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Precision Agriculture and Site-Specific Management: Current Status and Emerging Policy Issues

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Summary

Precision agriculture (PA) is a suite of information technologies that can support a farm-based and site-specific crop management system in agricultural production. PA is not a single technology or farming system, but rather a cluster of different techniques. PA uses advanced information technologies to identify and to evaluate temporal and spatial variation in cropland. Rather than apply inputs of production, e.g., fertilizers, pesticides, seed, or water, uniformly across a field, a grower using PA techniques can apply inputs more efficiently based on the biophysical variability of different areas of a field. Proponents argue that PA can increase the yield potential of a farm while reducing the costs from inefficiently applying inputs. Further, by applying fertilizers and pesticides in more efficient amounts, proponents argue that farmers would reduce the environmental effects of over-application. Because PA is in the early stages of adoption, however, these benefits have been difficult to measure to date. Returns to investment in PA have also been mixed according to available research. Questions persist about the appropriate scale of analysis and measurement needed to validly assess the potential benefits of PA. Adopters of PA to date have disproportionately been larger corn, soybean, and wheat producers, which may be partly attributable to the early commercial availability of PA technology, such as yield monitors for these crops; but no hard evidence has emerged that PA technologies are size-biased or crop-specific. PA appears to offer the greatest future potential benefits where a variety of inputs are used and input costs are high, sub-field spatial and/or temporal variability is high, and adverse environmental effects, especially on water resources, must be reduced.

Several bills have been introduced in recent Congresses to increase support for public research on PA development. Several public and land-grant universities have also initiated new programs in PA technology and development; additional research and development are supported by the Agricultural Research Service. In contrast to many previous U.S. technological innovations in agriculture, however, PA is currently being developed and promoted largely by private companies. Further diffusion of PA technologies could raise several public policy concerns that the Congress may wish to address. These include questions about the role of public research, education, and extension services; future effects on the organization of production; intellectual property issues associated with ownership and control of the agronomic databases created for individual farms; and other public or appropriate public-private roles to help growers gain access to and achieve some of PA's potential benefits.

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Introduction

Over the past decade, information technologies have fundamentally transformed many industrial areas. These technologies, undergirding advanced telecommunications, data acquisition and information processing, and commerce, have become core elements for many contemporary production and marketing processes. Not only have they permitted the modification of existing activities, they have also become the catalyst for fundamentally redesigning production processes and for creating original products and processes. The manufacturing and service sectors already have seen significant changes to their production processes through information technologies, while the agricultural sector has benefitted less. Agriculture's reliance on information technology, however, is beginning to change rapidly, with many promised benefits according to proponents.

Rapid technological change always has been a central characteristic of U.S. agriculture.[2] Growing competitive pressures stemming from international agricultural markets, improving yields, and new environmental concerns lead farmers to seek and adopt technological innovations. The emergence of new technologies in conjunction with new demands on the agriculture sector from a range of interest groups are setting the broad context for further changes in U.S. agriculture. Along with changes in the structure of agricultural production (e.g., increased contractual arrangements, greater concentration in some sectors, changing government policies and regulations), an increased acceptance and reliance on information technologies by farmers is also altering U.S. agricultural production.

Expectations that farmers would rapidly adopt computers, for example, are now beginning to be realized. In 1999, computers were owned or leased by approximately 40% of U.S. growers, up from 31% in 1997.[3] The predominant use initially was for financial applications, i.e, bookkeeping, business management. In 1999, 29% of U.S. farms had Internet access compared to 13% in 1997. Farms with sales greater than $250,000 per year, which are considered to be commercial or full-time farms, had

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[1] Prepared under supervision of Jeffery Zinn, Senior Analyst in Natural Resources Policy

[2] Cochrane, W.W. *Development of American Agriculture*. Minneapolis: University of Minnesota Press, 1979.

[3] USDA. National Agricultural Statistics Service. "*Farm computer usage: access, ownership, and use by state and U.S., 1997 and 1999.*"

double the rate of computer ownership, business management use, and Internet access relative to farms with sales of less than $250,000 per year. Farms with sales greater than $250,000 also account for the great majority of total U.S. agricultural output, so that the bulk of agricultural output today is likely from farms using computers in some aspect of their operation. Growth in adoption of information technology for the agricultural sector as a whole is now consistent with other sectors – approximately 3% per year. The largest impact of computers in agriculture until recently has been in the support industries, but producers are increasingly finding potential benefits from computer technologies, including precision agriculture.

Precision agriculture (PA) (also called site-specific crop production, prescription farming, and soil-specific crop management) refers to a suite of technologies that use sensing and geo-referencing innovations to apply more precise inputs based on a field's biophysical variability. The objective of PA techniques is to quantify and manage the spatial and temporal variability existing in virtually every field. This is accomplished by remote sensing technology, by local sensors, or by using the integrated data in a geographic information system (GIS) as the basis for identifying particular management zones that may require different amounts or types of inputs.

How a farmer might use PA:

Growers might typically adopt a PA system using GIS software to permit growers to capture, store, manipulate, analyze, and display a wide variety of data referenced to the specific points on the Earth's surface determined by the Global Positioning System (GPS) or other remote sensing technology. Growers can then add data on other attributes of a field's variability, e.g., soil moisture, pest densities, weather, soil compaction, to the GIS to create a multi-layered, field-specific information system for guiding management decisions for more precise application of inputs by variable rate technologies (VRT). Producers first determine the variability within their fields by relating crop production and/or soil attribute data collected over several growing seasons to geographic coordinates using a GPS monitor mounted on a combine. While crop yield data are insufficient in and of themselves to understand the actual source of field variability, when they are joined to digital soil maps, farmers have two significant layers of information about field variability that can be integrated into the GIS and supplemented by other layers of agronomic data as needed. Growers use the GIS to guide their VRT to continually adjust input applications as they operate their equipment based on the biophysical variability of the various zones they have identified in their fields (See the glossary on pages 14 and 15 for definitions of selected terms associated with PA)

The goals of PA are increased yields and reduced costs with fewer negative environmental effects from inefficient input application. PA seems to offer the greatest potential benefits where inputs are varied and cost is high, field variability is high, high-valued crops are grown, and environmental effects, especially to water resources, must be reduced. PA is foremost a sub-field management system that can specify rules for guiding input application based on past, current, or expected conditions. PA may potentially do for agriculture what just-in-time production and shipment tracking technologies have essentially done for manufacturing: Managing temporal and spatial variability in the production process for more efficient decisions.

Private companies have dominated PA's technical development to date. In contrast, basic agricultural technological research has predominantly been a public undertaking. This difference may suggest a changing role between public and private sectors in agricultural innovation. For example, the increasing importance for the role of professional crop specialists in PA could presage change in the traditional role of extension personnel; and the need for computer knowledge and skilled data analysis suggests potential new demands on agricultural education and extension. Creating site-specific GIS databases through service contracts with input suppliers also raises issues about ownership and control of these databases. PA also may contribute to new contractual arrangements through proprietary ownership of agricultural input systems, e.g., PA data could become a new part of existing proprietary seed-herbicide "packages." This could have implications for current farm structure. Given PA's potential environmental benefits, there is precedent for a public role in research that has little likely commercial benefits and is therefore less likely to be assumed by the private sector, e.g., sensor development for environmental monitoring.

Socioeconomic Factors in Adoption and Use of PA

Technological Costs and Development Trends. Farmers face significant start-up costs before they can exploit the potential of PA to achieve long-term advantages. Much of the capital and labor costs of PA are in acquiring equipment and developing a baseline data set. These costs include yield monitoring, crop scouting, and soil testing over multiple growing seasons and learning how to use remote sensing technology, GIS data, and VRT. Individuals may either buy this technology directly and learn how to use it, or they may contract for various services with vendors, including independent crop consultants and input suppliers. Most adopting farmers will likely purchase some hardware and develop some expertise and contract for other support services. Some illustrative equipment and service costs might include the following:

- A yield monitor for corn, wheat, or soybeans could cost $4000-$7000.
- Soil sampling has been estimated at $3-$7 per acre, considerably more if samples are deeper or taken more frequently and in smaller grids.
- A truck-mounted computer system and GIS software could add $3000 to the cost of a PA system.
- Service costs including soil sampling, yield monitoring, crop scouting, GPS receiver and, in some regions, a satellite signal subscription;[4] VRT controllers and fertilizer application (additional

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[4] The Department of Defense recently made its GPS signal accurate to 20 meters. Farmers who do not need greater accuracy than this will no longer have to buy a differential correction. A public provided national differential GPS network is also expanding and should make the GPS signal more widely available in the future. As this network expands into new regions,

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cost over uniform application rates) have been estimated at $13-$26 for a grower and $2.50-$14.50 for a dealer on a per acre basis.[5]

- Weather Services International, a private vendor, currently charges $5-$7 per acre to subscribe to their basic weather service and $10-$20 to obtain their integrated weather data packages.[6]

Digital soil maps based on grid sampling are generally expensive to acquire and some soil attribute data may require periodic updating. Soil grid sampling could become a high annual expense, but different sampling densities based on indicators such as yield monitoring data or soil attributes can reduce the costs of sampling where little variability exists or where information about variability of a particular area in the field is of little benefit. For example, one of the most efficient uses for yield maps is to identify those areas where yields are significantly lower than the field average. Often the production problems in these areas can be readily identified and corrected, leading to increased future revenue.

Other sensor-based applications, sometimes referred to as "on-the-go" sensing or local sensors, are also becoming an important part of PA technology. A sensor mounted on a machine or truck senses the field condition, e.g, soil pH, nitrogen content, pest population, soil compaction; an on-board computer sends the data through an algorithm; and a real-time signal goes to a VRT applicator, also mounted on the machine, to deliver a precise application of fertilizer or pesticide. Soil nutrient sensors, optical plant sensors, pest population sensors, and soil property sensors are currently in use; research on other sensors is underway, e.g., moisture density sensors and plant disease sensors. Accurately synchronizing sensor measurement with the desired input application, however, has proved somewhat problematic to date. For example, a bulk spreader moving at 25 mph passes over approximately 37 feet each second, making optimal accuracy difficult to achieve.

Remote sensing technology is yet another technical development in PA. For growers who need it, remote sensing, either from airplane or satellite platforms, permits improved spatial, temporal, and spectral resolution compared to other sensing devices such as on-the-go sensors or grid sampling. This technology could be very beneficial for decisions regarding irrigation, pest and disease control, etc. that have to be made during the growing season. Also the potential for this technology to determine the cause, size and location of sub-field variation in plant vigor is increasing with developments in the new hyper-spectral sensors. Some work is underway to develop sensors that detect nitrogen deficiency and water stress. Such data will improve the efficiency of professional crop scouts who can quickly find low

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[4] (...continued)
farmers who need more precise spatial accuracy may no longer have to purchase a satellite subscription fee.

[5] National Research Council. *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management.* National Academy of Science Press. Washington, D.C., April, 1997.

[6] Weather is a critical and largely uncontrollable variable that can alter the outcomes of a PA system under the best of circumstances. Weather data, nonetheless, can become an important layer of information in a GIS.

vigor/stressed areas within large fields. Timely delivery of this information over the Internet is now also possible.

Research continues to improve yield monitors and VRT. A yield monitor is often the first piece of equipment PA growers acquire. Yield monitors allow producers to map yield variability. These maps can then be used to assess changing production practices. Accurate measurement can be difficult as calibration can be a challenge. The fastest growing area of yield monitoring technology is currently in grain-harvesting combines although there is research underway on monitors for other crops such as cotton, root crops, and fruits. Lack of yield monitors for high-value crops, e.g., fruits and vegetables, is possibly a barrier to adoption of PA techniques for some operations. Given the limits of current sensing calibration and the absence of a universal standard of yield measurement, the available grain sensing systems must be calibrated for each type of grain and for each type of machine. Finally, a relatively wide variety of commercially available VRT exists for liquid and dry chemical application, for planting, and for manure spreading. Most of these systems rely on electronically controlled hydraulic systems. Precision irrigation technologies are also beginning to be developed in drip and center-pivot irrigation systems. Again, accuracy of application can be lower than desirable, especially in systems that do not have the capacity to anticipate rate changes as the VRT moves across a field or, in the case of precision irrigation, to control water application involving a large number of nozzles.

PA technologies are evolving rapidly. There is, however, little standardization of measurement among manufacturers; companies are designing and developing their own equipment and proprietary software systems. Ongoing research is likely to establish what works better and at what cost in particular production areas and with particular crop systems. Producers who adopt PA are likely to encounter a relatively steep learning curve with many of the GIS software packages, especially in collecting data that can be analyzed and translated into useful information for changing management practices in the field, according to anecdotal information in the farm press and on various Web sites. Learning costs can be expected to fall as adoption of PA spreads, as equipment becomes more standardized, as equipment calibration becomes more reliable, and as research supports the value of different techniques and different data comprising particular GISs.

Socioeconomic Aspects in Adoption and Diffusion of PA. A grower's anticipated return on investment in PA technologies will most likely govern the decision to adopt PA techniques. Increased yields and/or reduced input costs could generate significant net revenue gains to an individual farmer. The more input-intensive crops (e.g., sugar beets, vegetables, potatoes, cotton) generally are more highly valued on a per acre basis. This suggests that growers planting these crops might see the greatest incentives to adopt PA techniques, especially if they could reduce the costs of expensive inputs. Most adopters to date, however, appear to grow low-value, bulk commodities, e.g., corn, soybeans, and wheat, which may be partly due to the early development of yield monitors for these crops.

Researchers are studying the profitability of PA. One of the more detailed economic reviews of PA adoption to date examined phosphate and potassium fertilizer applications on wheat, potatoes, and corn.[7] The authors concluded that when all costs were included (including education and training), PA was rarely profitable for the farm operations studied. If other, more costly inputs (e.g., pesticides, seed) could be applied on a site-specific basis, however, the likelihood of profitability could increase, although another study showed that profit actually decreased with an increase in the variability of input requirements.[8] If PA is adopted by more producers, costs of training and education and the technologies themselves are likely to decrease. Finally, at least one study has shown that variable rate application may not be the key factor in PA profitability.[9] Rather, this study showed that it could be profitable in some cases to use PA to determine the optimal *uniform* input application.

Information on the adoption of PA is fragmentary and unsystematic. Adoption, however, is likely to vary across crops, farming systems, and geography. Because PA is not a single technology or farming system, each combination of GIS data and technologies has its own array of costs and benefits. In a comprehensive study of 950 corn growers in 16 states, PA adopters tended to be younger, full-time operators, better educated, and currently using computers for business management than non-adopters.[10] Adopters also had less diverse operations, a higher debt-to-asset ratio, and operated larger and more profitable farms. Total acres farmed, acres harvested, asset values, return on equity, and net income each were between 1.5 to 3 times larger for adopting farms. Over half the adopting farms had annual sales of $250,000 or more; less than 20% of non-adopting farms were of that size. This suggests that PA may be used in a higher percentage of total agricultural production than percentage of farms data cited earlier might indicate. Over half the adopters were in Indiana, Illinois, and Iowa, and overwhelmingly specialized in cash grain production. Two-thirds of the non-adopters were located in the other 13 states in the study, suggesting some geographic concentration in current adoption patterns.

Socioeconomic models of adoption patterns suggest that farmers positioned to realize the greatest returns will more readily adopt new technologies. This might mean that farmers who are currently not highly efficient in their management of inputs would find early adoption of PA most beneficial. Yet, farmers who have adopted PA or who might be expected to adopt it in the future appear to be those who already use relatively sophisticated approaches to input application and who would, in comparison to less efficiently managed operations, possibly realize fewer initial profit advantages

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[7] Lowenberg-DeBoer, J. and S.M. Swinton. "*Economics of site-specific management in agronomic crops.*" Department of Agricultural Economics Staff Paper 95-14. Purdue University, 1995.

[8] Hennessey, D., B.A. Babcock, T.E. Fiez. "*Effects of site-specific management on the application of agricultural inputs.*" Report 96-WP-156, Center for Agriculture and Rural Development, Iowa State University, 1996.

[9] Schnitkey, G., J. Hopkins, and L. Tweeten. "*An economic evaluation of precision fertilizer applications on corn and soybean fields.*" Paper presented at the annual meetings of the American Agricultural Economics Association, San Antonio, TX, July 1996.

[10] Daberkow, S.G. and W.D. McBride. "*Survey results: Adoption rate of site-specific crop management technologies among U.S. corn growers.*" *Modern Agriculture* 1 (7)(Fall) 1998.

by adopting PA. Several studies of technological adoption have also noted the importance of the compatibility of an innovation with current practices, that is, the innovation complements existing practices rather than wholly replaces them, at least over the short term.

Adoption of PA for sub-field management is a refinement of good whole-field management. Since 1977, agricultural research and extension services have promoted Best Management Practices (BMPs) to growers for improved profitability and improved environmental practices, e.g., soil conservation, pesticide record-keeping.[11] Soil testing and crop scouting, both long-standing BMPs, are also central to the success of PA. Adding small-area soil grid sampling and integrating other data into a GIS, for example, are perhaps smaller incremental steps for growers already using BMPs than for farmers who have not adopted BMPs or who use BMPs inconsistently. Some research has indicated that large farms have adopted BMPs significantly more often than small farms.[12] Growers who have never soil tested or never crop scouted might be expected to see in PA a uniquely attractive set of practices that could, in time, significantly improve their operational efficiency over current practice.[13] Yet, these growers appear less likely to have adopted PA techniques to date and, given the importance of prior BMP adoption, may only slowly adopt PA in the future. In a statistical test of differences between PA adopters and non-adopters, with respect to nutrient soil testing and crop scouting, PA adopters had significantly higher levels of use with these BMPs than did non-adopters.[14] Differences in management and technical skills as well as initial costs of BMP adoption might help explain why some growers have adopted BMPs and others have not. These indicators suggest that adoption and diffusion of PA techniques may not be as straightforward as existing adoption models of agricultural technology might predict, and further attest to the site-specificity in growers' decisions to adopt PA techniques for their cropland.

Would-be adopters desiring to contract for PA services have found that vendors of these services are concentrated in potentially high-demand areas, i.e., areas where large, commercial operations predominate. PA is also more likely to attract farmers who are already comfortable with computers and are not daunted by the information complexities of PA. As the technology matures and as the socioeconomic profile of PA's potential returns on investment become clearer, however, more growers are likely to consider at least some of the PA technologies either through direct purchase or, perhaps more likely, through contracting for PA services from private suppliers, especially with growth in the private supply of PA expertise.[15]

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[11] BMPs were implemented as requirements of the 1977 amendments to the Clean Water Act.

[12] Tweeten, L. *"The structure of agriculture: Implications for soil and water conservation." Journal of Soil and Water Conservation* 50(4), July-August, 1995.

[13] Only about a third of acres planted to major field crops was soil tested for nutrients. Pest scouting was practiced on slightly more than half of the acreage planted to major crops. USDA. *Cropping Practices Survey*,1994.

[14] Daberkow, S. and W. McBride. *"Socioeconomic profiles of early adopters of precision agriculture technologies."* *Journal of Agribusiness* 16(2), Fall, 1998.

[15] Over the past five years there has been significant growth among agrochemical dealers in

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Individual farm returns on PA investment will vary by the management skills of operators, by the biophysical properties of each field, and by the interactive effects of altering various inputs based on the site-specific database. The limited data on economic returns showing mixed results is perhaps not unexpected given the difficulty of maintaining any consistency of the system between comparative sites. Even side-by-side farm comparisons reveal significant biophysical variability between fields; and potential profitability of PA is highly correlated with the biophysical variability of the setting to which it is applied. No research could be located that has examined the economics of PA for an agro-ecological region, for a single production system, or across all dimensions of a production system.[16] The economic research available is based disproportionately on large operations with relatively low-valued crops and inexpensive inputs, variables that are perhaps less conducive to producing significant profit advantages under a PA system. Research is currently underway on other production systems (e.g., cotton, fruits and vegetables, forestry) that will clarify the picture on returns on PA investment. Changes that might attract other growers to invest in PA include cooperative arrangements to share technology, or training, equipment leasing, and standardization of PA technology.

The rate of adoption does not appear to be uniform among crop systems either. Farm press reports and regional agricultural meetings suggest that many adopters of yield monitors have been corn, wheat, and soybean growers. Trade press reports information reveal that adopters also include some Florida tomato growers, California vegetable, grape, and orange growers, Arkansas cotton growers, Massachusetts cranberry growers, and Northwestern foresters. The variety of adoption rates among different crops may suggest the importance of examining PA adoption rates from a crop-specific perspective or that the crop is less important than other variables in the decision to adopt. For example, some PA practitioners have stated that producers are using PA information to document yields on rented farmland which may be useful for negotiating new leases and equitably dividing up crop production on crop sharing arrangements. PA also may be used for loan applications, proving yield history for crop insurance, and documenting losses for crop insurance purposes.

USDA data indicate that among the computer users noted above, about 64,000 farms (about 3.2% of total farms) also used computer-aided chemical application or GPS technologies in 1995.[17] More recent unpublished USDA data (1998) indicate only a slight increase in acquisition of these PA technologies, perhaps suggesting a

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[15] (...continued)
qualifying to become Certified Crop Consultants, a program administered by the American Society of Agronomy. Private consultants are likely to become an important means by which PA knowledge is transmitted.

[16] Some studies of Western sugar beet production have indicated that PA holds substantial promise in improving the efficiency of nitrogen application. Adding more nitrogen increases yield but lowers beet quality. PA potentially offers the technical capacity to optimize the application for yield and quality.

[17] Sommer, J.E., R.A. Hoppe, R.C. Green, and P.J. Korb. *"Structural and Financial Characteristics of U.S. Farms, 1995: 20th Annual Family Farm Report to Congress,* AIB-746, ERS-USDA, December, 1998.

continuation of the initial phase of the adoption process.[18] It is, however, reasonable to regard PA as an extension of mechanization and an elaboration of existing chemical-based agricultural practices, two technological systems that researchers regard as encompassing significant scale economies and that have contributed to changes in farm size and the industrialization of the farm sector.[19] In that sense, PA may be regarded more as an evolutionary technology reinforcing certain existing agricultural practices rather than as a revolutionary one that holds the potential to radically alter existing production practices.

Given its character as a site-specific set of practices, PA, in contrast to many earlier agricultural technologies, seems likely to develop as customized systems specific to each producer's operation even as the basic technologies become more standardized. The particular PA package for each farm will be based on the biophysical variables that are being addressed. The biophysical variability of cropland makes it likely that different farms will find different combinations of data in a GIS most useful. A soil map based on small area sampling, for example, is likely to provide more useful information to a grower whose soil variability is high throughout a field than it would to a grower whose soils are more uniform. Similarly, a farm with a more varied topography may find digital elevation modeling (DEM) very useful while for another grower with level fields, such information would add little or no benefit to crop management decisions.

Environmental Aspects of Precision Agriculture

PA is used within field boundaries, but environmental issues in agriculture transcend these boundaries. Ecological and health implications of using chemical fertilizers, soil fumigants, herbicides, and insecticides in large amounts are central targets of environmental reform. Farmers increasingly find themselves under pressure to improve their output efficiency while reducing the adverse environmental effects of necessary inputs. Proponents of PA have strongly emphasized its potential to significantly reduce these effects. Others, however, doubt that PA techniques can address many of the key factors that produce negative environmental outcomes.[20] There is little convincing evidence to date for either position.

Field-level studies do suggest that more accurate calibration of inputs can reduce over-fertilization and excessive use of pesticides at the farm level. To the extent that such reduction improves the environmental performance of individual farms, PA would seem to offer some improvement over current practices. Research at the

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[18] Classic studies of adoption and diffusion of technology have identified a characteristic S-shaped curve that models the socioeconomic process of adoption: a slow takeoff followed by a rapid phase of adoption followed by a slow and steady diffusion across a production sector. See Rogers, Everett M. *Diffusion of Innovation, 4th Edition.* New York: Free Press, 1995.

[19] Wolf, S.A. and F.H. Buttel. *"The political economy of precision farming." American Journal of Agricultural Economics*, 78(December),1269-1274. 1996.

[20] Groffman, P.M. *"Ecological constraints on the ability of precision agriculture to improve the environmental performance of agricultural production systems."* Pp. 52-64 in J.V. Lake, G.R. Bock, and J.A. Goode, eds., *Precision Agriculture: Spatial and Temporal Variability of Environmental Quality*, New York: Wiley Press, 1997.

watershed or regional scales may produce better evidence than field-level studies about the environmental effects of PA, but these studies will have to wait for widespread adoption of PA. Moreover, because environmental problems are not evenly distributed, where PA is widely adopted becomes central to its potential success for reducing them. It is possible that PA could produce less environmental improvement in commercial-scale agriculture than individual field tests indicate. Growers who find they can reduce certain inputs could be offset by other growers who learn they are under-fertilizing or using sub-optimal levels of pesticides and decide to increase their inputs. In assessing PA's future potential for improving environmental quality, the scale at which one examines PA becomes significant: Producers are motivated primarily by considerations of their own actions and their own costs; those concerned primarily with what PA potentially offers in terms of environmental improvements are concerned with agricultural producers as an aggregate.

A reduction in agriculture's impact on water resources through more efficient application of fertilizers and improved drainage management could potentially become a significant environmental benefit of PA. Controlling non-point runoff from U.S. farms is considered to be the most significant water quality need, according to EPA's nationwide survey.[21] Water quality impairment from cropland sediment alone has been estimated to cause between $2 and $8 billion per year in damages across the country.[22] Farms and ranches, however, have been largely exempt from most regulations governing water, air, and land that other industrial sectors must adhere to.

The Clean Water Act of 1972 (§303) required states to establish ambient water standards for surface water. Few states, however, have set the total maximum daily loads (TMDL) of pollutants to improve the quality of remaining pollutant-impaired water bodies as required by the Act. A number of lawsuits since 1992 led the EPA to issue a requirement in 1997 that states must develop specific schedules for TMDLs of impaired waters, including those impaired by non-point source pollution, within the next 8-13 years. A recent agreement between EPA and USDA has extended this time to 15 years.[23] There is some uncertainty whether agricultural operations other than large, confined animal enterprises legally fall under the TMDL requirement. If it is determined that they do, PA could potentially play a significant role in helping implement the TMDL program requirement through development of a site-specific management program to control non-point sources of pollution.[24] Recent legislation

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[21] EPA. *National Water Quality Inventory: 1996 Report to Congress.*

[22] ERS-USDA. *Agricultural Resources and Environmental Indicators: Agricultural Handbook 712.* Washington, DC, 1997.

[23] EPA. Office of Water. *Joint Statement of the Department of Agriculture and the Environmental Protection Agency Addressing Agriculture and Siliviculture Issues within EPA Revisions to TMDL and NPDES Rulings.* May, 2000.

[24] Most agricultural pollution is classified as "non-point" and is not subject to controls under the Clean Water Act. The TMDL program is designed to target waters that are impaired even after point-source control measures have been applied. If agriculture is determined to fall legally under the TMDL program, as a recent federal district court case in California

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(H.R. 4502), however, was proposed to prohibit EPA from imposing new rules regulating TMDLs from non-point sources; and S. 2417 would leave power to regulate TMDLs in the states while increasing state funding for non-point source control. On May 22, 2000, H.R. 4502 was referred to the Subcommittee on Water Resources and Environment. S. 2417 was referred May 18, 2000 to the Committee on Environment and Public Works Subcommittee on Fisheries, Wildlife, and Drinking Water. Hearings were held; and on July 11, 2000 EPA issued final regulations to revise the TMDL program.

Agricultural policies to reduce the environmental effects of crop production usually have been based on the combination of voluntary participation and incentives to attract participants including various technical assistance and cost-sharing arrangements. Idling agricultural acreage has also been a policy measure for reducing adverse environmental effects while limiting supplies of commodities. However, pesticide registration, drainage for wetland modification, protection of endangered species, and pollution from large confined-animal operations are four areas where some agricultural practices have been regulated.[25] PA has potential value for reducing the need for regulation in some situations by documenting/monitoring pesticide and fertilizer use, and by identifying environmentally sensitive areas where reduced inputs may be appropriate. Each of these measures could play a significant role in the development of site-specific control programs where run-off is shown to be a source of non-compliance under the TMDL requirement noted above. With heightened environmental awareness and increasing urban/suburban development also encroaching onto rural agricultural areas, more farmers are likely to find themselves under public pressure to reduce the environmental effects of agricultural production, especially those that adversely affect the quality of their neighbors' lives and its impact on water resources.

The National Research Council also has recently recommended development of a national strategy to combat nitrogen and phosphorus pollution in coastal waters after its research showed that synthetic fertilizers have contributed to more than 50% of the doubling of nitrogen and phosphorus pollution from 1960-1990.[26] There is evidence based on contingency-valuation methods suggesting that, in shifting from a logic of maximizing output to one of reducing inputs, farmers would accept some reduction in output per acre in return for avoidance of a moderate environmental

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[24] (...continued)
(Prosolino, *et al*. v. EPA, No. C. 99-01828WHA, March 30, 2000), suggests it may, control of non-point pollution will be site-specific. For further information on agriculture and water quality see CRS Report RL-30437, *Water Quality Initiatives and Agriculture* and CRS Report 97-831 ENR, *Clean Water Act and Total Maximum Daily Loads (TMDLs) of Pollutants.*

[25] EPA was empowered to review each pesticide to ensure it met minimum risk criteria. These criteria were altered by the Food Quality Protection Act of 1996 and EPA has not completed details of their implementation of the new criteria.

[26] National Research Council. *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution.* National Academy of Science Press. Washington, DC. April, 2000.

risk.[27] Also, some suggest that cost savings can sometimes outweigh lost income. Databases on chemical use generated by PA could also help farmers meet any future environmental standards as well as provide a long-term record of input applications, which may potentially help future land sales.

Current Status of Precision Agriculture at the Federal and State Levels

Although the emerging innovations of PA are being developed and promoted largely by private companies, there has also been a public presence in PA development. Recent Congresses considered several bills to promote agricultural research and extension targeting PA and PA technologies. Three bills were introduced in the 104th Congress to amend the Competitive, Special, and Facilities Research Grant Act and one to amend the research categories in the Fund for Rural America. None of these bills was enacted.

Three relevant bills were introduced or re-introduced in the 105th Congress. An original bill (S. 1150) to address high priority national agricultural concerns and to reform, extend and eliminate certain agricultural research programs was enacted as P.L.105-185, The Agricultural Research, Extension, and Education Reform Act of 1998. Section 403 of P.L.105-185 sets general research priorities and authorizes grants to study and promote components of PA technologies and to integrate research, education and extension efforts in PA. Section 403 (b) (2) limits funding under this section to those projects that the Secretary determines are unlikely to be privately financed; and §403 (c) (6) specifically targets research on the applicability of PA for small and medium-size farms. In further defining these grant priorities, §403 (d) (3) appears to limit funding for certain projects that would investigate how PA might enhance environmental quality stemming from a reduction in the use of inputs. Section 403 (d) (3) gives priority to research that demonstrates the *efficient* use of agricultural inputs rather than *uniform reduction* in the use of inputs. As noted above, however, growers may be willing to accept some trade-offs in total output in return for a reduction in adverse environmental impact. Research on this relation and on PA's contribution to an overall reduction in input use would seem to be foreclosed by this subsection. Congress has not appropriated funding under this authority to date. Section 401 of P.L.105-185 authorizes a new 5-year Initiative for Future Agriculture and Food Systems research that has PA as one of six priority mission areas (coupled with natural resource management). About $113 million is available for research grants for the Initiative and this has been appropriated only for FY2000.

At least eight public or land-grant universities have established PA research institutes or laboratories: Purdue, University of Georgia, Oregon State, University of Minnesota, University of Arizona, Texas A&M, University of Missouri, and North Carolina State. In 1996, the Cooperative State Research, Education, and Extension Service (CSREES) reported funding about $9 million to PA-related research at land-grant universities. The Coastal Plain Experiment Station in Georgia received $3.4 million between 1991 and 1993 to construct the National Environmentally Sound

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[27] Lohr, L., T. Parker, and L. Higley. *Farmers risk assessment for voluntary insecticide reduction.*" *Ecological Economics* 30(1)(July), 1999:121-130.

Production Agriculture Laboratory where PA is a major element of the research program. The Agricultural Research Service (ARS) also invested $4.4 million in PA-related research in 15 locations in 1995. According to the ARS Budget Office, the agency spent $20.4 million on PA from 1996 through 1999. For 2000, it has allocated $7.7 million for PA-related research. In addition, the ARS Subtropical Research Laboratory in Weslaco, Texas is the site of RESOURCE 21, a project designed to launch four solar-powered satellites for remote sensing that will support PA. This public-private venture is being developed under a USDA Cooperative Research and Development Agreement (CRADA) involving six partners and the ARS.

Other Federal agencies conducting research and development with PA applications include the Department of Energy (e.g., Idaho Engineering Laboratory) and the National Aeronautical and Space Administration (e.g., LandSat, Commercial Remote Sensing Program at Stennis Space Center). It also should be noted that the U.S. Department of Defense has, quite unintentionally, probably had the largest federal investment in PA with its launching and maintenance of the 24 Earth-orbiting satellites that comprise the GPS.

Congressional Interest

Congressional interest in PA involves several issues, including the role of public research and education, PA's potential effects on U.S. farm structure, and questions of data ownership and control.

Role of Public Research and Education. Inasmuch as PA is evolving largely under private auspices, potential roles for the land-grant universities are unclear. If PA is truly a new paradigm for agricultural production, as some observers believe, the traditional role of extension agronomy, for example, may not be as well-suited for the managerial demands that PA places on the grower as extension was for many previous agricultural innovations. In addition, some observers believe that the land-grant institutions are not well-equipped to provide the highly skilled data analysis that will be needed by farmers. Several land-grant universities, however, have begun research programs in PA (See the list of Websites in the Bibliography) and the University of California-Davis now offers a minor in PA in its Department of Biological and Agricultural Engineering. An increase in the number of private crop consultants in PA, either as independent contractors or as employees of agro-input firms, also may suggest changes in the traditional role of land-grant university research and extension. More private crop consultants could make public education and extension programs for PA redundant. On the other hand, some farmers may perceive crop consultants with ties to agro-input firms to be less than objective in some of their managerial recommendations and may consider the perceived neutrality of land-grant extension agents and university researchers to be a valuable asset. Land-grant researchers could help guide future PA developments. Regionally specific socioeconomic and environmental analyses will be necessary to gauge the potential of PA as it becomes more widely used. These usually have been publicly-supported areas of research by land-grant scientists and extension personnel.

Traditional models of agricultural research and extension services may not be adequate to some of the challenges of PA, which is based on site-specific characteristics. Most agricultural research, by contrast, generalizes from a representative sample (or experimental data) to a larger population. Extension personnel apply the validated research results to individual cases. That model may be less useful to PA analysis than it was for earlier agricultural innovations. A grower needs to interpret the data from a PA system so that the information can be used to make field-level management decisions. Growers need to know how to integrate the information for precision application decisions when a series of field characteristics, e.g., soil quality, disease, pests, weather assumes a particular configuration. Traditional research and extension systems do not provide for this level of precision interpretation. Some land-grant education and training programs may opt out of providing PA extension education, letting private crop consultants take over this role, whereas others might opt to change their education and training programs to better reflect the specificity of PA-related knowledge. Several Midwestern 2-year colleges have new PA education and training programs that could help provide publicly supported extension services to PA adopters. Graduates of these and other PA programs at 2-year colleges in collaboration with traditional extension services might become a significant public source of regional expertise in PA.

PA's Effects on Farm Structure. Some observers argue that smaller farms could gain from PA because they are often operated under tighter labor constraints where automation might enhance field monitoring capabilities, especially if the operator is a part-time producer. Other observers argue that net benefits of PA are greater for large farms and that the comparative advantages of small farms for focusing on individual, high-value plants could be lost when larger producers gain an ability to do the same. As discussed above, there is no evidence that PA exhibits bias favoring larger producers, although a profile of early adopters does suggest that the majority are large, well-financed commercial operations.

If a tendency toward scale bias does exist, it could be like many technical innovations in agriculture that research has shown to have contributed to increasing the gap between large commercial operations and smaller operations. Given existing differences in computer and information management skills between typical large operators and smaller ones noted above, PA's data complexities could further widen this divide. Absence of viable public involvement in PA could have the effect of making it more likely that large farms benefit more from PA. The private sector is more likely to put its major resources, e.g., data analysis services, VRT services, in those areas where their returns are likely to be the highest. That will probably mean, for the near term, in areas such as the Northern Central corn belt where nitrogen, herbicides, and phosphorus applications can be most significantly affected.

Other effects on farm structure are also possible. Creation of proprietary seed-chemical-PA "packages," for example, also could conceivably increase costs to farmers or create conditions where contract farming arrangements become more common.[28] While larger, better capitalized growers may find such contractual

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[28] Monsanto, a corporation currently developing PA technologies, charges a technology fee for the use of its Roundup Ready soybeans and Bt corn, a proprietary genetically engineered seed. This is a new way of profiting from agricultural technology. Proprietary ownership of

(continued...)

arrangements attractive, smaller farm operations that do not enter into these arrangements could be at a disadvantage. Some research discussed above also suggests that older or less educated farmers may find the information volume and computer-use skills that PA requires a significant barrier. This does not mean that PA necessarily forces older, less educated farmers out of farming, only that it may be an additional factor either separating them further from more financially successful growers or expediting their decision to exit farming. Limited-resource farmers, including minority farmers, most with annual gross sales under $25,000, may also find the costs to adopt PA techniques prohibitive.

Previous technological changes have contributed to changes in the structure of U.S. agriculture. Socioeconomic research on PA will provide a clearer picture of its potential for accelerating such change. Should new contracting arrangements develop between farmers and proprietary owners of farm inputs, for example, research on the dynamics of this process could better inform policy makers who wish to respond. Expanded efforts in public education for developing computer skills, including bringing educational opportunities to farms, could enhance the possibilities of smaller farmers adopting PA techniques. Existing funding mechanisms through CSREES and ARS may provide a means for supporting regional research and extension should the demand for PA arise in areas unlikely to be serviced by private companies.

PA is developing in the context of a number of significant changes affecting agriculture and the rural sector more generally.[29] Given the adoption patterns observed for PA to date, smaller operations, especially those located in areas not dominated by larger, commercial operations, may find that their opportunities to participate in PA are limited. The implications of under-serving certain areas with PA services might become part of a broader examination of changes in the structure of agriculture and the role of public policies in responding to these changes. If, for example, the private sector's domination of PA development is part of a more fundamental change in the way future agricultural innovation might progress, how public policy might respond could become a significant issue before Congress.

Data Ownership and Control. Arguably the most valuable commodity generated by PA is the data acquired to create site-specific recommendations about particular fields. With the large amount of data that will be collected, intellectual property issues may emerge about data ownership, storage, access, disposal, and protection. Currently, public institutions have more fully developed systems of privacy protection and disclosure than does the private sector. Increased contract production, with proprietary control over production inputs and outputs, and potential private sector domination of PA data systems, could create conflict over who owns farm-generated data and who may have or grant access to it. Growers' groups have expressed some concern that without appropriate safeguards, PA data could provide the means for monitoring a farmer's operation either by state agencies for compliance

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[28] (...continued)
PA databases could confer similar advantages to a firm.

[29] Welsh, Rick. *The Industrial Re-Organization of U.S. Agriculture: An Overview and Background Report.* Policy Studies Report #6, Henry A.. Wallace Institute for Alternative Agriculture, 1996.

or by private firms for the creation of proprietary products. Moreover, depending on how data controls develop, information collected by a contractor could be copyrighted or protected under trade secrets and sold to others, even without the farmer's permission. Farmers have expressed concern about being able to exert a right over the intellectual property in some form.

Databases such as those created for PA presumably could be protected under copyright law (17 USC, §102). Protection is granted by copyright law irrespective of the form or medium in which the data are embodied. If the database exhibits original, creative expression through the selection, arrangement, or coordination of the data elements, copyright protection subsists in these facets of the database.[30] International law on intellectual property rights in databases is emerging that could conceivably impinge on issues of ownership and use of databases created for PA.[31]

The traditional land-grant approach to research involved developing basic knowledge and technology at university and agricultural experiment stations and then disseminating it to farmers through the Extension Services. With PA, the farm itself becomes the source of valuable knowledge. Because this knowledge is valuable, there is an incentive to convert it to intellectual property, especially if the creator of the knowledge is a private firm. The land-grant system's orientation was toward the creation of generalized knowledge; PA is directed at the creation of information that is "context-specific/decision-focused knowledge."[32] With PA technologies, farmers can acquire data about their own operations, bypassing the need to adapt agricultural experiment station research to their own operations. This shift in how agricultural information is generated and used, and the potential for someone other than the farmer owning and using the site-specific knowledge may create intellectual property issues for agriculture that are similar to ones that the manufacturing and service sectors have addressed.

The 106th Congress is currently considering legislation on intellectual property concerns in databases. H.R. 354, Collections of Information Antipiracy Act, would amend Title 17 of the U.S. Code to provide broad copyright protection to databases and the facts that generate them. Last reported action on the bill was its discharge by the Committee on Commerce and placement on the Union Calendar (Calendar No. 212) on October 8, 1999. Although this bill does not directly address the site-specific databases that would be created through PA techniques, it would seem to offer additional protection to the creator of the database. If the creator of the database is, for example, an employee of any agricultural business and not the grower, it is unclear

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[30] For more information on the legal basis of database protection, See CRS Report 98-902, *Intellectual Property Protection for Non-Creative Databases*.

[31] Databases are protected as a "content industry" within the information industry and are defined in Article 2 as "collections of (other) materials such as texts, sounds, images, numbers, facts or data ...." World Intellectual Property Organization, *Draft Treaty on Intellectual Property in Respect of Databases*, Diplomatic Conference on Certain Copyright and Neighboring Rights Question, December, 1996.

[32] Boehlje, M. *"Information and technology transfer in agriculture: the role of the public and private sectors."* Pp. 23-38 in Steven A. Wolf, ed. *Privatization of Information and Agricultural Industrialization.* Soil and Water Conservation Society, CRC Press, 1998.

where ownership and use rights might lie. Because the source of the facts presumably protected is a farmer's cropland, it is unclear whether the protection would lie with the facts in the database or the facts associated with the grower's land on which the database is developed.

H.R. 1858, the Consumer and Investor Access to Information Act, is designed to promote electronic commerce by improving consumer access to electronic databases. Last reported action on the bill was its discharge by the Committee on Judiciary and placement on the Union Calendar (Calendar No. 213) on October 8, 1999. It is a narrower bill than H.R. 354 in that it would extend copyright protection to the databases but not to the facts in them. As in H.R. 354, the kinds of databases created under PA are not specifically identified in the bill, and there may be differences between PA databases and those that these bills are designed to protect. If Congress wishes to specify that farmers own and control site-specific PA databases, regardless of whether they are created by the farmer or by someone contracted by the farmer, bill language might be added.

As noted above, public institutions generally have stronger privacy rules than the private sector. Central storage and control over the data in a public institution, e.g., data warehousing at a land-grant institution, for example, might provide a mechanism to increase farmer control. With appropriate protections (e.g., no owner identification), such an arrangement might also provide a publicly accessible database of regional adopters of PA techniques that would be useful to land-grant and other researchers as well as to extension personnel.

Other Public and Public-Private Roles in PA

Enhancing potential society-wide benefits such as improved environmental quality may be an appropriate public sector responsibility. Most sensor research in the private sector, for example, is currently targeted toward crop production and quality. Sensor development targeted to environmental measuring (e.g., pesticide residue, pollution loading, indicator species detection) holds potential benefits for society more generally. If promoting adoption and diffusion of PA for its environmental potential becomes desirable, different policies for agricultural production may give farmers different incentive to adopt.

Farmers currently have little incentive to deal with most environmental externalities of agricultural production; thus new technologies like PA that hold some promise for ameliorating environmental effects may not be valued by producers as highly as having changes to policy that increase that value. However, policy incentives encouraging growers to raise its importance in their production decisions, as is occurring for other industries, may enhance their interest in adopting PA to reduce some of the adverse environmental impacts of contemporary agricultural production. For example, if buying and selling pollution credits, already adopted in a few areas of environmental regulation, was authorized for agriculture, that policy measure could rely on PA data to document crop herbicide and fertilizer applications. In addition, the Environmental Quality Incentives Program (EQIP) might be used for cost-sharing the adoption of PA techniques where significant environmental improvement was possible.

Rural areas generally have less of the advanced information technology infrastructure that PA requires, and incentives to meet these needs may be insufficient for private companies. The cost of making differential correction of the GPS signals varies depending on the location of reception towers. Some areas of the US receive this correction from public sources such as the U.S. Coast Guard system; individuals in other areas must purchase the differential correction from private vendors. Recently, however, the Department of Defense ended its selective availability (SA) of the GPS signal (which made the signal less accurate for civilian use) and made it accurate for civilian use to approximately 20 meters. Additionally, most rural areas lag in access to the effective communication systems and high-speed data connectivity that will become increasingly significant for adoption of PA. These technologies include an advanced telephone system called a digital subscriber line (DSL), cable modem technology, satellite technology and land-based wireless technologies.[33] The private sector may be less likely to invest in high-speed data connectivity in rural, dispersed markets than in more urban or suburban areas where the cost to serve each user would be less. The lack of broadband connectivity may also act as a deterrent to some PA service providers. Conversely, the availability of broadband connectivity may make those locations more attractive to some private providers of PA services.

Changing pubic attitudes and an environmentally oriented marketplace may increase pressure on the agricultural sector to improve its environmental performance. This has been happening in confined-animal feeding operations, but pressure to redesign some other agricultural systems is growing. A number of policy questions could arise if this pressure continued to grow. For example: Could taxation be linked with environmental performance in revenue neutral ways for the agricultural sector? Could PA techniques play a role in reducing environmental regulation and in switching to performance-based measures? Could research on coordinating PA with environmental policy facilitate this switch? Would increased public funding for basic research on PA-related subjects be appropriate? Would public/private collaboration on pre-competitive PA research and development, e.g., environmental sensors, on new environmental performance incentives, and on other market-based mechanisms be appropriate? For example, might advances in remote sensing technology become useful tools in regulatory compliance for environmental quality?

Conclusion

Research in the public and private sectors is currently developing and assessing PA technologies and documenting the benefits and costs of adopting PA in particular areas and for particular crops. Research on PA's economic returns, on its potential to reduce adverse environmental effects, and on its adoption profile is hardly conclusive. As results from PA-related research are evaluated over the next few years, proponents will probably be in a much stronger position to advocate PA's benefits. A small but active presence for PA in several land-grant universities and within ARS may help to better define potential benefits of PA and clarify when, where, and to what degree these benefits may be achieved.

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[33] From more information see CRS Issue Brief 10045, *Broadband Internet Access: Background and Issues.*

The private sector is likely to continue its research into many PA-related areas, especially those that offer market and profit potential, including: improving sensors to more precisely monitor crop production and crop quality characteristics; standardizing and refining the calibration of VRT; designing and developing new PA equipment for higher-value crops; simplifying GIS data acquisition and interpretation; and refining remote sensing technologies. The National Research Council report on PA (See Bibliography) also noted the lack of what it called "decision support systems" research to quantify the complex relationship between the quantity of an input and yields within a changing bio-physical environment in a grower's field. The basic knowledge to link precise data and precise recommendations is a significant gap. While traditional research and extension information models do not appear to provide well for PA interpretation at this point, the area of "decision support research" may not be attractive to the private sector, suggesting a role for public research and extension.

Private sector firms seem convinced that larger commercial growers in bulk commodities will continue to find adoption of some PA techniques or contracting for some PA services valuable. Growers in other crop systems, as well as perhaps in livestock and range-land management systems, will likely draw from this experience to help make their own decisions on adoption, especially if the technologies become less expensive, if training and support are provided, if early on-farm data collection and analysis suggests that an operation is a good candidate for PA, and if producers see their neighbors and friends adopting PA.

Over the longer term, agronomy experts generally believe that PA seems likely to develop a viable presence in agriculture, concentrated in some regions and for some crops. PA seems likely to take many forms with some growers adopting individual techniques of PA and others adopting highly sophisticated PA systems. Large commercial operators, younger on average, with strong computer and technical skills, seem likely to remain the modal PA adopters. As further research on the economic and agronomic benefits emerge, some farmers will continue to adopt and others will decide against it. Database ownership, control, and privacy concerns may cause some producers to bypass PA until these questions can be satisfactorily answered. Several broad issues could become the focus of congressional review, including, (1) intellectual property issues in PA databases; (2) PA's role in moving from a regulation-based to a performance-based environmental policy for agriculture;[34] and (3) PA's role in the larger context of the changing industrial structure of U.S. agriculture.

PA will increasingly become part of the technological fabric of changes and pressures facing farmers, distributing its costs and benefits varyingly across the agricultural sector. PA seems unlikely, however, to be a single cause of any

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[34] The emphasis in performance-based policies, e.g., market-based controls, information management systems, is on achieving measurable environmental results with flexible, innovative policy tools versus a prescriptive regulatory policy approach that tells a company or community how to manage a pollution problem. See Howes, J., D. John, and R.A. Minard, Jr., *Resolving the paradox of environmental protection."* *Issues in Science and Technology* 14(4), summer, 1998.

significant shift in agricultural production's dominant trajectories. It may produce significant economic and environmental benefits at acceptable costs on some farms, in some regions, and perhaps for entire production systems; but it may also offer only marginal benefits to others.

Glossary

Base Map. A binary digital map that is the outline of a field with its proper coordinates. Data collected within the field by a yield monitor can be defined in location by the base map.

Choropleth Map. A thematic map such as a soil image where spatial data is displayed through the use of shading or color variations.

Crop Scouting. Precise assessments of the spatial distribution of pest populations and crop performance. The data from crop scouting, collected weekly in some cases, can be tied to specific coordinates on the grower's base map permitting the targeting of pesticides where and when they are most needed.

Differential Correction. Correction of the GPS signal to make it more accurate. The uncorrected signal is currently about 20 meters. Correction of the signal is done from a second GPS receiver at a known fixed location. A corrected signal can be accurate to about 1-3 meters. The Coast Guard, FAA, Corps of Engineers, and the Department of Transportation provide corrected GPS signals. In many areas of the country where these publicly provided corrections are not available, commercially available services sell corrected GPS signals to subscribers who need greater accuracy than 20 meters.

Digital Elevation Models (DEMs). Digital representation of topographic data. These models can enhance the validity of soil survey maps by factoring in the slope/gradients of a sub-field area. Topographic variation in a field can influence soil quality, seed germination time, or moisture holding capacity of otherwise similar soil types.

Digital Soil Mapping. Fields are divided into grid cells defined by a GPS receiver. Cells are approximately 2-3 acres. Larger scale resolution is also possible and, depending on the fields biophysical variability, perhaps necessary for more precise input application. Soil sample data from each cell are transferred to a digital map that is then used for variable rate application.

Expert System. Often regarded as a branch of artificial intelligence (AI), an expert system is designed for solving particular problems in a particular area, e.g., agriculture or medicine. Using the stored knowledge base developed through the GIS, an expert system would define rules for timing pesticide application aimed at specific pests, or when to begin tilling, or when to apply fertilizers for optimum performance. These decision rules are modified by soil, pest, weather conditions, and other data integrated into the GIS.

Geographical Information Systems (GIS). A combination of computer hardware, software, and geographic data designed to capture, store, manipulate, analyze, and display data that is referenced to specific points on the earth's surface. The capacity to perform many sophisticated spatial operations on these data differentiates GIS from simple mapping software.

Geo-reference System. A coordinate system tracking specific points on the Earth's surface. An example of such a system is the Universal Transverse Mercator system (UTM), a commonly used map projection that uses a set of transverse Mercator positions for the globe that are divided into 60 zones, each covering 6 degrees longitude with an origin of the central meridian and latitude of 0 degrees.

Global Positioning System (GPS). Most PA will make use of the U.S. Department of Defense's 24 earth-orbiting satellite system to assign map coordinates. These satellites emit radio signals at precise intervals accurate to a billionth of a second. Through triangulation, a ground-based receiver translates the time lag between emission and reception of the signals into precise geographic coordinates on the targeted cropland.

Ground-based Sensors. Sensor-based application of inputs implies that sensors on the VRT can measure information in real-time and make the necessary precise adjustments. Ground-based sensors, also called real-time or local sensors, have been developed for measuring soil nutrient status, soil physical properties, and plant qualities. Research into other sensors is underway.

Point Sampling. A method of soil grid sampling where a sample is taken in a 10-30 foot radius at the center point of each grid cell (See digital soil mapping).

Precision Agriculture (PA). An emerging set of farming techniques whose fundamental feature is assigning geographic coordinates to the biophysical variability of cropland for improving efficiency of inputs. PA's technology consists of four major components: a Global Positioning System (GPS) receiver, a yield monitor, a digital soil map, and variable rate application technologies (VRT). Data from these components are integrated through a geographical information system (GIS). The concept of PA focuses on the use of advanced information technologies in assessing and managing temporal and spatial variation in cropland.

Remote Sensing. Data from light reflectance collected by instruments in airplanes or orbiting satellites. The data can estimate vegetation characteristics, e.g., efficiency of nutrient uptake, on small areas within a field. High resolution (e.g., 1-5 meters) satellite images are currently available to producers from private vendors (e.g., Space Imaging, Inc. will sell high-resolution satellite images from the satellite IKONOS during the 2000 crop season).

Variable Rate Application Technologies (VRT). Computer-controlled equipment continually readjusts the input application. Soil grid data provide the prescription for the particular fertilizers or pesticides to be applied to each grid. A GPS receiver in the truck enables the computer to recognize where it is in the field. Computer-controlled nozzles can then vary the types and amounts of inputs according to the soil fertility or pest population maps. Similar equipment is also available to vary seeding rates for some crops.

Yield Monitoring Systems. Area-specific yields in the field are measured using combine-mounted sensors or volume meters. A display of the yield weights and moisture content of the grain every few seconds is translated to bushels/acre. When used in conjunction with a GPS receiver mounted on the combine, estimates of yield can be assigned to areas of a field to create a yield map. Proper calibration of yield monitors can give a load accuracy of from within 5% of true yield under normal operating conditions.

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John Deere: [http://www.johndeere.com/greenstar]
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[http://bae.ncsu.edu/programs/extension/agmachine/precision]
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