Computers and Electronics in Agriculture
36 (2002) 113–132

Computers and electronics in agriculture

www.elsevier.com/locate/compag

Precision agriculture—a worldwide overview

Naiqian Zhang [a,*], Maohua Wang [b], Ning Wang [a]

[a] Biological and Agricultural Engineering Department, Kansas State University, Manhattan, KS 66506, USA
[b] Research Center for Precision Agriculture, China Agricultural University, Qinghua Donglu, Beijing 100083, People's Republic of China

Abstract

This article provides an overview of worldwide development and current status of precision-agriculture technologies based on literatures generated mainly during the past 2 years. The topics include natural-resource variability; variability management; management zone; impact of precision-agriculture technologies on farm profitability and environment; engineering innovations in sensors, controls, and remote sensing; information management; worldwide applications and adoption trend of precision-agriculture technologies; and potentials of the technologies in modernizing the agriculture in China.

Keywords: Precision agriculture; Site-specific crop management; Sensor; GPS; GIS; Remote sensing

1. Introduction

Agriculture production systems have benefited from incorporation of technological advances primarily developed for other industries. The industrial age brought mechanization and synthesized fertilizers to agriculture. The technology age offered genetic engineering and automation. The information age brings the potential for integrating the technological advances into precision agriculture (PA) (Whelan et al., 1997).

The factual base of PA-the spatial and temporal variability of soil and crop factors within a field—has been appreciated for centuries. Before the completion of agricultural mechanization, the very small size of fields allowed farmers to vary

* Corresponding author. Tel.: +1-785-532-2910; fax: +1-785-532-5825
E-mail address: zhangn@ksu.edu (N. Zhang).

0168-1699/02/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S0168-1699(02)00096-0

treatments manually. However, with the enlargement of fields and intensive mechanization, it has become increasingly more difficult to take account of within-field variability without a revolutionary development in technologies (Stafford, 2000).

PA is conceptualized by a system approach to re-organize the total system of agriculture towards a low-input, high-efficiency, sustainable agriculture (Shibusawa, 1998). This new approach mainly benefits from the emergence and convergence of several technologies, including the Global Positioning System (GPS), geographic information system (GIS), miniaturized computer components, automatic control, in-field and remote sensing, mobile computing, advanced information processing, and telecommunications (Gibbons, 2000). Agricultural industry is now capable of gathering more comprehensive data on production variability in both space and time. The desire to respond to such variability on a fine-scale has become the goal of PA (Whelan et al., 1997).

After more than 10 years of development, PA has reached a crossroad with much of the necessary technology available but with the environmental and economic benefits yet unproven (Stafford, 2000). Many technological innovations have been presented but development of agronomic and ecological principles for optimized recommendations for inputs at the localized level is generally lagging. Many farmers are uncertain as to whether to adopt available PA technologies on their farms. Motivations for widespread uptake of PA technologies may come from strict environment legislation, public concern over excessive use of agro-chemicals, and economic gain from reduced agricultural inputs and improved farm management efficiency. After all, success of PA technologies will have to be measured by economic and environmental gains.

2. Spatial and temporal variability

Variabilities that have significant influences on agricultural production can be categorized into six groups.

2.1. Yield variability

Historical and present yield distributions.

2.2. Field variability

Field topography—elevation, slope, aspect, and terrace; proximity to field boundary and streams, etc.

2.3. Soil variability

Soil fertility—N, P, K, Ca, Mg, C, Fe, Mn, Zn, and Cu; soil fertility as provided by manure; soil physical properties-texture, density, mechanical strength, moisture content, and electric conductivity; soil chemical properties—pH, organic matter, salinity, and CEC; soil plant-available water-holding capacity and hydraulic conductivity; and soil depth.

2.4. Crop variability

Crop density; crop height; crop nutrient stress for N, P, K, Ca, Mg, C, Fe, Mn, Zn, and Cu; crop water stress; crop biophysical properties—leaf-area index (LAI), intercepted photosynthetically active radiation, and biomass; crop leaf chlorophyll content; and crop grain quality.

2.5. Variability in anomalous factors

Weed infestation; insect infestation; nematode infestation; disease infestation; wind damage, and hay damage.

2.6. Management variability

Tillage practice; crop hybrid; crop seeding rate; crop rotation; fertilizer application; pesticide application; and irrigation pattern.

Among these variability types, yield variability is often considered the ultimate dependent variable, whereas most other variability types are treated as independent variables. The most extensively studied independent variable to date has been soil nitrogen fertility level. In fact, most variable-rate technologies (VRT) for chemical applications have been developed on nitrogen-fertilizer applicators.

Many types of variability are both spatial and temporal in nature. Weed infestation serves as an example. Spatial weed-patch patterns may change during the crop-growing season. Variabilities in climate parameters are mostly temporal in nature. However, intensive precipitation monitoring across fields is also important to assisting decision making for fertilizer applications (O'Neal et al., 2000).

3. Managing variability

Managing the variability can be achieved by two approaches: the map-based approach and the sensor-based approach. With available technologies of GPS, remote sensing, yield monitoring, and soil sampling, the map-based approach is generally easier to implement. This approach requires the following procedure: grid sampling a field, performing laboratory analyzes of soil samples, generating a site-specific map, and, finally, using this map to control a variable-rate applicator. A positioning system, such as a GPS, is usually required for this approach. The sensor-based approach, on the other hand, measures the desired properties, such as soil and plant properties, using real-time sensors in an 'on-the-go' fashion and controls variable-rate applicator based on the measurements. For the sensor-based approach, a positioning device is not always needed.

Most experimental precision-agriculture systems are map-based systems, because most on-the-go sensors for monitoring the field, soil, and field variability are too expensive, not sufficiently accurate, or not available. Spatial databases have been generated using various GIS systems by integrating maps derived from remote sensing, soil sampling, yield monitoring, and various sensors. Advanced geo-statistical methods are used to analyze the spatial and temporal variability (Pena-Yewtukhiw et al., 2000). Crop-modeling techniques have been incorporated to develop yield potential maps as a base for fertilizer prescription (Werner et al., 2000). These maps can be used to predict variability in crop growth and crop disease based on projected climatic conditions. Thus, PA provides an ideal tool for agricultural risk assessment and rational farm-work scheduling.

4. Management zone

Site-specific applications of agricultural inputs can be implemented by dividing a field into smaller management zones that are more homogeneous in properties of interest than the field as a whole. A management zone is defined as 'a portion of a field that expresses a homogeneous combination of yield-limiting factors for which a single rate of a specific crop input is appropriate' (Doerge, 1998). Thus, management zones within a field may be different for different inputs, and delineation of management zones for a specific input involves only the factors directly influencing the effectiveness of that input in achieving certain goals.

A management zone also can be delineated by more than one specific crop inputs. In this case, a single rate is applied for each of the specific inputs within a zone. The number of distinct management zones within a field is a function of the natural variability within the field, the size of the field, and certain management factors. The minimum size of a zone is limited by the ability of the farmer to differentially manage regions within a field. If a GPS is involved to control the application or to guide the implement, there seems no reason for restrictions on the shape of the zone. However, in reality, the pattern in which the application equipment traverses the field should be considered when delineating the management zones (Kvien and Pocknee, 2000).

The concept of management zone may be perceived as a setback from the early PA concept of 'farming by foot'. However, management zones are more practical to implement. Delineating management zones involves spatial filtering to reduce effects of noise in measurements of individual factors. Removal of excessive details in within-field variability simplifies the shapes of the zones and, thus, reduces the requirements for VRT equipment. Chang et al. (2000) compared different approaches to classify nutrient management zones. Zhang and Taylor (2000) introduced methods of delineating management zones using morphological- and spatial-filtering tools.

5. Impact of precision agriculture

The impact of PA technologies on agricultural production is expected in two areas: profitability for the producers and ecological and environmental benefits to the public.

5.1. Profitability

PA allows precise tracking and tuning of farm production. PA technologies provide farmers with opportunities of changing the distribution and timing of fertilizers and other agrochemicals based on spatial and temporal variability in a field. Farmers can make economic analyzes based on the variability of crop yield in a field to obtain accurate assessment of risk. For example, a farmer could verify that, for 70% of the time, 75% of the barley grown in a field would yield 3.8 tones. By knowing the cost of inputs, farmers can also calculate the cash return over the costs for each hectare. Certain parts within a field, which always produce below the breakeven line, can be isolated for the development of a site-specific management plan (Goddard, 1997).

The economic benefits resulting from PA, however, have proven difficult to measure (Lowenberg-DeBoer, 1996). Griffin et al. (2000) compared VRT with uniform-rate technology (URT) for phosphorus application on a rice and soybean rotation in Arkansas and found that the profitability of VRT was highly sensitive to both residual P and soil clay content. Even when VRT was found profitable on silt loam fields, switching from URT to VRT during a 10 year planning horizon may be unadvisable, as increased revenue from yields does not cover the cost for VRT implementation. If a whole-farm approach, which takes all cropping activities and resource limitations into account, is adapted, PA technologies may prove to be beneficial for improving profit potential and for reducing the risks (Oriade and Popp, 2000).

5.2. Environment

Strict environmental legislations have been present in countries like USA, Australia, UK, Denmark, and Germany. In the near future, European Union directives may well be established that will force farmers in member countries to significantly reduce usage of agro-chemicals. PA provides the means of precise and targeted application, recording of all field treatments at the meter scale, tracking from operation to operation, and transfer of recorded information with the harvested products. (Stafford, 2000), all of which would assist in enforcement of the legislations.

Although the environmental benefits of PA have not been systematically and quantitatively measured (Lowenberg-DeBoer, 1996), some researches have revealed positive evidences. Nitrate leaching has been a major problem in potato cropping systems, especially in coarse-textured soils. A study conducted in two adjacent fields, one treated with URT for nitrogen fertilizer and the other with VRT, has demonstrated the effect of VRT in reducing the ground water contamination (Whitley et al., 2000). With the availability of topographic data for fields implemented with PA technologies, the interaction between tillage and soil/water erosion can be examined and, thus, reduction in erosion can be achieved (Schumacher et al., 2000).

6. Engineering innovations

While agronomists are playing the leading role in PA development, engineers have worked diligently to provide technologies needed to implement PA practices. Engineering innovations for PA involve development of sensors, controls, and remote-sensing technologies.

6.1. Sensors

Robust, low-cost, and, preferably, real-time sensing systems are needed for implementing various PA technologies. Commercial products have become available for some sensor types. Others are currently under development.

6.1.1. Yield sensors

Grain yields are measured using four types of yield sensors-impact or mass flow sensors, weight-based sensors, optical yield sensors, and γ-ray sensors. Most major agricultural equipment companies provide optional yield-mapping systems for their combine harvesters. Yield sensing techniques for major crops are approaching maturity. For forage crops, yield monitors using a displacement sensor, a load cell, a capacitance-controlled oscillator, and an optical sensor have been studied. An optical sensor measuring spectral radiance in the red and NIR wavebands was used to estimate yield during cropping seasons and to guide VRT for nitrogen fertilizer (Solie et al., 2000). A simple, low cost, and automatic yield mapping system was developed to generate yield maps of hand-harvested crops (Schueller et al., 1999). A continuous mass-flow type yield sensing system, equipped with load cells and a vibration-resistant angle transducer along with a DGPS, was developed to collect spatially variable yield data for tomato in real-time (Pelletier and Upadhyaya, 1999)

6.1.2. Field sensors

Commercial sensors receiving and processing GPS signals have become affordable for most farmers in developed countries. Handheld GPS receivers provide positioning accuracy within ±100 m. Differential GPS (DGPS) reduces the error to ±2m. A relative positioning GPS brings the error down to the sub-centimeter level. This accuracy can be maintained for moving vehicles using a real-time kinematic (RTK) GPS. Dux et al. (1999) used a geo-referenced audio recorder with a speech-recognition capability to generate field maps during field scouting. This system allows users to record visual observations on crop growth, weeds, diseases, or other anomalies while walking or riding an ATV within a field. Yule et al. (1999)

developed a data acquisition system to monitor in-field performance of an agricultural tractor. Performance parameters mapped during field operations were used to analyze field variabilities of topology, soil type, and soil moisture content, and to identify areas in field needing remedial actions.

6.1.3. Soil sensors

A near infrared (NIR) soil sensor measured soil spectral reflectance within the waveband of 1600–2600 nm to predict soil organic matter and moisture contents of surface and subsurface soils (Hummel et al., 2001). An on-line, real-time soil spectrophotometer measures soil spectral reflectance in the visible and NIR wavebands at a ground speed of 3.6 km/h. Field tests demonstrated linear relationships between reflectance at certain wavelengths and various soil properties, including soil organic matter and moisture content (Shibusawa et al., 2000). A soil electrical-conductivity (EC) sensor based on a four-electrode method has proven effective in detecting several yield-limiting factors in non-saline soils (Lund et al., 2000). In France, an eight-rolling-electrode sensor was developed to measure soil EC at three depths (Dabas et al., 2000). Combining a soil EC probe with an automated penetrometer, soil subsurface can be mapped (Drummond et al., 2000). A soil EC sensor using the electromagnetic-induction method is a non-contact sensor. EC measured using this sensor correlated well with a soil productivity index, which combines effects of bulk density, water-holding capacity, salt, and pH (Myers et al., 2000). EC measured before planting can be related to plant-available-water-holding capacity (Morgan et al., 2000). A penetrometer equipped with a near-infrared reflectance sensor measured soil penetration resistance as well as moisture content and organic matter (Newman and Hummel, 1999). A penetrometer combined with a soil EC sensor can be used to measure soil hardpan (Clark et al., 2000). Soil moisture-content sensors were designed under different physical principles, including time-domain reflectivity (TDR), standing-wave ratio (Sun et al., 1999), and depolarization of a laser light (Zhang et al., 2000a). A ground-penetrating radar was used to produce a contour map to indicate clay lenses, which govern the magnitude and direction of ground-water movement (Dulaney et al., 2000).

6.1.4. Crop sensors

Thai et al. (1999) used a field spectral-imaging system with a liquid crystal tunable filter in peanut and cotton fields. A near-ground scanning radiometer mounted on a tractor mapped vegetative-indices (Stafford and Bolam, 1998). Sudduth et al. (2000) designed an electromechanical sensor to count corn plants. Cotton plant height was measured using mechanical fingers and infrared light beams (Searcy and Beck, 2000). Grain protein and oil content sensors are currently under development. A cotton mass-flow and strength sensor was developed using a halogen lamp and an NIR light (Keskin et al., 1999). An infrared thermometer was used to measure canopy temperature to control irrigation events (Evans et al., 2000). A capacitance sensor, a sensor measuring power required at the PTO shaft, a microwave sensor, and a NIR sensor were tested to measure moisture content of forage (Marcotte et al., 1999). An on-line, real-time spectrophotometer developed by Anom et al. (2000) was used to map plant water, nutrient, disease, and salinity stresses. It was projected that development in gene manipulation of crop plants may further enable differentiation between these stress types (Stafford, 2000). Michels et al. (2000) designed an infrared plant-temperature transducer to sense plant temperature changes caused by water stress. Ahmad et al. (1999) used a chlorophyll meter coupled with a DGPS to map nitrogen stress in corn. A multispectral radiometer was employed to detect crop salinity stress. Rial and Han (1999) studied the performance of a commercial complex permittivity sensor in measuring ionic nutrients.

6.1.5. Anomaly sensors

Several weed sensors are commercially available. Tian et al. (1999) developed an intelligent sensing and spraying system to identify weed-infested zones with a high accuracy. Feyaerts et al. (1998) designed a weed sensor using an imaging spectrograph. Wang et al. (2001) developed an optical weed sensor based on a study on spectral characteristics of weeds, crops, and soil. An infrared plant-temperature transducer developed by Michels et al. (2000) was used to sense plant temperature changes caused by greenbug infestation.

6.2. Controls

6.2.1. VRT agro-chemical applicators

Many manufacturers are now producing controllers, sprayers, air spreader, anhydrous ammonia systems, and herbicide applicators for VRT applications. Bennett and Brown (1999) developed a direct nozzle injection system for herbicide application. Swisher et al. (1999) designed an optical sensor to measure flow rates of granular fertilizer in air streams for feedback control of a variable-rate spreader.

6.2.2. Automatic guidance systems

An automatic guidance system can position a moving vehicle within 30 cm or less using high-precision DGPS. It may replace conventional equipment markers for spraying or seeding and may serve as a valuable field-scouting tool (Goddard, 1997).

6.2.3. Robotic harvesting systems

Japanese researchers proposed an advanced, automatic follow-up vehicle system and an autonomous vehicle for multiple farm operations (Iida et al., 1998). Harvesting robots for tomato, cherry tomato, cucumber, strawberry, grape, and watermelon were already commercialized. It is predicted that more robotic harvesting systems will be commercialized in early 21st Century (Umeda et al., 1999).

6.2.4. Networked systems

A distributed control system using controlled area network (CAN) communication between individual sensors and actuators, a supervising controller, and a navigation system was designed and installed to control spray droplet size and application rate for agricultural chemicals (Stone et al., 1999).

6.3. Remote sensing

Remote sensing techniques have seen limited use in PA due to the need for high spatial resolution images. According to recent literature, remotely sensed images have been used to predict nitrogen need in corn (Scharf and Lory, 2000), to estimate cotton lint yield (Li et al., 2000; Hendrickson and Han, 2000), to assess insect damage in wheat (Riedell et al., 2000), to detect spider mite in cotton (Fitzgerald et al., 2000), to assist in insecticide application (Seal et al., 2000), to estimate clay concentration of surface soil (Chen et al., 2000), to detect weeds (Varner et al., 2000), to quantify hail or wind damage in crops (Erickson et al., 2000), or to detect and classify anomalies (unusual phenomena) (Carter and Johannsen, 2000).

Satellite remote sensing has held out much promise for within-field monitoring but has yet to demonstrate hard evidence for complete success. Problems include timeliness, cloud cover, cost, poor spatial resolution, and lack of processing to produce image data of use to the crop managers. Hyperspectral sensing is a relatively new technology that is capable of providing information over a nearly continuous spectrum in the visible, NIR, and MIR wavebands. Images acquired from hyperspectral sensors have been used for estimation of crop vigor and yield prediction; discrimination between crops, weeds, residue, and soil; and quantitative measurements of crop water content and leaf area index. Measurement in the MIR band also has potential for providing information on plant nutrient and soil properties (Deguise and McNairn, 2000).

7. Information management

After more than a decade of research and practice, PA has accumulated a huge amount of data and is now facing a serious problem of ‘data overflow’. For the spatial/temporal information that has been collected, there is an urgent need for tools specifically designed for data storage, processing, management, and analysis. There is also a strong need for data-exchange standardization.

7.1. Field-level GIS

General-purpose GIS packages, such as ARCVIEW, IDRISI, and SURFER, provide many functions, some of which offer little value to PA applications. Most of these packages are expensive and require computer platforms that are not usually possessed by farmers. To address the urgent need for PA applications at the field level, many commercial GIS packages, such as the software packages introduced by AGRIS Corporation, Farm Works™, Agri-Logic, Inc., John Deere Precision Farming Group, Case Corporation, Rockwell International, and RDI Technologies, Inc., have been developed (Ess et al., 1997). Some systems directly interact with DGPS devices or yield sensors to acquire location and yield data in real time. Runquist et al. (2001) developed a field-level GIS (FIS) containing analytical functions for spatial data analysis in PA research.

7.2. Data interchange standardization

PA technologies are information-based technologies. As the amount of data generated from both mobile and static sources increases, a need for standardized data communication and standardized file and data trasfer has been recognized. Great efforts have been made to establish an international standard (ISO 11783) for communication protocols on mobile, agricultural and forestry machines using CANs to provide exchangeability between sensor and actuator products provided by different manufacturers and to allow modular design of new products. File and data formats have been standardized in ISO 11787 (referred to as 'ADIS'—agricultural data interchange standard) and are in use by some manufacturers. With these standards, information can be exchanged smoothly and efficiently between sensors, processors, controllers, and software packages produced by different manufacturers (Stafford, 2000).

8. Worldwide applications

PA research started in the US, Canada, Australia, and Western Europe in mid-to-late 1980s. Although a considerable research effort has been expended, it is still only a portion of farmers who have practiced any type of PA technologies. Implementation of PA has mainly been through utilization of existing field machinery by adding controllers and GPS to enable spatially-variable applications. To date, the leading application of PA still is the site-specific application of fertilizers.

In Australia, monitoring and mapping the spatial variability in small-grain crop yields have received much publicity. Crop-yield monitors are available for potato, peanut, and forage harvesters and, still under development, for cotton harvesters to monitor both quantitative and qualitative parameters. The total number of grain yield monitors operating in Australia is below 200 at present, comparing to USA, which has between 5000 and 10 000 operating units (half with DGPS capability). The movement towards PA in Australia is considered not strong (Whelan et al., 1997).

In Japan, the Ministry of Agriculture has started to invest in PA research projects, focusing on sensing and controls related to agricultural mechanization. Japan is characterized by a small-scale and labor-intensive agriculture based on individual plant management. Japanese agriculture has faced many serious problems during the past two decades, including rice-production surplus, rapid reduction in agricultural workforce, shift in farmers' age group, and growing environmental concerns. Japanese agriculture is diverse in field size, crop variety, field elevation, water management scheme, climate, soil, and the like. It was believed that PA technologies can fit into different farm scales only after a reorganization of the agricultural structure (Shibusawa, 1998).

Despite the fact that most PA experiments were concentrated on VRT applications of fertilizers and herbicides, diverse types of PA technologies have been experimented throughout the world. Reports on PA experiments in China, Korea, Indonesia, Bangladesh, Sri Lanka, Turkey, Saudi Arabia, Australia, Brazil, Argentina, Chile, Uruguay, Russia, Italy, The Netherlands, Germany, France, UK, United States, and Canada have been found in recent literatures.VRT application of lime has been proven successful in the southeast region of the US (Heiniger and Meijer, 2000). VRT also was tested on corn hybrids and seeding rates in Colorado (Shanahan et al., 2000). Bauer et al. (2000) conducted field tests in Missouri to determine optimum planting densities in different fields. A similar experiment conducted in Kansas showed no economic benefit by varying planting rate (Zhang et al., 1999).

In California, potentials of PA technologies in rice production are being evaluated through an intensive study (Roel et al., 2000). Also in California, an experiment was conducted to study the feasibility of PA technologies in tomato production (Rosa et al., 2000). In Costa Rica, an experiment was conducted to apply PA technologies in a banana plantation. The system allows farmers to link to a soil database and to make site-specific decisions on soil fertility- and disease-related problems through yield monitoring. A cable system was used to replace expensive DGPS (Stoorvogel and Orlich, 2000).

Johnson and Bradow (2000) studied the effects of a number of soil properties, including soil Mn, Mg, and K, on cotton fiber quality in Louisiana and believed that PA technologies may be applied to improve the quality. Gimenez and Lamothe (2000) conducted a field experiment in Uruguay to assess the benefit of site-specific Zn management and concluded that profit obtained by VRT of Zn application may reach $50 per hectare.

PA also was used to optimize irrigation operations. In South Carolina, plant water stress was monitored using infrared thermometers on a center-pivot irrigation system to control the system operation (Evans et al., 2000). In Arizona, Adamsen et al. (2000) studied surface irrigation systems and found that water application is inherently non-uniform in these systems because of the spatial and temporal variability of soil infiltration characteristics. Thus, adjusting the irrigation system's physical design or developing management practices specific to individual fields may prove to be beneficial to the farmers. McKinion et al. (2001) applied a PA approach to cotton production in Mississippi to automate the calculation of optimum water and N rates. They believed that PA coupled with crop simulation models and GIS can optimize yields while minimizing water and nitrogen inputs.

Site-specific pest control has been tested in different crops. In the UK, potential for varying nematicide-rate in potato fields was studied by Stafford and Evans (2000). Site-specific control of northern corn rootworms was studied in South Dakota (Ellsbury et al., 2000).

McLaughlin and Burtt (2000) used draft sensors on a three-point hitch of a tractor to record draft data and made a tillage-energy map in Ontario, Canada. Such maps may provide an additional, inexpensive map layer for soil-related information for PA applications. Draft force on a mouldboard plow was recorded by Hayhoe et al. (2000). They applied Fourier analysis on the periodical draft signals and found that lower frequency components of the signals may be related to local spatial variability in soil physical properties, such as soil moisture, soil texture, organic matter, and soil strength/compaction. In Wisconsin, Schuler and Lowery (2000) used a TDR sensor in subsoiler shanks to measure soil moisture content while subsoiling. The signal was used to control the subsoiler operating depth to match varying soil conditions.

PA technologies were experimented in hay and forage production in Quebec, Canada (Marcotte et al., 1999). Sensors that continuously measure the weights in the baler and the trailing wagon and sensors that simultaneously measure mass flow and moisture content were tested. Successful development of these sensors may enable several PA applications, including cultivar selection, optimization of hay or silage additives, yield mapping, and forage crop management.

PA technologies also have been used in forest production. In Washington, GPS receivers and dataloggers were used to track activities of log harvesting machines (Reutebuch et al., 1999).

9. Adoption trend

In 1998, a nationwide survey was conducted by USDA over nearly 8500 agricultural producers in the US. According to the survey results, it was estimated that, by 1998, only four percent of all farms used one or more PA technologies for crop production. However, there is a significant variation in adoption rates by specific technology, region, farm size, farm type, and operator characteristics. The most widely adopted technologies were grid sampling (2% of all farms) and VRT for fertilizer (2%), followed by yield monitoring (1%) and yield mapping (1%). Variable-rate seed and pesticide application and remote sensing technologies were used only on less than 1% of all farms. Farm size, measured in terms of gross sales, was positively correlated with adoption rate. Grain/oilseed farms were found to have the highest rate of adoption (14%) primarily because of the widespread availability of yield monitors. Adoption rate for specialized fruit, vegetable, and nut farms is 5%. The main PA technology used in these farms was VRT for pesticide control (Daberkow and McBride, 2000).

Cook et al. (2000) found that farmers in Australia are adopting PA technologies more slowly than expected. They attribute the slow adoption to four factors: (1) cost of adoption, (2) lack of perceived benefit from adoption, (3) unwillingness to be early adopters, and (4) lack of technology delivery mechanism. Although the cost, lack of perceived benefit, and conservatism among farmers have indeed caused the slowness in adoption, the problem in delivering the PA technologies to farmers has been identified as the major obstacle. Delivering PA technologies to farmers requires knowledge and skills that most consulting agencies currently do not possess. The conservatism of the consultancy sector seemed to create more difficulties than the conservatism of farmers in adopting PA technologies.

In the UK, a survey was conducted among 25% of about 350 farmers who are currently conducting yield mapping using GPS. Results of the survey showed that the adopters of yield mapping have passed the first stage of initial uptake and enthusiasm and are now standing at the second stage of PA implementation. Farmers adopting yield mapping are in urgent needs for good advices from agronomists on interpreting yield maps and converting them into management plans. Yield mapping information needs to be integrated with farm decision-support systems (Griffin, 2000).

A similar survey conducted in Arkansas indicated that early PA adopters represent less than 20 percent of Arkansas farmers. These adopters are young, educated, computer using, experienced farmers with large amounts of acreage predominantly devoted to rice and soybeans. While agricultural industry representatives are helping promote PA technologies, Cooperative Extension Service personnel have served as the main source for technical consultation. Farmers are waiting for research results on profitability of various PA technologies before increasing their investment significantly to adopt more technologies (Popp and Griffin, 2000).

The following barriers need to be overcome before PA technologies can be widely implemented in a fast pace:

1) Data overflow for farm management. This problem has to be overcome by developing data integration tools, expert systems, and decision support systems.
2) Lack of rational procedures and strategies for determining application requirements on a localized basis and a parallel lack of scientifically validated evidence for the benefits claimed for the PA concept.
3) Labor-intensive and costly data collection. Development of rapid sensing systems must take place before PA can be widely practiced.
4) Lack of technology-transfer channels and personnel. Educational programs involving researchers, industry, extension specialists, and consultants are urgently needed.

PA technology will likely gain more recognition when additional benefits, such as reduced environmental burdens and increased information flow, are recognized as a part of its rewards (Auernhammer, 2001).

10. New trends in PA research

The following new trends in PA research have been observed from recent literature:

10.1. Integrated approaches

Most researchers have used the map and sensor approaches separately to address individual PA problems. However, a group of scientists in Germany are making an effort to integrate these two approaches for VRT application of nitrogen fertilizer. This requires development of reference values of crop-specific nitrogen requirement, on-line sensing of nitrogen and water conditions in plant and in soil, integration of remotely-sensed data, real-time data acquisition and transmission, and establishment of data base for universal use of site-specific fertilization and economic/ecological evaluations (Auernhammer et al., 1999).

Because mixed and, sometimes, conflicting results and opinions regarding the use of PA technologies exist, a more aggressive team approach to determine the economics and viability of current and future PA strategies is needed. Johnson et al. (2000) initiated a field research project in Minnesota, involving a partnership between university research and extension specialists, farmers, and agribusiness sectors to analyze the economic and biological impact and to assess risks related to different PA strategies.

10.2. Forward-looking approaches

Dynamic characteristics of farm operations require a forward-looking approach to respond to fertilizer, pesticide, and water needs proactively in portions of a field. A research project conducted in the Netherlands used sensors, simulation models, and real-time weather data to keep track of actual conditions in field. Warning signals were generated once deficiency was detected. Crop production could thus be maximized without exceeding chemical application limitations imposed by environment legislation (Van Alphen et al., 2000).

10.3. Internet-based information network

In Germany, an effort is made to develop an Internet-based communication and information network for all aspects of the agribusiness, including farms, cooperatives, farming companies, contractors, dealers, and suppliers, in order to develop an integral management strategy for the entire agribusiness, enabling more farmers to participate in and benefit from PA technologies (Lutticken, 2000).

11. Potential applications in China

Technological progress in PA has attracted attention of Chinese agricultural engineers since mid-1990s (Wang, 1998). Entering the information-based economy era, the time lag of developing countries in adopting new technologies has greatly reduced (Wang, 1999b). It has been predicted that adoption of PA technologies in China will take the following path (Wang, 1999a):

1) Deliver modernized, information- and knowledge-based, agricultural-management system concept to farmers through PA experiments to gradually convert existing empiric-based farming practices to information-based, modern agriculture.
2) Practice PA technologies in large-scale, government-run farms or experimental farms first. In rural areas, introduce pre-assembled, pre-proofed PA technique modules to farmers through extension services or social services, while accumulating experiences from PA experiments. Gradually expand the scale of PA applications as the farm sizes increase.

3) Extend the concept of PA into precision livestock husbandry, precision horticulture, precision post-processing, and precision management.
4) Develop information- and knowledge-based technology modules to provide strong support to agriculture. These modules may include DGPS, GIS, sensors and data-acquisition systems for detecting spatial variability of soils and plants, yield monitors, yield mapping systems, precision water-saving irrigation systems, spot sprayers, animal identification systems, information-management and decision-support systems, and multi-media systems.

References

Adamsen, F.J., Barnes, E.M., Hunsaker, D.J., Bautiska, E., Clemmens, A.J., 2000. Surface irrigation and precision crop management. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Ahmad, I.S., Reid, J.F., Noguchi, N., Hansen, A.C., 1999. Nitrogen sensing for precision agriculture using chlorophyll maps. ASAE paper No. 99-3035, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Anom, S.W., Shibusawa, S., Sasao, A., Sakai, K., Sato, H., Hirako, S., Blackmore, S., 2000. Soil parameter maps using the real-time spectrophotometer. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Auernhammer, H., 2001. Precision farming the environmental challenge. Computers and Electronics in Agriculture 32 (2001), 31–43.

Auernhammer, H., Demmel, M., Maidl, F.X., Schmidhalter, U., Schneider, T., Wagner, P., 1999. On-farm communication system for precision farming with nitrogen real-time application. ASAE Paper No. 99-1150, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Bauer, M.G., Davis, J.G., Sudduth, K.A., Drummond, S.T., 2000. Agronomic and economic evaluation of variable-rate seeding on Missouri soils. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Bennett, K.A., Brown, R.B., 1999. Field evaluation of a site specific direct injection herbicide sprayer. ASAE Paper No. 99-1102, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Carter, P.G., Johannsen, C.J., 2000. Agricultural cropland anomaly classification system for use with remote sensing data. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Chang, J., Clay, D.E., Carlson, C.G., Clay, S.A., Reese, C.L., 2000. The influence of different approaches for identifying inorganic N and P management zones on fertilizer recommendation. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Chen, F., Kissel, D.E., West, L.T., Adkins, W., 2000. Estimation of soil clay concentration with ATLAS sensor data. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Clark, R.L., Kissel, D., Chen, F., Adkins, W., 2000. Mapping soil hardpans with the penetrometer and electrical conductivity. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Cook, S.E., Adams, M.L., Bramley, R.G., 2000. What is obstructing the wider adoption of precision agriculture technology? Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Dabas, M., Boisgontier, D., Tabbagh, J., Brisard, A., 2000. Use of a new sub-metric multi-depth soil imaging system (MuCEp c). Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Daberkow, S.G., McBride, W.D., 2000. Adoption of precision agriculture technologies by US farmers. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Deguise, J.C., McNairn, H., 2000. Hyperspectral remote sensing for precision agriculture. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Doerge, T., 1998. Defineing management zones for precision farming. Crop Insights 8, 21.

Drummond, P.E., Christy, C.D., Lund, E.D., 2000. Using an automated penetrometer and soil EC probe to characterize the rooting zone. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Dulaney, W.P., Daughtry, C.S.T., Walthall, C.L., Gish, T.J., Timlin, D.J., Kung, K.J.S., 2000. Use of ground-penetrating radar and remotely sensed data to understand yield variability under drought conditions. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Dux, D.L., Strickland, R.M., Ess, D.R., 1999. Generating field maps from data collected by speech recognition. ASAE Paper No. 99-1099, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Ellsbury, M.M., Malo, D.D., Clay, D.E., Clay, S.A., Carlson, C.G., 2000. Spatial distribution of soil-dwelling stages of northern corn rootworm in relation to measurable soil and crop characteristics. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Erickson, B.J., Johannsen, C.J., Vorst, J.J. 2000. Using remote sensing to detect stand loss and defoliation in maize. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Ess, D.R., Parsons, S.D., Strickland, R.M., 1997. Evaluation of commercially-available software for grain yield mapping. ASAE Paper No. 97-1033, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Evans, D.E., Sadler, E.J., Camp, C.R., Millen, J.A., 2000. Spatial canopy temperature measurements using center pivot mounted IRTs. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Feyaerts, F., Pollet, P., Gool, L.V., Wambacq, P., 1998. Sensor for weed detection based on spectral measurements. Proceedings of the Fourth International Conference on Precision Agricultyre, 19–22 July, St. Paul, MN, pp. 1537–1548.

Fitzgerald, G.J., Maas, S.J., DeTar, W.R., 2000. Multispectral multitemporal remote sensing for spider mite detection in cotton. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Gibbons, G., 2000. Turning a farm art into science—an overview of precision farming. URL: http://www.precisionfarming.com.

Gimenez, A.E., Lamothe, A.G., 2000. Site specific management: Zinc deficit in an irrigated corn field. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Goddard, T., 1997. What is precision farming. Proceedings of Precision Farming Conference, January 20–21. Taber, Alberta, Canada.

Griffin, S.J., 2000. Benefits and problems of using yield maps in the UK—a survey of users. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Griffin, T.W., Popp, J.S., Buland, D.V., 2000. Economics of variable rate applications of phosphorus on a rice and soybean rotation in Arkansas. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Hayhoe, H.N., Lapen, D.R., McLaughlin, N.B., Topp, G.C., Curnoe, W.E., 2000. Spectral analysis and filtering of measurements of mouldboard plow draft. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Heiniger, R.W., Meijer, A.J., 2000. Why variable rate application of lime has increased grower profits and acceptance of precision agriculture in the Southeast. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Hendrickson, L.L., Han, S., 2000. A reactive nitrogen management system. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Hummel, J.W., Sudduth, K.A., Hollinger, S.E., 2001. Soil moisture and organic matter prediction of surface and subsurface soils using a NIR sensor. Computers and Electronics in Agriculture 32 (2001), 149–165.

Iida, M., Umeda, M.M., Suguri, M., 1998. Automatic Follow-up Vehicle System for Agriculture. ASAE Paper No. 98-3112, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Johnson, R.M., Bradow, J.M., 2000. Potential for precision management of cotton fiber quality. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Johnson, G., Lamb, J., Rehm, G., Porter, P., Strock, J., Hicks, D., Eash, N., Eidman, V., Potter, B., 2000. An integrated approach to precision farming research. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Keskin, M., Dodd, R.B., Han, Y.J., Khalilian, A., 1999. Attenuation of different types of electromagnetic radiation by cotton fiber as a function of mass. ASAE Paper No. 99-1053, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Kvien, C., Pocknee, S., 2000. Introduction to Why Management Zone. National Environmentally Sound Production Agriculture Laboratory (NESPAL), College of Agricultural and Environmental Science, The University of Georgia.

Li, H., Lascano, R.J., Barnes, E.M., Booker, J., Wilson, L.T., Bronson, K.F., Segarra, E., 2000. Autoregressive analysis of cotton lint yield: plant spectral characteristics and field variability. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Lowenberg-DeBoer, 1996. Economics of precision farming: payoff in the future. URL: http://pasture.-ecn.purdue.edu/ ~ mmorgan/PFI/pfiecon.html. Purdue University, IN, USA.

Lund, E.D., Christy, C.D., Drummond, P.E., 2000. Using yield and soil electrical conductivity (EC) maps to derive crop production performance information. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Lutticken, R.E., 2000. Development of an Internet-based communication and information network to progress the implementation of precision agriculture. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Marcotte D., Savoie, P., Martel, H., Theriault, R., 1999. Precision agriculture for hay and forage crops: a review of sensors and potential applications. ASAE Paper No. 99-1049, American Society of Agricultural Engineers, St. Joseph, MI, USA.

McKinion, J.M., Jenkins, J.N., Akins, D., Turner, S.B., Willers, J.L., Jallas, E., Whisler, F.D., 2001. Computers and Electronics in Agriculture 32 (2001), 213–228.

McLaughlin, N.B., Burtt, S.D., 2000. Spatial mapping of tillage energy. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Michels, G.J., Piccinni, G., Rush, C.M., Fritts, D.A., 2000. Using infrared transducers to sense greenbug infestation in winter wheat. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Morgan, C.L., Norman, J.M., Wolkowski, R.P., Schuler, R., Lowery, B., Morgan, G.D., 2000. Two approaches to mapping plant available water: EM-38 measurements and inverse yield modeling. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Myers, D.B., Kitchen, N.R., Miles, R.J., Sudduth, K.A., 2000. Estimation of a soil productivity index on calypan soils using soil electrical conductivity. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Newman, S.C., Hummel, J.W., 1999. Soil penetration resistance with moisture correction. ASAE Paper No. 99-3028, American Society of Agricultural Engineers, St. Joseph, MI, USA.

O'Neal, M.R., Frankenberger, J.R., Ess, D.R., 2000. Spatial precipitation variability in the choice of nitrogen fertilization rates. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Oriade, C., Popp, M., 2000. Precision farming as a risk reducing tool: a whole-farm investigation. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Pelletier, G., Upadhyaya, S.K., 1999. Development of a tomato load/yield monitor. Computers and Electronics in Agriculture 23 (1999), 103–117.
Pena-Yewtukhiw, E.M., Grove, J.H., Beck, E.G., 2000. Nonparametric geostatistics/probabilistic sourcing of nitrate to a contaminated well. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Popp, J., Griffin, T., 2000. Adoption trends of early adopters of precision farming in Arkansas. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Runquist, S, Zhang, N., Taylor, R., 2001. Development a field-level geographic information system. Computers and Electronics in Agriculture 31 (2001), 201–209.
Reutebuch, S.E., Fridley, J.L., Johnson, L.R., 1999. Integrating realtime forest machine activity with GPS positional data. ASAE Paper No. 99-5037, American Society of Agricultural Engineers, St. Joseph, MI, USA.
Rial, W.S., Han, Y.J., 1999. Using complex permittivity to assess the volumetric water content of agronomic soil. ASAE Paper No. 99-3114, American Society of Agricultural Engineers, St. Joseph, MI, USA.
Riedell, W.E., Hesler, L.S., Osborne, S., Blackmer, T.M., 2000. Remote sensing of insect damage in wheat. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Roel, A., Plant, R.E., Pettygrove, G.S., Williams, J.F., Young, J.A., Deng, J., 2000. Interpreting yield patterns for California rice precision farm management. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Rosa, U.A., Upadhyaya, S.K., Koller, M., Josiah, M., Pettygrove, S., 2000. Precision farming in a tomato production system. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Scharf, P.C., Lory, J.A., 2000. Calibration of remotely sensed corn color to predict nitrogen need. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Schueller, J.K., Whitney, J.D., Wheaton, T.A., Miller, W.M., Turner, A.E., 1999. Computers and Electronics in Agriculture 23 (1999), 145–153.
Schuler, R.T., Lowery, B., 2000. TDR soil moisture sensor for a subsoiler shank. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Schumacher, J.A., Lindstrom, M., Schumacher, T., 2000. An analysis of tillage and water erosion over a complex landscape. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Seal, M.R., Dupont, K., Bethel, M., Johnson, J., Willer, J.L., Hood, K., Hardwick, J., 2000. Development and implementation of large-scale spatially variable insecticide experiments in cotton. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Searcy, S.W., Beck, A.D., 2000. Real time assessment of cotton plant height. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Shanahan, J., Doerge, T., Snyder, C., Luchiari, A., Johnson, J., 2000. Feasibility of variable rate management of corn hybrids and seeding rates. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.
Shibusawa, S., 1998. Precision Farming and Terra-mechanics. Fifth ISTVS Asia-Pacific Regional Conference in Korea, October 20–22.

Shibusawa, S., Anom, W.S., Sato, H., Sasao, A., 2000. On-line real-time soil spectrophotometer. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Solie, J.B., Thomason, W.E., Raun, W.R., Needham, D.E., Stone, M.L., Wan, J., Johnson, G.V., Washmon, C., Lukina, E.V., 2000. In-season N fertilization using INSEY. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Stafford, J.V., 2000. Implementing precision agriculture in the 21st century. Journal of Agricultural Engineering Research 76, 267–275.

Stafford, J.V., Bolam, H.C., 1998. Near-ground and aerial radiometery imaging for assess spatial variability in crop production. Proceedings of the Fourth International Conference on Precision Agriculture, July 19–22, 1998. St. Paul, MN, USA.

Stafford, J.V., Evans, K., 2000. Spatial distribution of potatocyst nematode and the potential for varying nematicide application. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Stone, M.L., Giles, D.K., Dieball, K.J., 1999. Distributed network system for control of spray droplet size and application rate for precision chemical application. Paper No. 99-3112, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Stoorvogel, J.J., Orlich, R.A., 2000. An integrated system for precision agriculture in bananas. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Sudduth, K.A., Birrell, S.J., Krumpelman, M.J., 2000. Field evaluation of a corn population sensor. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Sun, Y., Wang, M., Zhang, N., 1999. Measuring soil water content using the principle of standing-wave ratio. ASAE Paper No. 00-3127, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Swisher, D.W., Sudduth, K.A., Borgelt, S.C., 1999. Optical measurement of granular fertilizer flow rates for precision agriculture. ASAE Paper No. 99-3111, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Thai, C.N., Evans, M.D., Greene, G.C., 1999. Integration of a personal liquid crystal monitor to a field spectral imaging system. ASAE paper No. 99-3053, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Tian, L., Reid, J.F., Hummel, J.W., 1999. Development of a precision sprayer for site-specific weed management. Transactions of the ASAE 42 (4), 893–900.

Umeda, M., Kubota, S.S., Iida, M., 1999. Development of 'Stork', a watermelon-harvesting robot. Artificial Life Robotics 3, 143–147.

Van Alphen, J.B., Stoorvogel, J.J., Peters, P.D., 2000. An operational, forward-looking approach to precision agriculture: a case study for Dutch arable farming.

Varner, B.L., Gress, T.A., Copenhaver, K., Wax, L.M., Spragne, C.L., Tranel, P.J., 2000. Detection of cockleburs (*XANTHIUM STRUMARIUM* L.) in soybeans using hyperspectral imagery. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Wang, M., 1998. Development of 'precision agriculture' and engineering technology innovation, Transactions of the CSAE, 15(1). Chinese Society of Agricultural Engineering. Beijing, People's Republic of China.

Wang, M., 1999. Series lectures on technology development in 'precision agriculture' and technological innovation in agricultural equipment. Agricultural Machinery 1999, 2–11.

Wang, M., 1999. Technology development in 'precision agriculture' and technological innovation in agricultural equipment. In: Cui, W. (Ed.), Digital Earth. China Environmenal Science Press, pp. 47–53.

Wang, N., Zhang, N., Dowell, F.E., Peterson, D.E., 2001. Design of an optical weed sensor using plant spectral characteristics. Transactions of the ASAE 44 (2), 409–419.

Whelan, B.M., McBratney, A.B., Boydell, B.C., 1997. The Impact of Precision Agriculture. Proceedings of the ABARE Outlook Conference, 'The Future of Cropping in NW NSW', Moree, UK, July 1997, p. 5.

Werner, A., Doelling, S., Jarfe, A., Kuhn, J., Pauly, S., Roth, R., 2000. Deriving maps of yield-potentials through the use of crop growth models, site information and remote sensing. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Whitley, K.M., Davenport, J.R., Manley, S.R., 2000. Difference in nitrate leaching under variable and conventional nitrogen fertilizer management in irrigated potato systems. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Yule, I.J., Kohnen, G., Nowak, M., 1999. A tractor performance monitor with DGPS capability. Computers and Electronics in Agriculture 23 (1999), 155–174.

Zhang, N., Taylor, R., 2000. Applications of a field-level geographic information system (FIS) in precesion agriculture. Proceedings of Fifth International Conference on Precision Agriculture (CD), July 16–19, 2000. Bloomington, MN, USA.

Zhang, N., Taylor, R., Schrock, M., Staggenborg, S., 1999. Applications of a field-level geographic information system (FIS) in decision making for precision agriculture. ASAE paper No. 99-3046, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Zhang, N., Sun, Y., Wang, N., Wang, M., Loughin, T., 2000a. Effectiveness of a polarized laser light for measuring soil moisture content. Transactions of the ASAE 43 (6), 1963–1968.