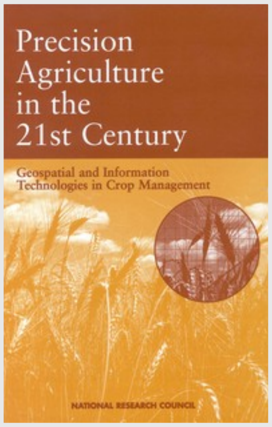

Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management

DETAILS

168 pages | 6 x 9 | HARDBACK
ISBN 978-0-309-05893-3 | DOI 10.17226/5491

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Site-Specific Farming, Information Systems,
and Research Opportunities

Board on Agriculture

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

NATIONAL ACADEMY PRESS • 2101 Constitution Avenue, N.W. • Washington, D.C. 20418

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This report has been prepared with funds provided by the U.S. Department of Agriculture, Research, Education, and Economics, under agreement number 59-0700-4-139, and by the U.S. Department of Energy, Lockheed Martin Idaho Technologies Company, Idaho National Engineering and Environmental Laboratory. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Library of Congress Cataloging-in-Publication Data

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, Board on Agriculture, National Research Council.
p. cm.
Includes bibliographical references and index.
ISBN 0-309-05893-7 (cloth)
1. Precision farming. I. National Research Council (U.S.).
Committee on Assessing Crop Yield: Site-Specific Farming,
Information Systems, and Research Opportunities.
S494.5.P73P73 1997
338.1'6—dc21 97-45268
CIP

Additional copies of this report are available from National Academy Press, 2101 Constitution Avenue, N.W., Lockbox 285, Washington, D.C. 20055; (800) 624-6242 or (202) 334-3313 (in the Washington, D.C., metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

COMMITTEE ON ASSESSING CROP YIELD: SITE-SPECIFIC FARMING, INFORMATION SYSTEMS, AND RESEARCH OPPORTUNITIES

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Preface

The land grant university system and the Agricultural Research Service have been enormously successful at creating and transferring a knowledge base to local farming communities for production of large quantities of crops at low cost. Recently, external influences such as global trade, environmental concerns, and consumer preferences have been creating new pressures for the agricultural industry. The need to accommodate production and marketing changes has put our agricultural research institutions in a new and unfamiliar setting.

Information technologies can facilitate a response to market and societal pressures. Techniques are available for making precise measurements and continuously updating field conditions. However, our ability to acquire data through tools such as on-the-go sensors, yield monitors, and geographically referenced databases has surpassed our ability to interpret this data. Even more importantly, information that is adequate today may be insufficient to meet tomorrow's needs of producers, agribusiness managers, and society. Our universities and laboratories will need to radically alter their approaches to accommodate this information overflow.

For this reason the Research, Education, and Economics agencies of the U.S. Department of Agriculture, with additional support from the U.S. Department of Energy's Idaho National Engineering Laboratory (operated by Lockheed Martin Idaho Technologies Company), requested that the National Research Council's Board on Agriculture convene a study committee to explore the potential for developing, coordinating, and using these information-handling tools for research, on-farm applications, and formulation of agricultural policies. Questions addressed by the committee included:

- How can evolving technologies aid producer decision making in agricultural crop production?
- What are the incentives for adoption and barriers to implementation of these information technologies?

- What are the environmental, economic, and social implications of precision agriculture?
- What are the appropriate roles for the public and private sectors in improving and disseminating these technologies?

Early on in its deliberations, the committee identified the scope of its report to include adoption and effectiveness of information technologies (the Internet, for example) that affect operations in the farm field. The committee was convinced that information technologies should optimize decision making, recognizing that a producer must manage for multiple goals. The committee adopted an approach that could accommodate numerous aspects of crop management that are interrelated and vary in time and space.

Despite being challenged by a lack of comprehensive data, the committee drew on its collective experience, knowledgeable opinions of experienced individuals, and reasoned judgment to develop many of its findings. The committee used multiple sources of information, such as national meetings and a literature review, to aid its deliberations. Invited experts (producers, input suppliers, crop consultants, and university scientists) provided their input on a number of topics:

- Potential of information-intensive management of crops;
- Rural development and size-neutrality issues;
- Producer perspectives on adoption and limitations of precision agriculture;
- Changes in relationships between producers, suppliers, and markets; and
- Environmental implications of precision agriculture.

In this report, the committee recognized the potential for precision agriculture to fundamentally alter decision making on the farm. The basic agronomic knowledge necessary to support new farm management systems will need to be generated in new laboratories—on the farm. Research partners will have an opportunity to study relationships among crops, weather, pests, and soil biology in real time. This report offers a new paradigm for research, development, and transfer of information technologies.

The committee chose to take a cautious but optimistic view, recognizing that some important questions will need to be answered before precision agriculture demonstrates the benefits that would justify widespread adoption. The future is not clear, and structural changes already are occurring on farms and in service industries. However, information technologies are expected to be powerful tools that will enable us to learn from internal on-farm processes. It is the committee's hope that this report will provide the reader insights on the future of information technologies in crop management and appropriate roles for the public sector.

STEVEN T. SONKA, *Chair*
Committee on Assessing Crop Yield:
Site-Specific Farming, Information Systems,
and Research Opportunities

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Executive Summary

Agricultural managers have for decades taken advantage of new technologies, including information technologies, that enabled better management decision making and improved economic efficiency of operations. The extent and rate of change now occurring in the development of information technologies have opened the way for significant change in crop production management and agricultural decision making. This vision is reflected in the concept of precision agriculture.

Precision agriculture is a phrase that captures the imagination of many concerned with the production of food, feed, and fiber. The concepts embodied in precision agriculture offer the promise of increasing productivity while decreasing production costs and minimizing environmental impacts. Precision agriculture conjures up images of farmers overcoming the elements with computerized machinery that is precisely controlled via satellites and local sensors and using planning software that accurately predicts crop development. This image has been called the future of agriculture.

Such high-tech images are engaging. Precision agriculture, however, is in early and rapidly changing phases of innovation. Techniques and practices not anticipated by the committee will likely become common in the future, and some techniques and practices thought to hold high promise today may turn out to be less desirable than anticipated.

The technologies and practices of precision agriculture offer the potential to fundamentally alter agricultural decision making. The use of large machinery and hired labor have caused many farmers to think of large fields as the basic management unit. Even though farmers know from experience that yields are higher in some parts of the field than in others, conventional management practices have focused on applying inputs at a uniform rate to an entire field. Information technologies permit the modern grower to obtain detailed explicit information at a small scale common to farming practices of earlier times but with considerably more information, enabling them to efficiently manage the land at these finer scales.

This report defines precision agriculture as a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production. Precision agriculture has three components: capture of data at an appropriate scale and frequency, interpretation and analysis of that data, and implementation of a management response at an appropriate scale and time. The most significant impact of precision agriculture is likely to be on how management decisions address spatial and temporal variability in crop production systems. A key difference between conventional management and precision agriculture is the application of modern information technologies to provide, process, and analyze multisource data of high spatial and temporal resolution for decision making and operations in the management of crop production. Advances in the technologies will be an evolutionary process and they will continue to be adapted for agricultural decision making.

Precision agriculture is best considered a suite of technologies rather than a single technology. Farmers whose operations have numerous characteristics—different crops, weather, pest complexes, and marketing arrangements—will undoubtedly use varying components of this suite. Nevertheless, all of these components have the common feature of increasing the information intensity of agriculture. The committee thus singled out this unifying feature, information technology-enhanced management, as the identifying characteristic of precision agriculture, and the report refers to this feature in making generalizations about precision agriculture, not the use of specific types of equipment. The report focuses on technologies for managing crops, but aspects of the report may be extrapolated to other production systems, such as livestock and forestry.

The report also focuses on public policy issues relevant to precision agriculture. Most of these concern research and development of precision agriculture technologies. Many of the technologies at the core of precision agriculture today—satellites, sensors, and geographic information systems (GIS)—are unusual for agriculture in that they were developed outside the traditional agricultural research, development, and dissemination (RD&D) system and were imported from industries not traditionally associated with agriculture. It is anticipated that investments in development and diffusion of precision agriculture by the private sector will continue at a rapid pace. Finding the appropriate role for traditional agricultural R&D institutions vis-à-vis these technologies has thus been a challenge. This report presents some guidelines for determining the appropriate role of public agricultural RD&D institutions and recommends courses of action based on those guidelines.

Other findings center on the implications of precision agriculture for broader social concerns, primarily the structure of agriculture, rural employment, environmental quality, and data ownership. These implications depend on developments that cannot be predicted accurately. The committee identified factors likely to be influential and drew on experience with similar technologies to assess the likely weights of these factors.

A FUNDAMENTAL PARADIGM SHIFT FOR AGRICULTURAL RESEARCH SYSTEMS

Historically, the productivity of U.S. agriculture has been fueled by a research and educational system that was largely funded by the public sector and whose effectiveness is envied around the world. In this unique partnership, research problems and findings were communicated through the Cooperative Extension Service. The U.S. Department of Agriculture (USDA) and land grant university researchers conducted the scientific analyses necessary for continual enhancement of production agriculture's efficiency. New knowledge was created in experimental plots and extrapolated to fit actual farm situations.

Precision agriculture is changing the way in which agricultural research can be accomplished. The generation of massive amounts of data on farms will enable dynamic experimentation that could supersede the use of traditional controlled experimental plots. Information technologies can produce quantitative data that will complement qualitative whole-farm case studies. On-farm research will reflect actual farming practices. Further, the agricultural system may need to evolve so that innovation and learning can exploit both traditional research plot experiments and information captured from actual field operations. Farmers engaged in precision agriculture will likely be transformed from research clients into research partners.

> *Precision agriculture requires new approaches to research that are designed explicitly to improve understanding of the complex interactions between multiple factors affecting crop growth and farm decision making. USDA and land grant universities should give increased priority to such new approaches by reallocating personnel and budgets.*

Understanding the complex interactions among the multiple factors affecting crop growth is the foundation of any attempt to improve management systems. Incorporating information about variability in soils, moisture, nutrients, and pest populations into decision making requires an understanding of crop growth in an environmental context. Traditional plant and soil science research has not been designed to provide this kind of information, however. The current paradigm is that of the controlled experiment, in which one or a few factors are varied while all others are held constant. Such an experimental design corresponds poorly to a real farm context, in which multiple factors vary simultaneously. Such experiments provide little information about how responses to variations in any one factor change as other conditions change. Furthermore, they are frequently designed to yield qualitative results or quantitative estimates of responses to changes in inputs or other variables over a range so limited as to preclude estimation of responses to the range of conditions found in production fields. As a result, standard research results are frequently of little value in designing spatial models intended for improved decision making.

Precision agriculture will necessitate a systems approach to experimental research. In this regard, precision agriculture is similar to the application of systems principles in sustainable agriculture and ecologically-based pest management strategies. What makes precision agriculture different is the capability to capture data on the production practices actually applied in fields and on the results achieved. Moreover, systems principles are needed to improve farm decision making, not for themselves alone. Research approaches from ecology and economics, in which multiple factors vary simultaneously and statistical methods are used to identify the effects of variations in individual variables, are likely to be more productive than traditional approaches. Crop science research for precision agriculture should be designed explicitly to produce results that can be used in economic or statistical decision models by decision makers. This research will also need to be interdisciplinary, drawing on expertise in a range of subject areas such as agronomy, plant science, genetics, soil science, entomology, meteorology, weed science, plant pathology, ecology, and economics.

The potential of precision agriculture is limited by the lack of appropriate measurement and analysis techniques for agronomically important factors. Public sector support is needed for the advancement of data acquisition and analysis methods, including sensing technologies, sampling methods, database systems, and geospatial methods.

A basic premise of precision agriculture is that more and better information can reduce the uncertainty producers face in decision making and the unmeasured variability in agronomic conditions. Measurement can reduce the uncertainty of decision making without changing the biological variability that occurs in crop production. While the use of information is not new to agriculture, the potential exists for a vast increase in the timeliness and amount of information if additional means of data collection and analysis become available. Only a few commercial sensors are available today. Efforts continue by both private companies and the public sector to develop real-time sensors for additional agricultural indexes. Current sampling and analytical techniques are not designed for managing small units or for in-field decision making. For example, nutrient assays that require soil sampling and physical/chemical analyses are slow and costly. Current mapping techniques are limited by a lack of understanding of the geostatistics necessary for displaying spatial variability of crops and soils.

New information technologies will be required to make the more detailed and timely decisions necessary for precision agriculture. Introduction of new sensing techniques will enable the collection of an unprecedented number of soil, crop, pest, and weather observations. Maps created from the data can be used during field operations to make more precise and timely application of inputs. Crop production and monitoring will be improved with development of accurate and cost-effective data acquisition and analytical techniques.

Involvement of both public and private sectors is needed to undertake fundamental research, develop field applications, evaluate the utility of sensing techniques, and—more importantly—answer questions about what information to acquire and at what frequency (i.e., which variables warrant investment in information acquisition and at what levels). Scientific expertise in university and federal laboratories should be focused on determining biological, physical, and chemical principles that may result in improved or expanded sensing techniques. Agencies should recognize the ongoing contributions of industry to precision agriculture sensing and analytical techniques and concentrate their efforts on areas for which there is little incentive for the private sector to invest. Technology transfer mechanisms should be used to promote movement of practical sensing techniques into the marketplace. Collaborative efforts among researchers in the public and private sectors should be focused on sensing techniques that hold potential for accuracy, high spatial resolution, and inexpensive operation.

Multidisciplinary research will be needed to match measurement methods and analytical techniques with crop production questions of interest—to effectively understand and use information about the true variability of measurable parameters within farm fields. Database management and image processing methods are needed to extract useful information from very large data sets. Geostatistical methods must be advanced both to more effectively sample and to more accurately interpolate sparse data subject to instrument and sampling errors. Spatial analysis methods and spatially explicit components in crop models should be evaluated and calibrated under field conditions, and incorporated into GIS to facilitate accurate analysis and inference from collected precision agriculture data.

In the twenty-first century, agricultural professionals using information technologies will play an increasingly important role in crop production and natural resource management. It is imperative that educational institutions modify their curricula and teaching methods to educate and train students and professionals in the interdisciplinary approaches underlying precision agriculture.

Adequately trained professionals will be required to form the bridge between precision agriculture and science and technology. New and emerging technologies such as GIS, the global positioning system, and remote sensing and weather station data will be used in crop models and decision support systems as aids in the farm manager's decision-making process. A broad view of training is needed to ensure the beneficial use of precision agriculture:

- To be successful, prospective employees will need to have the disciplinary depth and analytic skills for understanding spatially variable data. This should be provided by various educational institutions, including the land grant universities and technical colleges.
- Existing professional advisers, including independent consultants, will need continuing education and remote-site learning in precision agriculture technologies because they will be called on to help interpret information for managers who make decisions at the farm level. These professionals may already have valuable field experience that will be enhanced with training on a systems approach to farm management. Technology providers are filling some training gaps. Additional support is needed by state extension personnel and professional societies.
- The professional societies associated with agriculture, biology, earth sciences, and environmental sciences could provide guidance in identifying necessary course work for new professionals and additional training for existing personnel.

THE VALUE OF INFORMATION WILL INTENSIFY WITHIN PRODUCTION AGRICULTURE

Agriculture, with its related supply and marketing activities, is a major component of the U.S. economy. Precision agriculture, if adopted widely, could enhance the viability of this sector of the economy by adding a fundamentally new component of value to agriculture's traditional assets of land, labor, and capital. That new source of value is the enhanced capability to learn from the data and experiences explicitly captured within precision agriculture operations. Production agriculture could experience a change similar to that in several other sectors of the economy over the past decade where more effective application of information technology led to the realization that information, and the ability to learn from operations, is an important economic asset.

The agricultural production and marketing system does not have a tradition of understanding and measuring the value of information from operations or the systems that create that value. In other sectors, shifts in market power between suppliers and customers have occurred in similar settings. The experiences of the agricultural sector do not prepare it well for understanding the implications of these changes, even though they could affect research, public sector involvement, and the achievement of economic and environmental gains.

Precision agriculture will require clarification of intellectual property, data ownership, and data privacy rights. The extension service should play a leadership role in providing education on existing law pertaining to these issues.

Precision agriculture will involve, even require, the acquisition and processing of data by a variety of off-the-farm vendors, including crop consultants; farm cooperatives; seed, fertilizer, chemical, and equipment dealers; aerial and satellite remote sensing companies, and software systems providers. Information technology will generate valuable data not only for the producer but for others in agricultural production and marketing. Protection of a producer's data and its availability to others will influence the effectiveness of precision agriculture.

Intellectual property rights and data privacy protections are evolving areas of judicial and legislative activity. Existing legal precedents and contract forms for protecting a producer's data will need to be adapted for precision agriculture. Producer and industry associations have been developing legal templates and forms for producers to use in asserting ownership over precision agriculture data. It will be important to find a balance between protecting individual privacy and securing benefits to multiple users. Leadership by public agencies, such as the extension service, will be needed to develop legal instruments and language to clarify rights and responsibilities of data use and dissemination to producers, crop consultants, and others involved in the data stream.

Data collected for use at the subfield and field level have additional value for research, testing, evaluation, and marketing when assembled into regional databases. Mechanisms are needed to create and use this value, including data collection and transfer standards; institutions for collecting, managing, or networking data; and policies to facilitate data sharing and access while protecting proprietary interests and confidentiality.

The collection and analysis of georeferenced data from individual farm fields provides an unprecedented opportunity for gaining new insights into the functioning of agricultural systems. Such data sets can provide competitive advantage for private companies and be an invaluable resource for producers and public sector researchers. However, individual farmers may not readily agree to freely contribute their farm's data to a larger pool of data. Commercial companies may not readily release or share data sets they have assembled with universities or the USDA, even though the data might benefit and facilitate research across broader areas. Public agencies, such as the extension service, will be needed to provide leadership in this process by promoting models and templates for data sharing, providing examples of the benefits of sharing and aggregating data, and providing protection for data privacy rights.

One can easily visualize significant benefits from compiling and analyzing data sets generated from precision agriculture. However, care must be taken to ensure the completeness of such data sets so that they will be sufficient to address present-day problems and questions that have yet to be formulated. Because some of these data sources serve more than agricultural purposes (weather, geographic information, and global positioning data), they have their own set of standards. Other data structures (variable-rate technologies, on-the-go sensors, and yield monitors) will be totally focused on agricultural applications and will need to be interfaced with nonagricultural sources. To facilitate this process, standardized formats for data collection, storage, and transfer must be identified. The importance of metadata data standards that define measurement conditions and quality control increases as data from sources outside the farm are used in decision making. Because of the breadth and depth of such data sets, a consortium of public and private sector scientists and practitioners continues to play an invaluable role in formulating, evaluating, and communicating standards.

UNCERTAINTY OF PUBLIC ROLE

The introduction of precision agriculture comes at a particularly interesting time relative to the public sector's role in agriculture. The 1996 Farm Bill and international trade agreements negotiated in the 1990s appear to have accelerated a trend toward diminishing the federal government's role in providing price stability in the marketplace. Conversely, the regulatory influence of government entities regarding environmental and food safety issues appears to be increasing. In recent years, the role of private sector firms in agricultural research and development has increased markedly. As noted earlier, precision agriculture may alter the public sector's role in research and development.

Much of the technology embodied in precision agriculture was developed outside the traditional agricultural research establishment, and it is argued that private sector initiatives will be sufficient to develop precision agriculture to its full potential. However, there continues to be an important public sector role in areas where the private sector cannot completely capture a return on its investment. As noted earlier, the public sector will need to provide fundamental principles for private sector development of sensors and crop models. The exact nature of the public sector's role is likely to evolve as precision agriculture matures and as other forces in the agricultural setting evolve, but these roles deserve careful and ongoing attention.

> *Unbiased, systematic, rigorous evaluations of the economic and environmental benefits and costs of precision agricultural methods are needed. USDA should facilitate and coordinate evaluations conducted through collaborations of public agencies, professional organizations, commercial organizations, and producers.*

Producers require a diverse set of information sources if they are to most accurately and rapidly evaluate the economic opportunities of precision agriculture. Considerable information and advertising are provided by firms supplying the information technology. Although useful, information from these firms will be scrutinized carefully because of the natural commercial interests of these suppliers. Many innovative growers are experimenting with the technologies on their farms, but few producers have the scientific expertise or resources to design and implement a scientific investigation. As an information source, the usual farmer "coffee shop" network cannot account for site-specific differences among farms. Producers considering adopting precision agriculture are, therefore, particularly interested in unbiased, objective assessments of precision agriculture's performance under various conditions and in different regions, summarized to indicate the crops and soil conditions for which precision agriculture is likely to be profitable. Acceptance and support for precision agriculture similarly depends on the extent to which potential environmental benefits and efficiency gains are actually achieved by particular crop systems.

There is a lack of comprehensive data to determine the profitability and environmental benefits of precision agriculture systems. Because precision agriculture is designed to address specific sites in farm fields, evaluations of precision agriculture must be framed in the context of the specific crop and resource conditions on which it is applied and the mix of technologies and practices used. Evaluators should compare precision agriculture systems with conventional uniform management systems, recognizing that precision agriculture enables changes to crop systems beyond variable-rate application of inputs (i.e., soil quality).

Precision agriculture evaluation activities should be undertaken by both the public and private sectors. Organizations in both sectors should work together to avoid possible biases in evaluating efficacy of the technologies.

USDA is in a unique position to facilitate and coordinate evaluation and research activities among federal agencies. USDA, and its affiliated land grant system partners, have the agronomic knowledge necessary to evaluate the effectiveness of specific information technology-based innovations in precision agriculture. Where federal agencies outside agriculture have some basic technological components and expertise necessary to advance precision agriculture, collaboration in that evaluation should be encouraged. Producers and other customers for precision agriculture technologies should be encouraged to search for multiple sources of information when deciding whether to adopt particular components of precision agriculture technology.

Evaluations should be formally conducted using rigorous scientific and statistical methods, ensuring that differences in system performance are statistically significant. System evaluations are appropriate on technologies that are installed, maintained, and operated as specified by the manufacturer. The crops, soils, initial conditions, and geographic areas over which the results are likely to hold should be clearly stated so that results can be appropriately extrapolated to unstudied situations. Detailed reporting of protocols must be included so that experiments can be repeated. Full disclosure of funding sources and of financial interests of researchers, as is currently part of many university reporting systems, will aid users in evaluating research findings.

The methods and purposes of publicly funded data collection activities should be periodically reviewed and adjusted to ensure that data are accessible and useful for precision agriculture, as well as supportive of other public and private purposes. The National Cooperative Soil Survey should revise existing procedures to make more effective use of information technologies, farm-generated data, and new concepts in soil science.

Public sector investment in data collection and management is often driven by obsolete mandates or narrow programmatic purposes. As the ability to collect, manage, and—particularly—share data improves with advances in information technologies and as budgets for public data collection decline, it becomes even more important to gather data that balance specific agency and program requirements with broader purposes. For example, simple modifications in data collecting or processing methods could make data more useful for precision agriculture. USDA has an opportunity to facilitate data activities among agencies for precision agriculture. Under USDA's leadership, agencies should:

- more effectively coordinate data collection activities among agencies,
- use accepted data and metadata data standards,
- periodically review the purposes of data collection (i.e., user needs assessment),
- periodically review methods of data collection, and
- make information gathered with public funds easily accessible at low cost (with appropriate safeguards for the anonymity of any producer-supplied datasets).

The National Cooperative Soil Survey (NCSS), a partnership of the Natural Resources Conservation Service with local and state agencies and land grant institutions, has been generating soils information for several decades. Much of the variability that is managed with precision agriculture methods arises from variability in soil properties. Practitioners report, however, that current soil surveys satisfy few of their soils data requirements. The soils data are not at an appropriate level of detail nor are the indexes required by precision agriculture the same as those provided by soil surveys. Digitizing existing data is not sufficient, either in terms of data resolution or content. Thus, the NCSS process should not be used to collect the detailed information required to support precision agriculture at the subfield level.

NCSS could be useful to precision agriculture by providing technical support but will need to modify its soil taxonomy approach to more effectively characterize soil property variability and soil landscapes. Consultants and producers need some assistance in improving data quality standards and data management methods. Guidance and logistical support on soils data collection and management provided by NCSS could be exchanged for access to soils data useful for other public purposes, such as planning and watershed management. The assembled data sets could not compromise a land manager's proprietary interests; more precise data could be used with agreements that agencies maintain the confidentiality of data at the finest resolution. Similarly, public agencies such as the Natural Resources Conservation Service or U.S. Geological Survey could trade data (i.e., high-resolution digital orthophotographs) for more detailed soils data to incrementally improve the public stock of soils data.

A primary issue for agencies involved in collection of remote sensing data is subsequent processing of raw imagery. Georectification and data volume reduction are needed for most applications of these data. To be useful for precision agriculture, these data may need to be further processed into images depicting crop-relevant conditions, such as greenness or soil moisture. Public and private roles in data management and processing should be balanced to protect public interests while supporting private initiatives.

> *High-speed data connectivity is needed in rural areas to support precision agriculture. Agricultural organizations and agencies should work collaboratively with public agencies and industries to ensure adequate rural connectivity.*

Precision agricultural techniques are data intensive and geographically dispersed. The interrelated network of agricultural service providers and producers will increase the need for data transfer capabilities. The current reliance on manual transport of data is inconvenient, expensive, and prone to data loss. Telephone networks represent the most likely source of electronic communication in rural areas. The Telecommunications Deregulation Act of 1996 allows major telecommunications providers to concentrate their services in the most profitable sectors. In the near term, this could diminish the potential for telecommunication services in rural areas.

Strong federal-state-industry partnerships will be required to meet the national goal to provide high-speed data connectivity to all American schools by 2000. State extension programs should become involved in these partnerships to ensure that American farmsteads have the communications technology necessary for precision agriculture. Agricultural organizations should be aware of both the need for a better rural communication system and the potential for degradation of the current service under the deregulated market.

IMPLICATIONS OF PRECISION AGRICULTURE

A committee objective was to explore what impact the adoption of precision agriculture technologies would have on economic, social, and environmental variables. Because precision agriculture is in early stages of adoption, a rigorous analysis of its impacts and development of conclusions is not feasible. The committee identified four policy issues that should be examined in greater detail when (and if) precision agriculture becomes widely accepted.

Adoption Patterns

It is difficult to generalize about the expected adoption process for precision agriculture, because precision agriculture is a suite of technologies and practices used to improve agricultural decision making rather than a single technology. Producers, consultants, input suppliers, and researchers will use these tools in various combinations. For example, some producers will use Internet linkages to discover marketing opportunities whereas others will implement precision agriculture for in-field decision making. Because agriculture is heterogeneous, precision agriculture will vary across crops, geography, and farming systems. Further, it will be impossible to have a sound understanding of the sector-wide effects of precision agriculture on key variables such as profitability, farm size and structure, rural areas, and the environment unless adequate data are available on the extent and rate of adoption.

Precision agriculture is a convergence of information technologies and agronomic sciences. Evaluation of its diverse innovations will not be consistently favorable nor will the adoption process occur uniformly over time. On the basis of studies of similar innovations, such as irrigation technologies, the greatest long-term potential of precision agriculture may be in geographic areas or in production systems where input costs are high or crops have high value.

Precision agriculture will probably evolve as a combination of services and products. New independent services related to precision agriculture could arise but also are likely to be provided by existing crop consultants and input suppliers. In the latter case, a consultant or supplier would purchase equipment and depreciate the capital costs over many acres providing producers with data collection and management services. Alternatively, producers may choose to establish the hardware and software equipment in their operations. However, it is likely that a combination of services and products will result in which services are needed to customize precision agriculture systems for each producer's operation.

Farm Structure

Adoption of precision agriculture innovations is unlikely to be uniform across farm types and sizes. Production systems include a wide range of operations, some of which are typically performed by the producers and others by the service providers. Even though technically possible, adoption of precision agriculture at the level of each farm unit can be impeded by various factors such as access to capital, management sophistication, and presence of local service providers. Although farm size may make a difference in access to all precision agriculture techniques, all farms will likely have access to some of the techniques in the long term.

Experience with earlier information-intensive agricultural technologies, such as integrated pest management, indicates that in the long term there should be relatively few, if any, systematic differences across farm size in either access to or advantage from precision agriculture implementation. Smaller operations that cannot afford to purchase information technologies may buy the services provided by consultants. However, there is concern that in the short term, smaller-scale farming operations may have less access to consultants than would larger farming operations, and that consultants will be concentrated in areas of higher demand. More direct evidence is needed to determine the potential effect of farm size on diffusion of these technologies.

Numerous economic, social, and technological factors interact to alter the distribution of farm sizes in American agriculture. Factors such as global trade, tax policy, and consumer preferences also contribute to more vertically integrated, coordinated operations. The potential effect of adoption of precision agriculture technologies should be considered in the context of these other factors.

Rural Employment

In general, the capability to integrate and support the hardware and software tools of precision agriculture is currently lacking in rural communities. Therefore, widespread adoption of precision agriculture will depend on economic incentives to enhance the support infrastructure in rural America. Those support needs include human and social capital and an adequate communications base. Human capital needs will likely be met by a combination of service providers located in rural areas and the development of products embodying expert information that can be imported from areas already rich in human capital. Market forces and government policies will determine which, if either, of these approaches dominates.

When effectively and widely used, precision agriculture will be data intensive and will generate those data in remote locations. An effective communication system will be a critical factor in the adoption of these technologies. Additionally, high-speed data connectivity is essential for precision agriculture to attain its full potential.

Environmental Quality

Precision agriculture may simultaneously improve farm profitability and reduce environmental spillover from agriculture. Thus, potential improvements in environmental quality may be an important reason for using precision agriculture technologies. This view is rooted in the sensible belief that agricultural pollution comes from inputs that do not reach their target. Calibrating input usage more precisely should increase the percentage of applied inputs taken up by crops, thereby simultaneously reducing economic waste and emissions into the environment. Field-level agronomic studies show that precision agriculture may permit large reductions in fertilizer and pesticide application rates without sacrificing crop yields.

Limited experience with precision agriculture and more extensive experience with similar technologies, however, suggest that precision agriculture will likely result in less environmental improvement than indicated by field-level agronomic studies. Moreover, some field level studies show that reductions in fertilizer or pesticide applications may not result in reductions in ambient concentrations of chemicals that cause environmental damage, presumably because natural degradation rates change in response to changing application rates. Economic factors may also limit reductions in chemical application rates at the field level and in the aggregate. At the field level, precision agriculture technologies may increase crop response to inputs such as fertilizers or pesticides. For example, technologies that allow producers to change application rates in response to changes in soil moisture, pest infestation levels, or other growing conditions will likely increase marginal fertilizer and pesticide productivity. Similarly, better information about soils may induce farmers to increase their estimates of yield potential. In such cases, use of these inputs is unlikely to be reduced as much as anticipated, and it may even become profitable to increase input application rates. At the regional level, precision agriculture technologies may create incentives for farmers to expand the cultivation of crops that use these inputs relatively more intensively, resulting in higher total emissions of agricultural pollutants even if emissions per unit area fall. Such research should concentrate on broader-scale effects, however, such as impacts at the watershed or ecosystem, rather than field-level effects, and should consider the impacts of economic incentives as well as agronomic considerations.

Some producers may adopt precision agriculture technologies with the expectations that the technologies will generate environmental benefits. However, economic incentives to adopt precision agriculture so as to improve existing environmental quality will exist only in settings where farmers bear at least a share of the costs of agricultural pollution. Although precision agriculture may be a means of effecting reductions in agricultural pollution, it is not a substitute for agricultural pollution control policy.

Because precision agriculture technologies and services are seen as another profit arena for agribusiness (and an entry into agribusiness for other information technology providers), the status quo of capital- and chemical-intensive forms of agriculture will be maintained and in many areas bolstered. Conceptually, precision agriculture could contribute to organic farming and systems commonly referred to as reduced-input agriculture; however, this may not be considered profitable by technology providers. Determination of environmentally sound uses of precision agriculture is an appropriate public sector role.

POTENTIALS FOR PRECISION AGRICULTURE

The committee believes that precision agriculture offers new and emerging technologies to address information needs for management of crop production. Widespread adoption of precision agriculture technologies will constitute a new way to practice agriculture at ever finer spatial and temporal resolutions, offering the potential to be both more economically and environmentally efficient. However, precision agriculture technology is new and largely unproven. Widespread adoption depends on economic gains outstripping the costs of the technology.

Lessons from the adoption of other agricultural and information technologies urge caution in anticipating the growth of precision agriculture use. Widespread adoption of precision agriculture methods will create some changes in farm operations and social institutions that can be anticipated and, where they are negative, mitigated. Many of the important findings in this report deal with the range of public policy responses to precision agriculture's evolution and adoption.

1

Dimensions of Precision Agriculture

The management of agricultural production is undergoing a change, both in philosophy and technology. Until recently, agricultural managers have generally made decisions regarding fields based on average conditions within those fields, with data that was often sparse and qualitative in nature. Soil fertility was determined by compositing soil cores into a single sample that was intended to best describe conditions across a field. Field scouting for crop condition or pest infestations was done at a few locations within the field, and observations often have been more qualitative than quantitative. For the most part, whole fields have been considered to be the basic agricultural production units, and have been managed for the mean condition or, in the case of pest management, managed intensively to overcome variability within that field.

Historically, a desire to improve production efficiency and farm income has stimulated interest in innovative technologies. Advances in technology, as well as other factors such as farm policy have contributed to increases in the size of individual farmsteads and fields within a farmstead. With this larger scale of operation, the potential for the individual to effectively manage variability by observation and experience has declined precipitously. In addition, as individual farm fields increased in size, within-field variability has generally increased. A major feature of today's precision agriculture is that it allows producers to manage previously unmanaged variability as well as the increased variability resulting from increased field size. In other words, precision agriculture will allow several geographic units currently being managed as a single entity (a field) to be addressed as individual decision-making units. Managers will be able to respond to the distinctive agronomic characteristics that exist within the subunits, in contrast to today's approach of addressing the average needs of several units or extreme conditions in parts of the field, such as pest outbreaks in small patches.

The incorporation of information technologies into agricultural production practices began in the mid-1980s and has increased sharply in recent years. While the use of information in agricultural decision making is not new, agriculture is experiencing a vast increase in the amount of information available, and in the timeliness and means by which information can be collected, analyzed, and used to manage inputs and outcomes of agricultural practices. The application of new information technologies in agriculture is known by several terms, including precision agriculture, precision farming, and site-specific management. A variety of definitions have been offered for the concept of integrating information technologies with agronomic practices. Most authors have focused on the ability to obtain data and to vary production inputs on a subfield basis. While this is an important aspect, there are other geographic scales at which information can be obtained and used to facilitate site-specific management. The committee chose to view precision agriculture broadly, adopting the following definition:

> *Precision agriculture is a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production.*

A key difference between conventional management and precision agriculture is the application of modern information technologies to provide, process, and analyze multisource data of high spatial and temporal resolution for decision-making and operations in the management of crop production. Advances in the technologies will be an evolutionary process and they will continue to be adapted for agricultural decision making.

Precision agriculture has three components: capture of data at an appropriate scale, interpretation and analysis of that data, and implementation of a management response at an appropriate scale and time. Each particular manageable factor has its own scale of variability. Area-wide management of insects and weather forecasting for crop management decisions are examples of variables that are managed at a scale larger than the individual field. Other factors like soil fertility and pest distributions can vary significantly at the subfield level and over the growing season. Therefore, it is natural and important to perceive precision agriculture in terms of finer spatial or temporal units of decision making.

PRECISION AGRICULTURE AND AGRICULTURAL MANAGEMENT

Advances in information technology and their application in crop production, which are labeled as precision agriculture in this report, are creating the potential for substantial change in management and decision making in agriculture. The word *potential* in the previous sentence is critically important. The various technologies and practices that will make up tomorrow's precision agriculture are only emerging, being tested and refined, and implemented or rejected today. This process is further enhanced by the dynamic nature of advances in information technology. A capability that is technically or economically unfeasible can become feasible as a result of a technological innovation occurring well outside the arena of agricultural technology development or agricultural research. Thus the process by which precision agriculture is adopted could be fragmented and discontinuous. Therefore, it is impossible to specify the precise dimensions and characteristics of the precision agriculture of the future.

Precision agriculture could materially affect on-farm decision-making processes that depend on implied knowledge gained by observation and experience. While its precise dimensions continue to evolve, the following features characterize most precision agriculture applications in use or under development:

- Data capture tends to be electronic, automated, and relatively inexpensive.
- Data capture can occur more frequently and in more detail.
- Information, either captured as a part of field operations or purchased externally, can be considered separate input into the production operation. (It is also a feature of integrated pest management and sustainable agriculture concepts.)
- Data interpretation and analysis can be more formal and analytical.
- Scientific decision rules are applicable to actual farming operations.
- Implementation of the response can be more timely and more site specific.
- Performance of alternative management systems can be quantitatively evaluated.

The long time lags between input decision making, application of inputs, and observation of yields in crop production systems make it difficult to evaluate decision-making effectiveness. The chance for misinterpreting results is further heightened when inputs and outcomes are observed rather than measured. The difficulty of learning in such settings is not constrained or unique to farmers. Considerable research has documented that human decision making is more likely to suffer bias and misinterpretation when (1) feedback loops are long between the time the decision is made and the outcome occurs and (2) cause/effect linkages are not simple (Einhorn, 1980; Hogarth and Makridakis, 1981). These two characteristics apply to traditional crop production settings.

The uncertainties associated with the rapid evolution of information technologies and the dynamics of the process of adopting precision agriculture represented a significant challenge in the preparation of this report. However, these same uncertainties provided considerable excitement and a sense of mission for the project. Tomorrow's precision agriculture will be significantly affected by actions in the public and private sectors today.

The focus of this committee, therefore, was not on predicting a single future. Rather, members chose to recognize the uncertainties inherent in the future evolution of precision agriculture and to emphasize possible paths and the implications of those paths. Further, the study recommendations define key actions that society can undertake to extend the dimensions of precision agriculture where they are deemed most desirable.

GEOGRAPHIC CONTEXT: SCALES IN THE SPATIAL SPIRAL

Agricultural production systems vary in many ways, including scale of operation, commodities produced, and philosophical approaches to management. Current production systems draw on diverse approaches and knowledge bases. For any approach, information technologies will play an increasingly important role in agricultural production and natural resource management. This impact will be felt directly through the coupling of newly acquired information with recently developed tools for agricultural production, on-demand products and services, and increased access to information and services.

A number of scales characterize crop production systems of today. These scales might be viewed as a continuum ranging from individual plants in a field to plant populations, fields, farmsteads, and regions. Others have used this Lewin-Kolb model of hierarchies as an organizational structure to study complex issues such as pesticide regulation and diversity in agroecosystems (Olson et al., 1995). Consider this continuum in the form of a spatial spiral ascending from the subfield to national geographical levels (Figure 1-1). As we move up the spiral we

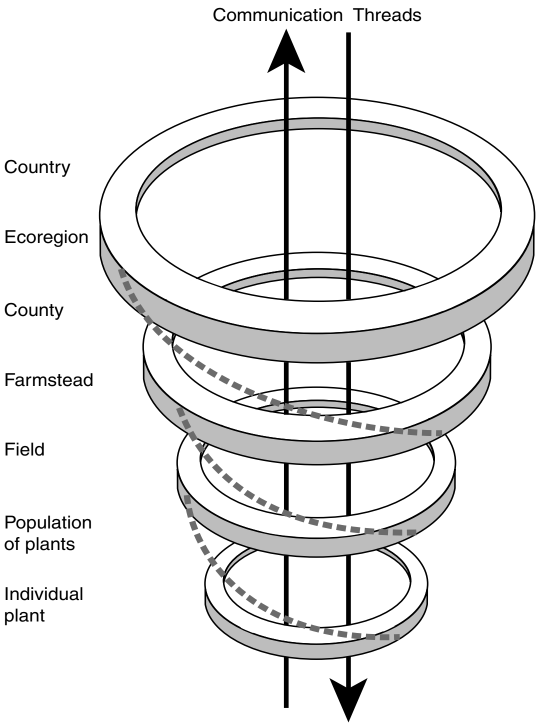


FIGURE 1-1 Scales in a spiral. A number of scales characterize crop production systems of today. In precision agriculture, an unprecedented amount of spatial and temporal data may become available at the individual plant, farm, and regional scales. At each scale various processes will influence crop production. A goal is to determine an optimal scale for data collection and management response. Communication technologies will provide connecting threads up and down the spatial spiral.

move from individual plants to fields and regions. Fresco (1995) underscores the need to relate phenomena or outcomes to processes occurring at both higher and lower level scales. The goal is to determine an optimal scale at which each process is to be studied, one in which variability is minimal. For example, if plant population is dependent upon small-scale variation in soil physical and chemical properties, then varying seeding rates may require information and hardware capable of rate changes every few centimeters. Such information may reside locally in a nearby computer in a farmhouse. At a wider scale, real-time weather information collected from locally placed weather stations may provide irrigation or area-wide pest management information in a timely manner to improve decision making for a field, farmstead, or county.

Communication technologies will provide connecting threads up and down the spatial spiral. Telephone, high-speed digital lines, and wireless communications are needed to link the various levels together. For example, digital data could be collected by an on-the-go yield monitor in a combine, sent via a wireless cellular link to the operator's home computer, and retrieved via a high-speed Internet connection by an agricultural chemical dealer. The dealer may then add the yield data to a nutrient management analysis and send recommended fertilizer application rates for various subfield units back to the farm operator's computer.

Different scales of assessment are being used to investigate aspects of crop-environment systems. Scale can be considered for both information sources and management actions. Depending on the situation, data from different scales may be combined and used to determine management actions at another scale. For example, a producer deciding what crop and variety to plant (field scale) may consider the available forward contracting prices (national or global scale), the availability of custom field operations (farm scale), and a field map of soil water-holding capacity (subfield scale). With precision agriculture methods, such decisions can be made with more objective data. Some of the uncertainty factors can be reduced with the information technologies of precision agriculture, although the extent to which this will be feasible and of value to the grower is not clear.

Information technologies permit the modern producer to obtain detailed spatially explicit information at the scale of entire farms but with information sufficient for efficiently managing the land at the fine scale. Most of the new precision agriculture technologies can be used to disaggregate information—for example, to characterize soil, yield, nutrients, and water variation within fields—as well as to assemble regional information. Perhaps the ultimate disaggregation would be to look at agricultural fields as a collection of individual plants. The extent to which data are disaggregated or reassembled for different spatial units depends on the nature of the management problem and the resolution of the data gathering techniques. Decision makers will need to consider the spatial heterogeneity of the area being managed and the relative value of the information. (A brief review of the impact of information technologies on current management decision processes can be found in Chapter 2.)

Subfield Management

The potential for individually managing small areas, whose size is determined by local characteristics and crop value, is one of the most enticing aspects of precision agriculture. The ability to repeatedly locate a specific site and measure agronomic characteristics provides an opportunity to optimize management throughout the production area. Subdividing a field into small management units may improve both the economic and environmental sustainability of crop production systems.

The earliest advocates of precision agriculture took the approach that management decisions should be based on soil characteristics, assuming that similar soil series could be managed as homogeneous units. Subsequent research showed that for many soils, nearly the same nutrient variability exists within the mapped soil series as among them (Sadler et al., 1995). Even precise management based on variability of the physical and chemical properties within soil types may or may not be sufficient for optimal management of crop production activities.

As producers try to manage smaller areas, the law of limits comes into play more strongly. For any given site, from year to year, the most limiting factors to crop growth can change from nutrient or moisture availability (deficit or excess), to disease or insect pests, to weather factors. In fact, the limiting factor may change within the growing season as the crop matures and its needs change. For improved decision making, managers must be aware of the limiting factors for each subfield unit and be able to modify management at that scale. The determination of the most limiting factors is currently both difficult and expensive, and these costs are considered by decision makers. All of these concerns point to the need for analytical systems and technologies that can determine the important factors and decision-support systems that can use available data.

Some management factors exhibit a relatively small amount of variability. For example, levels of less mobile soil nutrients (i.e., potassium and phosphorus) may exhibit little variation in crop response within some fields that have received heavy fertilizer applications for many years. These crops may be subject to greater variability from other influences—such as weather, nitrogen, diseases, and insects—particularly if the time frame for assessing the performance of a method is short (i.e., a single growing season). Similarly, technologies that work well for one cropping system or biophysical setting may not work in another. Efficacy testing should be done for a variety of settings and systems and over several growing seasons.

Beyond Subfield Management

It is unarguable that an individual grower's precision agriculture data has substantial additional value when combined above the subfield level with similar data from other production operations. Management strategies consistent with our definition of precision agriculture are currently practiced, and new strategies will be developed that address spatial and temporal variability at the scale of the whole field and larger. While this report focuses on subfield level precision agricultural practices, a discussion of two key larger-scale strategies follows.

Data Warehousing

Large amounts of spatially referenced data on individual fields are, or soon will be, generated by yield monitors, real-time and remote sensors, on-the-ground sampling and observation by producers and consultants. This site-specific information will have value for use within individual fields in ways discussed in Chapter 2, but will also have value when combined with data on the same variables collected for nearby fields. Seed, chemical, and machinery agribusiness, among others, are assisting growers in data collection and interpretation. In a number of cases, agribusiness is providing financial assistance so growers will share data with the agribusiness itself. Several companies have promoted a concept of data aggregation which permits growers as well as an agribusiness free access to participant's data. Still others have promoted concepts of data collection in which data could be purchased by third parties. Many growers have expressed opposition to any of their data being shared with others. However, most growers do agree that there is economic value in the learning that results from data sharing and that may increase the likelihood of vertical integration of agricultural operations. Though it is unlikely that a commercial interest will freely share information to which they have purchased rights and made further investments, other groups may see benefits from voluntary sharing. Grower clubs such as Practical Farmers of Iowa have been successful models of farmer-directed research in which land grant or private sector consultants act as facilitators in planning and implementing research trials. The idea is for a number of growers to implement similar practices of interest in their farm operation (i.e., row-spacing, herbicide dose and timing, cultivar selection) in statistically sound on-farm experiments (Stroup et al., 1993). In these clubs, data are openly shared to identify desirable practices in local growing areas. Imagine the same grower clubs now sharing spatially referenced data from experiments where growers agree to apply similar agronomic practices. The potential to create locally derived recommendations from locally collected data is a fascinating prospect. In effect, a version of this vision is in practice today with the private crop consultant. By working with numerous growers, the consultant is afforded the opportunity to observe how diverse recommendations can affect crop fitness, yield, and production efficiency in farming enterprises as small as several acres to those that extend over thousands of acres. Such an approach would require growers to openly share data with fellow producers.

Landscape Analysis

There are opportunities to link management decisions at various levels to improve soil and water quality. The National Research Council's report on Soil and Water Quality (National Research Council, 1993) described the inherent links between farming systems and the landscape. Management practices to improve input use efficiency and reduce erosion can improve the quality of the surrounding watershed. The Committee on Long-Range Soil and Water Conservation recommended use of landscape buffer zones that connect farms and fields, provide widespread protection to waterways, and prevent soil degradation. Focusing on the impact of within-field production practices on adjacent ecosystems changes the unit of analysis to the landscape scale for studies on agricultural nonpoint sources of pollution. Landscape analysis considers effects of farming practices on larger areas than a specific crop field. Coordinating information at various levels could enhance protection of the environment. For instance, tracking production practices across a watershed could be useful in targeting areas with soil and water quality problems (National Research Council, 1993).

Regional Management

The appropriate scale for management will vary according to the factor most limiting to productivity. Manageable factors such as soil fertility or weed competition may vary significantly at a subfield level, thus input use can be based on subfield units. However, there may be more utility in managing other factors at a field or farm level. For example, because insects migrate over areas larger than a field, monitoring their movements on a regional scale may be appropriate. Acquiring other regional data also may improve the accuracy of the decision-making process.

Information provided to producers that is regional in nature, can have a direct impact on local management decisions. Evapotranspiration is typically monitored using networks of weather stations that cover large areas. Regional data also interacts with more site-specific data that producers can incorporate into their decision making. The California Irrigation Management Information System (CIMIS) is a computerized crop weather information system that producers can access by modem or the Internet to obtain hourly and daily weather conditions. Producers combine regional evapotranspiration data and local soil- and crop-specific coefficients for their fields to determine the daily water use and water demand of their farms (see Box 1-1).

It is unclear how to appropriately use data collected at different spatial scales together to help make better decisions. There are significant statistical and modeling issues to be addressed. Precision agriculture will greatly increase the amount and perhaps the availability of geographic data snapshots for many cropping fields, which will increase the demand for these analytical techniques.

BOX 1-1
California Irrigation Management Information System

California has more than 10 years of experience operating the California Irrigation Management Information System (CIMIS), a computerized crop weather information system that growers can access by modem or the Internet to obtain hourly and daily weather conditions. The first five weather stations went on-line for research from May 30th to June 7th, 1982. Stations number one and two were installed in Fresno County, numbers three and four were installed in Santa Cruz County, and number five was installed in Kern County. By the end of 1982, 27 stations were operating. After three years of research and testing, CIMIS was made available to the general public on July 1, 1985 (Eching et al., 1995; Eching and Moellenberndt, in press). Ninety CIMIS weather stations are now in use throughout California, with information generated from a number of sensors at each site which are directly linked to a computer. The stations are ground referenced with latitude, longitude, and elevation readings.

CIMIS is an excellent example of current technology that provides information on crop water requirements. Growers use the CIMIS weather system and soil- and crop-specific coefficients for their fields to determine the daily water use and water demand of their farms. Vendors may combine these data with data from other sources and provide specialty products tailored to weather information needs for specific crops.

CIMIS is operated by the State Department of Water Resources in cooperation with the University of California, local water districts, and various agencies. The information gathered at each site includes maximum, minimum, and average air temperatures and relative humidity readings. Data are also collected on precipitation, evapotranspiration, dew point, vapor pressure, average soil temperature, wind speed and run, and solar radiation.

Evapotranspiration data represent water loss from soil evaporation and crop transpiration and referenced to water use for a healthy grass; values must be multiplied by a crop coefficient developed for various growth stages. Evapotranspiration data are used as an aid in irrigation scheduling. Growers and consultants use the information to maintain crop water-use budgets by comparing how much water has been applied to a

BOX 1-1 Continued

field with how much water the crop is using each day. Water use can be projected and water can then be ordered from the local irrigation district for delivery to the field before the crop depletes the available water in the soil. The crop water-use information does not take into account the application efficiency of various irrigation systems, however, nor does it calculate the leaching requirement for salt-affected soils.

Information from CIMIS weather stations used for assessing crop water requirements is widely disseminated through various means of communication. Farmers in the San Joaquin Valley can listen to the radio for daily early morning agricultural reports that include evapotranspiration values and crop coefficients for numerous crops. The information is supplied to the radio station by agricultural consultants as a service to the industry.

A CIMIS report is part of a weekly newspaper (*Ag Alert*) published by the California Farm Bureau Federation in Sacramento. The weekly reference evapotranspiration information is shown in a histogram, along with comparison data from the corresponding week of the previous year and an average year. Growers with computers and modems can access daily and weekly evapotranspiration data directly from CIMIS, through several sites via the Internet, or from the Agri-Tech Information Network maintained at California State University-Fresno. Growers can call a contact at the University of California-Davis for crop coefficient information.

Growers and businesses that subscribe to the Data Transmission Network (DTN) satellite information service on-line can access daily and monthly CIMIS weather data for all 90 operating stations in the state. The computer hardware and satellite dish are owned by the company providing the service, so there is no need for individuals to invest in expensive computer equipment.

All levels of producers, regardless of farm size, have many ways to access the CIMIS weather information. Crop water-use data are available for the current season and from historical databases, some of which go back to 1982. The major efforts made by the California agricultural industry in disseminating CIMIS evapotranspiration data should be used as an example of how to saturate a production region with important information which has been shown to aid decision making.

BOX 1-2
The Crop Consultant of Tomorrow

It's early Friday morning in late June. John pours his first cup of coffee, turns on his computer, and reviews the list of fields he will visit today. With the click of his mouse, he opens a client list and downloads weed, insect, and nutrient application maps created by his farmer clients as they cultivated their corn fields late yesterday afternoon. At the same time, satellite images of crop greenness are downloaded for 12 fields. These images complement others collected earlier this year and in preceding years. When John reads these images into his geographic information system, he extracts information about pest risk with several decision tools for pest management and nutrient use efficiency. John transfers the information from his kitchen computer to the lap-top in his pickup truck. Before heading out the door, he reviews the maps of each of his fields to determine how to best use his three crop scouts that day. On-the-go sensing supplemented by smart or directed sampling is a very important part of John's management efficiency plan and has resulted in timely crop management decisions which would otherwise have been missed. After visiting each of the 12 fields, John sits with his farmer client and reviews summary maps of variability in crop moisture, canopy closure, and pest pressure. John knows the best decisions are made when their collective wisdom—his and the farmer's—is aided by the new types of information. John knows his clients have diverse opinions and management philosophies. Some want little help from advanced information technologies whereas others value the added information.

ENABLING TECHNOLOGIES

A fascinating aspect of precision agriculture is that a single technology is not being undertaken to improve a single practice. Instead, across the crop-production sector of the United States, precision agriculture is emerging as the convergence of several technologies with application to several management practices. However, every technology is not necessarily required or applicable for every practice on all crops, and development and enhancement of several of the potentially relevant basic technologies are being driven by forces outside of the agricultural sector. Thus it is difficult to develop a generally accepted view of the dimensions of precision agriculture. Every area of information technology—microelectronics, sensors, computers, telecommunications—is in an evolutionary process of continuous improvement. As these introductions take place, some products will become economically feasible for agricultural applications. In Box 1-2, describing a vision of tomorrow's crop consultant is considered. According to

BOX 1-2 Continued

Later that summer, John and his co-workers turn their attention to calibrating yield monitors on his clients' combines. Data logging devices in the combine cab are simultaneously tested for accuracy and ease of operation. In this way, John's clients are able to collect yield maps while logging spatially referenced data and notes about weed patches, insect damage, and other concerns in the field. These new maps are transmitted through wireless communication to John's office. After harvest is completed, John visits one of his clients for postharvest evaluation of the growing season. The field maps, data from other Internet sources (i.e., weather data), and the cumulative collective wisdom make for a constructive discussion. Because of John's information-intensive approach, several management successes and problems become evident that may otherwise have gone undetected. For example, one cultivar significantly outperformed two others grown in the same and adjacent fields. They also note that weed problems were less severe with this cultivar. By detecting and treating the weeds during harvest the farmers can skip the preemergence treatment the following year. Their discussion continues. A new concept emerges from John's business: the value of shared information. A subset of his 23 clients agree to share insights gained from this new information-intensive approach to farming. Later in the autumn, a group of 11 growers meet to discuss their successes and challenges. Through their discussion they learn that certain cultivars consistently outperformed others and some were less tolerant to herbicides. Several producers comment that the information helps them to plan better schedules for harvesting and for use of shared machinery.

this vision, while many precision agriculture technologies are available for use, individual producers will assemble those technologies that address given management issues in their particular production systems. The following discussion provides a broad overview of the precision agriculture technologies and practices that are or soon will be available. For more detailed information, the reader may want to access additional literature sources such as Pierce and Sadler (1997); Robert et al. (1995); and Robert et al. (1996).

Research and development of many technologies used in precision agriculture have occurred outside the agricultural community. In the past century, of course, other developments such as the internal combustion engine, electrical power, telephone, and weather satellites produced outside of agriculture have been introduced to the agriculture sector. Precision agriculture technologies such as the global positioning system (GPS), geographic information systems (GIS), and remote sensing have their core constituencies outside agriculture. Crop and soil sensors operating on farm machinery, variable-rate fertilizer applicators, and yield mapping systems are technologies that have been developed within the agriculture sector by private industry. Other economic sectors have supported the research and development of some of these technologies, which is a financial benefit to agriculture. Precision agriculture involves the integration of these information technologies with agronomic knowledge.

Georeferenced Information

Georeferencing refers to relationships among data based on their geographic locations. This spatial emphasis implies a new way of looking at agricultural information and site variability. Although spatial variability has always been recognized, data comparisons have often been made without specific information on site location, yielding qualitative results. Comparisons of data detailed from specific locations which are obtained from specifications by using various precision agriculture methods will be one of the important new techniques that can improve farm management.

The value of a database for precision agriculture practices increases when the data layers are spatially referenced to each other. Co-registration of data will become critically important as management units get smaller and as more precise field data (location precision from submeter to a few centimeters) become available. It is expected that data referenced to physical location will allow different types of information to be compared and quantitatively analyzed at multiple locations. For example, physical properties of soil core samples collected from a field could be compared with other spatially explicit data available for decision making, such as characteristics of the mapped soil unit and topography, yield monitor data, and irrigation, nutrient, or pesticide applications recorded during variable-rate applications.

Global Positioning System

The Global Positioning System (GPS) is a system of satellites emitting electronic signals that can be received by mobile field instruments sensitive to the transmitting frequency. Positioning is achieved through the use of simultaneously received satellite transmissions from four or more satellites above the horizon. With a constellation of 24 satellites, any location on earth can have four or more satellites in view for 24 hours each day. By referencing the satellite's exact location and the time the signal takes to travel between the transmitter and the receiver, the location of the receiver can be determined by triangulation.

Use of the GPS receiver allows latitude and longitude coordinate information to be associated with data obtained from a specific site on the field. The GPS can also be used to provide navigational guidance, enabling a producer to revisit a spot in the field and check the efficacy of management decisions. The GPS is an essential field component for most mapping-based precision agriculture and other measurements of field characteristics that would be used to determine product application maps. Even for operations with real-time sensing and control of inputs, GPS positioning will be valuable. If the sensed parameters and application rates are recorded and georeferenced, these data can be included in the management database. Adoption of GPS and other spatial referencing technologies will have a widespread impact on data collection and analysis.

The positions provided by GPS receivers currently are not sufficiently accurate for dynamic real-time precision agriculture uses. Various errors, including those introduced by the U.S. Department of Defense (DOD) for security purposes (selective availability), contribute to the inaccuracy (National Research Council, 1995c). The present system under selective availability has an accuracy of about 100 meters. However, technical solutions are available to improve the positioning accuracy. A technique known as differential correction is widely used to remove the effects of the error sources. Position error is determined by using one or more fixed base stations to compare the calculated position with the station's known location. By combining the error values with the GPS signals, position accuracy can be improved to about 2 meters or less. The augmented positioning is known as differentially corrected GPS (DGPS). These corrections can be made either by software in a postprocessing operation or by hardware for real-time positioning. Most precision agriculture operations require the availability of real-time positioning, necessitating the transmission of the differential correction signals to the GPS receivers in the field. Differential correction procedures are cumbersome, prone to signal loss, or expensive depending on the method used to generate and transmit the differential correction signal.

Commercial applications of georeferencing systems will grow dramatically over the next decade, both in agriculture and other industries. Some commercial businesses offer real-time differential correction services in space-based or land-based networks to their subscribers. Many of these providers are focused on non-agricultural industries and so do not adequately cover rural areas with their signals. The U.S. government provides differential correction signals through Coast Guard beacon signals, but access to these signals is limited to areas near navigable waterways (coastline and rivers). The Russian government continues to operate its GLObal Navigation Satellite System (GLONASS) which could augment basic capabilities of GPS. Since GPS and GLONASS use different time standards and coordinate systems, these differences will need to be corrected by combined receivers (National Research Council, 1995c). Receivers that use techniques such as carrier phase tracking (Real Time Kinematic) offer higher accuracy, but have higher costs.

Several other factors can limit the application of GPS in precision agriculture. Time delays for updating signals may limit the utility of DGPS for on-the-go sensing, particularly for high-speed operations such as aerial applications. System inaccuracies make data collected along a crop row appear to suddenly shift, creating map displays that do not match actual travel paths. Signals can be severely degraded by moderately inclement weather conditions, foliage and electromagnetic radiation. Position data are not always available at the one-second frequency that is expected, so data gaps are created (data dropouts). Increasing the accuracy and reliability of GPS will increase its acceptance by producers and its utility for geographic referencing in precision agriculture applications.

Geographic Information Systems and Mapping Software

Digital geographic data that can be stored, analyzed, integrated, and displayed in different representations, form the core of precision agriculture. The software packages used to handle such data, Geographic Information Systems (GIS), are available with a wide range of capabilities and costs, but all are able to graphically display georeferenced data. Although a single data layer (i.e., yield data) can be mapped with the use of less-sophisticated software, more complex relationships (i.e., temporal patterns or multivariate comparisons) are best performed with full-function GIS packages. The data layers derived from combinations of raw data can generate information about spatial variability among factors in crop production. It is expected that adequately co-registered data will be quantitatively analyzed through the use of geostatistical and other procedures.

Available GIS software ranges from simple map display systems to fully functioning systems capable of analyzing and integrating complex spatial databases. Some data can be stored as polygons within which the attributes (i.e., soil types) are considered to be homogeneous. Data can also be stored in a uniform array of grid cells or pixels with homogeneous attributes, which is the format used for remote sensing images and U.S. Geological Survey digital elevation maps. Most fully functioning GIS programs today can be converted between these formats, which has made it easier to combine data from different sources.

Among the most important roles for GIS are the database functions for farm record keeping and for comparing management decisions, yields, pest activity, groundwater quality, and other concerns related to past and current practices. GIS can store farm records of inputs and outputs in a spatial array. For instance, data on crop rotation, tillage, nutrient and pesticide applications, yield, soil type, roads, terraces, or drainage tiles can be stored in a GIS. Data layers can be derived from digital orthophotography. GIS will enhance other components of precision agriculture such as yield monitoring and farm-based research (i.e., crop modeling and efficacy testing) as well as provide better record keeping for producers. Such software has the potential to integrate all types of precision agriculture information, interface with other decision support tools, and output (printed or electronic maps) that can be used in precision applications. A key to realizing the promise of a dynamic GIS will be development of connections between the relational database and the decision support system. A disadvantage of the current generation of geographic information systems is the complexity of the software and the steep learning curve involved in using and interpreting spatial data in a valid and robust way. The limitation with some commercial software is that spatial relationships among data layers often cannot be rigorously quantified; only visual relationships can be made. This situation is rapidly changing as several vendors are developing fully functional GIS programs intended for use on PCs. This should lead to software and hardware systems that are more user friendly and less expensive. In addition, firms are emerging in the marketplace that can provide GIS services or software tools to growers and field consultants. There is an urgent need to make fully functional GIS easier for nonspecialists to learn and use in order to transfer this technology to the agricultural community.

GIS can be used with a spatially distributed process model as the basis for subsequent decisions on precision agricultural practices such as variable-rate applications. Several classes of models should be considered as part of the suite of tools for precision agriculture.

Yield Mapping Systems

Yield mapping systems record the relative spatial distribution of yield while the crop is being harvested. These systems collect georeferenced data on crop yield and characteristics such as moisture content. The resulting maps can dramatically illustrate the areas of yield variability from either natural processes or agricultural practices. Because yield is a primary factor in most management decisions, precise yield maps are desired to confirm spatial treatment decisions.

Yield monitors have been developed for only a few crops, primarily cereal grains. Reliable monitors for vegetables, fruits, cotton, and other high-value crops are currently under development but are not yet widely available. Yield is more difficult to monitor for fruit or vegetable crops that are harvested manually or repeatedly. Use of machine-mounted yield monitors currently is limited to crops that are mechanically harvested in a single pass, such as potatoes, sugar beets, and processing tomatoes. Other techniques such as remote sensing may provide alternatives to yield monitors. The use of precision agriculture techniques in non-grain crops may be limited by the lack of appropriate yield monitoring systems.

Since 1992, grain yield mapping has been done by using mass flow and moisture sensors to determine grain mass and using GPS receivers to record position. Yield monitors measure wet grain flow, grain moisture, and area harvested to determine moisture-corrected yield per acre. Because the mass-flow measurements are made in the combine's clean-grain conveying system, there is a shift in harvester position between the point where the grain is actually cut and the location of the machine where it is measured. This shift results in dynamic inaccuracies that currently cannot be completely removed by subsequent data processing. Field totals (with recommended calibrations) are considered more accurate than are small subfield yield measurements. Although yield monitors have been promoted widely, further yield monitor refinements are needed to improve their accuracy for precision agriculture applications.

Variable-Rate Technologies

Precision agriculture was pioneered by domestic U.S. industry, beginning with the conception and implementation of Variable-Rate Technology (VRT). VRT applicators spatially vary the application rates of agricultural inputs such as seed, fertilizer, and crop protection chemicals. VRT systems include specialized controllers that vary specific material flow rates, even multiple product rates simultaneously, in response to a desired change in the local application rate (on-the-go). VRT systems can be designed in different ways depending on the products to be applied and the source of the information utilized to specify local rates.

Present commercial VRT systems are either:

(1) Map-based, requiring a GPS/DGPS georeferenced location system and a command unit that stores an application plan of the desired application rate for each location within the field, or

(2) Sensor-based, which does not require a georeferenced location system, but includes a dynamic command unit that specifies application through real-time analysis of soil and/or crop sensor measurements, for each location within the field as it is encountered.

Historically, VRT methods were introduced by industry during the mid-1980s. Dry nitrogen, phosphorus, and potassium fertilizer application rates were simultaneously varied on commercial spreader applicators based on a predetermined map strategy (developed from earlier data collection such as photographically derived soil maps or grid sampling). Farmer-owned machinery has been equipped with VRT for fertilizer applications requiring a standard liquid blend. In this case, product application rates are based on soil properties measured in real-time. Limited use has been made of sensor-based VRT by commercial applicators to date. Herbicide application responsive to soil organic matter (Gaultney and Shonk, 1988) is the singular exception (McGrath et al., 1990).

Commercially available sensors employed for VRT include those responsive to organic matter, cation exchange capacity (CEC), topsoil depth, soil moisture, soil nitrates, and crop spectral reflectance. Proponents of real-time sensor-based VRT application have observed that soil and crop conditions are more variable than measurements obtained from current map based methodologies. Optimal crop management results are not expected from current GPS/DGPS/GIS methodologies which are limited to one sample and one control change per second. The application of nitrogen fertilizer in response to measurements of side-dress soil nitrates and CEC (Colburn, 1991) and the application of nitrogen fertilizer in response to wheat nitrogen status as detected by spectral reflectance (Stone et al., 1996) are two examples of on-the-go sensing based VRT which do not rely on GPS/DGPS or GIS systems.

Real-time sensors offer some benefits over map-based techniques for VRT. Real-time sensing is a direct and continuous measure of the attribute of interest thus allowing the user to reduce the amount of unsampled area in a given application. In map-based applications, maps are based on a limited number of samples thus creating the potential for errors in estimating conditions between sample points. An additional uncertainty is associated with GIS due to the temporal disconnection that occurs when samples are mapped at some point in time and a response is made at some later time. In the case of dynamic variables such as soil nitrogen content or pest distributions, significant change in the amount and distribution of the attribute of interest can take place during that time (Sudduth et al., 1997; Wollenhaupt et al., 1997).

Sensor based VRT is employed on Midwest farm equipment to:

- Vary anhydrous ammonia application in response to soil type variations.
- Vary planting population in response to soil CEC and topsoil depth variations.
- Vary herbicide rates in response to soil organic matter variations.
- Vary starter fertilizer in response to soil CEC variance.
- Vary nitrogen fertilizer at side-dress time in response to soil CEC, topsoil depth, and soil nitrate levels.

Map-based VRT is employed in the high-volume commercial (contracted) application of phosphorus and potassium fertilizers and lime using high-flotation applicators. Map-based variable-rate application systems for farm tractor use are widely available for liquid fertilizers, anhydrous ammonia, herbicides, and seeds. Map-based VRT controls for water and fertilizer are also available for center pivot irrigation systems.

Because of the additional capital and maintenance expense for high volume, pneumatic or liquid material control systems in high-flotation VRT, application costs are higher than for conventional floater application technology. Floater VRT application of granular fertilizers is typically \$2 to \$3 per acre higher than non-VRT applications.

Costs for upgrading tractor-mounted application controllers to add VRT capability are often nominal. Upgrading a controller to allow for automated adjustment of application rates is a minor technical departure, representing only a software/hardware interface. However, the producer must also have a computer that manages GIS data and sends rate change commands to the controller, and a GPS/DGPS receiver. Such a system can be assembled by more technologically sophisticated producers. In other cases, a VRT system may be more complex and costly, incorporating multiple chemical injection hardware and GIS/GPS/DGPS systems as an integrated, dealer-installed unit. Regardless of the type of VRT system utilized by a grower, implementation of a map-based VRT system requires full consideration of all related costs, including data acquisition, the GIS and GPS/DGPS to create and execute application maps, and the often time-consuming intellectual capital investment in learning how to successfully use all components of the technology.

The cost of obtaining and interpreting soil test information on which to base floater or tractor-based application rates is a limiting factor in the site specificity of map-based VRT. Soil samples normally are acquired at a rate of one sample per 2.5 acres to reduce costs for collection and analysis. In an Illinois test, fertilizer requirements based on 2 grid sizes were compared to uniform application rates. With a grid size of 0.156 acre, recommended fertilizer rates decreased dramatically resulting in a fertilizer savings of $18.00 per acre compared to $0.25 per acre savings with a 2.5 acre sized grid. The cost to collect the samples on the more detailed grid, however, far exceeded any savings in fertilizer costs (*Illinois Agri-News, 1996*). One key to improving the efficacy of map-based VRT is the development of additional cost-saving, higher sampling density sensor methodologies.

Groundbased Sensors

Basic research is needed to investigate soil and crop processes applicable to development of ground-based sensing systems. Sensors offer the opportunity to automate collection of soil, crop, and pest data at a level of intensity not economically feasible with manual sampling and laboratory methods. Fields are highly heterogeneous. Increased sampling will result in accurate characterization of within-field variability. Improvements to VRT and crop modeling are expected to advance rapidly with a higher spatial density of measured soil and crop parameters. Sensors are needed that are fast, efficient, and can assess factors important to crop production.

Moran et al. (1996) concluded that the information from ground-based sensors is needed for soil organic matter, soil moisture, cation exchange capacity, nitrate nitrogen, compaction, soil texture, salinity level, weed detection, and crop residue coverage. These parameters as well as soil pH, and availability of phosphorus and potassium cannot be ascertained by remote-sensing technology. Moreover, the use of real-time ground-based sensors provides the grower control over timing of data acquisition not possible with satellite or aircraft sensing techniques.

Sensors have been developed or are under way to measure soil and crop conditions including soil organic matter, soil moisture content, electrical conductivity, soil nutrient level, and crop and weed reflectance (Sudduth et al., 1997). Continuous, real-time electrochemical soil chemical constituent sensors are currently available for nitrate measurement and are dedicated to specific application in corn side-dress applications. A real-time acoustic soil texture sensor and a real-time soil compaction tester are also under development at Purdue University (Liu et al., 1993; Morgan and Ess, 1996).

Some important real-time indexes may be determined by their relationships to other variables rather than by direct determination. Soil conductivity is appropriate for concurrent real-time assays of salinity, soil moisture, organic matter, cation exchange capacity, soil type and soil texture. Recently, this work was extended to non-saline soil methods in combination with electrochemical constituent sensing which separates components of direct contact conductivity (Colburn, 1997). Conductivity component analysis is employed for georeferenced data gathering and analysis by several commercial companies as well as for VRT in midwest crops. Apparent soil conductivity using electromagnetic methods is an indicator of clay content, depth to claypan, soil water content, hydraulic characteristics, productivity (Kitchen et al., 1996), and as a promising substitute for yield monitoring (Jaynes et al., 1995).

For immobile constituents (i.e., phosphorus and potassium), industry has not yet chosen to introduce real-time sensors. In some cases, phosphorus and potassium levels in the corn belt states where VRT was first used, are very high, and field availability has been found to exceed producer needs for the current crop year and the near future. In other regions, such as western states, lower availability of immobile nutrients is common. For these nutrients, discontinuous nutrient sensor mapping methods have the potential for gathering and analyzing soil samples in separate field operations. Three systems are under development by government and academia which automatically extract and analyze soil samples for phosphorus, potassium, and nitrates (Adsett and Zoerb, 1991; Birrell, 1995; Morgan and Ess, 1996).

There exists the potential for a vast increase in the timeliness and amount of information if additional means of data collection and analysis become available. Sensors will play an important role in supporting technology for precise applications of nutrients, pesticides, and other inputs. Only a few commercial sensors are available today. Efforts continue by both private companies and the public sector to develop real-time sensors for additional agricultural indexes. Basic research in the sensors arena is fundamental to an improved understanding of the variations in site-specific crop production in a wide variety of regional production systems.

Remote Sensing

Remote sensing—the acquisition of information from remote locations such as an airplane or satellite—is a potentially important source of data for precision agriculture. In the long term, remote sensing could provide numerous forms of information, both spatially and temporally. However, improvements are needed in the analytical products and delivery systems if remote sensing is to meet its promise for precision agriculture.

For more than 30 years remote sensing has been envisioned as a valuable source of information for crop management. The pioneering research of Colwell (1956) showed that infrared aerial photography could be used to detect loss of vigor of wheat and other small grains resulting from disease. Although much research and development was directed at large-area crop inventory applications of satellite data in the 1970s (MacDonald and Hall, 1980), much less attention

BOX 1-3
Remote Sensing Vegetation Indexes

One of the earliest digital remote sensing analysis procedures developed to identify and enhance the vegetation contribution in an image was the vegetation index (VI), a ratio created by dividing the red by the near-infrared spectral bands (Tucker, 1979). The basis of this relationship is the strong absorption (low reflectance) of red light by chlorophyll and low absorption (high reflectance) in the near-infrared by green leaves. A form of this ratio, in digital and map formats, is one of the principal data products that will be provided to producers for crop assessment. Dense green vegetation produces a high ratio, while soil, plant litter, and geologic minerals have low ratio values, thus yielding a maximum contrast (Baret and Guyot, 1991; Huete et al., 1994; Verstraete and Pinty, 1996; Verstraete et al., 1996).

A number of related indexes have been developed that minimize the effects of atmospheric and/or soil variation. The Normalized Difference Vegetation Index (NDVI), the ratio of the difference between the red and near-infrared bands divided by their sum, is the most widely used VI (Huete and Tucker, 1991; Kaufman and Tanre, 1992). Although, these indexes correlate to various plant parameters linked to the leaf area, it has been hard to determine precisely what plant property is being sensed (Baret and Guyot, 1991; Myneni et al., 1995; Pinty et al., 1993). The ratios correlate most closely with the fraction of absorbed incident photosynthetically active radiation, and for this reason the indexes can be inputs to models for estimating evapotranspiration and crop growth (Asrar et al., 1984; Myneni and Williams, 1994; Sellers, 1985). Although many other band combinations and analyses could provide important additional information for agriculture, these VIs will be the most widely used because they are easy to produce and closely associated with particular crop processes.

has been directed at crop management applications. Satellite data have not had spatial resolution, temporal frequency, and delivery times sufficient for the needs of production agriculture. In addition, supporting technologies and infrastructure have not been available. Nevertheless, the understanding of crop spectral and radiometric relationships gained from past research is relevant to crop management applications (Bauer, 1985).

Jackson (1984) described the potential for remote sensing in crop management, and stressed that it is critical to provide frequent coverage, rapid data delivery, spatial resolution of 5 to 20 meters, and integration with agronomic and meteorological data into expert systems. These points were reiterated by Moran et al. (1997) in a recent review of the potential of remote sensing to acquire information for identifying and analyzing site-soil spatial and temporal variability within fields.

In the past 10 years there have been rapid advances in acquiring and processing multispectral imagery with multispectral video by using digital cameras from aircraft. This approach has the flexibility of aerial photography acquisition and the advantage of digital multispectral imagery (Moran et al., 1996; Pearson et al., 1994). Although most planning and effort are going into the development of satellite systems, aircraft-acquired imagery may continue to be needed when extremely high resolution imagery is required. Aircraft platforms also provide an opportunity for developing and testing new sensors (i.e., thermal infrared and hyperspectral sensors) for future satellite systems.

A sequence of remotely sensed images over time can provide information about crop growth and the spatial variation within fields. Detailed spatially distributed multitemporal information, in visual form, is not readily obtainable from conventional crop management systems or from site-specific crop management methods. Remotely sensed images (i.e., color infrared aerial photographs or multispectral images acquired from satellites or airplanes) show spatial and spectral variation resulting from soil and crop characteristics. These images show the state or condition of fields when the images were acquired. One of the most useful aspects of remote sensing is its ability to generate images showing the spatial variation in fields caused by natural and cultural factors. This information is not limited by sampling interval or geostatistical interpolations (Moran et al., 1997). Images acquired at different times during a season can be used to determine changes such as growth rates and condition. These data, in turn, can be compared with data from previous years and may be helpful in predicting yield.

Commercial interest is growing in the potential of remote sensing to contribute to site-specific crop management, particularly as precision agriculture techniques are being developed and the possibility of routine, frequent acquisition of remote sensing data by satellites seems likely. Several earth-observing satellites are scheduled for launch over the next decade by governments and private industries. By 2005, 40 or more land observation satellites are expected be available (Stoney, 1996). Many of these satellites will acquire imagery with spatial resolutions ranging from 1-3 meters for panchromatic images to 3-15 meters for multispectral imagery. Others will have resolutions of 10-30 meters but with additional spectral bands, including thermal infrared on LANDSAT-7. Still other systems will collect radar data at varying resolutions. These sensors have promise for many types of measurements beyond identifying crop type, including monitoring crop stresses and condition, soil properties, and moisture. A major research challenge is the development of robust image analysis methods for agriculture, and a major educational need is training satellite data providers to meet agriculture needs.

BOX 1-4
Contemporary Remote Sensing Technology

The technologies that can contribute to site-specific crop management—remote sensing, the global positioning system, yield monitors and mapping, geographic information systems, variable-rate application technology, computers, and electronic communication—are currently converging. Rapid growth in precision agriculture is stimulating renewed interest in developing remote sensing, especially from satellites, for crop management applications. Imagery acquired from continuously orbiting satellites operated by commercial companies will enhance the possible applications and utility of remote sensing, and farmers will not have to contend with the challenges of collecting photographs. Fritz (1996) suggests that despite high development costs, satellite systems will be cost competitive with aerial imaging systems. He indicates that per unit of coverage, satellite imagery may be only one-half the cost of aerial imaging.

The changes in U.S. policy resulting from the 1992 Land Remote Sensing Policy Act and the 1994 Presidential Directive on LANDSAT Remote Sensing Strategy specifically encourage commercial system development and operation and have led to several companies developing plans to launch satellite systems in 1997 through 1999. The new imaging satellites will acquire panchromatic (1- to 3-meter spatial resolution) and multispectral (4- to 15-meter resolution) imagery over swaths of 6 to 30 kilometers. At least two companies are targeting agriculture and precision farming as either the primary application or as a major target of their planned marketing and sales efforts.

Remote sensing products could play an important role in site-specific crop management, and there is also excellent market potential for the acquisition, processing, and delivery of remote sensing information. Perhaps no other application of remote sensing requires data so often over such large geographic areas. However, infrastructure to meet this requirement is not currently in place. Widespread application and successful adoption of remote sensing data products are not likely until such an infrastructure is developed; cadres of people who understand the relationships between crop-soil properties and remote sensing are especially important. Similarly, more information and study on integration and use of spatial information in crop management is needed as well as opportunities for training in the use of spatial information. It will be very important for systems and data products to be based on crop producer needs, and for provisions to be made for farmers and others to develop an understanding of remote sensing.

Crop Production Modeling

A broad range of spatially explicit crop response models is needed to evaluate the efficacy of precision agriculture methods and provide the basis for precise recommendations. Many models for predicting how crops respond to climate, nutrients, water, light, and other conditions already exist, yet most of these do not include a spatial component appropriate to precision agriculture applications (Sadler and Russell, 1997). GIS can provide the means to run the model continuously across an extensive area using data that reflect continually varying conditions. Time series and other temporal analyses can aid in predicting final crop yield. Current models may be extended to account for spatial effects, such as edge effects along field boundaries. In the ecological and biometeorological literature, however, several spatially explicit models have been developed to predict hourly, daily, and annual rates of evapotranspiration and photosynthesis, and several spatially distributed hydrologic models predict surface and subsurface flows. Mesoscale climate models can resolve cells as small as 5 to 10 kilometers for predicting weather conditions.

Pests are not dispersed evenly throughout the environment. To the extent that the factors influencing their spatial distribution are understood, their dispersion and potential for damage can be modeled. GIS can be used for spatially variable data for these factors. As with crop response models, a distinct pest model can be run continuously across a landscape, using GIS to input data to the model and display results (loosely coupled model), or a spatially explicit model can be created within the GIS software (tightly coupled model). GIS can provide the basis for multiscalar effects, for example, incorporating results of a regional pest pressure model into a system for generating within-field recommendations based on locally variable conditions.

A crop growth model could be used as a decision aid for determining different yields based on varying plant populations, which could help a producer decide when to plant or replant areas within a field based on plant population data and risk factors for various soil types. Having to make a decision to replant a field that is in a questionable condition is perhaps the hardest decision a producer faces. Any information to aid such decisions and reduce risk would be valuable.

In many crop production areas, landscape factors can cause dramatic variations in yield. Landscape elements affect many properties relevant to plant growth, including soil texture, soil organic matter, and temperature. Landscape morphology affects soil moisture available to crops by its influence on drainage and catchment area. Soil surveys typically do not have sufficient resolution to capture this variability in enough detail to support precision recommendations; even field-based sampling on a regular grid may miss relevant soil-landscape features. Stratifying sampling density on the basis of landscape features may be more cost effective and informative than a simple grid. GIS allow users to create and manage digital elevation or digital terrain models created by photogrammetric methods (analysis of stereo pairs of aerial photographs) with new techniques using interoferometric radar or by continuous three-dimensional coordinate measurements with in-field equipment. Precise recommendations can be made to the extent that the relationships are understood between soil properties and surface morphology (i.e., slope, slope length, aspect, curvature, landscape position, catchment area, and drainage) derived from digital elevation or digital terrain models.

Crop models do not offer a panacea for problem solving; they are limited in their ability to simulate various parts of a biological system. Most of the crop and pest models available or developed to date were not designed to be used for managing spatial and temporal variation. It is not clear whether a predictive model, an explanatory model, or a hybrid approach will be more appropriate for precision agriculture. Alternatively, data mining and other techniques may be used to extract valuable information from large amounts of stored data. However, crop modeling is currently an important tool for gaining a theoretical understanding of a crop production system.

Decision Support Systems

Decision support systems (DSS) are used in agriculture for tactical, strategic, and policy-level decision support. Because producers are continually faced with making tactical decisions, such tools are becoming increasingly useful on the farm. However, few DSS are in general use by agricultural producers today, in part due to difficulty in use and limited information provided—from their point of view. They have been used to aid in decisions that are complicated by large amounts of information and data. A simple conceptual diagram of a DSS is shown in Figure 1-2 (Petersen et al., 1993). Data collected by a consultant, obtained through a weather forecasting service, or acquired through a sensing operation are analyzed and linked with appropriate decision rules that identify actions to assist in producer decision making.

DSS rules are not developed to make a single recommendation but rather to provide decision makers with choices; decision support systems should be seen as sources of valuable tactical information. As is the case for crop modeling and current management recommendations, DSS have been developed for whole fields, and subfield variation has been largely ignored. Although subfield tactical decisions have been practiced by producers for many years (i.e., rouging, spot-spraying or rope-wicking residual weeds, or spot-treating chinch bugs in sorghum), most management practices are implemented for whole fields.

The relationship between the scale of an operation and the resolution and variability of sample data used in a DSS is important. To demonstrate this point, consider the appropriateness of using DSS in two sites with widely differing characteristics. The variation in the assessed attribute used in the DSS is high at one site and low at the other. The DSS may be adequate for whole-field decisions at the site with low variability but not appropriate for the site with high variability.

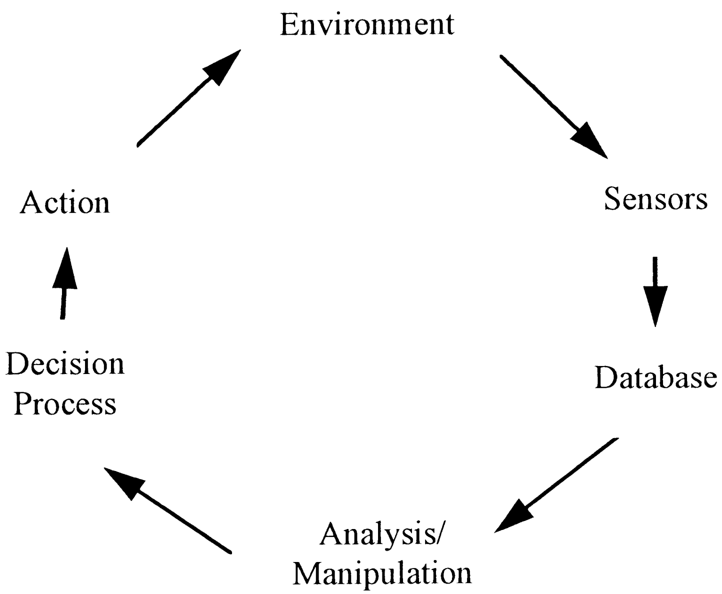


FIGURE 1-2 Conceptual diagram of a decision support system. Tracing the steps in the figure, information can be viewed as flowing from the environment via instrumented or human sensors as data to a database. The information as data is analyzed and manipulated for storage or transmission to a user as part of a decision process. The information processed for a decision results in an action to be executed within the environment. After the action is carried out, the environment is again monitored to begin a new cycle of information flow. Thus, information flows to and from the environment in an endless loop that begins with sensing and ends with action. A DSS integrates expert knowledge, management models, and timely data to assist producers with daily operational and long-range strategic decisions. SOURCE: Petersen et al., 1993. Reprinted with permission; copyright 1993, Agronomy Society of America, Crop Science Society of America, and Soil Science Society of America.

The site with high variability may require a DSS in which other attributes are assessed or the whole field is subdivided to overcome the variation. Assessing the relationship between attribute variation and DSS performance has been largely ignored in relation to pest management and only superficially addressed regarding soil fertility.

Similarly, decision support systems do not address the problem of spatial heterogeneity. This is true for weed management DSS such as HERB, WeedSOFT, and PC-Plant Protection, and for insect and disease management programs; irrigation and crop selection programs are all whole-field based. Researchers recently combined weed management DSS with spatial weed infestation maps to determine the value of spatial information in pest management. In these simulations, pest density at individual locations in fields was used for the infestation level input to the DSS. Lindquist et al. (in press) found that a treatment map based on spatial information (800 observations) was a great improvement over use of the mean field population. The simulation indicated that, on average, herbicide use would be reduced by 30 percent to 40 percent with such an approach. Christensen et al. (1996) also found herbicide reductions of 30 percent to 40 percent when they mapped weed populations in several cereal grains in Denmark. In each case spatial data were used to run an economic-threshold-based DSS.

Although such simulations show that subfield management could lead to significant changes in management practices, numerous questions remain unanswered. First, the issue of risk of improper decisions is a real concern to consultants and producers. DSS have only recently begun to be used for many large acreage crops. Their slow adoption has partly resulted from concern over risk of nonperformance. Consultants are providing a service to a client and are concerned that the client be pleased with the outcome of their service, and the producer is concerned about the real agronomic impact of uncontrolled pests and the social implications of infested fields. Another concern is that the long-term effect of spatial management on infestation level and distribution is largely unknown. Seed production by uncontrolled plants and egg or cyst production by insects and nematodes may result in infestations growing or in spatial orientations changing in ways that make GIS maps less valuable. Such concerns require studies to assess these longer-term impacts on precision agriculture.

There is also the question of the extent to which a knowledge base exists for subfield decisions. For example, relatively little is known about the suitability of crop cultivars for specific soil types or cultivar-fertility-pesticide interactions. Little is known about the interactions between agronomic practices and their environment at the subfield scale. A solid knowledge base will become more important as a foundation for more information-intensive practices. Additionally, as the complexity of databases in DSS grows, the inputs needed to initiate these applications will also grow. For example, two years ago, the University of Nebraska released a weed management DSS that required little information on soil type. In the most recent release, the user can determine the potential risk to ground and surface water contamination from pesticide use, but the user must be familiar with the specific soil type in that field. Also program developers will be challenged to make these decision aids easy to use. In the example, county soil maps are being incorporated in the new version of WeedSOFT; the user will find the field on the county map and click on the location and the DSS will do the rest.

To develop the needed database, researchers will need to approach parameterization used to aid decision making in a new way. Rather than restricting data collection to a handful of research station field trials, researchers will have to find a way to use producers' fields as laboratories. Harnessing spatially referenced data collected on individual farmsteads makes it possible to set parameters for data sets within localized areas. Such an approach would allow DSS to incorporate local parameters, which has not been possible due to the cost of parameterization and of programming expertise. It is likely that future development and maintenance of decision support systems will be accomplished through land grant, Agricultural Research Service, consultant, producer, and other information service provider consortia.

LOOKING TO TOMORROW

Information technologies have the potential to provide considerable amounts of useful information for decision making in precision agriculture. A suite of tools will be used to assess and manage agronomic factors important to crop production. For these new tools to function properly, however, they will need to be user friendly for producers and consultants. Information technologies will produce enormous data sets on crops and their interactions with their environment. The challenge remains as to how to convert these data into useful suggestions to aid in the decision-making process for the producer.

2

A New Way to Practice Agriculture

Modern U.S. production systems have evolved to unprecedented levels of production efficiency. These advances have resulted from germ plasm improvement, use of synthetic fertilizers and pesticides, and use of advanced agricultural machinery. These production inputs have resulted in greater efficiency despite the fact that detailed management data regarding the particular crops was generally unavailable.

The availability of new kinds of information about production fields, farmsteads, products, and markets opens the door to new ways of practicing agriculture. Information technologies offer an unparalleled ability to characterize the nature and extent of variation occurring in agricultural fields and to develop optimized management strategies for these conditions. At the field and subfield scale, information about the spatial heterogeneity of site characteristics makes it possible to manage the variation rather than attempting to overcome the variation with sufficiently high uniform rates of agricultural inputs. Because of the complex interactions of factors affecting agricultural production, uniform and spatially variable management will result in different inputs and outputs.

CHANGES IN FARM MANAGEMENT RESEARCH

Precision agriculture changes a farm manager's philosophy, because focus of attention changes from average field conditions to the variation of those conditions. The research methods that have contributed to today's production efficiency may not be the most appropriate for the future. Agricultural research has focused mainly on identifying robust strategies such as input use recommendations or farming practices that can be generalized and applied across a diverse set of envi-

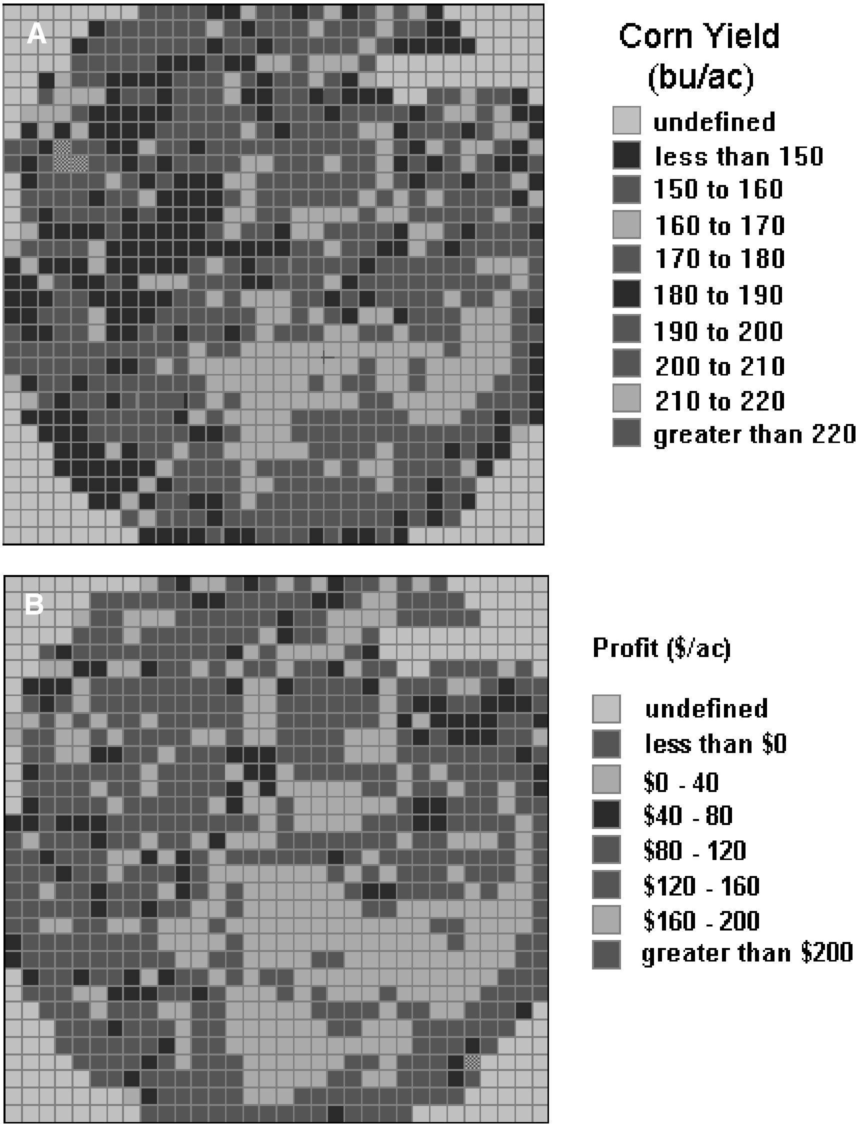


FIGURE 2-1 Crop yield and profit maps. A. Raw yield as measured on average over 25 × 25 meter cells. B. Profit variability within the field. Profit for each cell is calculated using the yield for that cell and production cost estimates for irrigated corn in North Texas. Conventional management was used over the entire field. The images above were collected from an irrigated corn field in the panhandle of Texas. The yield variability is extreme, compared to other fields in the area. However, it does document the yield and profit variability that can be found in the producer's fields. SOURCE: Maps developed by Stephen Searcy, Texas A&M University.

BOX 2-1
Linking Crops, Information Technology, and Decision Making

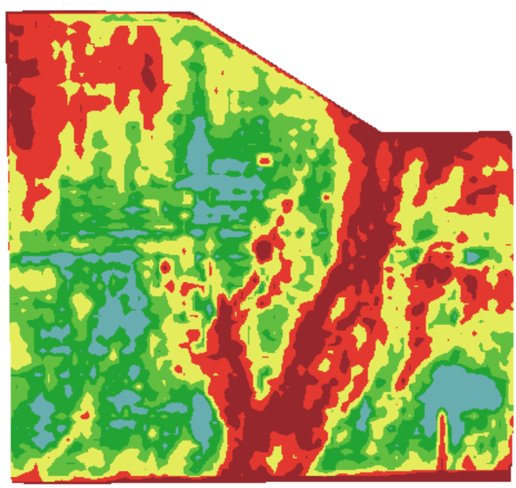
INTEGRATING PRODUCTION AND MARKETING DECISIONS

In the future, producers may use crop status data and predictive crop growth models to make more precise input and marketing decisions. Producers would like to monitor crop growth to more accurately determine crop irrigation, pesticide application, and harvesting schedules. Crop assessments have the potential to increase accuracy of yield estimates in advance of harvest. More precise harvest date and yield information could be useful at producer cooling facilities, processing plants, and in the marketplace. Processors want to optimize production and maintain efficiency by controlling the flow of raw commodities entering their plants. Many grocery stores need to arrange purchases of produce three weeks in advance of harvest and release advertisements prior to the harvest date. More accurate information on crop yields and harvest dates is important in markets where a consistent supply of commodities is necessary to meet consumer demand. It is likely that increased crop status information will impact decision making not only in a producer's operation, but throughout the food and delivery system.

VEGETATIVE GROWTH TO FRUIT DEVELOPMENT

By monitoring trends in vegetative growth, a producer may more accurately match production inputs to crop needs. Observed shifts in crop

Computer enhanced vegetation map of a cantaloupe field using aerial imaging technology. SOURCE: Data acquired by RESOURCE21 for Fordel, Inc., Mendota, California.



BOX 2-1 Continued

growth patterns may provide important clues to critical plant physiological changes. In the vegetative stage of plant growth, foliage acts as a sink for carbohydrates. As a plant shifts from vegetative to reproductive growth, plant resources are allocated to fruit development. Crops have been studied in some production areas to determine timing of fruit development. For instance, cotton shifts toward foliar senescence and crop maturity six weeks after initiation of first flower. The shift in carbohydrate allocation of cotton helps growers determine the last dates for irrigation and application of defoliation pesticides. After fruit development begins, the cotton plant is sensitive to overwatering; additional water could stimulate a surge of vegetative growth that would interfere with cotton boll maturation. Producers have observed that cantaloupe changes from vegetative to fruit growth three and a half weeks after bloom stage. A more accurate prediction of this shift would enable melon growers to schedule irrigation and harvesting schedules more precisely.

MONITORING CHANGES IN CROP GROWTH

Remote sensing images acquired over the growing season allow a producer to monitor crop condition and to compare performance among field sites having different cover densities. Development of crop growth

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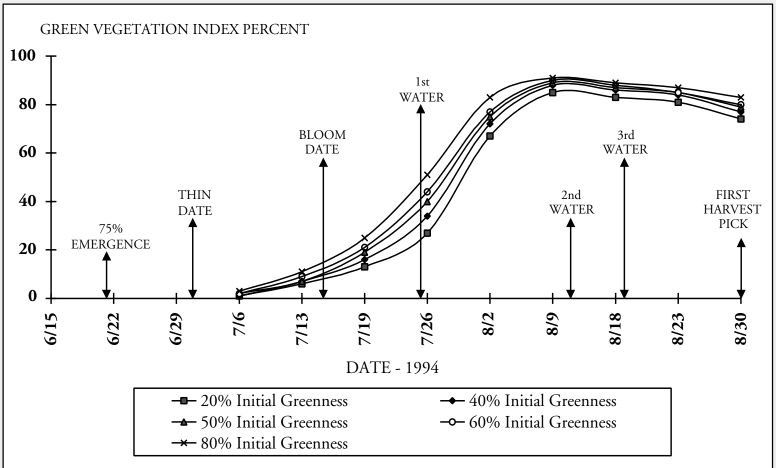

Changes in crop growth, open pollinated cantaloupe. SOURCE: Data processed by Jack Paris, California State University, Fresno, GeoInformation Technology Center; Enhanced by John LeBoeuf, Fordel, Inc.

BOX 2-1 Continued

graphs from remotely sensed vegetation indexes has the potential to better inform growers of the approaching harvest date. Within the field, relative differences in the vegetation index can show whether a crop is developing uniformly at any one time or over the growing season. The aerial image shown is a computer enhanced green vegetation map of a 140-acre cantaloupe field. Ten meter resolution aerial images of the field have been acquired eight times over the summer. Data collected from sites with varying levels of crop growth have been extracted from the images to show the pattern of their development (see graphs Changes in Crop Growth). The graphs illustrate how seasonal progression in crop canopy growth can be tracked for five sites that initially are at different growth performance levels (i.e., 20 percent initial greenness). Changes in the growth rates of each site are seen clearly as are changes in the relative ranking late in the season of sites at 80 percent and 60 percent initial greenness. The crop relative growth rate declines when the growth shifts to fruit production. Superimposed on the crop development graphs are key dates showing the relationship between crop condition and management decisions. Seasonal changes in plant cover and biomass can be linked to predictions of future crop growth, harvest timing, and yield estimates. When these kinds of data are used in a crop production model it can assist in farm management decisions. This capability will be important in irrigated agriculture as producers could manipulate water inputs or fertilizers to advance or slow down crop maturity. The ability to follow changes in crop development for specific field locations is an emerging area of precision agriculture.

ronments. Precision agriculture strategies attempt to adjust field practices to accommodate known variability of important factors. As practiced today, precision agriculture is primarily based on a few parameters, such as soil nutrients or weed maps. Understanding the impact of multivariate interactions is a challenge to both producers, consultants, and scientists. The amount and complexity of available information has increased at a phenomenal rate. Growers will have access to large databases, but the ability to extract useful information will have to be developed. Agriculturists may find themselves uncertain about what information to use and how it can add value to production systems.

Systems Approach

Crops are integrators of the biophysical environment within a field. Crops express their genetic potential and reaction to local soil, pest, and climatic conditions through the quantity and quality of harvested product. Interactions occurring among these agronomic factors affect crop performance; for instance, weather conditions favoring growth of an insect vector can lead to outbreaks of viral diseases, resulting in damaged crops. A systems approach to agronomic management considers multiple interactions occurring in an agroecosystem (National Research Council, 1989, 1996b). Manipulating agroecosystems to achieve greater productivity depends on an understanding of the relationships among agronomic factors. The potential for generating large, detailed data sets presents a challenge for agricultural scientists who are developing tools to further the understanding of those interactions and their effects on yield. Agricultural scientists can use data sets generated under experimental conditions, as well as those generated by producers in attempting to understand the interactions in cropping systems. The adoption of precision agricultural management is most likely to occur for those factors and interactions for which there is enough understanding to accurately predict the outcomes and economic value of actions to manipulate the crop in its agroecosystem.

Mapping spatial yield patterns is a logical step in visualizing field variability. However, a yield measurement in itself cannot explain the cause of variation. Information is more valuable when causal relationships can be determined between various data sets describing a field. Yield maps can be superimposed on maps of other data collected from the same location. The analysis of these data layers with a GIS and other analysis tools may reveal spatial relationships among agronomic components contributing to yield variation (Skotnikov and Robert, 1996).

Spatial and Temporal Variation

The most significant impact of precision agriculture on crop production systems is likely to be on how management decisions are made and on the time-space scales that are addressed, not on actual production practices. Precision agriculture techniques may increase efficiency of input use by allowing the producer to manage the crop on both a spatial and temporal basis with prescriptive rather than prophylactic treatments. The management of a crop production system involves many decisions, all of which are interrelated and ultimately affect profit. Crop production is subject to uncertainty due both to stochastic processes (primarily weather) and to unmeasured variability in agronomic conditions (i.e., soil fertility). Precision management tools may improve decisions related to site conditions, thereby reducing this aspect of uncertainty in the management system. However, the performance of precision agriculture depends on the interaction between site conditions and stochastic factors. Stochastic factors such as weather often have a greater impact on yield variability than variations in soil productivity. For example, a study comparing variable-rate and uniform application of superphosphate on narrow leafed lupine (Cook et al., 1996) found that variable-rate application based on nutrient response curves estimated using data from a single year performed poorly because the estimated nutrient response function did not take variability in weather conditions into account adequately. Other studies have similarly shown low correlation between yield and applied fertilizer when weather conditions and other important factors are not included in nutrient response modeling (Huggins and Alderfer, 1995). If subfield management is to be successful, it must be based on techniques that encompass the simultaneous effects of the most important factors influencing yield, rather than individual factors taken in isolation. For example, successful variable-rate application strategies will likely be based on nutrient response curves that incorporate soil characteristics, weather conditions, and other factors in addition to applied fertilizer.

The ability to respond to changing production conditions is likely to be as important as understanding variability in beginning-of-the-season production conditions (i.e., in soil productivity). Farmers make judgments on input use conditional on likely yields for a field given anticipated weather conditions. This balance between anticipated income and expenditure on inputs is subject to considerable uncertainty. Precision agriculture techniques that allow the producer to manage initially for a lower yield goal and still respond to seasons in which yield potential is greater than normal could substantially ameliorate the effects of that uncertainty. Such an ability to respond to temporal variability would be particularly desirable for handling weather-related risk. For non-irrigated production areas, perhaps the greatest threat to crop production is lack of sufficient moisture to mature the crop. Low soil moisture often causes farm managers to opt for lower initial chemical and fertilizer application rates and thus forego additional crop production should weather conditions turn out more favorable than anticipated. Similar situations occur when the potential for leaching in light sandy soils limits the amount of nitrogen that can be applied in a single application (Booltink et al., 1996).

Precision management systems can be envisioned that could respond to the yield potential of the crop as it varies within the growing season. This more reactive approach to spatially and temporally variable conditions will depend on the ability to economically assess the need for and delivery of production inputs. Crop status data and predictive models that could accurately estimate yield several weeks or months before harvest could improve marketing decisions. A current example of this capability is the use of cotton growth modeling. Cotton phenological development assessments and historical weather data have been successfully used to predict lint yield during the growing season (Landivar and Hickey, 1997; Plant et al., 1997). An indeterminate crop such as cotton lends itself to in-season management, as the plant will put on fruit that will never result in mature lint. Early knowledge of yield potential could affect financial decision making related to inputs (whether to apply crop protection chemicals) and marketing (adjustments of forward contracts). While cotton growth modeling has been done on a whole-field basis, its predictive capability may be improved with the intensive data sets that result when using subfield management (Landivar and

Searcy, 1997). Producers face many factors that can be managed or will affect management decisions. The complete realization of precision agriculture's potential may depend on development of predictive crop models that can vary and co-vary the manageable factors on a specific farmstead. It is unclear whether such an approach will rely on detailed mechanistic models, models based on a wealth of data generated for a given farmstead, or a hybrid of these two approaches.

MANAGEMENT FACTORS

The management factors in a precision agriculture system are essentially the same as those in a conventional crop production system. Producers can control some of these factors and can only react to others. Factors such as nutrient management have been emphasized in the development of precision agriculture whereas others, such as pest management, have received relatively little attention. Management factors can be subdivided into two groups: those that can be managed with today's technologies and those for which new management methods are promising but require further development. However, because precision agriculture methods are still developing, all factors will likely experience advancements and improvements.

Precision agriculture is based on the availability of intensive data about important agronomic indexes. The process of obtaining these data has a cost and, at least for some factors, the greater the data requirements, the greater the cost. As a result, producers and their advisors must decide how detailed the required data should be. The practicality of the data often depends on how long the information has value in management decisions. Indexes such as soil type and topography have long-term usefulness. The investment in obtaining this information will have returns for many growing seasons. Factors such as nutrient availability (except nitrogen), soil-borne pathogens, and perennial weed infestations may exhibit intermediate usefulness because they change slowly. Available soil moisture, nitrogen availability, and insect pressure are examples of short-term dynamic indexes. The accuracy of the information about any of these factors degrades over time and may be thought of as having a half-life. Cost-benefit analysis could be used in precision agriculture by considering the half-life of the information, the potential returns from its use, and the cost of obtaining and analyzing it. However, the half-life of agronomic indexes can only be estimated.

Methods of adding value to data sets also have potential, and are in need of study. For example, spatial data on soil variation could be used to regulate fertilizer requirements, but also may be useful in regulation of herbicide rate and for directed sampling of pest distributions (Fleischer et al., 1997; Johnson et al., 1997). Recent studies have shown that targeting of sample sites based on other known characteristics of the field (typically topology and soil type changes) can result in more accurate maps, often with fewer samples (Hollands, 1996; Wang et al., 1995).

A precision agriculture approach to crop management requires producers to consider information about production units in the same manner as production inputs such as fertilizer or irrigation. As the technologies for measurement of important agronomic indexes improve, producers may have to evaluate precision management for all aspects of production systems. The following sections attempt to briefly address the potential for precision management strategies for factors that impact crop production. Each section deserves a detailed examination, but the intent here is to highlight possibilities, while leaving the in-depth examination to others.

Crop Genetics

Crop productivity depends on the genetic makeup of the plant variety and the response of the variety to its environment. Varieties are selected for particular genetic traits (i.e., drought tolerance, resistance to diseases and insects, and yield). In a precision agriculture scenario, producers try to match crop variety and populations with various conditions that exist in a field. The introduction and maintenance of transgenic varieties requires sophisticated management techniques. For example, the use of Bt-enhanced seed varieties (cultivars engineered to contain *Bacillus thuringiensis,* a bacterium that produces a protein toxic for insect pests) requires the planting of nontransgenic varieties in refuge areas to avoid the development of resistance. The requirements for refuge areas vary with the intended management practices, and precision agriculture techniques may predict the optimum location for each variety.

Similar potential exists for the use of herbicide-resistant varieties. If there is a yield penalty associated with the varieties containing the herbicide-resistance gene, the producer may wish to plant that variety only where weed problems exist. Variable-rate technology planters can change the variety being planted in each portion of the field. However, if resistant and non-resistant varieties are mixed in the same field, the planting sites for each would have to be recorded and used in any subsequent herbicide applications in order to ensure that susceptible plants are not sprayed. Changing varieties to manage for drought-prone soils has also been proposed.

Plant Population

Knowing when to change the plant population density for optimum yield in fields with known variability would benefit a producer and could be done by varying the seeding rate on a planter or grain drill. Preliminary data indicate that a positive net return can be achieved by varying plant population according to depth of topsoil (Barnhisel et al., 1996). If a producer expected fair-to-poor conditions for germination and emergence of seeds on productive soils, the seeding rate could be increased. Competition from weed pressure may be reduced by increasing the seeding rate at planting (Mortensen et al., in press). Increasing the seeding rate in small-grain crops in California can help control Johnson grass and smart weed. Plant population data could also be used to check on the effectiveness of precision planters that drop seeds at a set spacing up the row, which is an important manageable factor when expensive hybrid seed is used. Improved knowledge of field conditions and pest pressure can help a producer make planting decisions.

Although seeding rates can be adjusted at planting, many factors can affect the plants throughout the season. Varying seeding rates may not necessarily result in an expected plant population distribution. Knowing the actual plant population at harvest time is important in interpreting yield maps and for management decisions made throughout the growing season. Technology currently under development for corn in the Midwest will measure variability of a plant population and plant spacing (Birrell and Sudduth, 1995; Easton, 1996; Plattner and Hummel, 1996). Information gathered across a field will generate a data layer that can be compared with yield maps, desired seeding rates, or weed maps. These devices are still in the developmental stage but illustrate the potential for using sensing techniques to gather useful information as a part of normal field operations such as cultivation or harvesting.

Soil Variability

Soils vary significantly as a result of regional geological origins and past and present cultural practices. At the highest level of resolution, soil physical, biological, and chemical properties vary vertically, horizontally, with treatment, and with time. For example, variable distributions of soil nutrients in fields may result from improperly adjusted mechanical application equipment (Bashford et al., 1996; Olieslagers et al., 1995). In other cases, past practices, such as an old feedlot, can generate local pockets of higher organic matter producing healthier plants than surrounding areas. Thus, natural variability patterns and management practices need to be considered in assessments of soil spatial variability.

Soil layers that restrict rooting depth are a major concern in many areas. Electromagnetic induction techniques have been used to assess the presence of and depth to claypan layers (Doolittle et al., 1994). Limited work on assessing soil compaction has indicated a potential profitable return to site-specific tillage operations instead of whole-field subsoiling (Fulton et al., 1996). Soil physical, chemical, and biological properties have dramatic effects on crop production. However, only a few commercially available sensors can assess these properties in the field. Practitioners are limited to sampling and laboratory analysis for determination of in-field variability, which is costly and time consuming. The number of commercially available sensors will be a limiting factor for precision agriculture in the immediate future.

FIGURE 2-2 Soil and crop variability observed in remote sensing. This image was acquired over fields in the Sacramento Valleys near Davis, California by a NASA airborne sensor on August 20, 1992. The area has diverse crops from fruit and nut orchards, tomatoes, corn, alfalfa, and safflower growing on deep loam soils. At this time many of the summer crops have been harvested and soil variation within and between soil units is evident. Despite the low spatial resolution needed for many precision agriculture applications (about 20 m by 20 m, or 400 m^2), relative to new spaceborne sensors that can provide 1-5 m resolution, the connection between some soil patterns and apparent crop growth differences is evident in the fields. Non-uniform growth conditions within fields are common. SOURCE: Data acquired by NASA Advanced Visible Infrared Imaging Spectrometer (AVIRIS) and processed by University of California, Davis Center for Spatial Analysis and Remote Sensing (CSTARS).

Soil Fertility

The concept of using information about variability to manage specific sites in a field is not new. Farmers of ancient times were keen observers of crop performance and recognized benefits from spreading different amounts of manure and liming materials on different kinds of soils (Kellogg, 1957). In the 1620s, colonists observed site-specific fertilizer practices of Indian farmers who placed fish directly at the roots of each corn plant. In 1929, researchers Bauer and Linsley suggested marking a field in 3-foot pace intervals in the north-south and east-west directions to determine field position for variable application of limestone materials (Goering, 1993). Today's information technologies have the potential to generate more sophisticated assessments and responses to within-field heterogeneity and variation in soil fertility.

Uniformity trials have been used to study soil heterogeneity by simply planting a crop that was uniformly managed throughout the growing season. The field was divided into small segments and crop yield was measured on each segment. Crop yield variability among segments was the measure of varying levels of soil fertility in the field. Crop yields obtained from a uniformity trial were plotted on a map, and field segments having similar yields were connected by smooth lines. These yield maps were interpreted as soil fertility contour maps. LeClerg et al. (1962) made two general conclusions from these early uniformity trials:

- Soil fertility variations are not distributed randomly but are to some degree systematic; that is, contiguous field segments are more likely to be alike than are segments separated by some distance.
- Soil fertility is seldom distributed so systematically that it can be described by a mathematical formula.

A common strategy in soil fertility management is to match fertilizer inputs with crop needs. The goals of this mass balance approach are to increase nutrient uptake efficiency and minimize fertilizer losses. Fertilizer rate recommendations for immobile nutrients (i.e., phosphorus, potassium, and zinc) are based almost entirely on soil test levels calibrated for a specific crop, soil type, and climate. Nitrogen fertilizer rates are based on estimates of yield potential (average or spatial) with corrections or credits for nitrogen in soil profile, legume, manure, and soil organic matter sources. Recently, producers have been encouraged to adjust timing of fertilizer applications to reduce environmental risks. For example, nitrogen losses due to leaching can be reduced by minimizing the time between application and plant uptake (Killorn et al., 1995). Conventional approaches to soil testing based on averages are inadequate for characterizing temporal and spatial variation of soil properties.

The most widely used precision agriculture technique is probably the management of soil nutrients and pH. Precision management of soil nutrients can increase profit in two ways. The first is improved crediting of residual nutrients

BOX 2-2
Site-Specific Forestry Management

Modern forestry practices require extensive harvest planning to maximize or optimize harvesting while maintaining yields from forests over many decades. Forest management today must consider forest ascetics and scenic vistas, historic and archeological sites, competing uses for recreation, grazing, and other extractive uses like harvesting for mushrooms, medicinal plants, ornamentals, and mining of mineral deposits.

Many forestry companies have adopted the use of models within a GIS to aid in site-specific management of forest resources. The economic value of forest products is sufficiently high to justify extensive use of site-specific technologies.

Management plans include decisions about modes of logging, such as by helicopter, tower, line, or chain, which depend on topography, stand condition, and distance to roads. GPS is used by timber cruisers to identify specific trees for harvest and locations of harvested trees are entered into the GIS database. GIS is used to predict the potential for soil erosion after logging, especially if the site is close to a stream, and to develop mitigation strategies. This allows erosion models based on actual soil characteristics, topography, and site conditions (i.e., cover type) to be used in developing spatially explicit erosion hazard estimates over the site rather than arbitrary rules like distance to roads or streams.

Evaluation of off-site nutrient and herbicide transport are other concerns. Fire hazard is another risk factor that can be minimized using spatially explicit models for site management and mitigation. Fire risk and fire hazard models require a digital terrain model, information about the fuel load and its vertical and horizontal distribution, and weather information. Foresters may also use site-specific forest mensuration models to predict tree growth that consider site-specific soil fertility and moisture

remaining in the soil after a crop is harvested. This works best for less mobile soil chemical properties such as phosphorus and potassium concentrations or pH. Nitrogen is more mobile and requires more frequent sampling to assess the appropriate credit levels. Nitrogen remaining in the soil after harvest may be available to the next crop, unless temperature and rainfall conditions result in leaching or volatilization. More accurate crediting of residuals can reduce costs and environmental load where overapplications would have occurred, and can improve yields for locations that would have been undertreated. Second, precision management of soil nutrients allows the producer to set variable yield goals for fields that do not have a uniform productive potential. With variable yield goals, inputs for a

BOX 2-2 Continued

conditions, and microclimatic differences. Dynamic growth models of varying complexity aid in developing a long-range yield plan for a site.

Annual remote sensing images, like LANDSAT Thematic Mapper and aerial photography are frequently used to assess reforestation success, erosion, competition from shrubs, and tree mortality. This use is predicted to increase as the next generation of satellites becomes available. The new satellites will permit information extraction about canopy condition beyond properties related to total foliage display. High spatial resolution radar, LIDAR (an acronym for light detection and ranging), and optical sensors will obtain information about forest structure and biomass distribution. More frequent temporal coverage will permit earlier detection of insects and other environmental stresses.

Many charismatic, endangered, and sensitive wildlife species require forests with late successional structural features to provide forage, nesting, and perching locations. Forests with standing and down dead trees, open gaps and spatially distributed forest patches, corridors for migration, vertical and horizontal crown complexity, and other pattern features may be mapped and tracked in a GIS. In addition, GIS based models using remotely sensed information provide a mechanism for evaluating the impact of site-specific logging on wildlife habitat conditions necessary for protection of these species. Other forestry applications for site-specific methods include mapping the spread of insects and fungal pathogens, to regional impacts of air pollution, like acid deposition and ozone, on forest health and species specific mortality. As competing demands for conservation, recreational use, and economic extraction increase, GIS databases, using GPS linked site data, and remote sensing monitoring, offer the hope that site-specific methods can be used to optimize management decisions.

specific area of the field can be matched with the expected yield, and supplied at a more economically optimal level (Hergert et al., 1997). Additional on-farm research is necessary to determine the economic returns from different approaches to soil fertility management in precision agriculture.

The evaluation of soil nutrient levels across a field is typically performed by taking soil samples, analyzing them for nutrient content, and interpolating values between the sampling points (Wollenhaupt et al., 1997). Figure 2-3 shows a field with the sites where soil samples were taken, and a resulting interpolated phosphorus map. The actual values for soil phosphorus concentration are known only at the sampled points; all other values are estimated. Both the method used for

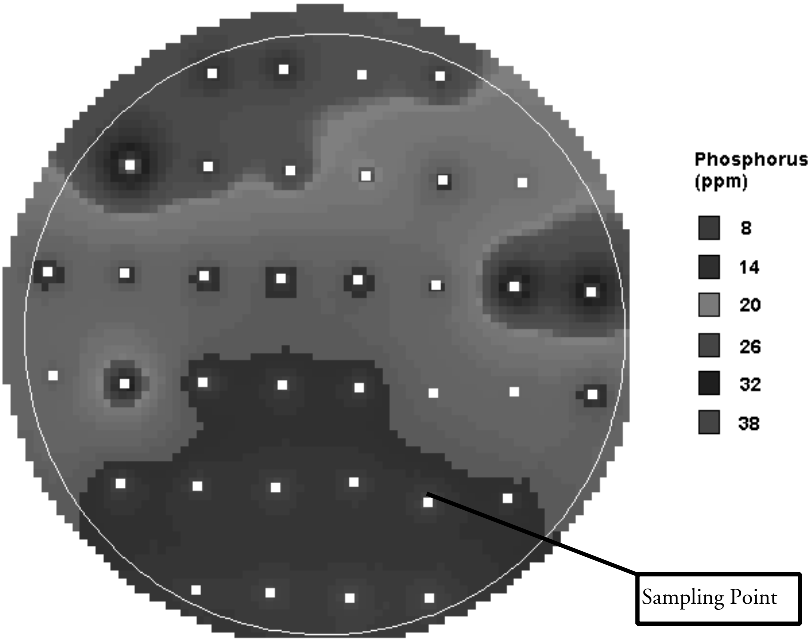

FIGURE 2-3 Map of soil test phosphorus. This figure shows a field with the sites where soil samples were taken and a resulting interpolated phosphorus map. The actual values for soil phosphorus concentration are known only at the sampled points. All other values are estimated. Both the method used for locating the sample points and the interpolation methods are important to the accuracy of application maps that might be derived from such a layer. SOURCE: Stephen Searcy, Texas A&M University.

locating the sample points and the interpolation methods are important to the accuracy of application maps that might be derived from such a layer.

Although procedures vary with the supplier, many fields have been grid sampled to determine nutrient levels. Grid sampling involves overlaying a grid on the boundaries of a field; the grid spacing used may be uniform or may have a wide range of resolutions. Soil properties can vary at any level of resolution and with sampling date. Because inherent field variability is not well understood, determination of grid resolution has been based mostly on costs. Obtaining and analyzing soil samples is expensive; thus, the number of samples included in the grid is based on the potential return from improved nutrient management. For example, one sample may be collected from a 10-acre field of grain, whereas two or more samples may be collected from each acre of a higher value crop such as potatoes.

The sampling techniques used are determined by the type of data analysis to be performed. Suggested sampling techniques include taking samples at the center point of a uniform grid, randomizing sample locations within each grid cell, and targeting sampling based on nonuniform field characteristics such as slopes or changes in soil type (Wollenhaupt et al., 1994; Wollenhaupt et al., 1997). No single sampling methodology has been determined to be optimum, and this continues to be a problem due to differential field characteristics, crop response, and profit potential. Grid sampling and nutrient mapping are most useful for nutrients considered to be relatively stable over time. The information gained from sampling and mapping soil phosphorus, potassium, various micronutrients, and pH is often used for three to five years, allowing sampling and analysis costs to be amortized over several growing seasons. Grid sampling has also been used for nitrogen, primarily on higher value crops (Schneider et al., 1996). Because variable-rate fertilization is still a relatively new technique, little information is available to describe the long-term effects on soil productivity.

A variety of techniques are used to analyze data from samples collected in a grid pattern. The scientific community frequently uses a geostatistical technique known as kriging to interpolate between widely dispersed data points. This involves calculating variances between multiple data pairs and predicting values at unknown points as a function of distance and expected variance from known sample points. This computational technique is intensive and has not been widely adopted by agricultural software vendors. Commercially available agricultural GIS programs often use a simpler form of an inverse distance-weighted calculation that requires fewer computations and less judgment by the user. These methods of interpolation generate new point values based on the distance to the various neighboring sample and a weighting scheme. Wollenhaupt et al. (1997) describe several different interpolation techniques, and suggest that no one technique is clearly superior. They point out that a proper strategy for sampling is of much greater importance than interpolation method. A promising nonparametric surface generation technique that uses an averaged shifted histogram method could improve efficiency in analyzing point data sets (Scott and Whittaker, 1996; Whittaker and Scott, 1994). An increased knowledge base in geostatistical methods should improve interpretation of precision agriculture data.

Sampling for soil characteristics has inherent problems with resolution and accuracy at non-sampled locations. With appropriate sensors available, real-time techniques can give data on a much finer scale, eliminate the need to estimate values, and contribute to enhanced VRT methods. Although a few sensors are currently available, more capability, including fine scale resolution, for sensing important crop and soil parameters are needed.

Pest Management

The spatial and temporal complexity of pest behavior provides an opportunity to integrate numerous strategies to manage pests in agroecosystems. The ability to integrate information from a variety of sources will be necessary for the pest management decision-making process. With the state of precision agriculture technologies today, site-specific pest management is limited to less mobile pests, such as weeds. Insects are difficult to characterize in a timely and economic manner. Because insect populations can change rapidly in a few days, the half-life of data on insect densities would be short.

The complex nature of pesticides and their use in the environment creates a need for information and guidance in the decision-making process. The safety and regulatory aspects of pesticide use have placed a monitoring and reporting burden on producers in some agricultural production regions that is most easily managed with a GIS database and automated recording of applications. Improved pest management is likely to increasingly use precision agriculture technologies, with potential benefits to farm workers, the environment, and our food supply.

Pesticide Management

Producers are interested in saving on input costs and applications. Environmental improvements may be derived by reducing pesticide use through precision application of chemicals only to areas with pest infestations instead of treating entire fields at uniform rates. Results of analyses of weed populations in 12 Nebraska fields show that postemergence herbicide applications could be reduced 71 percent for broadleaf weeds and 94 percent for grass weeds if only infested areas were treated (Johnson et al., 1997). Weed seedling density varied from 10 to 41 seedlings per meter of row length on fields with low to severe weed infestations. Associated crop losses varied from 20 to 43 percent. The authors estimate that herbicide use could be reduced 30 to 72 percent if real-time sensing and discrimination of weed species could be accomplished. Such site-specific determinations for spraying could also increase crop yields when whole-field spraying is not justified because average weed infestation is below the economic threshold.

Precision agriculture techniques can aid in making decisions on the rate of pesticides applied across a field. Detailed field maps can identify soils that are prone to leaching problems. Many agricultural chemicals, especially pre-emergence herbicides, are labeled for different application rates based on soil conditions. Soil texture and percentage organic matter are important for identifying the correct application rate of these materials. An example of this is trifluralin (Treflan), which has different rates for three different soil texture classes: coarse sand (light soils), silt (medium soils), and fine clay (heavy soils). The lowest rates are for the coarse sandy soils that are more apt to leach materials.

Pest control is an area for which both the spatial and temporal aspects of precision agriculture could contribute to environmental improvement. Pests could be managed not only by specific areas but also by timing treatment according to damage thresholds arrived at by integrating scouting reports, remote sensing, and on-the-go sensor input; rather than by using fixed prophylactic treatments. Although spot treatments to target pests may reduce pesticide use, there is little evidence that this management strategy is profitable after the cost of obtaining the pest density data is included. An increased understanding is needed of the cost effectiveness and social benefits from managing pests with precision technologies.

Farmworker Safety

The use of differentially corrected GPS (DGPS) may reduce pesticide handler exposure to toxic pesticides. For aerial applications of pesticides, pilots formerly depended on pesticide handlers on the ground to guide them across fields to be sprayed. With DGPS technologies, pilots can substitute instrumentation for human labor to maintain proper patterns of application. Pesticide handlers do not need to be exposed to the agrichemicals.

Weather

Weather is perhaps the dominant factor in crop production and is certainly one of the greatest sources of uncertainty. However, it is not a manageable factor. At best, producers can react to recent weather conditions and predict the effect of future weather patterns suggested by historical probabilities. Some meteorological indexes, such as temperature, humidity, and solar radiation are relatively constant over large areas or regions. Rainfall can be highly variable, even on the subfield scale. Efforts to incorporate weather data into precision agriculture techniques, especially decision-support tools, will be extremely important in attempts to understand the interactions of the many factors influencing a crop.

Suppliers

Newer satellites and Doppler radar are key components of spatially distributed weather information. The current sensors will be expanded by the addition of several new systems to be launched over the next decade, which will provide unprecedented weather information in terms of spatial detail and temporal frequency. For example, the new National Oceanic and Atmospheric Administration GOES-8 satellite obtains weather data every half-hour at a spatial resolution of one kilometer, providing an important link in making detailed, spatially distributed weather information available at the farm level. The GOES-8 satellite acquires vertical sounder data on humidity, temperature, and other properties at a spatial resolution of four kilometers. These data can be used to model regional and mesoscale atmospheric conditions to provide the agricultural community high-resolution information on current and predicted conditions. Doppler radar images are updated every 15 minutes. Many additional satellites, from both public and private sectors, are expected to be launched over the next decade for weather observation.

The private sector has become increasingly important in the supply of weather service information to the agricultural community. Weather service providers offer satellite dishes and computer hardware and software that bring detailed, timely weather information to farms. Satellite receivers, modems, and Internet connections have brought weather data to the agricultural community in various formats, from short-range hourly and daily weather data to predictions of weather conditions spanning time periods from immediate hourly predictions through weekly, monthly, quarterly, and annual forecasts. These services are mainly focused on regional weather summaries, but customization may be possible if a market exists for field- or subfield-scale weather data. That market is not likely to develop unless precision agriculture tools are designed to include site-specific meteorological data. These services may include data inputs from weather stations established at or around farms. Automated portable weather stations with data loggers, modems, and software are commercially available for direct weather observation within the farm, but these are generally limited to one per farm.

The rapid proliferation of weather service information providers in the agricultural sector, many with on-line access, has set the stage for accessing other types of information for farm management. Providers already bundle information from public and private sources and combine weather data with crop models to provide specialized data and services to their agricultural customers. Access to real-time information via satellite links allows producers to use the information without significant investments in expensive computer hardware and software and without substantial time investments in processing raw data to obtain desired information. Use of these services may spur the adaptation of other site-specific technologies.

Monitoring Precipitation

Precipitation is the primary weather index watched by most producers. Satellite images, Doppler radar, and interpolated weather station data are being used to create county- and field-level rainfall maps with updates every 15 to 30 minutes; the updates allow a producer to watch an approaching storm front as it moves into and across a region. For precision agriculture, estimates of subfield rainfall amounts would be of great value.

Relative Humidity

Humidity readings are especially important for forecasting the infestation and spread of fungal pathogens, such as downy and powdery mildew. Humidity is also important in biological control programs for monitoring conditions favorable for introduction of beneficial insects and mites. Daily humidity maps are among the products offered by weather information suppliers.

Harvest

Many management factors associated with harvest affect both the quality and quantity of marketable product. Precision agriculture harvesting techniques have been focused on quantitative measurements (yield and moisture content). The yield data obtained during the harvest operation are a critical input to any precision management system. However, data sets that describe subfield variation of crop development also have other implications. Producers must be concerned with the quality aspects of their products. Product quality can be as important a determinant of profitability as quantity.

In the future it may be possible to map product quality as well as yield. Real-time quality sensors do not exist, but predictive crop models may be a substitute. If crop growth models can use subfield-scale data to predict product quality, a producer may be able to avoid harvesting a portion of the field, for example, that has a high probability of containing aflatoxin. If a cotton field has areas with significant differences in lint quality, the producer may choose to operate the pickers so that the cotton would be placed in modules with more uniform qualities. With sufficient knowledge of the product quality, GIS and differential global positioning system technologies could be used to schedule harvest operations to optimize marketing opportunities.

Marketing

Marketing is often considered to be the most important factor in the profitability of agricultural production. Precision agriculture techniques have not yet been developed to the point of significantly affecting crop marketing decisions. However, the availability of a detailed data set that describes the growing conditions and all chemical applications used in the production of a crop can have economic value. Product identity and documentation can be particularly important for products intended for human consumption. The use of detailed data sets to predict yields several weeks in advance of harvest would be of great value in a marketing plan that uses forward contracting or options. The communication technologies associated with precision agriculture could potentially provide marketers of agronomic products more complete information on market trends.

SUMMARY: EFFECT ON MANAGEMENT

The previous sections have described the various ways in which precision agriculture will affect crop management. Some of the practices described are based on documented experiences with these new technologies. Others are the committee's best guess at future developments and their results. It is likely that some predictions may be wrong, others may be technically possible but will never become economically feasible, and unforeseen tools, techniques, and applications will be developed. Regardless of the accuracy of our vision, the crop management practices of the twenty-first century will be significantly affected by these information technologies.

Crop yields typically represent only a small portion of the genetic potential of the plants. The loss of yield potential is attributed to the many limiting factors that can affect a plant during its life. The previous sections have described some of those factors, and the decisions that producers can make over the course of a cropping season. Precision agriculture has the potential to affect crop management practices by reducing or removing the effects of limiting factors. It seems clear from the evidence to date that precision agriculture technologies will be used in the management of some factors for some crops in some regions. Major limitations to adoption in a broader range of cropping systems include an incomplete understanding of agronomic parameters and their interactions, the cost of obtaining site-specific data, and a limited ability to integrate information from sources with varying resolutions and timing. There are many possibilities for incorporating detailed information into management decisions. The realization of those possibilities will depend on creative scientists and engineers inventing and improving the tools of precision agriculture.

3

Adoption of Precision Agriculture

CURRENT STATUS AND LIKELY TRENDS

Precision agriculture is still in its infancy, and information about the extent to which precision agriculture technologies are used is fragmentary. This section summarizes what is currently known about use of these technologies and attempts to draw on experience with existing information-intensive agricultural technologies to generalize about likely future adoption patterns. The section begins with a survey of current evidence regarding the adoption of precision agriculture technologies, then reviews the literature on agricultural technology adoption, and finally discusses likely adoption patterns for precision agriculture.

Status of Current Adoption

Precision agriculture is a suite of technologies rather than a single technology. Components of that suite of technologies currently in use include GPS receivers; GIS data bases; variable-rate application equipment for seed, fertilizers, and pesticides; grid soil sampling; low-volume irrigation; yield monitors; sensors for soil fertility and weed populations; and remote sensing imagery. Different configurations of components of that suite will be suitable for different operations. It is therefore somewhat misleading to speak generally about the extent of adoption of precision agriculture. By any measure, however, adoption of precision agriculture technologies is extremely limited at present.

Variable-rate application equipment is perhaps the most widely used precision agriculture technology. About 1,600 flotation fertilizer-application systems, map-driven variable-rate technology (VRT) systems, and on-the-go sensor tractor-based application systems have been sold. Thirteen percent of the respondents in a Purdue University study of agricultural chemical dealers were applying fertilizer by using controller-driven VRT (Akridge and Whipker, 1996).

Grid soil sampling also appears to be among the more popular precision agriculture technologies. The same Purdue University study found that 29 percent of the agricultural chemical dealers responding to the survey were pulling grid samples for their customers, whereas 15 percent were mapping fields (Akridge and Whipker, 1996).

Computers are a central component of information-intensive agriculture. Fewer than 10 percent of the 1.9 million producers and ranchers in the United States own computers. Commercial yield monitors are available for corn, soybean, and wheat harvesting. Approximately 2,000 yield monitors (cumulative) were in use in the 1995 growing season. This figure increased to about 9,000 in 1996. Midwest corn and soybean growers are currently the major buyers (A. Meyers, Ag. Leader Technology, personal communication, June 13, 1997).

Diffusion of New Technologies

There is a large body of economic and sociological literature on technology adoption in general, as well as on information-intensive agricultural technologies such as computers, integrated pest management (IPM), low-volume irrigation systems (drip, center-pivot, and other sprinkler systems), and the California Irrigation Management Information System (CIMIS), which combines localized weather information with field-level soil moisture monitoring to improve irrigation management. The history of the diffusion of these earlier information-intensive technologies offers insights into the likely prospects for current precision agriculture technologies.

It has long been recognized that new technologies diffuse gradually. Technological diffusion typically follows an S-shaped path over time. In the early years after a new technology is introduced, it is generally used by only a small percentage of those who could benefit from using it. As time passes, the rate of adoption tends to increase and diffusion becomes more rapid. Finally, after the majority of those who stand to benefit from using the technology have begun using it, the rate of diffusion slows again.

It is important to distinguish between two key variables characterizing the diffusion process: the extent (or ceiling) of adoption and the rate of adoption. The adoption ceiling pertains to the long term, when the diffusion process approaches completion. The rate of adoption pertains to the short term, while the diffusion process is in progress. Griliches's (1957) work on hybrid corn established that both the adoption rate and ceiling are influenced by economic factors. The adoption ceiling is influenced almost entirely by economic factors. In the short term, however, the rate of adoption is influenced by factors such as learning, risk and risk preferences, information, and human capital as well as by profitability considerations.

Determinants of Long-Term Adoption

Profitability is the principal determinant in the long term of adoption of new technologies in agriculture and elsewhere—technologies that are more profitable will be used. However, adoption of any farming technology is unlikely to be universal because agriculture is characterized by a high degree of heterogeneity. Farming conditions vary markedly among regions and crops because of differences in climate, soils, topography, water availability, government programs, and other factors. As a result, the profitability of any given agricultural technology may differ greatly across regions and crops, so that producers in one region find unprofitable what producers in another find extremely profitable.

Differences in climate are arguably the major source of heterogeneity in agriculture. They lead to differences in crop productivity and thus in the long-term profitability of adopting new agricultural technologies. In his classic study, Griliches (1957) found that ceiling rates of hybrid corn adoption varied across states. Ceiling rates in the Corn Belt approached 100 percent but were much lower in states with lower corn productivity. Differences in climate also result in differences in pest pressure that affect ceiling rates of IPM adoption. For example, the use of scouting services for cotton crops is more prevalent in the Delta states than in Texas or California (Economic Research Service, 1995b), which are drier and are thus less subject to pest pressure.

Differences in land quality (i.e., soils and topography) are a second major reason for heterogeneity in agriculture and for differences in ceiling rates of adoption of agricultural technologies. For example, low-volume irrigation technologies (drip and center-pivot) increase the efficiency of water use more on land with sandy soils and greater slopes and thus are more likely to be adopted by producers operating those types of land (Caswell and Zilberman, 1986; Dinar et al., 1992; Lichtenberg, 1989; Negri and Brooks, 1990; Shrestha and Gopalokrishnan, 1993). Adoption of conservation tillage has similarly been more widespread among producers operating more erodible land (Economic Research Service, 1995a; Ervin and Ervin, 1982; Gould et al., 1989; Lynne et al., 1988).

Differences in cost structure are frequently another source of differences in ceiling adoption rates. For example, use of low-volume irrigation technologies is more widespread in areas where water prices are higher, so that savings in water costs are more likely to outweigh initial investment costs for drip systems (Caswell and Zilberman, 1985; Dinar and Yaron, 1990; Dinar et al., 1992; Negri and Brooks, 1990; Shrestha and Gopalokrishnan, 1993). The use of computer services is more widespread among dairy operators than other kinds of producers because computerization reduces the management time and cost involved in herd improvement (Huffman and Mercier, 1991; Putler and Zilberman, 1988).

Information-intensive technologies such as low-volume irrigation or chemigation frequently increase yield. These yield increases are worth more for higher-value crops, suggesting that ceiling adoption rates of information-intensive technologies will be greater for these crops. For example, adoption of drip irrigation systems has been greater for higher-value crops (Caswell and Zilberman, 1985; Dinar et al., 1992), as has the use of CIMIS for irrigation management (Parker and Zilberman, 1996). Adoption of drip irrigation for sugar in Hawaii has been greater on farms where yield differentials between drip and sprinkler systems are higher (Shrestha and Gopalokrishnan, 1993). Adoption of center-pivot irrigation systems in the High Plains has been greater for corn than wheat or sorghum because corn yields are more responsive to irrigation (Lichtenberg, 1989).

New agricultural technologies may spur expanded production of specific crops or livestock. Thus, the number of potential adopters of these new technologies may exceed the number of producers currently in the industry. Similarly, the extent of adoption (i.e., as measured in acreage on which the technology is used) may exceed the current size of the industry. New farming methods have frequently allowed expansion of cultivation into areas that were previously considered unsuitable. Examples include irrigated corn production on the sandy soils of the High Plains through use of center-pivot irrigation (Lichtenberg, 1989) and expansion of orchards and vineyards onto hilly areas in California through use of drip and sprinkler systems (Caswell and Zilberman, 1986).

New agricultural technologies may also turn out to have advantages that were largely unanticipated when they were introduced. As a result, ceiling adoption may differ significantly from initial expectations. For example, sprinkler irrigation is used in preference to drip systems for citrus in California because it provides frost protection (Caswell and Zilberman, 1985). Frost protection is similarly an important motivation for the use of CIMIS, which was designed mainly to improve irrigation scheduling (Parker and Zilberman, 1996).

Determinants of the Speed of Diffusion of New Technologies

The speed at which the diffusion of new technologies occurs depends on a variety of factors, including:

- how rapidly information about new technologies spreads;
- how risky the new technology is perceived to be and how rapidly those perceptions change;
- how rapidly producers can adapt to using new technologies, which depends in turn on education and other forms of human capital;
- how rapidly learning-by-doing and learning-by-using occur; and
- how rapidly producers of the technologies improve reliability, cost, and ease of use.

(See, for example, David, 1975; Feder, 1980; Feder and O'Mara, 1982; Feder et al., 1982; Jensen, 1982; Mansfield, 1963; Stoneman, 1981).

Less is known about the performance of newly introduced technologies because producers lack experience using them. As a result, the new technologies tend to be viewed as less productive, more costly, and riskier than established technologies. Initially, only a few producers will find using them worthwhile. These early adopters tend to have greater human capital or be more accepting of risk. Other producers may believe that the new technologies will not be profitable enough to justify the cost of adopting them (the cost of new equipment, plus the costs of restructuring farm operations and training) or may be too averse to risk to adopt the new technologies even if they appear to be more profitable (until the expected improvement in profit is large enough to outweigh the risk). Risk aversion on the part of lenders may also prevent early adoption by limiting producers' ability to borrow money to invest in new technologies. Aversion to risk may also lead producers to test new technologies partially at first (i.e., trying them out on a field or trying out key components of a system). Larger operators may be more diversified against risk and thus be more willing to test out new technologies partially. Finally, some producers may find the new technologies less profitable than current technologies given the productivity of their existing capital stock (Salter, 1960).

As producers gain experience with the use of the new technology, either directly or through improved information, estimates of the return to using them tend to rise whereas perceptions of their risk tend to fall. Perceptions of risk and return for new technologies change over time in response to several factors.

The first such factor is the rate at which information about a new technology spreads to potential users. The classic model treats the process of information flow as proceeding largely through word-of-mouth, so that it mimics the spread of an epidemic. The greater the potential profitability of a new technology, the faster information about it is disseminated (Mansfield, 1963). In agriculture, technology-transfer programs within cooperative extension services and marketing by equipment manufacturers, dealers, and consultants all work to spread information about new technologies. Potential profitability affects the flow of information and thus the speed of diffusion through its effect on marketing efforts. Technologies that promise greater increases in returns tend to be marketed more aggressively, so that information about them reaches potential users more rapidly. Once the profitability advantages of a new technology are well established, lenders may also promote adoption of it to their clients.

Marketing can also have negative effects on the spread of accurate information. Overzealous marketing can create inflated expectations about performance. Producers disappointed by the gap between promise and performance in initial trials may come to underestimate the potential profitability of new technologies. For example, the gap between inflated claims about drip irrigation in the 1970s and actual performance of drip systems produced an adverse reaction among producers that significantly retarded the spread of this technology.

The second factor in changing perceptions is the user's direct experience with the technology. As producers use the new methods they may come to perceive them as more profitable and less risky. In some cases increased familiarity alone changes perceptions. The spread of computer use in agriculture illustrates this learning-by-using. Producers began with simpler programs (spreadsheets and word processing) and then branched out into more sophisticated management systems after becoming more familiar with computers in general (Putler and Zilberman, 1988). In other cases, user experience with new technology can lead to improvements that actually make the technology more profitable to use, rather than simply changing perceptions about profitability. For example, the performance of early drip irrigation systems was often poor because drip lines clogged. User experience with clogging problems led manufacturers to redesign the drip systems, which led in turn to accelerated diffusion of these systems (for example, Shrestha and Gopalokrishnan, 1993).

Third, the cost of producing and installing equipment for the new technology frequently falls over time because of improvements in technology design and cost reductions resulting from production experience of the manufacturers (i.e., learning-by-doing). Lichtenberg (1989), for example, showed that increases in irrigated soybean and corn production in the Northern High Plains were due in part to falling costs of center-pivot irrigation systems. Kislev and Shchori-Bachrach (1973) argue that learning-by-doing played a critical role in the spread of winter vegetable production in Israel. Initially, only the most skilled producers were able to produce winter vegetables. Over time, these producers developed standard methods for vegetable cultivation under Israeli conditions, which less-skilled producers were increasingly able to use.

Finally, the profitability of a new technology relative to existing ones may rise over time as the existing capital stock ages and becomes less productive (Salter, 1960). As producers replace their existing equipment, they tend to invest in equipment embodying the new, more productive technologies.

Information-intensive technologies may have high fixed costs, either in terms of equipment purchases or in terms of acquiring the skills necessary to use them. The economic theory of investment suggests that adoption of such technologies may be discontinuous over time, because uncertainty about future conditions makes waiting a preferred option (Dixit and Pindyck, 1993). In some cases rapid diffusion has occurred after periods of extreme conditions resulted in substantial alterations in expectations about future prices. Examples include the rapid diffusion of drip irrigation in California during the droughts of 1976–1977 and 1988–1991, when water prices rose sharply and water availability declined sharply; conservation tillage during the energy crisis years of the 1970s, when energy prices rose sharply; and center-pivot irrigation in the High Plains after the grain price spikes of 1973–1974 (Lichtenberg, 1989).

It is important to recognize that producers are buying the services of the technology, not the equipment that embodies the technology. Purchasing those services does not necessarily require purchasing the equipment, although equipment purchase may be the most economical means for some. There are many other ways of packaging and selling those services, such as equipment rental, custom operations for hire, or consultant services. For example, in early years, sellers of drip irrigation systems rented equipment to producers rather than requiring its purchase. As noted above, scouting services are typically delivered by crop consultants, in the form of pest management recommendations. Laser leveling, which requires investment of substantial sums in machinery, is typically provided by custom service similar to grain harvesting.

Effective and profitable use of information-intensive technologies such as precision agriculture requires high human capital, which thus plays a critical role in the technology diffusion process. The greater the availability of such human capital, the more rapid the spread of technology. Producers with greater human capital are more likely to adopt new technologies, as has been documented for computers and computer software (Huffman and Mercier, 1991; Putler and Zilberman, 1988) and IPM (Fernandez-Cornejo, 1996; Fernandez-Cornejo et al., 1994; Harper et al., 1990; Napit et al., 1988; Wearing, 1988).

Human capital can consist of producers themselves if they have the necessary education or computer training, as documented in the studies mentioned above. Alternatively, producers may rely on consultants who make recommendations derived from the use of these new technologies. Operations that are sufficiently large may hire specialized workers to provide these services. For example, in 1994, 29 percent of cotton producers performed field scouting themselves, 48 percent relied on consultants for scouting services, and 5 percent used employees (Economic Research Service, 1995b). Similarly, diffusion of precision agriculture has been more rapid in areas with larger numbers of dealers and consultants to provide advice and service (Wolf and Nowak, 1995).

In the short term, lack of access to consultant services may limit the speed of diffusion of new technologies. Over time, however, consultant and training services should become more available in areas with high demand, as chemical and equipment dealers and independent consultants respond to opportunities to start up or expand business operations. The public sector frequently also plays an important role in training and thus augmenting the supply of human capital in agriculture. For example, land grant universities have provided the basic training in crop and pest management sciences underlying IPM, and extension agents in many states provide specific pest management training needed to implement IPM (see, for example, Carlson, 1980; Zilberman et al., 1994).

The preceding discussion suggests that the diffusion of precision agriculture technologies may proceed unevenly over time. Like computers, precision agriculture initially is likely to require significant learning, both by users and by equipment suppliers. Time may be needed for these learning effects to improve performance, reduce costs, and increase reliability sufficiently to make this technologies attractive to large numbers of producers. Precision agriculture requires significant supporting infrastructure in the form of skilled labor, software development, and hardware availability—all of which may take time to develop. Moreover, some precision agriculture equipment is costly, so that potential users—

whether producers or crop consultants—may prefer to wait until uncertainties about costs and reliability have been reduced sufficiently to make investment attractive.

Long-Term Potential of Precision Agriculture

The long-term potential of precision agriculture depends on its profitability (i.e., the extent to which benefits, such as of increases in yield and savings in input costs, outweigh the cost of purchasing the services). Available evidence indicates that the cost of many precision agriculture services is modest, especially when spread over sufficient acreage, as can be done by a custom applicator (Table 3-1). These costs are comparable to the fees charged for insect and weed scouting on major crops, which are about $3 to $6 per acre. Remote sensing imagery similarly has a modest cost when spread over sufficient acreage. Raw satellite imagery data can cost as much as $80,000 per season, but data providers can sell processed images for specific fields for as little as $7 to $8 per acre (Lamb, 1996). By way of comparison, fertilizer, lime, and gypsum costs for corn in the United

TABLE 3-1 Estimated Costs of Precision Agriculture Services

Item	Cost per Acre	Source
Farmer Cost[a]		
Grid soil sampling (plow depth, 3-acre grid)	$3-7	Lowenberg-DeBoer and Swinton (1997) Giacchetti (1996)
Grid soil sampling (4-foot depth, 3-acre grid)	$16-22	Berglund and Freeburg (1995)
Yield monitor	$1.45-1.66	Lowenberg-DeBoer and Swinton (1997)
GPS receiver	$0.75-1.45	Lowenberg-DeBoer and Swinton (1997)
Scouting package, weekly	$4	Giacchetti (1996)
VRT controllers, various applicators	$1-5	Lowenberg-DeBoer and Swinton (1997)
Variable-rate fertilization application (additional cost over uniform)	$3-7	Lowenberg-DeBoer and Swinton (1997) Giacchetti (1996)
Dealer Cost[b]		
DGPS receiver	$0.23-0.79	Kohls (1996)
Grid soil sample unit	$0.62-1.60	Kohls (1996)
Yield mapping computer and software	$0.33-1.16	Kohls (1996)
Liming application unit	$1.09	Kohls (1996)
VRT fertilization unit	$0.22-10.00	Kohls (1996)

[a]Assumes 3-year useful life for equipment, 6 percent interest rate, 3 percent repair cost, and 1,000 acres.

[b]Assumes 3-year useful life for DGPS receiver and yield mapping computer and software, 5-year useful life for liming application unit, 10-year useful life for soil sampling and VRT equipment, 6 percent interest rate, 3 percent repair cost, and 5,000 acres.

States averaged $46 per acre in 1994, custom operations averaged $10 per acre, and total variable cash expenses averaged $147 per acre. Capital replacement on corn averaged $33 per acre (Economic Research Service, 1996).

The central characteristic of precision agriculture is the use of detailed information to reduce the impact of heterogeneity of production conditions on output by allowing producers to calibrate inputs according to conditions at the subfield scale. For example, growers can combine tensiometer information on soil moisture at subfield levels with prediction of evapotranspiration derived from weather forecasts hourly or daily, so that producers can vary irrigation water application to match water demand at the subfield level. Similarly, variable-rate applicators combined with fertility mapping allow producers to vary fertilizer application rates in response to natural variations in soil fertility. Calibrating inputs according to conditions at subfield levels is likely to result in increased yields. For example, diminishing marginal productivity of nutrients suggests that yields obtained under variable-rate fertilizer application will generally exceed those obtained under uniform application calibrated according to average soil fertility. Within variable-rate application, areas within a field having higher than average fertility should receive lower fertilization than under uniform application, while areas having lower than average fertility will receive higher fertilization than under uniform application. Yields in areas with higher-than-average fertility will be lower under variable-rate application than under uniform application, while yields in areas with lower-than-average fertility will be higher. As long as low-fertility areas account for a sufficiently large share of the field, variable-rate fertilizer application will result in an increase in yield for the field as a whole.

The preceding discussion suggests that precision agriculture is likely to have a greater profitability advantage than current farming methods in areas where production conditions are more heterogeneous and in areas where input costs are higher, because cost savings from more precise input application are likely to be greater in such cases. Similarly, precision agriculture is likely to have a greater profitability advantage than current farming methods for higher-value crops because yield increases resulting from more precise input application (should they occur) are worth more in such cases.

The handful of peer-reviewed, published economic assessments have examined the relative profitability of varying fertilizer application rates on small grains in response to differences in natural soil fertility. These studies thus involved relatively low-value crops and inexpensive inputs, conditions under which precision agriculture technologies should have relatively small profitability advantages. Carr et al. (1991) obtained mixed results when comparing profitability of wheat and barley grown in central Montana between fields where nitrogen, phosphorus, and potassium were applied uniformly and those where application rates of these nutrients were varied to meet recommended application rates for yield goals on different soil types. Returns net of variable costs were significantly higher under variable-rate applications than under uniform-rate applications in

BOX 3-1
The Paradox of Information Technology and Its Economic Effects

Despite the vast sums of investment and the enormous allocation of human talent devoted to the application of information technology in business, it has been a continual challenge to quantitatively document the economic benefits of information technology. This evaluation problem occurs at the level of the individual firm, the industry, and the economy. Although examining the overall effectiveness of all types of information technology applications is clearly not the purpose of this report, recent research results on this topic can provide lessons to shape our expectations of the likely economic effects of precision agriculture.

Innovative applications of information technology tend to attract considerable media attention, often based upon anecdotal evaluation. For example, American Airline's Sabre reservation system received considerable attention not only for gaining advantage for American Airlines but also for altering the way competition occurred in that industry (Buday, 1986). Although instructive and useful, anecdotal and case study evidence can tend to be overly optimistic regarding the eventual economic impacts of such innovations. Often, the time and costs associated with the failed projects that were necessary to achieve the successful projects are not accounted for (Leonard-Barton, 1995). Critical examination of reports of information-technology-based success, which do not include careful economic evaluation, is appropriate. Clemons's 1986 comments still apply to reports of innovations in information technology in general, as well as for the technologies associated with precision agriculture: "Surely much is media hype or current business fad . . . . There is now a large, and largely anecdotal, literature, most of it referencing similar stories of technologically directed competitive triumphs. How much do we understand? . . . . How many of the stories are true, or accurately reported?" (Clemons, 1986).

The economic gains from innovative applications of information technologies tend to be spread over several years. This may occur in part because the effects on performance are not immediate. Further, the effects of learning often are critical in determining eventual benefits. Here learning includes becoming proficient in how to operate the technology. More importantly, organizational learning is required to discover how to alter business systems to take full advantage of the innovation. Peffers and Dos Santos (1996), for example, examined the impact of the introduction of ATM machines across 2,534 U.S. banks over the period 1974 to 1984. Their findings indicate that the effects on business performance of ATM adoption can be best described by exponential and logistic models, implying that the benefits were small at first but increased rapidly

BOX 3-1 Continued

after a few years. Their study stresses the importance of longitudinal analyses, as empirical cross-sectional studies conducted soon after initial implementation would tend to report minimal benefits even if the eventual benefits were large. Further, the results of this analysis stressed that long run enhancements in performance did accrue to the early adopters of the ATM technology.

Reports of information technology innovation tend to stress the potential for innovating firms to gain sustainable competitive advantages in their markets. However, the widespread use of information technology throughout business and society has increased the chance for rapid and successful imitation of innovations based upon information technology. Kettinger et al. (1994) found that five years after information technology innovation, 21 of 30 firms had suffered competitive declines in market share, profit, or both. A recent analysis by Hitt and Brynjolfsson (1996) carefully separates the effects of information technology on productivity, business profitability, and consumer surplus. This study examines 367 large U.S. firms for the period 1987-1991. Their findings indicate that spending on information technology resulted in increased productivity and increased consumer value but unchanged business profitability. These results conform to the notion that adoption of information technology may tend to be more of a strategic necessity than a source of differential sustainable advantage (Floyd and Wooldridge, 1990; Kettinger et al., 1994).

Although evaluating the effect of different levels of spending for information technology can be instructive at an aggregate level, doing so provides little guidance to individual managers nor does it explain why firms that adopt similar information technology innovations experience differing levels of success. Exploring the role of information technology in the U.S. retailing sector, Powell and Dent-Micelle (1997) show that adoption of information technology innovations alone is not sufficient to explain differential firm performance. However, these findings demonstrate that some firms have achieved successful performance by leveraging information technology with intangible, complementary human and business resources. Building upon the resource-based theory of strategy (Barney, 1991; Rumelt, 1987; Teece, 1987), these results identify the interaction between resources (such as a corporate culture, integration of strategy and information technology implementation, and supplier relationships) with information technology innovation. Kelley (1994) documented similar interactions between the specific resources setting of individual manufacturing plants and the effectiveness of information technology innovation in those operations.

continued on next page

BOX 3-1 Continued

The preceding studies are from settings and situations that are markedly different than those of crop production. However, because aggressive adoption of information technology has been under way for some time in those other settings, they provide insights that are potentially relevant for the adoption of precision agriculture, as follows:

- Initial reports of innovation with information technology are likely to be based upon anecdotal evidence, which may lead to overly optimistic expectations and fail to accurately assess economic costs and benefits.
- Learning, and the time required to learn, is often essential to achieve total benefits. Therefore, slow rates of adoption should be expected in early years and cross-sectional economic analyses done soon after discovery are likely to understate long-run benefits.
- When barriers to imitation are relatively low, information technology based innovations may result in increases in productivity but no change in industry level profitability. In this situation, however, consumer well-being increases.
- Information technology innovations are adopted within the context of individual firms and effectiveness is significantly affected by the complementary human and business resources of each firm.

only one of five field trials; there were no significant differences in returns in the remaining four. In the fifth trial, the increase in returns from variable-rate application was sufficient to cover likely costs of soil testing (see, for example, Loewenberg-DeBoer and Swinton, 1997). In four out of the five field trials, however, variable-rate application was less profitable once the costs of soil testing were included.

Fiez et al. (1994) obtained similar results in a study of wheat production in eastern Washington. Net returns with variable-rate nitrogen application, where the rate was based on a constant nitrogen application rate per bushel of yield goal, were roughly equal to net returns with conventional uniform nitrogen application, where the application rate was determined the same way; inclusion of soil testing costs would make the variable-rate system less profitable. However, when variable nitrogen application rates were calibrated according to a non-linear nitrogen-response relationship, the variable-rate system was clearly more profitable, even with soil testing costs taken into account. Wibawa et al. (1993) also found that, because of the cost of soil sampling, uniform nitrogen and phosphorus application on barley and wheat in eastern North Dakota had lower yields but higher profits than variable-rate applications calibrated to meet standard yield goals.

Recent commercial developments also support the notion that interest in precision agriculture is likely to be greater on higher value crops. For example, sugar beet quality is sensitive to nutrient application and can suffer from both nutrient deficiencies and excesses. American Crystal Sugar Company, the largest sugarbeet producer in the United States, is owned by more than 2,000 North Dakota and Minnesota sugarbeet growers. This cooperative has increased its grid soil sampling in Minnesota's Red River Valley from 13,000 acres in 1995 to 130,000 acres (about 35% of the company's sugar beet acreage) in 1996 (Lilleboe, 1996).

Precision agriculture technologies may have important ancillary uses. For example, the purchase of remote sensing information on crop growth may permit closer marketing ties between producers and grain elevators by improving yield forecasts. As a result, even producers who experience relatively little within-field yield variability may find their share of the increased returns from improved marketing sufficient to make the use of such information profitable.

Evolution of Precision Agriculture

Precision agriculture services may be provided directly (i.e., for custom hire) or may be purchased in the form of hardware and software products embodying those services, or as combination of products and services. In all likelihood, both forms of obtaining precision agriculture services will coexist, with the exact combination depending on such factors as the size of the operation, the technical expertise of the operator, and the density of the local market for services.

Provision of Precision Agriculture Services

New services related to precision agriculture could arise independently but are more likely to evolve from services now offered by crop consultants and input suppliers. Nowlin (1993) estimates that crop consultants provide knowledge-based services on 16 percent of U.S. crop acreage, including 53 percent of cotton and vegetable acreage, 21 percent of corn acreage, and 13 percent of soybean acreage. A study of service offerings by 228 Wisconsin agricultural chemical dealers showed that although precision agriculture services accounted for only a small portion of total gross revenues, the percentage of firms offering these services was increasing (Wolf and Nowak, 1995).

A Purdue University survey of agricultural chemical dealers showed that between 39 and 47 percent of firms offering site-specific services were charging no fee for the service, folding costs into product prices instead. Input suppliers perceive impediments to providing precision agriculture services to include the cost of equipment (61 percent), mismatches with the kind of farming practiced in the area (18 percent), difficulty demonstrating value to producers (11 percent), and the need to train personnel (6 percent) (Akridge and Whipker, 1996).

Precision agriculture services can be provided to the producer through traditional distribution systems or by consultants. If services are provided directly to the producer, a consultant could design, integrate, and install a precision agriculture system (i.e., a combination of a global positioning system [GPS], yield monitor, and geographic information system [GIS]) for the operation, much as a computer consultant assists a small business with its computing needs. Alternatively, traditional input suppliers could be the primary customer, acting as general contractors for specific skills, expertise, and services provided by the technology consultant. If they have access to sufficient financial capital, technology consultants could invest in the computers, software, and equipment that suffer from rapid technological obsolescence. If the consultant leases precision technologies to the input supplier, then the producer can have access to the most advanced equipment. In return for their investment, the technology consultant can depreciate the capital costs over a larger acreage base. A variation of this scenario could be a technology consultant who either competes with or supplements the services of accountants, marketing consultants, or other financial assistants in automating all of the farm's electronic accounting and record-keeping functions.

Precision agriculture services will likely be provided locally. For example, computer software such as nutrient or pest management recommendation models will need to be adapted to local (even farm-level) conditions (which tend to vary substantially). Firm size will likely be small because the number of producers in a local area would be limited. However, hardware and software support channels for the service providers could be concentrated at the wholesale level.

Provision of Precision Agriculture Products

An alternative pathway of development of precision agriculture assumes that producers and their crop consultants will buy software and hardware products to implement precision agriculture, thus limiting their purchases of services. That is, the expertise and knowledge needed for precision farming will be embodied in machinery and software to a greater extent than in the services provided by consultants. Integrating the various hardware and software components into one system would provide a seamless flow of data, culminating in either a recommendation or the presentation of alternatives to the producer.

Several manufacturers (i.e., John Deere, Case, Rockwell, Ag Chem, and Crop Technology, Inc.) have developed integrated turnkey systems that combine GPS receivers, GIS software, crop yield monitors, and VRT hardware into precision agriculture systems. Object-oriented software modules could facilitate development of products, including software for mapping and decision support (Environmental Systems Research Institute, 1996; Macy and Dondero, 1996).

Companies providing precision agriculture products may not need to be located in most communities. Information technology companies could be concentrated in technical centers such as Silicon Valley or near universities where technical expertise is readily available. However, hardware and software support channels would need to be widespread and located at the retail level. Moreover, both software and hardware will likely need to be customized to match local conditions, creating a demand for locally based customizing expertise. This expertise could be provided through traditional farm supply sources, such as machinery dealers (especially for proprietary lines). Independent consultants may also prove economically viable in the market for hardware and software customization services, much as they have in various aspects of computer hardware and software sales, support, and training in other industries. Firm servicing the product market could be large in size and could dominate markets, especially if developed by or acquired by large industry leaders.

Combination of Products and Services

In reality, precision agriculture is not likely to develop purely as a service or as a product but probably will evolve as a combination of services and products. For example, individual producers may purchase and use some precision agriculture hardware and software themselves. Other producers could hire consultants who use the same or similar hardware and software. Still others may purchase the hardware and hire consultants to analyze the data and make recommendations. For example, growers with medium-sized operations and a high level of technical expertise will likely purchase a larger share of precision agriculture services in the form of hardware that they operate themselves. Part-time operators will likely purchase more custom-hired services because of constraints on their time and capital. Very large operators may both purchase equipment and hire full-time employees with the requisite technical expertise.

EFFECTS OF WIDESPREAD ADOPTION OF PRECISION AGRICULTURE

Three potential effects of precision agriculture have received public attention. First, widespread adoption of precision agriculture may affect employment opportunities in rural communities. Second, precision agriculture may affect the structure of agriculture, particularly the distribution of farm sizes. Third, more efficient and precise use of fertilizers, pesticides, and other purchased inputs may alleviate environmental spillovers from agriculture.

Effects on Rural Employment

Precision agriculture represents an increase in specialization, that is the division of labor, involved in agriculture. In adopting precision agriculture techniques, farmers substitute purchased information services (in forms as varied as consultant services, specialized equipment, and computer software) for some or all of their own personal-observation-based information collection and analysis. Diffusion of precision agriculture is thus likely to result in increased employment in agricultural support services, for example, equipment sales, computer software development, customization of equipment and software, and consultant services. The extent to which such increased employment occurs in rural areas depends largely on the combination of direct services and turnkey products through which precision agriculture services are delivered. The greater the extent to which growers purchase precision agriculture services directly, the greater will be the demand for locally based skilled technical labor such as crop consultants and computer software developers and customizers. Any increases in employment in the production of turnkey precision agriculture products are more likely to occur in areas where equipment manufacturers and software developers are currently located, which are largely non-rural.

Increases in rural employment caused by the spread of precision agriculture are likely to be modest. Farm-related employment is presently quite limited. The farm sector as a whole provides an estimated 1.7 million jobs, or 1.3 percent of total U.S. employment (Edmondson et al., 1996). On-farm labor accounts for at least 800,000 of those jobs (National Agricultural Statistics Service, 1996), so that employment in farm services of all kinds is at most 900,000. Precision agriculture is unlikely to generate substantial additional labor demand. Some precision agriculture equipment (i.e., variable-rate applicators) replaces other forms of equipment; neither the manufacture nor the sales of such equipment will require expanded employment. Sales of turnkey products will likely not require increases in sales personnel, although more skilled personnel may be needed to service such products. Software development and customization do not generally require extensive increases in employment.

Above all, the size of the market for precision agriculture products (both equipment and services) in the United States is limited. In 1994, there were an estimated 1.4 million households containing farm operators or managers in the United States (National Agricultural Statistics Service, 1996) and an estimated 2.1 million farm operations (Economic Research Service, 1996). But only a small percentage of those farm operations generate significant demand for farm equipment and services. In 1994, for example, 122,000 farm operations accounted for over 51 percent of total cash expenditures in U.S. agriculture and almost 58 percent of net cash income. An additional 224,000 farm operations accounted for over 22 percent of cash expenditures and 26 percent of net cash income. Thus, a total of 346,000 operations accounted for 74 percent of total farm cash expenses and 84 percent of net cash income, indicating a limited customer base for precision agriculture equipment and services (Economic Research Service, 1996). The sales volume of agricultural equipment like that used in precision agriculture is similarly limited. In 1990, less than 25,000 pieces of crop harvesting equipment and about 50,000 power sprayers and dusters were shipped in the United States. In 1991, farmers spent $604 million on planting and fertilizing machinery, $2,158 million on harvesting machinery, $167 million on cultivators and weeders, and $299 million on sprayers and dusters of all kinds—a total of $3.2 billion on the kinds of machinery that precision agriculture is likely to affect (National Agricultural Statistics Service, 1996). A market this limited in size is unlikely to support increases in employment that are large on a national scale, even if some rural communities eventually do experience substantial employment growth. As noted above, any gains in employment with precision agriculture will likely require workers with greater skills who would earn higher wages than is typical in rural communities.

Effects on the Structure of Farming

Some observers have argued that technological change, particularly the diffusion of information-intensive technologies such as precision agriculture, may increase concentration and further reduce the number of family farm operations (see, for example, Office of Technology Assessment, 1986). In an industry as competitive as agriculture, farm operations using less-profitable technologies are unlikely to remain in business. Producers using less-productive management approaches and supporting technologies may find it difficult to cover their production costs. Some producers who have difficulty adapting to new, technologically advanced farming methods may find it more lucrative to sell or rent their land than farm it themselves.

A hallmark of precision agriculture is the application of information to improve farm decision making. Precision agriculture thus tends to confer a competitive advantage on growers more at ease with or more highly skilled in the use of modern information technologies, who are likely to be younger and have more formal education. The spread of precision agriculture may accelerate older, less well-educated farmers into retirement from agriculture. It is important to recognize in this connection that exit from farming does not necessarily imply hardship, at least for farmers owning land. If precision agriculture is more profitable, its use should lead to increases in the value of land. Those exiting farming by selling or renting their land should thus be able to claim at least a share of the increased profit generated by precision farming methods.

It is also possible that the costs and benefits of precision agriculture vary systematically across farm size. There is concern in particular that the net benefits of precision agriculture are greater for larger operations. It is difficult to assess how the net benefits of precision agriculture vary across farm size because precision agriculture is a suite of technologies whose specific components differ across farms. In general, however, there does not appear to be an unambiguous size bias in precision agriculture or similar technologies.

Some considerations suggest that smaller operators will benefit less from precision agriculture than will larger operators. Precision agriculture substitutes somewhat for manual information collection and processing by the individual producer. Producers whose operations are small enough to allow them to know all parts intimately may benefit very little from automating information collection. Precision agriculture allows producers to reduce heterogeneity in farming operations, which permits improved profitability through reduced input expenditures, increased yields, or both. An alternative strategy to reduce heterogeneity, however, is to divide the farm into fields that are relatively homogeneous, permitting the same sorts of gains from uniform management. Producers whose operations are of a size that permits such intensity of management are unlikely to gain much from automation of information gathering and processing.

Other factors suggest the opposite—that smaller operators may gain more from precision agriculture than larger ones. The number of small farm operations is large. In 1992, 35 percent of all farm operators worked off the farm 200 or more days per year, whereas an additional 8 percent worked off the farm 100 to 199 days per year (U.S. Bureau of the Census, 1992). Automation may be more valuable to smaller, part-time producers, who operate under tight labor constraints and may otherwise be unable to increase their monitoring of field conditions. Automation may also narrow differentials in management by allowing smaller operators to access the same sophisticated strategies as larger operators. However, the current competitive advantage of some smaller operators—being able to focus on individual plants in high-value crops—may be lost when the adoption of information-intensive approaches enables larger operators to do the same.

There is similarly no clear-cut evidence that precision agriculture exhibits substantial economies of scale, so that larger operators find precision agriculture less costly on average (i.e., per acre) than smaller operators. Equipment such as variable-rate application units, GPS receivers, and computer hardware may decrease average costs because their capital costs can be spread over larger acreage. The data in Table 3-1 indicate that such economies of scale tend to be limited, however. Moreover, some smaller operators may be able to take advantage of economies of scale by hiring out themselves and their equipment for custom services. The cost of soil sampling depends on grid size, which in turn depends on the heterogeneity of soils within a field. Larger operators are more likely to have larger, more heterogeneous fields, and may thus find soil sampling more costly. Crop consultants typically charge a flat per-acre fee for their services, in which case the cost of these services does not vary with farm size.

Experience with similar information-intensive technologies fails to support the notion of a consistent size bias. As noted, the per-acre cost of scouting (a central component of IPM) is comparable to the per-acre cost of many precision agriculture technologies. The literature shows no consistent relation between farm size and the use of scouting. For example, Napit et al. (1988) examined factors influencing the use of scouting throughout the United States. They found that the value of farm sales was positively correlated with scouting on corn in Indiana, apples in New York, cotton in Texas and Mississippi, and alfalfa in the Northwest, but not correlated with scouting on soybean fields in Virginia, peanuts in

Georgia, apples in Massachusetts, or tobacco in North Carolina. Fernandez-Cornejo et al. (1994) found that larger vegetable producers in Florida and Texas were more likely to scout, but that farm size had no significant relationship to scouting on vegetables in Michigan, a finding they attributed to greater familiarity with IPM in Michigan. Fernandez-Cornejo et al. (1994) also found that farm size was not correlated with scouting for either insects or diseases for tomatoes in Florida. Additionally, Harper et al. (1990) found that neither the number of rice fields operated nor the acreage per field influenced adoption of sweep nets for monitoring stink bug pests on rice in Texas.

Low-volume irrigation involves much higher investment in equipment than most precision agriculture technology. Moreover, low-volume irrigation exhibits some economies of scale (i.e., pump size does not necessarily increase as farm size increases), suggesting that the returns to investment in this technology are likely greater for larger operations than smaller ones. Nevertheless, the literature gives no clear indication that larger farms are more likely to adopt this technology. Adoption of low-volume irrigation technologies has been more prevalent on larger sugar plantations in Hawaii (Shrestha and Gopalokrishnan, 1993), larger tree crop operations in the southern San Joaquin Valley of California (Green et al., 1996), and larger farms on the west side of the San Joaquin Valley (Dinar et al., 1992). By contrast, neither adoption of sprinkler irrigation in the western United States (Negri and Brooks, 1990) nor adoption of modern irrigation technologies in citrus groves in Israel shows a significant relation to farm size.

For both low-volume irrigation technology and scouting, farm size appeared to be positively correlated with adoption in areas which were in the early stages of the technology diffusion process and not correlated in areas in the later stages of the process. For example, low-volume irrigation has been used extensively in Israel for years, whereas interest in low-volume irrigation in California became widespread only during the drought of the late 1980s. Taken together, studies of information-intensive technologies such as low-volume irrigation and scouting show no consistent relationship with farm size over the long term, although they do provide some evidence that larger operators are more likely to be early adopters.

Differential access to precision agriculture products and services marketed by consultants is also a controversial issue. Some argue that consultants offer their services preferentially to owners of larger farms. Through its workshops, the committee heard from consultants who indicated that their services were offered on a per-acre basis, suggesting equal access of services to large and small farms. Few data indicate that consultants price their services according to farm size. However, it has been argued that input suppliers in competitive markets may offer their service at no charge or at a discount, so that growers in geographic areas under-served by input suppliers have less incentive to adopt precision agriculture technologies (Wolf and Nowak, 1995).

It is important to put these theoretical concerns in the context of current trends in the structure of farming. The number of farms in the United States has declined consistently over time. But the rate of decline has slowed considerably in recent years. Between 1969 and 1982, for example, the number of farms in the U.S. fell from 2.7 million to 2.2 million, an overall 18 percent decline, corresponding to an annual average rate of 1.4 percent. Between 1982 and 1994, the number of farms in the U.S. fell to under 2.1 million, a total decline of 8 percent, corresponding to an average annual rate of decline of 0.7 percent.

The Office of Technology Assessment (Office of Technology Assessment, 1986) distinguished five size classes of farms. Small farms (annual sales under $20,000) and part-time (annual sales between $20,000 and $100,000) rely primarily on non-farm sources of income. Small farms lose money on farming, at least on average. This group includes tax shelters, hobby farms operated as an amenity, and subsistence farms. Part-time farms earn 90 percent or more of their income from off-farm sources. Commercial farms (annual sales over $100,000) are divided into three classes: moderate (annual sales between $100,000 and $200,000), large (annual sales between $200,000 and $500,000) and very large (annual sales $500,000 and over). As Table 3-2 indicates, most of the decline between 1982 and 1994 occurred in small and part-time farms, while the number of commercial farms actually increased by 14 percent.

Most discussions of farm structure focus on moderate-sized commercial farms. This size category is believed to correspond most closely to the "family farm" that has long been considered the ideal of U.S. agriculture. As Table 3-2 indicates, the number of moderate-size commercial farms increased by 24 per-

TABLE 3-2 Trends in Farm Structure, 1982-1994

Size of Operation	Number of Farms (Thousand)		Percent of Sales	
	1982	1994	1982	1994
Small (Sales Under $20,000)	1,355	1,246	5.5	5.9
Part-Time (Sales $20,000-99,999)	582	472	21.9	17.9
Moderate (Sales $100,000-199,999 in 1982 Sales $100,000-249,999 in 1994)	181	224	19.1	23.3
Large (Sales $200,000-499,999 in 1982 Sales $250,000-499,999 in 1994)	94	74	21.0	15.9
Very Large (Sales $500,000 and Over)	28	48	32.5	37.1
Total	2,240	2,064	100.0	100.0

SOURCE: Economic Research Service. 1996.

cent between 1982 and 1994. Moderate-size farms increased their share of farm sales as well.

Overall, then, the spread of information-intensive agricultural technologies (i.e., computers, drip irrigation, IPM, precision agriculture) over the past 10 to 15 years has coincided with a strengthening of the commercial farm sector, especially its moderate-sized component, at the expense of part-time operations and operations too small to be commercially viable.

Processors and Vertical Integration

Increased information about market trends may lead to greater vertical coordination (i.e., contracting of designer crops and greater vertical integration in livestock industries) and in some cases removal of intermediaries (Beurskens, 1996). Producers may lose independence regarding planting decisions if commodity buyers (processors) can specify product characteristics (sugar content, size, etc.) and expect their demands to be fulfilled with precision technologies. Some find such increased specialization distasteful, arguing that increased reliance on information generated by consultants, input suppliers, and hardware dealers necessarily reduces the independence of producers.

Environmental Implications

Precision agriculture may create a win-win situation by simultaneously improving farm profitability and reducing negative environmental effect of agriculture. Potential improvements in environmental quality may be a compelling reason for society to favor widespread adoption of precision agriculture, but the extent to which producers adopt it depends on economic savings from more efficient input use, not on environmental impact.

Most of the enthusiasm for precision agriculture off the farm can be traced to the good environmental sense inherent in a concept that matches input application to plant needs. Precision agriculture could be a more disaggregated version of the kinds of best management practices already recommended at the field scale (Ogg, 1995). Furthermore, precisely matching fertilizer and pesticide inputs to the capabilities and needs of a crop for small areas, and applying them exactly when needed, is a logical way to limit the amounts of these materials added to the environment.

Agricultural pollution comes from inputs that do not reach their target (water or nutrients not taken up by plants, herbicides that do not come into contact with weeds, etc.). The inputs that contribute to pollution are thus wasted from a productivity point of view. Calibrating input usage more precisely should increase the percentage of applied inputs taken up by crops, thereby reducing economic waste and release into the environment. Adjusting fertilizer application rates to match variations in soil fertility at the subfield level should result in less excess nutrients and thus less runoff and percolation to groundwater. Applying pesticides to only those parts of fields with sufficient pest pressure to warrant treatment should result in less excess pesticide in the environment. Calibrating water application rates to match plant uptake rates (i.e., through low-volume irrigation) should reduce excess water applications and thus mitigate drainage problems (Caswell et al., 1990; Dinar et al., 1992; Shah et al., 1995).

The extent to which more precise input applications might reduce environmental conditions is by no means clear. A number of field-level experimental studies indicate that variable-rate nitrogen fertilizer application can reduce the nitrogen application rate needed to attain given yield levels. But these decreases in application rates have sometimes resulted in little or no discernible decreases in post-harvest soil nitrate concentrations, suggesting few if any, consequent benefits in terms of ground or surface water quality improvement (Kitchen et al., 1995; Redulla et al., 1996).

Synergy between VRT and biotechnology could also lead to environmental improvements. Biotechnology firms and seed companies are racing to manipulate the genetic makeup of commercial crops to include tolerance to herbicides (Sulecki, 1996). Beginning in the late 1980s, genetically engineered innovations such as imidazolidinone-tolerant corn, sulfonylurea-tolerant soybean, and Buctril-tolerant cotton varieties were developed. The natural insecticidal properties of *Bacillus thuringiensis* are being incorporated into corn, soybean, and cotton varieties. Although these genetically enhanced seeds can confer economic and environmental benefits when used on a whole field, they are likely to be more effective when applied on a precision basis. For example, if there are yield penalties associated with some of these varieties, they can be variably planted in areas with high weed infestation or areas in which sensors indicate higher organic matter that could be associated with a greater need for pre-emergence herbicide application. Precision application of seed enhanced by *B. thuringiensis* could reduce problems with development of resistance that would be accelerated if whole-field application were used. Variable-rate seeding may help match plant populations to soil conditions, and precision seeding with enhanced varieties can be used to apply seed enhanced with *B. thuringiensis* or herbicide tolerance in potential pest problem areas.

Apart from empirical studies, it is possible to envision situations in which precision agriculture both mitigates and exacerbates potential environmental problems associated with crop production. For example, variable-rate fertilization may counteract potential yield differences between steeper shoulder slopes and shallower back and foot slopes that were unfertilized or conventionally fertilized (Nolan et al., 1995). Increased soil cover, obtained on steeper slopes through VRT application, could reduce soil erosion, but increased application of nitrogen could increase losses to the environment if yield-limiting factors reduce nitrogen uptake. In another example, areas with droughty soils caused by rapid percolation may have lower levels of soil nitrogen because of greater leaching losses. VRT nitrogen application could exacerbate leaching if additional nitrogen is applied to counteract losses in these soils, or could mitigate losses if nitrogen were applied in greater synchrony with nitrogen uptake. Uncritical use of precision data indicating higher yield potential in certain parts of a field could lead to higher input use, especially if recommendations are formulated without any interest in reducing chemical use. Precision agriculture may make it economically attractive to expand production into marginal lands, which may create new environmental problems. For example, the spread of drip irrigation exacerbated groundwater depletion problems because it facilitated the expansion of tree crop production onto hillsides rather than substituting for less efficient gravity irrigation methods in flat areas.

Most studies of the environmental impacts of precision agriculture have concentrated on field-level effects. But the environmental impacts that matter most are generally those that occur in ambient pollutant concentrations. Unfortunately, there is little empirical evidence currently available that precision agriculture actually reduces delivery of pollutants to surface and groundwater and the atmosphere relative to conventional techniques. Moreover, there is good reason to believe that field-level effects do not scale up readily to ambient impacts. Just as with field-level management for potential environmental problems, the effect of reductions in erosion, residual nutrients, and pesticide applications achieved through precision agriculture focused on ambient surface and groundwater quality at the subfield level depends on the position of the field within the watershed and relative to important aquifers. Generally, reductions occurring at great overland distances from streams and lakes, or away from aquifers contributing to wellheads, will have smaller contributions to environmental improvement than similar reductions occurring closer to these water resources. Spatial patterns of farming activity within the watershed may have more of an impact on environmental quality than do improvements in environmental management within farm fields.

It is also worth underscoring that environmental improvements by themselves do not generally constitute an incentive for growers to adopt precision agriculture. In the long term, potential environmental improvements will constitute an economic incentive for adopting precision agriculture only in areas where producers bear at least a share of the costs of agricultural pollution. The problem of drainage in the San Joaquin Valley, California, is a case in point. As long as producers were able to dispose of drainage water at low cost into the San Joaquin River and Kesterson Reservoir, they had little incentive to lessen drainage problems by improving irrigation efficiency. After regulatory action resulted in severe restrictions on the use of these low-cost disposal outlets, producers began using low-volume irrigation equipment, leveling fields, shortening irrigation runs, and making other improvements in irrigation efficiency to reduce drainage accumulation (Dinar et al., 1992).

The use of precision agriculture data for environmental monitoring is also potentially a source of contention. The vast amount of site-specific data generated by precision agriculture methods may help allay regulators' concerns about the sources of environmental problems associated with agricultural production in particular areas. However, inappropriate use of such detailed data by regulators can be highly damaging to producers' interests, and fears of such misuse will undoubtedly make producers reluctant to share such data with government agencies. Ways must be found to cooperatively use data generated by precision agriculture for environmental improvement while safeguarding against abuses or inappropriate uses.

Precision data on nutrient and pesticide soil concentrations and application rates could help producers demonstrate that chemicals were applied in a legally and environmentally sound way, reducing potential liability for environmental problems. Such data could just as easily be used by regulators to prove the opposite. Decisions about data ownership and access will determine where the burden of proof lies in use of such data for environmental purposes.

CONCLUSION

Widespread adoption of precision agriculture may affect rural communities, the structure of agriculture, and environmental quality. Unfortunately, the data currently available are insufficient for judging reliably the effects of precision agriculture on farm profitability, rural employment, or environmental quality. The committee was thus able to arrive only at a few very general conclusions.

If precision agriculture becomes widely accepted, employment could increase in rural areas, especially through the provision of services such as crop consulting and software development and customization. Any changes in rural employment are likely to be modest, however. It is clear that training in computer applications will be essential for agronomists.

Precision agriculture is one of many factors contributing to change in agriculture structure. There is concern that small-scale producers will have less access to consultants providing precision agriculture services. There is no direct evidence indicating differential access. Some precision agriculture technologies exhibit economies of scale, albeit modest ones. Others are characterized by constant or decreasing returns in relation to scale. There is thus no unambiguous evidence indicating that precision agriculture favors larger operators. In general, neither economic theory nor experience with earlier information-intensive agricultural technologies indicates unambiguously that larger operations will have greater access to or advantage in using technologies such as those characterizing precision agriculture. Moreover, the spread of information-intensive technologies over the past 15 years has coincided with a strengthening of the moderate-size commercial farm sector.

The committee found no credible research that contains consistent evidence of environmental benefits from precision agriculture. Current theory suggests that environmental benefits should be expected in areas where fertilizer inputs are matched to crop needs. It is logical to conclude that precision agriculture should incorporate similar approaches to fertilization. The potential of precision agriculture technologies to reduce pesticide applications is still not well known. Some benefits may accrue from localized herbicide treatments. Precision agriculture may also lead to increases in input use, for example, by making profitable the expansion of crop production onto more vulnerable land, or by documenting prior underutilization of fertilizers or pesticides. More research will help to assess the environmental effects of management of small units compared with whole fields. Such research should concentrate on broader-scale effects, however, such as impacts at the watershed or ecosystem levels. It is by no means apparent that effects at the field level scale up to broader levels in any readily predictable ways.

Finally, experience with previous information-intensive technologies suggests that improvements in environmental quality will likely constitute a significant incentive for farmers to use precision agriculture only if producers bear at least a portion of the costs of agricultural pollution. Precision agriculture is thus unlikely to be a panacea for environmental problems in agriculture in the absence of other regulatory measures.

4

Public Policy and Precision Agriculture

PURPOSES FOR PUBLIC INVOLVEMENT

The development and diffusion of precision agriculture has proceeded with little explicit public input. Precision agriculture developed by assembling the components of technologies developed for purposes far removed from agricultural production. The private sector made a significant investment to tailor information technologies for agricultural applications, but the public sector agricultural research community contributed relatively little. It is anticipated that private sector investments in development and diffusion of precision agriculture will continue at a rapid pace. This chapter discusses roles appropriate to the public sector. The array of possible public sector roles ranges from research, education, and extension, to development of infrastructure for communications and institutional underpinnings for intellectual property rights. The committee examines the pros and cons of public participation in these roles, focusing on roles that provide public goods not likely to be addressed by private sector initiatives.

Despite interest by several pioneering Agricultural Research Service (ARS) scientists concerned with agricultural engineering uses for the global positioning system (GPS) and geographic information systems (GIS), precision agriculture has not been the subject of major U.S. Department of Agriculture (USDA) research initiatives.

Since 1990, both research and publicly funded extension efforts have been criticized for lagging behind the explosive development of precision agriculture. Innovative producers who were early adopters complain that they teach extension and research personnel and cannot obtain the research results and comparative field data that would validate claims of competing precision agriculture purveyors or systems. For example, little research has been conducted on interactions between soil characteristics that affect fertility recommendations—such as relative field elevation, nitrogen content, carbon content, and soil moisture—despite the recognition of substantial subfield variation in expected yield (Huggins and Alderfer, 1995; Larson et al., 1997; Pan et al., 1997; Vetsch et al., 1995).

Thus far, the public sector has primarily contributed to precision agriculture indirectly through large infrastructure investments outside of agriculture. The largest and most critical investment has been in GPS development and implementation, which was motivated by U.S. Department of Defense (DOD) needs for accurate and instantaneous navigational positioning across the world. The $12 billion invested since 1990 largely overlooked potential civilian spin-off applications, including those in agriculture (National Research Council, 1995c). Other public investments in remote sensing systems, particularly the National Aeronautics and Space Administration LANDSAT sensors, were at least partly motivated by potential applications in agriculture. Public investments in defense computer networks such as ARPANET, leading up to development of the Internet, benefited the entire computing and communications community, including agriculture. Other federal agencies such as the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and the U.S. Geological Survey also provided technical expertise to USDA relevant to precision agriculture. Private industry has made large investments in these technologies, as well, often leveraged on these public investments.

In 1995 the USDA Agricultural Research Service had $4.4 million directly invested in precision agriculture research projects at 15 locations (Agricultural Research Service, 1995). A general survey of ARS researchers done in mid-1996 showed 125 full-time-equivalent staff and $26 million in research activities generally related to precision agriculture, about half of which was directly related to precision agriculture topics and half to supportive research. Another 45 full-time-equivalent staff and $9 million were reported as Cooperative State Research, Education, and Extension Service (CSREES) funding for precision agriculture research to the land grant universities. However, many of the activities reported are only partially associated with precision agriculture and cannot be accurately separated from other research areas, such as integrated pest management, sustainable agriculture, conventional yield research plots and experiments, water quality research, and soil nutrient and productivity research.

As adoption of precision agriculture increases, explicit public policies could be formulated to foster or retard adoption. These should be focused on public benefits from adoption that do not compete with private industry objectives and cannot be realized exclusively by any one individual or company. An important reason for public involvement is to avoid any unintended consequences and dangers that might be caused by the increasingly widespread conversion to precision agriculture technologies. The committee identified ways that public involvement could be justified to further appropriate development and dissemination of precision agriculture already undertaken in the private sector:

- providing information on advantages and disadvantages of precision agriculture to potential adopters through research, development, and technology transfer and dissemination activities;
- providing education and human capital infrastructure;
- stimulating public data collection efforts;
- providing physical infrastructure in cases where there are substantial economies of scale; and
- protecting private property rights, particularly with respect to intellectual property such as software and data ownership.

The committee also perceived a role for government in helping set standards for data storage and transfer because of the existence of external networks. This chapter reviews each of these rationales for government intervention and discusses their applicability to precision agriculture.

RESEARCH AND DEVELOPMENT

The public sector in the United States has played a major role in research, development, and dissemination of new agricultural technologies for more than a century. Until the onset of World War II, agricultural research at USDA was the principal component of federal research and development efforts, accounting for almost 40 percent of all federal R&D spending (Mowery and Rosenberg, 1989). In 1991, by contrast, USDA research spending accounted for only 2 percent of federal research and development spending. Public sector agricultural research and development has changed little in real terms since 1980 (Fuglie et al., 1996). Agricultural research at the state level has been carried out by state agricultural experiment stations (SAESs) under the direction of the land grant university system created by the Morrill Act in 1862. The Extension Service was established as a cooperative venture between the state land grant colleges and USDA (National Research Council, 1995b).

Today the public sector apparatus for research and development of new agricultural technologies consists of USDA's research arms (Agricultural Research Service, Economic Research Service, and National Agricultural Statistics Service) and the network of SAESs. USDA helps set SAES research and development priorities through competitive grant funding overseen by CSREES. In 1992 total public research and development spending on agriculture was about $2.9 billion, or 46 percent of public and private agricultural research and development spending in the United States.

Until 1978, real expenditures on agricultural research and development from private sources equaled public expenditures (Fuglie et al., 1996). Since then, public funding has remained nearly flat at about $2.5 to 3 billion, while private investments have increased to nearly $4 billion. The totals mask a significant shift in emphasis in the type of agricultural research conducted by the private sector. In

1960, more than 80 percent of private research funding was for improving farm machinery or developing new food products or processing methods, while public research focused on increasing crop and livestock yields. By 1992, 60 percent of private research was also devoted to increasing crop and livestock yields by improving crop varieties, agricultural chemicals, animal breeding, feeds, and pharmaceuticals. These trends point toward more potential for competition between private and public agricultural research and development and a less clear-cut division of labor. Most of the research and development embodied in current precision agriculture technologies has come about either through public investments in defense and space technologies or by the private sector; there has been little investment in precision agriculture by traditional public agricultural research institutions. There is every reason to believe that private research and development investment in precision agriculture will continue to be made as long as there is potential for profit. What is not clear are appropriate roles for public research and development in precision agriculture that are not duplicative of private efforts and that can materially improve development and adoption.

Left to itself, the private sector will generally underinvest in socially desirable research for several reasons:

- Gains from research investments may be difficult to protect from competitors.
- Basic research may be too risky to justify investment.
- Potential markets for products of research may be too small.
- Traditional technologies may have fully captured the market.
- Available labor is not trained to use the new technologies.
- Clients may have no incentives to adopt products of research, particularly those that improve environmental quality.

Research and development are costly, and it is difficult for firms to appropriate the fruits of their research and development efforts because, once known, the results of those efforts can be copied easily and inexpensively. For example, competitors of a firm that has invented a new piece of equipment can reverse-engineer their own versions and thus produce equipment of equal or better capability without having to invest in the initial research and development.

Patents and other forms of intellectual property rights were designed to encourage the private sector to conduct research (Fuglie et al., 1996). Patent law is geared toward protecting inventions that embody new knowledge, not toward protecting what Huffman and Evenson (1993) term pretechnology science (i.e., scientific research applied to specific problem areas but not toward the development of products, inventions, or other patentable items), which is thus generally neglected by the private sector. For example, research on farming methods enhances knowledge about crop productivity under alternative management systems. Such pretechnology science cannot be patented, and the private sector has an incentive to engage in research of this kind only if the resulting knowledge is expected to increase sales of a particular product, such as a specific agricultural chemical or piece of farm equipment. At the same time, knowledge of this kind is too specific to be of interest from a general scientific point of view and thus tends to be neglected by purely academic researchers as well. Where the private sector does not have incentives to conduct such research, public sector research and development may be required to fill the gaps.

In some cases, research and development may be too risky for the private sector to undertake. Of particular importance are pilot inventions, the early prototypes of entirely new kinds of technology (Huffman and Evenson, 1993). For example, many crop breeding methods were developed at SAESs; private sector research on crop breeding became significant only after the introduction of hybrid seed technology provided a natural means for a firm to protect its investment, because producers were required to purchase new seed each year (Fuglie et al., 1996). In the pesticide industry, as well, innovations have come mainly from the private sector. Chemical companies do share information and conform to standards on toxicities, dangers, and other factors, and there is a private/public partnership in education and training for pesticide use. The key to cooperation and investment by the private sector has been regulation, combined with public research and extension programs which have protected producers and the environment from misuse of pesticides.

Markets for new technologies may sometimes appear to be too small to permit private firms to recoup their research and development costs, even if the invention would benefit society as a whole. In such cases, investment in private research and development will be lacking. In the long term, most of the benefits of technological improvements in agriculture accrue to consumers; competition eventually limits both producers and equipment suppliers to returns on investment equal to the cost of capital.

Traditional or conventional technologies may have fully captured the market, making it difficult for new technologies to emerge until some event occurs to disrupt markets. The long, slow development of conservation tillage illustrates the difficulty of penetrating a market that is dominated by conventional methods. Energy shocks in the mid- and late-1970s caused a disruption that conservation tillage, because of its resulting energy savings, could exploit, and conservation compliance policies added a further incentive to change from traditional tillage.

Available producer and hired labor may not have sufficient training to use new technologies, limiting market potential. Lack of training in GIS and GPS electronics may limit adoption of these technologies and retard investment in them by the private sector. Some investments in making the systems easier to use, understand, and interface with computer and other systems may overcome an initial lack of training in the labor force.

Finally, the private sector similarly has little incentive to engage in research aimed at enhancing environmental quality (i.e., by reducing pollutant emissions), even though the results of such research may be of great value to society. Because agricultural pollutants are generally not regulated, and because environmental effects are by-products of production that do not show up on the bottom line, producers may be unwilling to pay for products embodying such research. Technology development firms may thus have little or no incentive to engage in research to reduce environmental spillovers from agricultural activity. Increasing public concern for the environment may encourage technology providers and producers to adopt practices that enhance environmental quality, especially if they add little to production costs, but current legal or administrative requirements offer few direct incentives to do so (Fuglie et al., 1996).

The allocation of research and development spending suggests that the public sector has largely concentrated on the areas where market incentives fail to generate private sector research interest. In 1992 research on plant and animal production systems accounted for 34 percent and 24 percent, respectively, of SAES research and development spending, and environment and natural resources accounted for an additional 24 percent. Relative shares of spending on these research areas at SAESs have remained largely unchanged for the past 20 years. By contrast, private sector agricultural research and development in 1992 was concentrated on agricultural chemicals (37 percent) and development of end-use products (30 percent) (Fuglie et al., 1996).

A relatively new form of research collaboration is the Cooperative Research and Development Agreement (CRADA), authorized by the 1980 Stevenson-Wydler Technology Innovation Act and its 1986 amendment, the Federal Technology Transfer Act. This legislation permits federal laboratories to enter into agreements with universities, private companies, non-federal government entities, and others to link the laboratory's fundamental or pretechnology research capacity with the commercial research and marketing expertise of the private sector. The acts establish funding guidelines and rules regarding ownership of the intellectual property developed under CRADAs. Between 1987 and 1995, USDA entered into over 500 CRADAs, of which 227 remained active in 1995 (Fuglie et al., 1996). These agreements covered more than $61 million in research assets and resulted in 399 USDA patents generating $1.6 million in royalties in 1995. CRADAs were developed to increase the success of federal laboratories in introducing new enabling technologies to potential uses in the private sector (National Research Council, 1995a).

However, the National Research Council's Committee on Criteria for Federal Support for Research concluded that government resources supporting CRADAs could, in many cases, be better spent on other federal research initiatives. They based this conclusion on recent criticisms of CRADA effectiveness, difficulty in analyzing CRADA effectiveness due to data inadequacy, uncertainties over ownership of intellectual property, and the small number of new jobs created (National Research Council, 1995a). CRADA research often replaces research that private firms would undertake in the absence of governmental agreements and may be particularly problematic in situations where there are many start-up firms that could be potential CRADA collaborators. This situation characterizes many research areas in precision agriculture. Using CRADAs for precision agriculture research and development would blur the distinctions between basic and applied research that this committee propose as criteria for appropriate public and private research roles relating to precision agriculture technologies. Specifically with regard to agronomic and crop management topics, the committee concludes that the most valuable contributions public laboratories can make to precision agriculture are likely to be basic, pretechnology, nonappropriable research findings that can benefit all private sector developers of precision agriculture technologies. These findings do not lend themselves to and should not be the subject of exclusive intellectual property agreements embodied in CRADAs.

Priorities for public research and development in precision agriculture should be:

- to invest in research areas in which improved understanding of variability is likely to make the greatest difference in terms of crop production methods, farm profitability, or environmental quality; and
- to invest in research areas likely to be neglected by the private sector, despite good prospects for significant benefits to society.

While conceptually useful, practical distinctions between basic and applied research and fundamental technology development are increasingly blurred (National Research Council, 1995a). Nevertheless, this committee concurs with the National Research Council's Committee on Criteria for Federal Support of Research and Development that the federal government should encourage, but not directly fund, private-sector technology development, except in direct pursuit of government missions and to develop new enabling technologies for which government is the only available funder (National Research Council, 1995a). Their reasoning for this recommendation recognizes, as does this committee, that only where investments in research and technology cannot be fully captured by private sector firms is a prominent government role justified, particularly at the more applied end of the research spectrum. Development related to emerging technologies, such as precision agriculture, may be an exception best dealt with by government/industry partnerships, such as the Sematech industry consortium developed to pursue research in semiconductor manufacturing technology.

NEED FOR IMPROVED MEASUREMENT METHODS

The potential of precision agriculture is limited by the lack of appropriate measurement and analysis techniques for agronomically important factors. Public sector support is needed for the advancement of data acquisition and analysis methods, including sensing technologies, sampling methods, database systems, and geospatial methods.

Although many of the technologies making up precision agriculture are relatively mature (i.e., GPS, GIS, and remote sensing), there remains room for improvement in many technological areas directly related to agricultural applications. One of the most important of these is the development of local sensors that can be used on farm equipment to determine crop stage, soil conditions and chemistry, weed concentrations, presence of insects, and other variables important for crop growth. Public sector researchers should concentrate on the basic scientific principles that could underlie new sensor development and on the relationships between measurements from such new sensors and modeling of crop growth and yield. Private sector research and development is more appropriate for making the new sensors operational and marketable.

Another farm management problem of special importance is the determination of optimal sampling strategies. Some precision agriculture technologies function by permitting adjustment of farming practices (i.e., input application rates) to match variability in production conditions, such as soil nutrient levels or other aspects of soil quality. Determining the extent of variability is essential, not only at the subfield level, but at all spatial levels. Optimal sampling depends on trade-offs between potential savings in input expenditures, potential gains from increased yields due to improved management, and sampling costs (Hennessy et al., 1996).

Database and GIS systems include interpolation algorithms to predict data at intermediate points, but no existing research validates assumed projections under true agronomic variability in the presence of obvious measurement errors. Geospatial methods must be advanced and incorporated into GIS to facilitate accurate analysis and inference from collected precision agriculture data. The public sector should take the lead role in researching (a) the nature of variability within farm fields and at other spatial scales, (b) the required precision of compatible measurements that are to be included within GIS data sets, and (c) the fundamental geospatial analysis methods necessary for interlayer correlation analysis and inference.

Both the public and private sector have been involved in developing and disseminating standards for hardware, software, and data interpretation that could influence precision agriculture development and adoption. Such standards have been critical in the development of general computer technology (such as the ANSI, ASCII, and ISO 8211 data standards), and are emerging in GIS (such as the spatial data transfer standard and open GIS standards). Developing standards always involves a trade-off between ordering the chaos of individual systems and stifling creative breakthroughs in emerging technologies, and thus must be carefully managed.

From the perspective of the user, standardization would facilitate data interchange, particularly moving spatial data from one proprietary software package to another and to regional databases. Hardware interoperability would facilitate connection of technologies and equipment into a unified system (i.e., a VRT controller in a tractor cab communicating with separate rate controllers for seeds, liquid, and dry chemicals). Standards affecting data and hardware interchange affect the integration and ease of using these new technologies. Precision agriculture is technically possible today, in large measure, but requires a high degree of technical know-how and persistence, much as did the early personal computer systems.

Precision agriculture developers and vendors are torn between conflicting goals of responding to user needs and maintaining proprietary advantages, market niches, and demand for system and electronic consulting services. There are also some potential conflicts between publicly provided services and private vendors.

Most concerns in precision agriculture relate to spatial data standards, because many aspects of conventional database management and operating systems already have information technology standards developed by industry and public consortia. These include:

- government standards (i.e., the Federal Geographic Data Committee's Spatial Data Transfer Standard and ISO 8211),
- consortium standards (i.e., the Open GIS Foundation and the Agriculture Electronics Association [AEA]), and
- ad hoc or default standards (i.e., from dominance in the market, such as AutoCad DXF or Arc/Info Export).

Several paths of development and implementation could take place, with different trade-offs in timeliness, responsiveness, and enforceability.

In the arena of precision farming, the Agricultural Electronics Association was founded by the Equipment Manufacturers Institute in 1995 to bring together diverse interests in the field of electronics in agriculture. Membership has grown from 19 original members to over 100 companies, organizations, users, and university and government liaison members. Subdivisions within AEA include a User Council, Equipment Council, Hardware Council, and Software/Information Systems Council. AEA identifies, develops, and facilitates appropriate action to increase compatibility and interchangeability of electronics and information systems used in agriculture. AEA has made significant strides in promoting standardization, including addressing issues such as

- the interface between electronic equipment and specific connector, data, power and protocol requirements;
- compatibility of electronics and information systems with precision farming software;
- a standardized data "reader" interface between chemical labels and machines;
- environmental standards;
- livestock issues;
- development of a database standard;

- a common communication structure;
- standardized static and dynamic spatial data exchange formats; and
- data dictionary specifications in ISO 8211 format for yield (grain crops), soil fertility, and application crop plan characteristics.

NEED FOR UNBIASED EVALUATION

Unbiased, systematic, rigorous evaluations of the economic and environmental benefits and costs of precision agricultural methods are needed. USDA should facilitate and coordinate evaluations conducted through collaborations of public agencies, professional organizations, commercial organizations, and producers.

An appropriate role for public agencies is independent, objective evaluation of precision agriculture technologies. Private technology development firms and input suppliers have a natural commercial interest in promoting precision agriculture. Individual producers may have insufficient incentives or resources to conduct evaluations or make the results known because all producers in a region can learn from those experiences at little cost, creating a "free rider" problem. The benefits of having local information about the performance of precision agriculture technologies exceed those a single producer can gain, arguing for a public role. Moreover, producers may find it difficult to apply the experiences of a single farm to their own situations because they may not be able to make the appropriate adjustments for differences in conditions across sites. Site-specific factors can be so important in evaluating these technologies that the usual producer network will likely be inadequate for disseminating precision agriculture information.

Producers need unbiased assessments of precision agriculture's performance characteristics under various conditions. Public and private environmental organizations are also interested in unbiased evaluations of precision agriculture's environmental performance (Ogg, 1995). Acceptance and support for precision agriculture depends on the extent to which potential efficiency gains and environmental benefits are actually achieved.

USDA is in a unique position to facilitate and coordinate evaluation and research activities among federal agencies. USDA and its affiliated SAES partners have the agronomic knowledge necessary to evaluate the effectiveness of specific precision agriculture technologies and systems. Where federal agencies outside agriculture have some basic technological components and expertise necessary to advance precision agriculture, collaboration in that evaluation should be encouraged.

Producers and other customers for precision agriculture technologies should be encouraged to search for multiple sources of information when deciding whether to adopt particular components of precision agriculture technology. Producer decision-making processes are complex, and multiple sources of information would help to shape and confirm decisions. Evaluation does not necessarily imply that producers are not capable of making sound decisions or that input suppliers are untruthful in their claims. Research in the area of decision theory indicates that sound judgments are particularly difficult for humans in situations where there is considerable variability, where there are time lags between actions and results, and where there are multiple and complex cause-and-effect relationships. These three characteristics seem to apply to precision agriculture and its adoption and evaluation.

Several factors will make it difficult for public agencies to carry out such evaluations in the area of precision agriculture. The technology is changing so rapidly that evaluations of specific technology components have a very short useful life. Producers will not be well-served if equipment or products embodying technologies which have been evaluated cannot be compared with newer, more sophisticated versions that have not been evaluated. Products that have been validated in the field before submission for evaluation, whether prototypes by industry or federal expertise, should be compared on the same basis as existing commercial products. System evaluations are appropriate on technologies that are installed, maintained, and operated as specified by the manufacturer. Because the area is evolving so rapidly, technology developers may be reluctant to expose newly developed technology to public evaluation, risking loss of proprietary and trade secret information. Meaningful collaboration between private firms and public agencies, and between agencies, may not be forthcoming without considerable effort.

Over the long term, there is no substitute for carefully designed observation of economic and environmental results obtained by actual producers in real field conditions. For these experiments to be useful, side-by-side treatments and statistical control methods need to be used to distinguish precision agriculture technology's contributions from normal variation in resources, weather, and management. Given the systems nature of precision agriculture techniques and the importance of site-specific variability, on-farm experimentation performed in collaboration with producers will be necessary and desirable, compared with more traditional farms of plot-based research design (Alliance on Agricultural Information Technology, 1996). Research collaborators can mine a wealth of on-farm data and use regression analyses and other multivariate statistical methods to isolate the multiple sources of variations that influence economic and environmental outcomes of precision agriculture. These findings can provide invaluable guidance to producers on the expected benefits from adoption of precision agriculture technologies in their particular setting.

The accuracy and reliability of methods for collecting precision data need to be evaluated to ensure confidence in grid soil-sampling schemes, directed sampling, and yield monitor results (Blackmer and Schepers, 1996; Lamb et al., 1995). Similarly, the accuracy and reliability of methods for making precision applications of fertilizers, pesticides, irrigation water, and other inputs also need confirmation (Chaplin et al., 1995; Olieslagers et al., 1995). Finally, producers need confirmation that new methods of interpreting precision input information to develop recommendations for management changes are accurate and do improve economic and environmental performance over whole-field management methods (Booltink et al., 1996; Rawlins, 1996). Subfield fertilizer response relationships, economic pest control thresholds, and computer-based decision support systems derived from crop growth simulations need to be tested and evaluated under actual field conditions in a variety of circumstances (Heiniger, 1996).

Precision agriculture evaluation activities should be undertaken by both the public and private sectors. Organizations in both sectors should work together to avoid possible biases in evaluating the efficacy of the technologies.

Because of the site-specific nature of the farm fields that precision agriculture is designed to address, evaluation cannot be generalized and must be couched in terms of the specific resource conditions to which it is applied. Evaluations should compare precision agriculture systems with conventional, uniform management systems, and against each other, recognizing that precision agriculture enables changes beyond variable-rate application of inputs. Evaluation is part of an iterative continuous cycle of research, development, and deployment that is necessary for the technologies to evolve and improve.

NEED FOR NEW APPROACHES TO RESEARCH

Precision agriculture requires new approaches to research that are designed explicitly to improve understanding of the complex interactions between multiple factors affecting crop growth and farm decision making. USDA and land grant universities should give increased priority to such new approaches by reallocating personnel and budgets.

The most important research area of precision agriculture is development of theoretical and empirical knowledge to support improved crop models, farm management methods, and expert systems software. Much of the discussion of precision farming has revolved around measurement of variability through yield monitors, remote sensing, and digitized soil mapping. However, measurement means little if it does not result in better management. In this regard, precision agriculture is a systems approach to agricultural management, not dissimilar to the application of systems principles in other arenas since the 1950s, including environmental problems in the 1970s, IPM and sustainable agricultural systems in the 1980s, and watershed and ecosystem management initiatives in the 1990s. Precision agriculture is fundamentally an information technology that focuses people on the complexities and interrelatedness of agroecosystems in a holistic way. If systematic understanding of the cropping system is not captured in models, however, it is unlikely that the volumes of precision data on subfield variation can be meaningfully processed to provide improved management decisions. If such models cannot be developed, much of the potential of precision agriculture will not be realized.

Reliable crop models are the foundation of any attempt to construct data-driven, computer-based decision support systems that can effectively use precision data to make precision management changes, yet few such models exist. Theoretical and empirical understanding of crop yield responses to variations in nutrients and soil quality remains primitive. For example, fertilizer recommendations are based on rules of thumb, such as “one and a quarter pounds of nitrogen per acre for every bushel of yield goal for corn,” even though theory and evidence indicate that crop nutrient response is nonlinear and that yield will not respond to additions of some nutrients when others are limiting (Cerrato and Blackmer, 1990; Chambers and Lichtenberg, 1996; Frank et al., 1990; Paris, 1992; Paris and Knapp, 1989). Similarly, it is well-known in principle that crop productivity and crop nutrient response depend on elements of soil quality and tilth (such as structure, texture, organic matter, and water-holding capacity), yet there exists little quantitative modeling of these factors in crop production. Pest management presents a similar picture; treatment thresholds are frequently based on rules of thumb because there are no reliable crop-pest ecosystem models. Even if rules of thumb for nutrient and pest management are based on significant experimental data, the resulting recommendations are developed on an aggregated basis that ignores the other factors that vary within fields. “[Precision agriculture] departs from current nitrogen fertilizer guidelines that were primarily developed on a regional scale. . . . As a result, current nitrogen recommendations may have limited application to site-specific nitrogen management.” (Pan et al., 1997, p. 81). If modeled relationships can be developed that capture the effects of variation in factors that vary at the subfield level, better recommendations can be made.

Nutrients, pest management, and soil quality are obvious targets for public research because of their linkage to environmental quality. Nutrient pollution of both surface water and groundwater is a significant problem throughout the United States, and agriculture is a major contributor to nutrient pollution in many areas, such as the Great Lakes region, the Chesapeake Bay watershed, and the Mississippi drainage (where it contributes to Gulf of Mexico hypoxic zone problems). In many areas, reductions in nitrogen pollution resulting from improved nitrogen management could justify the use of variable-rate application and other precision farming methods even when reductions in fertilizer expenditures do not (Khanna and Zilberman, 1996). Public incentives, such as regulations, cost-sharing, or incentive payments, may be needed to spur adoption in such areas, if it is not otherwise profitable. Models of crop-pest interactions are important for devising improved ecologically-based pest management strategies. More judicious use of pesticides could reduce environmental damage. Investment in soil quality is a central tenet of sustainable farming systems. Models elucidating the relative contributions of the components of soil quality to crop yield could help improve the design of sustainable farming systems.

Development of such crop models will involve basic research into the effect of subfield variation in availability of nutrients for crop growth, the effect of variation in soil quality on crop nutrient uptake and pest (insect, weed, and disease) prevalence, and crop-pest ecosystem interactions. It will also involve applied empirical research attempting to quantify crop yield responses to nutrients, soil quality, and pest prevalence across the growing season for important crops in different locations. It will require interdisciplinary study involving agronomists, entomologists, economists, plant pathologists, weed scientists, and ecologists. Developing such models will not be an easy undertaking, and efforts requiring coordination across many disciplines are essential.

The current research model for crop sciences employs carefully controlled research plot experiments with replicated block designs in which only the factor of interest (i.e., fertilizer rate) is allowed to vary. Because precision agriculture has already been identified as a technology of some promise, detailed small-plot studies and technology-adaptation experiments may not be necessary (Gomez and Gomez, 1984; Gotway Crawford et al., 1997). Further, the system may need to evolve so that innovation and learning can exploit both traditional research plot experiments and information captured from actual field operations through precision agriculture. Precision agriculture has the potential to collect many layers of data for entire fields and record detailed variation in many variables that affect crop growth. Thus, precision agriculture could change the research paradigm from station-based plot studies to farm-based studies by (a) using more complex experimental designs, such as incomplete block designs, row-column designs, nearest neighbor designs, and split plot designs; (b) specifically incorporating spatial variability in experimental designs; (c) supplementing mean-based analyses with comparisons of entire distributions; and (d) using statistical methods such as multiple regression (Gotway Crawford et al., 1997). Under this paradigm, groups of producers would collect precision data; agronomic researchers would analyze the data with statistical methods to estimate how small changes in manageable factors affect crop yield in various resource and weather situations. The incentives for and obstacles to producer data sharing need to be fully explored and carefully understood if such cooperative on-farm research is to succeed (see sections on data ownership and privacy).

Improved farm management methods are equally necessary. At present, farm management models are based on budgeting, which assumes fixed input-output ratios. Recommendations based on improved crop models will likely need to be derived from nonlinear optimization, such as profit maximization, because such crop models will likely be characterized by variable input-output ratios which may change throughout the growing season. Stochastic optimization frameworks may be needed to take into account the random occurrence of rainfall. Dynamic optimization may also be needed to take into account changes in recommendations as the growing season progresses.

As discussed previously, it is not clear a priori that precision agriculture technologies will reduce environmental spillovers from agriculture. For example, if increased precision in application rates increases crop yields sufficiently, then producers may have an incentive to increase rather than decrease application rates. Thus, research explicitly aimed at elucidating the environmental effects of precision agriculture technologies should also be a priority (Larson et al., 1997).

Decision support system models force consideration of factors and interactions affecting the entire system. Therefore, work oriented toward developing such models requires institutional arrangements that cut across strict disciplinary lines. The relationships represented in such models are also inherently multivariate, lending themselves more toward on-farm research than plot-based studies. Reorienting research priorities toward model development and validation could thus alter institutional incentives for more holistic, farm-based, decision-oriented research efforts.

TRAINING AND EDUCATION NEEDS

In the twenty-first century agricultural professionals using information technologies will play an increasingly important role in crop production and natural resource management. It is imperative that educational institutions modify their curricula and teaching methods to educate and train students and professionals in the interdisciplinary approaches underlying precision agriculture.

For use of precision agriculture to become widespread, producers and prospective employees will need general computing skills and technical literacy. Specific skills needed by service specialists, such as high-tech equipment operators and GIS or GPS technicians, could be taught both through traditional four-year programs and vocational training. Consultants, system integrators, and others with an understanding of how to develop and apply precision agriculture will likely need postgraduate education. Successful training of users of information technologies will require disciplinary depth (i.e., agronomy, agricultural engineering, and soils) and analytic skills (i.e., spatial analysis and crop modeling), that is best provided by long-term education with emphasis on interdisciplinary synthesis. The mind-set that is needed to ensure the beneficial use of precision agriculture should be fostered in educational institutions, particularly in elements of programs that provide an understanding of technologies in a broader context. While some institutions have developed undergraduate courses and extension education programs in precision agriculture technologies, a more systematic reappraisal of their programs is needed.

The content and form of agricultural education and extension are evolving under a number of pressures. A recent National Research Council report documented problems with the current land grant system and provided recommendations for sweeping reforms (National Research Council, 1996a). Many of these were intended to provide better accountability to the broader social purposes for maintaining these institutions. Significant impetus for change comes from the declining public support for public education institutions in state and federal budgets. Increasing use of several kinds of distance education and on-the-farm research are examples of how the form of education and extension are evolving.

As part of the transition of parts of agriculture from agrarian to industrial processes, new domains such as precision agriculture are exerting a demand for new services. In this case, it is a demand for help in understanding whether and how to use the technologies and a demand for skilled graduates to design, implement, and operate the systems. Some of these training and education gaps are being filled by the private sector. A significant challenge faced by public education institutions is to evolve a role that allows them to serve a broader social purpose, to guide the technology and turn out graduates who understand precision agriculture in a broader socioeconomic and environmental context, while still providing useful practical skills to graduates and useful information to users of the technology.

Using systematic, holistic, information-driven production management as an organizing principle for agricultural education shifts the focus to encompass both the broader educational goals and the details of precision agriculture systems within a new framework. This synthesis could evolve from replacing narrow disciplinary frameworks with the concept of systems derived from crop modeling work (Stone, 1989).

Given the development of precision agricultural technologies outside traditional agricultural institutions, it is not clear who should provide scientific, technical, and managerial education needed for precision agriculture. In many cases, this expertise is provided by several university departments. Although it is unlikely that computer, geography, and engineering departments will begin teaching agronomy and other agricultural sciences necessary for precision agriculture, agricultural departments should seriously consider recruiting students with backgrounds in computer, geography, and engineering technologies that are driving precision agriculture. It needs to be determined whether, in the short run, it is more efficient to teach basics of agricultural sciences to students already familiar with the technologies used in precision agriculture or to do the reverse. Designers of continuing education curricula will perhaps have an easier task. Material will have to be developed for both technologically sophisticated students needing more agricultural science background and agriculturists needing more training in the technologies. The wisest course may be to overcome institutional barriers on campus and develop creative syntheses between computer, geography, and engineering departments and agricultural science departments for courses that draw on the strengths of each (see for example, National Research Council, 1997).

Similar to the demand being placed on research in public institutions, extension agents, consultants, suppliers, and others who “retail” information to farmers will have corresponding requests to provide help with understanding and using the technologies. Professional organizations involved in precision agriculture, such as the Alliance on Agricultural Information Technology, have already called for "clearinghouses," unbiased sources of comparative information on alternative precision agriculture methods which could be set up and operated by extension services or others who work directly with producers. A broader public purpose would be served if the clearinghouse function included unbiased comparisons of benefits, costs, and effects of precision agriculture adoption and use. Information service providers could help address specific problems that arise from precision agriculture and could play a role in promoting socially beneficial aspects, such as environmentally sound approaches. In the legal arena, templates, forms, and model contracts are needed to avoid conflicts associated with data ownership, intellectual property rights, and the protection of privacy.

The extension system would seem to be suited to such a public information role, but deficiencies in specialized scientific and technical training of current agents raises questions of capacity and capability. The rapid technological changes occurring in diverse areas of precision agriculture, including chemical pest management, environmental improvement, and farm electronics, present an enormous challenge to extension. Moreover, the need to integrate these technologies within a systems view of agricultural management makes its leadership in precision agriculture information problematic.

NEED FOR HIGH-SPEED CONNECTIVITY

High-speed data connectivity is needed in rural areas to support precision agriculture. Agricultural organizations and agencies should work collaboratively with public agencies and industries to ensure adequate rural connectivity.

The communications infrastructure such as satellites, high-speed telecommunications services, and the Internet will be essential if precision agriculture is to develop to its full potential. Extensive adoption of precision agriculture will depend on access to a modern information infrastructure in rural areas, particularly telecommunication services such as the Internet. Such communications services will similarly be essential for taking full advantage of the data-generation capabilities of precision agriculture technologies described previously.

Private industry may provide little of this communications infrastructure. Infrastructure investments are characterized by substantial economies of scale because the cost of building the infrastructure is high, whereas the cost of providing service to additional customers once the infrastructure is in place tends to be low. Firms can recoup the needed investment in infrastructure by charging sufficiently high access fees and usage charges. Such charges will tend to inhibit use, however, so that use by some firms and individuals will remain below efficient levels. Moreover, private industry may not find it profitable to provide infrastructure coverage to all of the areas of the country. In this case, benefits to society as a whole can exceed the investment costs. Rural areas may be particularly at risk because customer density is low.

Development of the communications infrastructure may be an important stimulus for rural economic development. Congress requested that the General Accounting Office study how Internet and high-speed telecommunications access for rural areas could be promoted for economic development purposes through new and existing federal programs (General Accounting Office, 1996). The Telecommunications Act of 1996, although not specifically addressing precision agriculture, regulates the competitive framework within which information technology services will be provided in rural areas. Within that framework, state telecommunications regulatory agencies, state and local governments and other rural institutions, such as university extension departments, will have an interest in encouraging rural access to advanced telecommunications. Access to skilled labor and up-to-date information about technical processes and market conditions have been important reasons for concentrating industries in certain locations in the past, leading to faster growth in urban than in rural areas (Krugman, 1993). Modern communications are reducing the advantages of geographic concentration.

If competitors of the United States in global food and fiber markets adopt precision agriculture technology more readily than do domestic producers and are perceived to gain an economic advantage, public policies encouraging precision agriculture adoption may be developed to maintain global competitiveness. The President's Council on Sustainable Development found precision agriculture to be one of the environmental technologies that offer potential for domestic economic development through increases to domestic productivity and development of export markets in environmental technology (Sustainable Agriculture Task Force, 1996).

Although the notion of universal access to telecommunications has been embodied in federal policy documents such as Principles for a National Information Infrastructure, it is unclear whether and how universal access will become a reality (U.S. Information Infrastructure Task Force, 1995). Some experts suggest that the competition created by the Telecommunications Act of 1996 will be sufficient; others believe federal subsidies comparable to the rural electrification programs will be needed. In either case, access to information services will affect rural areas. To the extent that it takes place in different forms and at different rates of implementation, equity issues will arise. Advocacy groups are already concerned about disenfranchisement of information-poor socioeconomic groups. This potential exists in rural areas, particularly areas without activities such as precision agriculture providing an impetus for commercial enterprises to provide services.

Fast, reliable Internet access in remote rural areas will affect precision agriculture approaches that rely on regional aggregation and distribution of data or communication with experts, such as crop monitoring or interpretations of field data. The Alliance on Agricultural Information Technology identified rural bandwidth, GPS differential correction, and digital orthophotography as key information technology components of precision agriculture that currently restrict its adoption (Alliance on Agricultural Information Technology, 1996). This information infrastructure is a significant focus of a Clinton administration initiative, the National Information Infrastructure Council and the related National Information Infrastructure Task Force. Although not specific to precision agriculture, these groups have provided a set of principles and recommendations that would result in significant improvement in data access for rural areas.

The components of an information infrastructure for precision agriculture include access to spatial technologies such as GPS and remotely sensed imagery, which will spill over into areas such as modernization of land records and land use planning. In much of the rural United States, local government land information systems are antiquated and unable to provide timely, reliable information for private or government land-related decision making. In some areas, precision agriculture will be a useful force in improving these systems, in addition to providing some of the automated data and spatial technologies that will be required.

CLARIFICATION OF INTELLECTUAL PROPERTY RIGHTS, DATA OWNERSHIP, AND DATA PRIVACY

Precision agriculture will require clarification of intellectual property, data ownership, and data privacy rights. The extension service should play a leadership role in providing education on existing law pertaining to these issues.

Intellectual property rights and data ownership are evolving areas of concern in terms of both information technologies and legislative and judicial activity. Precision agriculture raises some unique questions relative to data ownership because of the spatially extensive nature of the resources involved and because of its related information gathering systems, including remote sensing and third-party data providers. Despite the continuing evolution of intellectual property law, legal precedents from the computer industry and general business practice provide guidelines applicable to precision agriculture. Legal complications need not constrain adoption of precision agriculture technologies if the legal forms from other industries (copyright, trade secrets, and patents) can be translated to precision agriculture, allowing producers to abandon handshake agreements and formalize their legal rights to their data. Both the American Farm Bureau Federation and the Agricultural Electronics Association have been developing legal templates and forms for producers to use in asserting ownership over precision agriculture data. The extension service or legal experts associated with SAES could provide a valuable service by working with these and other groups, adapting the model legal forms for data disclosure relating to precision agriculture data, and ensuring that they receive widespread dissemination and adoption.

Data ownership issues could affect the adoption and value of precision agriculture. A balance between protections for individual data ownership and benefits to multiple users must be found. Two scenarios could result:

- If ownership cannot be or is not protected, there may be a chilling effect on the willingness of individuals to provide field and farm data to aggregate databases, whether publicly or privately established.
- If ownership protections require producers to jealously guard their individual data, broadening the value of individual data collection through regional aggregation for area-wide crop management research or recommendations will be retarded and made prohibitively expensive.

Providers of information services, such as fertilizer dealers providing precision application services, generally recognize the land owner or farm manager as the de jure owner of data. This probably is supported by law, because the producer is buying the information services from the provider. Ownership issues may be further complicated by contractual arrangements between producers and providers, data acquisitions or exchanges by providers or third parties, and attempts to copyright data compilations. However, mere possession of the data by service providers, supported by the provider's intellectual investment in storing and analyzing the data, may lead to appropriation of data rights, unless the operator's rights are specified with appropriate legal documents.

Although these concerns are novel for agriculture, many of the same issues have been faced by other industries. Some tools, such as copyright, cannot protect raw data but can protect the expression of ideas or concepts embodied in the data, such as a set of recommendations, a computer model, or a compilation of the data. Trade secret protection does not apply to raw data unless the producer can show that the data he collects, or pays to have collected for him, meet the specific criteria for trade secrets. The data must derive independent actual or potential economic value from not being generally known to other persons who could profit by it, and the producer must show that reasonable efforts were made to maintain that secrecy, such as a nondisclosure agreement, a license agreement, or some other legal instrument that restricts access and disclosure to others. Once such legal forms deriving from other industries are adapted to the peculiarities of precision agriculture, many of the issues of data ownership will be resolved.

Because of the proprietary nature of computerized systems, the producer may get data in a format useable only by the provider, who may then exercise de facto control over the data. These are not legal ownership issues, but issues of technology and technological competence. The producer's recourse, in this example, may be the expensive one of paying for data conversion to the nonproprietary format so another provider can work with the data. This may be financially onerous but it presents no legal barriers to clear data ownership.

The value of individual field and farm data increases when it is collected across a region and integrated with data from other sources and other farms (see section on data assembly and aggregation, below). Aggregating data has implications for ownership as well. Some farm organizations have asserted a right to create such collections, presumably to provide better information services to members and to develop regional strategies (American Farm Bureau Federation, 1995).

Once the producer fails to assert ownership over precision data, compilations and abstractions from that data may be difficult to protect. If data are not handled as trade secrets, they become part of the public domain and proprietary rights are lost. Although raw data cannot be copyrighted, compilations of raw data that have been selected and arranged in creative ways can be protected through copyright (Feist Publications, Inc. v. Rural Tele. Serv. Co. Inc., 499 U.S. 340 [1991]). Vendors with regional databases can protect content to the extent allowed by merger doctrine. "When the expression of an idea is inseparable from the idea itself, the expression and the idea merge . . . ." (Holland, 1994). That is, copyright can protect a unique way of managing, analyzing, or displaying the data that merges inseparably with the data and that cannot otherwise be copyrighted.

Intellectual property rights in precision agriculture products and software are protected in the same way that other computer hardware and software are protected. Copyright and patent laws apply to these creations just as for creative products of other industries. In general, the more basic the scientific finding underlying a new development, the less protection these traditional property rights instruments afford. Patents and other forms of intellectual property rights to knowledge were created to mitigate the problem of underinvestment in research and development. Patents confer a temporary monopoly (17 years) on the fruits of research, allowing patent owners to recover the costs of research. As discussed above, intellectual property rights do not apply to pretechnology science (Huffman and Evenson, 1993).

Another body of law governs privacy issues associated with ownership and use of data by governments relative to individuals. Traditional privacy issues such as personal information on health and income are protected from disclosure by statute. For example, responses to the Census of Agriculture are protected from disclosure and can be published only in aggregate form. Land information in the public record is generally considered part of public domain (i.e., land ownership and real property taxes), including farm ownership and management information for federal conservation cross-compliance and many state programs.

Some forms of remote sensing may already cross the threshold into invasion of privacy (depending on purpose, access, etc.). This may depend on the degree of intrusiveness or "subjective expectation of privacy" (Gabrynowicz, 1996). Regulatory access is often a test of the Fourth Amendment (illegal search and seizure). The boundaries between public and private collection and use (open records laws) may make it difficult to determine what is subject to the Freedom of

Information Act. A patchwork of laws, often poorly enforced, addresses restrictions on public agency use and disclosure of individual data (Onsrud et al., 1994). In GIS, private sector operations, fearing loss of data or proprietary advantage, have been reluctant to participate in multipurpose land information systems where their data would be intermingled with other data in a public system (i.e., private utilities participating in local land records systems). By analogy, public-private cooperation in precision agriculture could be inhibited.

Several groups advocated changes to current law to clarify intellectual property rights in databases. The National Information Infrastructure Task Force suggested several revisions to copyright law to incorporate changes related to information technologies without fundamentally changing the system (U.S. Information Infrastructure Task Force, 1995). The American Farm Bureau Federation (1995), in a white paper on information technologies, advocated statutory revision of the Copyright Act to protect databases developed from collections of farm- and field-specific information. The American Committee for Interoperable Systems argued that copyright should not be used to inhibit interoperability of operating systems and software across computer platforms (American Committee for Interoperable Systems, 1994).

Producers have expressed reservation that precision agriculture data may be used by government agencies for regulatory purposes. These new sources of information, however, will have the same privacy protections against use by government agencies as traditional sources of farm information, such as farm records, weigh bills, and other private documents.

NEED FOR DATA ASSEMBLY AND AGGREGATION

Data collected for use at the subfield and field levels have additional value for research, testing, evaluation, and marketing when assembled into regional databases. Mechanisms are needed to create these databases and make the data available for these additional uses including data collection and transfer standards; institutions for collecting, managing, or networking data; and policies to facilitate data sharing and access, while protecting proprietary interests and confidentiality.

As valuable as precision agriculture data may prove to be to individual landowners, much of the potential value of the huge amount of electronic data that could be collected by these technologies will not be realized unless the individual farm databases are consolidated into regional databases. These would not be averages or other statistical summaries of detailed data, but massive compilations of the detailed data itself, without information identifying individual farms from which the data are collected. Summaries might be made from these data for some purposes, but the detailed data needs to be accessible for analysis and modeling of relationships between inputs and outputs, including environmental outcomes;

the data also needs to be sufficient to control for other sources of variation. Analysis and modeling of crop responses to a variety of soil, weather, pest, and other crop management factors can best be done when the most complete range of variation is present in the data. An individual producer's database is limited to the trials and management actions that form the recent history on his or her farm, whereas a regional database would encompass a far greater variety of management responses to similar conditions. A regional database might include conditions that did not occur on an individual farm one year but could occur in the following years. Researchers, extension agents, input suppliers, commodity companies, and government officials as well as producers will be interested in such regional databases if they can be made available.

Despite the apparent benefits accruing from combining data into regional databases, it is by no means certain or inevitable that such data will be assembled. Information service providers that currently collect or are given precision agricultural data have proprietary interests in restricting access to their customer base, or in getting remuneration for access. In the absence of legal safeguards for data privacy, producers may be reluctant to share data on their operations in a freely accessible, voluntary regional database. Public agencies may not have the organization, knowledge, or resources to develop regional data sharing cooperatives that could allow effective use of such data.

Two kinds of obstacles stand in the way of creating regional databases from farm and field microdata. The first, and more surmountable, are technical barriers such as computer capacity (whether centralized or distributed as a network) and transfer standards and protocols. Second are institutional barriers, such as lack of clear leadership roles in establishing the databases, legal issues of data ownership and privacy discussed above, and issues of compensation and access. Many of these issues were discussed in relation to recommendations above and will not be repeated here.

Although many questions remain to be answered, data aggregation is already occurring, particularly in areas where precision agriculture is implemented by input suppliers that are, by default, collecting regional databases. There is thus some urgency to resolve outstanding issues before problems with existing data aggregations surface.

NEED FOR REVIEW OF PUBLIC DATA COLLECTION

The methods and purposes of publicly funded data collection activities should be periodically reviewed and adjusted to ensure that data are accessible and useful for precision agriculture as well as supportive of other public and private purposes. The National Cooperative Soil Survey should revise existing procedures to make more effective use of information technologies, farm-generated data, and new concepts in soil science.

Public sector investment in data collection and management is often driven by legislative mandates or specific operational missions. As the ability to collect, manage, and particularly share data improves with improvements in information technologies, and as budgets for public data collection decline, it becomes even more important to gather data that balance specific agency and program requirements with broader purposes. While the current extent of precision agriculture adoption limits what can be accomplished, agencies need to carefully examine precision agriculture, both to ensure that the agencies are providing data useful to producers using precision methods, if that is appropriate, and to assess the potential for using data collected on the farm to supplement or replace existing data collection efforts.

Finely detailed information about soil properties is fundamental to some types of precision agriculture. To generate such data, producers or consultants have used various strategies for fine-scale soil sampling, including grid sampling at various spatial frequencies and sampling schemes keyed to landscape characteristics, such as topography and drainage. In other forms of precision agriculture, the data may come from sensors, such as yield monitors, on-the-go sensors, or aerial photography. These applications may still benefit from detailed soils information available in a form that can be integrated with other digital data. For soils and other kinds of agricultural data that federal agencies have traditionally collected, widespread adoption of precision agriculture should motivate review of existing efforts and exploration of new opportunities in using precise data gathered on farms.

As an example of how precision agriculture has the potential to both change what data products are provided and how data is collected, we examine the National Cooperative Soil Survey (NCSS). NCSS, a partnership of the Natural Resources Conservation Service (NRCS) with local and state agencies and land grant institutions, has been generating soils information for several decades. Although originally focused on supporting agricultural uses of soils data, the mission of NRCS and NCSS is now a much broader one, that of managing the nation's soil resources and providing data and technical support "to help people conserve, improve, and sustain our natural resources and environment" (Natural Resources Conservation Service, 1995).

The NCSS products are not useful for precision agriculture for several reasons. First, the published Soil Taxonomy and the methods in the NRCS Soil Survey Manual are focused on the pedon concept and soil classification. These publications tend to be oriented toward soil homogeneity, whereas precision agriculture needs additional information about soil variability. Second, NCSS has had a goal of nationwide uniformity in their products, although the requirements of potential users vary widely. The result may be products that are compromises between the needs of many users but that do not completely suit any user. For example, the map scales chosen for detailed soil surveys (typically in the range of 1:12,000 to 1:24,000) are convenient scales for surveying and cartography but do

BOX 4-1
Federal Data Collection Efforts

Most federal data collection efforts centering around agricultural production are derived from an extension model where enumerators or scientists from federal agencies collected relatively sparse data from farms, summarized and analyzed the data, and published findings for state or regional aggregates, sometimes by broad classes of farms. The producer's role in this process was passive: responding to questions posed by agency personnel and receiving published reports, sometimes with assistance from extension personnel to see how the results applied to their producer's particular farm.

Precision agriculture data collection has the potential to revise this model in several important ways, because producers are now able to collect far more specific and detailed data more efficiently than federal agencies can. In this new paradigm, producers, or their consultants and suppliers, would collect the data on a precision basis, perhaps according to some standardized metadata protocol. The data would be gathered in centralized databases or data warehouses run by agencies, cooperatives, industry groups, or private enterprises. Agencies may pay producers for data collection or may pay intermediary data cooperatives or firms for access to the databases. Agencies may produce the same kinds of summary reports for the public as in the past, but may make available more specific and detailed analyses for individual producers, or may provide detailed databases for producers and their advisors to use. The producer's role in this system would be more active because the data collection would be designed primarily to serve the producer's information needs and only secondarily to contribute to a larger database. The agency's role would be less about deciding what questions to ask and more about investigating what can be learned from the available data. Some of the more prominent examples of federal agency data collection efforts that could be transformed in a world where precision agriculture is widely adopted are briefly explored below.

NATIONAL AGRICULTURAL STATISTICS SERVICE

The primary sources of information for the National Agricultural Statistics Service (NASS) are farmers and ranchers, livestock feeders, slaughterhouse managers, grain elevator operators, and other agribusiness personnel. NASS relies on survey respondents' cooperation in voluntarily supplying data for the reports, and NASS holds confidential all data on individual operations. Objective yield surveys are conducted during the growing season to monitor crop conditions and yields in thousands of fields by enumerators who count the number of plants and, later in the season, count and measure ears, pods, bolls, and so on. The crop devel-

BOX 4-1 Continued

opment data gathered through these objective yield surveys are used to forecast yields or project production (i.e., for wheat, cotton, soybean, potato, burley tobacco, onion, and a variety of fruit and nut crops). When the farmer harvests fields containing the plots, enumerators make their final visits to the sample plots to determine harvesting losses and estimate net yields. With new authority to conduct the Census of Agriculture, formerly in the Bureau of Census, NASS will collect information on the acreage in various farm uses, crops and livestock produced, and sales of agricultural products, as well as socioeconomic information on each farm operator and his or her family.

Information gathered by satellites supplements that collected by enumerators. Current satellite technology (LANDSAT and NOAA-AVHRR) applied to crop estimates has certain limitations; more frequent coverage is needed, and satellite scans can be rendered ineffective by cloud cover. Until commercial satellites overcome these restrictions, the NASS remote sensing program will remain limited. However, the data are excellent for timely views of large areas that are behind or ahead of previous seasons, or areas that are under stress caused by drought, excessive moisture, or disease. Widespread adoption of precision agriculture methods could provide more detailed data from a larger number of producers, while integrating soil and weather data which could lead to greater understanding of the causes of spatial and temporal variations in crop and livestock production. While the potential for such data collection is currently limited, NASS should investigate possibilities for precision agriculture data to augment conventional data collection methods in the future.

Economic Research Service

The Economic Research Service, working with NASS, annually collects data on farm costs and returns, land values, and resource and environmental aspects of farm production practices such as fertilizer and pesticide use. Surveys are designed jointly with NASS, and NASS enumerators collect the data in regular and special surveys. Geographic information systems and farm record databases developed on the farm could provide information superior to current surveys because they would provide data on soils, weather, and other important variables integrated directly with the economic data. Currently, physical factors affecting economic decision making must be inferred from other data sources.

National Resources Conservation Service

The Natural Resources Conservation Service (in addition to the Cooperative Soil Survey) conducts the National Resources Inventory (NRI), an area-based statistical sample of land cover and use, soil erosion,

continued on next page

BOX 4-1 Continued

prime farmland, wetlands, and other natural resource characteristics on nonfederal rural land in the United States (excluding Alaska). Inventories such as the NRI have been conducted since 1945 and are now conducted at five-year intervals.

The 1992 NRI is the most extensive inventory yet conducted, covering some 800,000 sample sites and representing some 75 percent of the nation's land area. Many of the data elements and definitions used to collect the 1992 data were developed to be comparable with data contained in the Commerce Department's Census of Agriculture and with databases managed by the USDA Forest Service, USDA National Agricultural Statistics Service, and the Interior Department's U.S. Geological Survey and U.S. Fish and Wildlife Service.

Precision GIS and farm record databases could provide information superior to that of the current National Resources Inventory because they could provide data on actual soil qualities such as nutrient content, organic matter, pH, and electrical conductivity directly at the site, rather than through inference from typical properties of that soil type. Precision farm data could also integrate economic data on input use, yields, and production with the physical data. Currently, data on inputs and outputs must be inferred from other data sources.

not have enough detail for site-specific decision support (i.e., precision agriculture, construction suitability, septic disposal, and land filling). On the other hand, these spatial scales have too much detail for more summary analysis (i.e., land use planning, land suitability, and regional groundwater analyses). Generation and automation of data at this intermediate scale may be wasted effort that satisfies few potential clients.

NCSS does not address precision agriculture's requirements for soils data. Soil interpretations provide typical characteristics of soils at surveyed sites but do not record observations of the characteristics of individual soils at these locations. The orientation is toward the other end of the detail-resolution spectrum, providing data for resource and environmental applications across extensive areas. In their examination of aspects of NRCS data activities, a blue ribbon panel articulated similar recommendations for changes within NRCS (Natural Resources Conservation Service, 1995).

Under the leadership of NRCS, NCSS has been making some steps in the right direction. For example, the Soil Survey Program Plan includes surveys that document information on soil landscape relations as well as soil taxonomy. This should result in better information on the reliability and variance structure of soil data. NRCS has been developing the National Soil Information System, a set of GIS and statistical tools for providing access, analysis, and manipulation of county-based soil survey information, including digital spatial data. The shift in orientation toward characterizing soil landscape relations and soil variability should benefit some kinds of precision agriculture (i.e., systems that include manipulation of soil-water relations through modeling of surface hydrology and soil characteristics). It is likely to be many years, however, before this kind of information is widely available and useable in a management context.

For NRCS and NCSS to provide useful information for a broad spectrum of precision agriculture, they will need to carefully review the needs of precision agriculture systems and methods. It is probably not appropriate or even feasible for NCSS to map soils at the level of detail required for many types of precision agriculture or to collect detailed soil characteristics in a fine grid. This activity has little public benefit and there is little justification for public investment. However, NCSS could play an important role in providing the information infrastructure for such detailed work by developing (a) data quality standards for detailed work in addition to the standards for development and automation of their current products; (b)methods for data collection, testing, and interpretation; and (c) procedures for accessing and archiving data by private soil consultants.

NRCS and other public agencies could also benefit directly from more detailed data collected on farms. Farm-generated data could be used to more effectively characterize soil variability and soil landscape relations within a region such as a major land resource area; in effect, the farm would serve as a research site. Such a public-private partnership would require NCSS to interact with a new group of users and to relax their push for uniform products. This scenario is based on the assumption that privacy and intellectual property rights issues could be resolved in such a way as to allow NRCS and NCSS access to at least portions of data collected privately. Site-specific data might be used only in model development and statistical inference and thus be made generally available only in aggregate or processed forms (this may require a Freedom of Information Act exclusion for the microdata about specific farms held by NCSS).

Issues parallel to those for collection of soil survey data exist with other data collected on farms by federal agencies. Agricultural statistical agencies should take steps now to assess the likelihood and speed of development of precision agriculture data collection and devise approaches to tap the enormous potential of such data flows. Pilot projects to develop data warehousing techniques and protocols could yield large dividends in accommodating an eventual shift from survey- to precision-based data collection. As precision agriculture becomes more widely adopted, precision data could at first supplement, and perhaps later entirely supplant, more traditional data collection paradigms based on agency surveys.

Federal agencies cannot immediately use precision agricultural data because the number of operators who have fully adopted precision agriculture and thus the acreage covered are minimal. Even if precision agriculture were widely adopted, numerous obstacles must be overcome before the data collection paradigm could change as described above.

For agencies to use producer-collected data, some institution will have to impose metadata standards specifying a minimum level of consistency in content, format, and protocols which producer-collected data must meet. This is not a trivial problem, as evidenced by the amount of time and coordinating efforts required to develop a spatial metadata standard for the data that federal agencies already collect themselves (Federal Geographic Data Committee, 1994; Federal Register, 1994; National Research Council, 1994). Whether government agencies take the initiative to develop data warehousing systems or cooperative or private enterprises emerge, order must be imposed to prevent the chaos that could result from simply gathering what individual producers collect.

Developing standards is fraught with many problems. First, the technologies used in precision farming are evolving so rapidly that standards may always lag implementation in the field. Second, companies in the hardware and software industries providing precision agriculture technology may want to maintain proprietary standards wherever there is a competitive advantage to do so. Encouraging developments from the Agriculture Electronics Association show, however, that there can be industry-wide cooperation on standards. Finally, the problems of data ownership, data privacy, and data sharing discussed above may limit producers' willingness to contribute data or to be bound by any standard.

If such a metadata standard does evolve, several legal barriers could thwart use of individual producers' databases. Protecting data confidentiality is a matter all federal statistical agencies take seriously. Access to microdata records and safeguards against disclosing an individual's identity in summary statistics are already issues with agencies collecting data. The problems will be much more complex if producers provide data directly from their own computer records. Any systematic use of precision agriculture data must safeguard the producer not only from the general public and competitors, but from other federal and state agencies that exercise regulatory and taxing power. Producers' precision data will not be forthcoming if the data can be used by the EPA to fine polluters or the Internal Revenue Service to second-guess tax returns.

Property rights concerning the data are also a consideration and a potential barrier. To the extent that producers perceive that there is economic value to the data beyond their farm gate, they could require payment for use of the data. Even if producers are willing to contribute data to the common good, they incur costs for collecting the data, developing systems to record and store the data, and transmitting the data to warehouses; the warehouse may then require reimbursement by agencies that use the data. Accommodating this reality will require a large adjustment on the part of agency administrators who currently obtain survey data from producers at no direct cost.

Finally, the sheer size of databases that could be developed from precision farm data collection is a barrier to agency use. The process of turning the resultant mountains of raw data into useable and useful information, without sacrificing its inherent geographic specificity and detail, is a formidable challenge unlike the one currently facing agricultural data agencies. The limiting constraint today is additional resources for more samples, whereas the limiting constraint in a precision agriculture data world may be the computer methods and power needed to store, process, and summarize the available data. The vaults of LANDSAT data tapes residing at the USGS Earth Resources Observation System data center in Sioux Falls, South Dakota, provide an instructive analogy. The raw download of data from almost 20 years of satellite operations, even though accessible, is so daunting a processing and interpretation task that only a small fraction of these data have been converted into relevant information. Summarizing the flood of data that could derive from two million precision farm databases would be that much more daunting.

POTENTIAL FOR PRECISION AGRICULTURE

The committee believes that precision agriculture offers new information technologies to address information needs for management of agricultural crops. Widespread adoption of precision agriculture technologies will constitute a new way to practice agriculture at ever finer spatial and temporal resolutions, and to improve use of information for crop management at all spatial scales. These new capabilities offer the potential for a more economically and environmentally efficient agricultural sector. However, precision agriculture technology is new and largely unproven. Widespread adoption depends on economic gains outstripping the costs of the technology. Exploiting the full potential of precision agriculture for environmental management will require fundamental shifts in public and private incentives for environmental management, and may require cost-sharing or other incentives for adoption. Lessons from the adoption of other agricultural and information technologies urge caution in anticipating the growth of precision agriculture use. Widespread adoption of precision agriculture methods will create changes in farm operations and in social institutions that can be anticipated and, where they are negative, mitigated. Many of the important findings in this report deal with the range of public policy responses to precision agriculture's evolution and adoption.

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APPENDIXES

Glossary

(CEC) cation exchange capacity, represents the total value of exchangeable hydrogen, calcium, magnesium, potassium, aluminum, and sodium cations in the soil. Cation exchange occurs on the surface of humus colloids and clay particles as well as on plant root surfaces.

center pivot irrigation, refers to a sprinkler irrigation system that consists of a long pipe with multiple water outlets that is pivoted about a center point by the motion of rolling towers that elevate the pipe above the crop.

(CIMIS) California Irrigation Management Information System, is a computerized crop weather information system available to the public and operated under the collaboration of the State Department of Water Resources, the University of California, local water districts, and various other agencies.

(CRADA) Cooperative Research and Development Agreement, is a type of federal agreement authorized by the 1980 Stevenson-Wydler Technology Innovation Act and its 1986 amendment, the Federal Technology Transfer Act. CRADA permits federal laboratories to enter into agreements with universities, private companies, nonfederal government entities, and others to link laboratory's fundamental or pretechnology research capacity with commercial research and marketing expertise of the private sector. The acts establish funding guidelines and rules regarding ownership of the intellectual property developed under CRADAs.

crop model, refers to a mathematical representation used to simulate crop growth.

(DGPS) differential global positioning system, is a method to improve the position accuracy of GPS by using a second stationary GPS receiver positioned at a known location. The second receiver computes the error in the signal by comparing the true distance from the satellites to the GPS measured distance.

(DSS) decision support systems, is an integrated system of expert knowledge, management models, and timely data to assist producers with daily operational and long-range strategic decisions.

drip irrigation, is a form of microirrigation in which water usually is delivered to the soil near the plants through a network of tubing with closely spaced, low-flow rate emitters.

evapotranspiration, refers to water loss from soil evaporation and crop transpiration. Evapotranspiration is typically monitored using networks of weather stations that cover large areas.

floater, refers to high flotation vehicles typically used by custom chemical and fertilizer dealers for field applications.

georeferencing, is the process of associating position information with data of any kind. Georeferencing is necessary to represent spatial relationships between data points.

(GIS) geographic information systems, hardware, software, data, organizations, and institutional relations to automate, manage, analyze, and display georeferenced information of and about the earth.

(GLONASS) GLObal Navigation Satellite System, is a space-based radionavigation system operated and managed by the military of the former Soviet Union.

(GPS) Global Positioning System, is a space-based radionavigation system originally designed primarily to provide highly accurate radionavigation capability to U.S. military forces, while also providing an unencrypted signal of degraded accuracy to civilian users. Positioning is achieved through the use of simultaneously received satellite transmissions from four or more satellites above the horizon. The GPS receiver allows latitude, longitude, and altitude coordinate information to be associated with data obtained from a specific site on the field.

grid soil sampling, refers to the method in which a field is divided into square sections (grids) of several acres or less. Samples may be collected from each section and analyzed for soil nutrients such as phosphorus and potassium.

ground-based sensors, refer to devices mounted on machines that travel over the ground and that measure local soil or plant conditions.

(IPM) integrated pest management, refers to pest management strategies based on judicious use of chemical pesticides with other management tactics such as cultivation methods, crop and varietal choice, attraction of natural enemies or other biological control methods, pheromone traps, and other ecologically-based measures.

kriging, is a geostatistical technique used to fit a model to a semi-variogram (a depiction of the spatial correlation between multiple data pairs), and using this function to interpolate values at unknown points as a function of spatial correlation.

multispectral, refers to an electromagnetic sensor that collects data in multiple spectral wave bands, typically visible and infrared, simultaneously.

(NDVI) normalized difference vegetation index, is the ratio of the difference between the red and near-infrared bands divided by their sum used to identify and enhance the vegetation contribution in a digital remote sensing analysis.

panchromatic, refers to an electromagnetic sensor that collects data in a single wave bands that span the colors of the visible spectrum.

post processing, is the differential correction of GPS positions at some time after the data are recorded.

real-time, describes sensing or control actions that occur instantaneously, or nearly instantaneously. An example of real-time sensing and control would be a device that optically recognizes a weed and immediately directs a spray onto that weed.

remote sensing, is the acquisition of information by a recording device not in physical contact with an object being studied. Devices such as cameras, radar, lasers, or radio receivers can collect information from remote locations such as airplanes or satellites.

scouting, as referred to in agriculture is a visual assessment of crop condition including growth stage/maturity, plant vigor, and presence of disease, weed, and insect pests.

(SA) selective availability, is a purposeful degradation in GPS navigation and timing accuracy that is accomplished by intentionally varying the precise time of the clocks on board the satellites, which introduces errors into the GPS signal. With selective availability, the civilian signal is limited to an accuracy of 100 meters, 95 percent probability. Military receivers with the appropriate encryption keys can eliminate the effects of SA and obtain an accuracy of approximately 21 meters (95 percent) probability.

spatial variation, refers to differences in field conditions, such as crop yield, from one location in a field to another.

temporal variation, refers to differences in conditions, such as soil nitrogen, from one sampling period to another.

turnkey system, refers to the integration of information technologies into a system that is ready to operate.

(VI) vegetation index, is a ratio created by dividing the red by the near-infrared spectral bands used to identify and enhance the vegetation contribution in a digital remote sensing analysis.

(VRT) variable-rate technology, refers to a system that varies the rate of agricultural inputs such as seed, fertilizer, and crop protection chemicals in response to changing local conditions.

yield mapping, refers to the process of collecting georeferenced data on crop yield and characteristics, such as moisture content, while the crop is being harvested. A yield mapping system combines the output of a yield monitor with the position information provided by a DGPS receiver.

yield monitors, are devices that estimate the yield per area by measuring the flow rate of the crop and the area covered by the harvester.

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