 1996).

Technology providers actively looked for examples of innovators who were using new technologies to strive for an advantage in the fiercely competitive fresh market fruit and vegetable industries. Being able to showcase users of practical applications of technology as case studies was looked upon as a necessary step to motivate other growers who were watching the innovators but who preferred to avoid risk and wait for identifiable benefits. The need for case studies became a road block as most innovators appeared very reluctant to identify quantifiable financial benefits gained by the use of new and emerging technologies. Fierce competition and strict confidentiality are to be expected in the fresh market arena just as quality attributes are required for most all horticultural products. Therefore, the search began for practical applications of new technology that could enhance the quantity of produce and / or quality factors.

Aerial remote sensing

Remote sensing (RS) digital sensors on board fixed-wing aircraft were brought into use in the San Joaquin Valley in central California in 1993. Resolution refers to the scale or amount of detail that an image observes (Quattrochi and Goodchild, 1997). In this case, 10 m (32.8 ft) spatial resolution images represent a ground pixel size of 10 × 10 m. Crop production in the San Joaquin Valley is totally dependent on supplemental water with furrow applications being the most common type of irrigation system. Weekly flights over cantaloupe (*Cucumis melo* L. Cantalupensis Group) and honeydew melon (*Cucumis melo* L. Inodorus Group) fields brought valuable information based on solar radiation energy reflected off leaf surfaces. Information was originally expressed as a green vegetation index (GVI) map with no statistical analysis of data provided. As the remote sensing service was continued into the following 3 years, the hard copy vegetation map was enhanced by including change detection maps and statistical analysis of data. The initial reason for getting involved in weekly flights was based on a perceived need for help in pest monitoring as the sweet potato whitefly (*Bemisia tabaci* Genn) was inflicting serious crop losses on cucurbit crops in the Imperial Valley of southern California. Further studies led to the naming of a new species called the silverleaf whitefly (*Bemisia argentifolli* Bellows & Perring) (Bellows et al., 1994). While imagery did not show immediate help in pest management, farm managers were pleasantly surprised when irrigation problems were quickly identified in calibrated and computer enhanced maps. Aerial imagery was acquired by weekly flights over rapidly growing melon crops and extensive ground truthing was performed to verify what was depicted. The following practical applications were identified and used in the decision making process.

WATER STRESS DETECTION. In irrigated agriculture, where water inputs can be controlled by the grower, information that is provided that can pinpoint areas of a field that are under stress from too much water or not enough water would be valuable. In production areas where water is a manageable factor, the timing, amounts, and placement of irrigation water becomes a critical input decision that greatly influences crop yields. If RS imagery can assist growers in scheduling irrigations, the technology would be used by more producers in areas with supplemental water. This would be a great advantage compared to farmers dependent upon natural rainfall to meet the plant's water needs. Plant stress detection is one of the major strengths of remote sensing and the following example was seen with RS imagery. A previously unknown 50 cm (20 inch) deep perched water table, located in the center of a 60-ha (150-acre) field, was identified in computer enhanced imagery so that scheduled irrigations could be modified to prevent over irrigation.

PREIRRIGATION WATER MANAGEMENT. Preirrigation of fields with moveable sprinkler lines frequently results in areas of the field where differences in the length of time from irrigation to planting negatively impacts on seed germination and plant population stand. These differences are due to a limited number of available sprinkler lines as the field is not solid set at one time. RS imagery identified stand problems and wet striping of soil across 804-m (2,640-ft) long fields when planting was performed into the most recently irrigated areas. These differences in soil moisture can be seen in the satellite image shown in Fig. 1 where preirrigation is shown on bare ground in the field identified by the letter A.

WATER MANAGEMENT IN SEASON. The turnaround time from acquisition, processing, and delivery of images to the user varied from 1 to 5 d. If imagery can be quickly delivered to the end user in 1 to 2 d, ground truthing can be performed to check on soil moisture. If water stress is verified, irrigation can be scheduled as water deliveries need to be placed at least 24 h in advance. Modification of watering of furrow irrigated fields by selectively adding longer irrigation periods and changing runs to portions of the field were made possible by farm managers using RS imagery.

SOIL COLOR MAPS. Color printouts have been used to identify variability in soil color and to direct soil sampling. Light colors depicted on the maps were suggested to represent sandy soils with lower water holding capacities and lower levels of organic matter. Darker colors depicted on the maps were suggested to represent clay soils with higher water holding capacities and higher levels of organic matter. Soil color maps provide another layer of information that can be used in a geographical information system (GIS) for comparison with vegetation maps. Soil color maps can also indicate drainage problems.

VARIETAL DIFFERENCES. Stress detection by RS imagery may alert a farmer or consultant to a variety that is better suited for various field and / or environmental differences. Imagery has been used to direct planting of more expensive hybrid seed varieties to take advantage of hybrid vigor in weaker areas of production fields where water holding capacity and organic matter were lower than the balance of the field which was planted with lower priced open pollinated varieties. In addition, RS images have shown differences in variety susceptibility to sucking insects such as melon aphids *(Aphis gossypii* Glover) which are vectors of plant viruses such as cucumber mosaic virus (CMV).

CROP DAMAGE ESTIMATES. RS imagery can be used to evaluate crop damage claims from natural events such as rain or hail storms. Man induced events such as pesticide drift problems or crop damage from equipment can be accurately assessed. As an example, RS imagery was used to assess crop damage when a new underground pipeline was installed across a planted field. Before and after pictures were analyzed for vegetative differences.

CROP ROTATIONS. Plant growth differences were identified by RS imagery when melons were planted in crop rotation after upland cotton (*Gossypium hirsutum* L.) versus melons planted after tomato (*Lycopersicon esculentum* Mill.) due to the varying irrigation strategies. Weak areas in melon fields with 268-m (880-ft) irrigation runs matched up with the previous tail ditch from cotton fields with 402-m (1320-ft) irrigation runs.

CROP YIELD ASSESSMENT. Yield analyses based on imaged vegetation maps have been evaluated to estimate crop yields and also to determine fruit size differences as measured by technicians in ground truthing activities. Numerous fruit and vegetable crops receive different prices for the various sizes picked. Marketing conditions may lead to situations where packers dictate the desired fruit size for crews in their daily harvest. Knowing the field location of size differences ahead of time allows harvest managers to direct picking and packing operations of perishable commodities.

FERTILITY PROBLEMS. Plant petiole samples for fertility analysis were routinely directed to areas where differences were seen in vegetation maps. If fertility analysis identifies nutrient deficiencies in certain areas of a field, then an application of water-run fertilizers can be made to portions of a field. The information can also serve as a long term benefit by identifying areas of concern for the producer in following crop seasons. This will help in site-specific applications of fertilizers and soil amendments such as lime, manure, gypsum, and sulfur.

CHANGE DETECTION. A series of RS images can be used for crop monitoring and in the detection of changes in vegetation. Tracking of GVI was used across a melon growing season to identify cutout where vegetation growth shifts to reproductive growth and to identify the amount of time from cutout to harvest to assist in the final irrigation before harvest (National Research Council, 1997). Being able to identify when a crop makes a significant shift in the allocation of plant energy sources from photosynthesis allow crop producers to watch for fruiting signals that the development cycle is coming to an end.

SELECTIVE HARVEST. Imagery can be used to assist field personnel in assessing crop health after harvest has started in crops that require multiple picks. Identification of areas of the field where the canopy was collapsing after multiple harvest picks of melons has been seen to be beneficial. Melons are hand harvested and field packed on machines riding across roadways for 15 d or more in a row. This allows for a directed harvest with field packing crews going into areas of a strong canopy that provides shade for melons and protects against sunburn instead of having crews walk entire fields later in the harvest period. Selective harvest decreases labor costs while maximizing work crew efforts.

PLANT DISEASE MANAGEMENT. Detection of plant stress induced from disease organisms is a major strength of RS technology. Mapping of plant disease impacts on melons from fusarium wilt (*Fusarium oxysporum* Schlechtend.: Fr. f. sp. *melonis)* along with other pathogens was performed to collect long term rotational information used in scheduling of various crops. Some plant pathogens become problems during periods of warm weather when the plant is under stress from a lack of water. The ability to detect problem areas in a field, which appears to the human eye as looking okay during routine ground truthing in field inspections, makes the technology a valuable tool worth the investment of time and money. If RS technology detects small problem areas caused by pathogens, timing of fungicides can only be enhanced if turnaround time is immediate.

WEED MANAGEMENT. Heavy weed pressure can change the reflectance characteristics of a crop. Mapping of perennial weed species such as field bindweed (*Convolvulus arvensis* L.) was used to direct preplant spot treatments with ground applications of glyphosate (Roundup) instead of traveling across the entire field looking for areas to be treated. Perennial weeds typically grow in concentrated areas and can spread across fields even during drought years. Weeds are first class thieves that rob water and nutrients away from the intended crop. Their vigorous root systems out-compete most cultivated crops. RS images that are combined with GIS and GPS equipment allows for specific mapping that aids in site-specific weed management (Hanson et al., 1995).

HIGH-QUALITY FIELD BOUNDARY MAPS. RS images have been used to produce high quality road maps for the delineation of field boundaries. Even though this typically is a one time use for RS images, it should be looked upon as a great example of how to show the capabilities of RS to a lot of producers. Many land owners, renters, and leaseholders would like to know the exact acreage involved in each field. This has been identified as a need and should be used aggressively as a way to get farmers, realtors, bankers, and insurance company personnel into using RS information.

TIME MANAGEMENT. The use of RS technology has a major strength in identifying problem areas that a grower, consultant, or ranch manager needs to look at as soon as possible after review-

Fig. 1 (above). A zoomed in view of a false color infrared satellite image taken on 30 May 1999 shows the California Aqueduct in western Fresno County. The pan-sharpened image combines 5-m spatial resolution data from the Indian Remote Sensing satellite with spectral data from the U.S. Landsat satellite. Healthy vegetation is shown by the color red with bare soils depicted in shades of blue and green. Field A illustrates preirrigation of bare soils with equidistant sprinkler lines. Field B is a 60-ha (150-acre) garlic (*Allium sativum*) field that is showing a high degree of vegetative variability.

ing images. This aids in time management as highly skilled workers can spend their time addressing potential problems and come up with solutions that can impact on crop yields. Lesser skilled workers such as field scouts can be sent into portions of a field that are not identified as a problem area while still performing ground truthing activities. It has been suggested that horticulturalists may be able to cover more acreage by better time management aided by the use of RS images in a crop monitoring service.

SATELLITE IMAGERY. The aerial remote sensing technology provider eventually decided to concentrate their marketing efforts in 1997 in midwestern U.S. corn and soybeans and abruptly ended service to California growers. With the loss of an aerial provider, which had intentions of launching a constellation of satellites for the precision agriculture market, end-users were forced to start looking for alternatives. As remote sensing images accompanied by raw data files became available, growers started to look at viable remote sensing providers who were already using existing satellite imagery. The use of 10-m (32.8-ft) resolution imagery provided nine times more pixels than 30-m (98.4-ft) resolution imagery which is typical of U.S. Landsat imagery (Verbyla, 1995). SPOT (Le Systeme Pour l'Observation de la Terre) satellite imagery has 10-m panchromatic (black and white) imag-

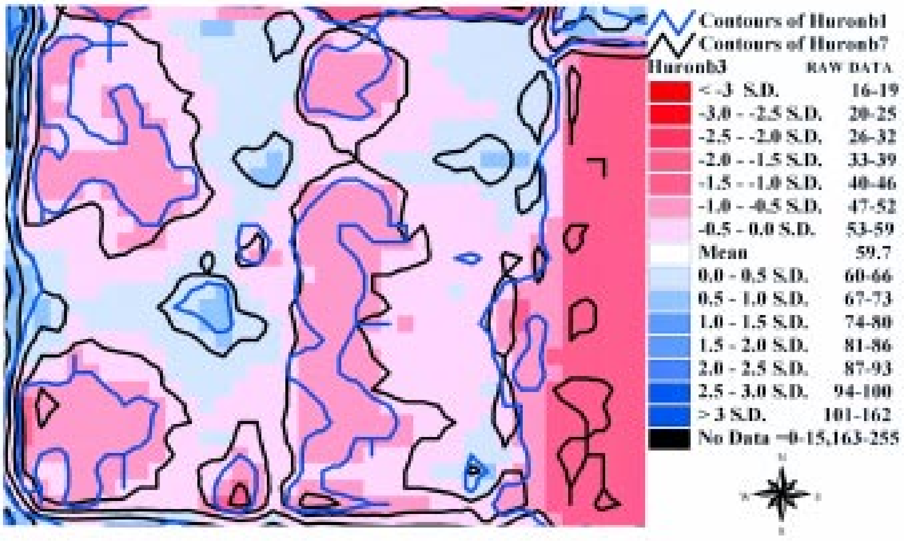

Fig. 2 (bottom). Raw data from digital (8-bit, 0 to 255) satellite sensors are analyzed for spectral differences to show vegetative variability depicted in Field B (garlic) in Fig. 1. A standard deviation analysis for chlorophyll and soil moisture is illustrated by use of red light (Huronb3) as the background color with contours outlined for blue light (Huronb1) and shortwave infrared (Huronb7). Original data files from color Landsat bands are used for spectral analysis by AgriDataSensing, Inc. (Fresno, Calif.) as a value-added service.

ery along with 20-m (65.6-ft) color imagery. Twenty meter resolution SPOT satellite imagery was matched up against 10-m resolution aerial imagery to check if soil or field variability, along with specific features, were shown with similar spectral responses. Soil features such as sandy streaks across fields were depicted in both types of imagery. SPOT imagery was previously offered in a single image map with all 36 sections located in a township. This format was fairly reasonable in price and was looked upon as a viable product for use by agricultural users. SPOT Image (Reston, Va.) changed their marketing strategy in early spring of 1999 and withdrew the township map as a product. This led to the evaluation and the use of Landsat imagery. Landsat imagery in full scene format by itself appears to offer rather limited use for site-specific crop management except in directing sampling efforts as the number of pixels per acre is limited to less than five. Landsat has six reflective bands with different spectral responses of 30-m spatial resolution obtained at an orbital altitude of 705 km (437 miles) (Short, 1999). Blue band 1 (450 to 520 nm), green band 2 (520 to 600 nm), and red band 3 (630 to 690 nm) represent the visible range of light in the electromagnetic spectrum. Band 4 (760 to 900 nm) is from the near infrared range while bands 5 (1,550 to 1,750 nm) and 7 (2,080 to 2,350 nm) cover portions of the mid infrared range. The thermal band 6 (10,400 to 12,500 nm) has a ground square pixel size of 120 m (393.7 ft) and is not used for analysis with the other bands due to the large difference in spatial resolution.

Various RS products are available by combining different bands of information. True color images are made by combining the three bands of the additive primary colors of blue (1), green (2), and red (3). True color images represent what our human eyes would see if we were looking down upon the earth. False color images are made by combining the three bands of near infrared (4), red (3), and green (2). Methods have been developed to fuse and combine information from high spatial resolution panchromatic imagery from the Indian Remote Sensing (IRS) satellite with coarse resolution color imagery from Landsat. The purpose of using a product made with imagery from two different satellites is to combine 5-m (16.4-ft) spatial resolution with 30-m spectral resolution. The pixels are resampled using a process called cubic convolution which takes the 16 nearest original data values and uses a weighted average for the new pixel value. The original values are lost but this method is used to offer smooth appearing changes across vegetation. The resampled product is offered as a pan-sharpened image that matches up with the quad format used by the U.S. Geological Survey (USGS) topographical maps of 7.5 min of latitude and 7.5 min of longitude. The technology provider, Space Imaging (Thornton, Colo.) offers the color digital orthorectified quads (DOQs) based on the same names used by the USGS topographical maps. Typical costs are $600 per color quad with the original data files included.

A false color image taken on 30 May 1999 of the Huron, California quad is shown in Fig. 1. The color red is used to highlight healthy vegetation with bare soils shown in shades of blue and green. The DOQ image shows the California Aqueduct in western Fresno County in the San Joaquin Valley. The image identifies a high degree of variability in a 60-ha (150-acre) garlic *(Allium sativum* L.) field identified by the letter B. The original data files of the color Landsat bands can then be used for spectral analysis by value-added service companies. Registration of imagery combined with improvements in computers have allowed for advanced spatial analyses of digital data. Numerous GIS software programs are available to allow data stacking with overlays to look for field variability comparisons between the different satellite bands. A standard deviation analysis using Landsat red band 3 as the background color with contours outlined for blue band 1 and shortwave infrared band 7 is shown in Fig. 2. The original 8-bit raw data is spread out from 0 to 255 with low numbers representing high absorption and low reflectance of solar radiation. Areas in the field that correspond to low numbers in band 3 represent very healthy vegetation where chlorophyll levels are high. High digital numbers correspond to ground pixel areas with high reflectance for that spectral band and thus low absorption. By analyzing different satellite bands, variability in chlorophyll, surface soil moisture, and leaf water content can be depicted. This allows for a "directed" sampling management plan based on information from sensors that verifies and enhances variability seen in infrared color composites. New uses for infrared imagery and analysis of satellite band data files are being identified by growers using furrow irrigation on garlic and drip irrigation on asparagus (*Asparagus officinalis* L.) crops.

High resolution satellite imagery is available from Space Imaging's IKONOS (Greek word that means picture) satellite which features 4-m (13.1-ft) color imagery in blue, green, red, and near infrared bands and 1-m (3.3-ft) panchromatic images. The use of high resolution pan-sharpened 1-m color imagery in site-specific crop management will only be limited by the creative imaginations of agricultural users. Satellite imagery offers an excellent view of crop production with virtually no purchase of hardware or equipment needed by the end-user to get started in site-specific management. High resolution satellite imagery is offered from various sources for the entire U.S. and also other countries.

Yield monitors

As yield monitors are developed for commodities that are machine harvested in a single pass, farmers will begin to analyze field maps that will indicate variability in yields. Yield monitors originally designed for use in potato (*Solanum tuberosum* L.*)* and sugar beets *(Beta vulgaris* L.) have been modified for use in tomato fields. Research and development of machine harvesters for cotton and processing tomatoes in 1997 brought the first commercial use of yield maps for non grain crops in California. Processing tomatoes are harvested one row at a time whereas most cotton fields are commonly harvested with four rows per pass. Yield monitors used while harvesting tomatoes have had to rely on data collected as tomatoes passed over load cells mounted with rollers. A change can be expected in the angle of the conveyor belt that transports harvested tomatoes to the loading trucks that ride alongside the harvest machine as it travels across the field. Improvements have been made by the addition of an inclinometer to measure the change of the angle of the loading belt as the operator raises or lowers the belt to minimize the drop involved during truck loading. Accuracy of tomato yield monitors is expected to be between 2% and 5% if correctly calibrated with actual truck weight data. Caution must be exercised if yield monitors are used in fields with wet and muddy conditions where soil collects on the moving belts. This is also a concern in potato and sugar beet yield monitors (Rawlins et al., 1995). It has been expected that the development of yield monitors for use in horticultural crops would become a catalyst for bringing about a change in how farmers manage their fields. The use of yield monitors may lead to the use of other technologies to provide more layers of site-specific information. Yield maps depict the final report card for a crop whereas remote sensing images can offer in-season progress reports.

Load cell sensors

A potential benefit to producers who use yield monitors with load cell sensors on their harvesters is to get timely information of truck load weights. Overloading of trucks has been a concern of the highway patrol who can ticket operators for driving overweight loads on public highways. The use of load cell sensors for truck load determination can be expected to surpass the use of yield monitoring equipment for the purpose of making yield maps.

Variable rate technology

In irrigated agriculture, the use of variable rate technology is becoming involved with the application of fertilizers and soil amendments. Due to the presence of alkaline soils in California, soil amendments such as composted manure, gypsum, elemental sulfur, or sulfuric acid can be applied in variable rates to match up existing field conditions. Variable rate applications are usually based on extensive grid soil sampling results but may also be directed by the use of RS imagery with fewer samples collected for lab analysis. Site-specific information relating to soil fertility offers growers a way to place inputs where they are needed and when they are needed. Being able to map important soil properties and physical characteristics is looked upon by horticulturalists and agronomists as a crucial need in order for consultants to provide valuable information for farm managers.

Site-specific decisionmaking

Recent developments in technology have shown that the cornerstone to successful farming is information. Innovative producers often are looking for a competitive advantage when they choose to use new information based technologies without the support of scientific literature. But ownership of information will not in itself create a competitive advantage for agricultural producers. The true power in information is in knowing how to use it. The use of RS imagery in high value commodities in California has been beneficial when ground truthing activities were performed to verify what was being depicted in the imagery. Aerial and satellite imagery acquired with digital sensors provide information about crop health and identify plant stress. Imagery provides for effective crop monitoring while ground truthing activities enhance diagnosis. Meaningful information can then be applied to a management response that is site-specific. The examples identified from horticultural production in California have the potential to be applied to other commodities. As site-specific management becomes adapted in other crop production regions, the decision making process used by farmers will be enhanced. Numerous other benefits of site-specific management will ultimately be discovered.

Literature cited

Bellows, Jr., T.S., T.M. Perring, R.J. Gill, and D.H. Headrick. 1994. Description of a species of Bemisia (Homoptera: Aleyrodidae). Ann. Entomol. Soc. Amer. 87:195–206.

Hanson, L.D., P.C. Robert, and M. Bauer. 1995. Mapping wild oat infestations using digital imagery for site-specific management, p. 495–503. In: P.C. Robert, R.H. Rust, and W.E. Larson (eds.). Site-specific management for agricultural systems. Amer. Soc. Agron., Madison, Wis.

KPMG Peat Marwick LLP. 1998. The satellite remote sensing industry: A global review. Space and High Technology Practice, Arlington, Va.

Moran, M.S. and E.M. Barnes. 1996. Opportunities and limitations of image-based remote sensing for precision agriculture. Position statement for the workshop on remote sensing of agriculture in the 21st century. USDA–ARS Water Conservation Lab.

National Research Council. 1995. The global positioning system. A shared national asset. Committee on the Future of the Global Positioning System and Commission on Engineering and Technical Systems. National Acad. Press, Wash., D.C.

National Research Council. 1997. Precision agriculture in the 21st century: Geospatial and information technologies in crop management. Committee on Assessing Crop Yield—Site-Specific Farming, Information Systems, and Research Opportunities. National Acad. Press, Wash., D.C.

Quattrochi, D.A. and M.F. Goodchild (eds.). 1997. Scale in remote sensing and GIS. Lewis Publ., Boca Raton, Fla.

Rawlins, S.L., G.S. Campbell, R.H. Campbell, and J.R. Hess. 1995. Yield mapping of potato, p. 59–68. In: P.C. Robert, R.H. Rust, and W.E. Larson (eds.). Site-specific management for agricultural systems. Amer. Soc. Agron., Madison, Wis.

Short, Sr., N.M. 1999. The remote sensing tutorial online handbook. 28 July 1999. <http://rst.gsfc.nasa.gov>.

Verbyla, D.L. 1995. Satellite remote sensing of natural resources. Lewis Publishers, Boca Raton, Fla.

Zilberman, D. 1996. Comments on precision agriculture. A presentation to the Committee on Assessing Crop Yield: Site-specific farming, information systems, and research opportunities. Univ. Calif., Berkeley.