GEORGE W. NORTON AND SCOTT M. SWINTON*

Precision Agriculture: Global Prospects and Environmental Implications

INTRODUCTION

Producers in industrialized countries have been inundated by ideas and information about precision agriculture (PA) and how new site-specific management (SSM) technologies will revolutionize their farm operations. Conjuring up 'Star Wars' imagery, farmers and their computerized machinery communicate with satellites while speeding up and down the information highway. The farm press has hailed the advent of these technologies as a win–win situation, with higher farm profits and improved environmental quality. Certainly the potential is there for greater economic returns and better environmental stewardship. But what exactly is precision agriculture, who is applying it, and where? Is the technology only relevant for developed countries and are there implications for markets? What is the likelihood that environmental benefits will be realized? This paper addresses these questions by drawing on literature, data and expert opinion.

WHAT IS PRECISION AGRICULTURE?

Before the advent of the tractor, farmers tilled small fields, making agronomic management decisions based on the special characteristics of each tiny parcel of land. When mechanization took over, it no longer made economic sense for producers to focus at the site-specific level. Uniform management over larger fields was more cost-effective, even though less precise pest, fertility and moisture control was achieved (Swinton and Lowenberg-DeBoer, 1998). The objective of precision agriculture is to allow farmers cost-effectively and more precisely to address spatial and temporal variability within large fields. A broad definition of precision agriculture based on one provided by the National Research Council (NRC, 1997) is: 'Precision agriculture is a management

*George Norton, Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA, USA. Scott Swinton, Michigan State University, East Lansing, MI, USA. The global scope of the adoption assessment was made possible by help from Stan Daberkow, Jon East, Harold Reetz, John Schueller, Hermann Waibel, Paul Winters, Ada Wossink and participants in the Precision Agriculture e-mail list server maintained by the University of Minnesota (*listserv@coal.agoff.umn.edu*). We thank Jess Lowenberg-DeBoer for helpful comments on an earlier draft.

strategy that uses information technologies to provide and process data with high spatial and temporal resolution, for decision-making with respect to crop production.' By encompassing performance measures (such as yield maps), this definition is broader than many input-oriented definitions (for example, Khanna and Zilberman, 1997). What makes PA possible is not one new technology, but the convergence of a whole suite of technologies (Swinton and Lowenberg-DeBoer, 1998).

The key innovation compared with conventional management is the application of modern *information* technologies. PA technologies are most often directed at spatial variability within fields, although some focus on temporal variation as well. Precision agriculture is based on addressing the variability of soils, pests, moisture, micro-climates and other factors that are present in agricultural settings, notably cropped fields. It relies on three major components: (a) capture of data at an appropriate scale and time, (b) interpretation and analysis of that data, and (c) implementation of a management response at an appropriate scale and time (NRC, 1997). We distinguish between two categories, the site-specific (SS) and the development-specific (DS). SS technologies focus on spatial management, usually for crops. DS technologies deal with temporal management and include applications to crops, livestock and pests. Our main concern will be the SS technologies as used in the capital-intensive computer-based systems that seem to have captured the term 'precision agriculture' in the popular press.

Site-specific management (SSM) relies heavily on four component sets of computer-based technologies: geographic information systems (GIS), global positioning systems (GPS), variable rate application (VRA) input systems and sensing technologies. Geographic information systems (GIS), as used in SSM, spatially reference layers of data about field attributes to help in managing small units and in comparing different types of information at multiple locations. Global positioning systems use mobile field instruments to receive satellite signals to identify the location of a piece of equipment in the field. Variable rate technologies use a computerized controller to vary spatially inputs such as seed, fertilizer and pesticides based on the needs calculated by linking GIS information to a specific field position. The VRA system may be map-based and use a GPS and a controller that stores a plan of the desired application rate for each location in the field. Alternatively, it may use sensing technologies that signal the controller to vary application rates based on real-time analysis of soil and/or crop sensor measurements. In-field sensing technologies do not necessarily require a GPS and permit relatively low-cost data collection about field characteristics such as organic matter, cation exchange capacity, top soil depth, moisture, soil nitrates and crop spectral reflectance.[1] VRA fits into existing systems relatively easily because it may be used for one or two inputs as a stand-alone practice without changing other elements of the system.[2]

Yield monitors are the most common SS sensing technology, with data typically being stored in a GIS and statistically smoothed for printing as a yield map. Farmers may use yield maps to identify problem areas in the field, often combining the information with soil sampling on a grid basis in the field.

Yield maps are used not only for VRA but also to suggest areas that would benefit from drainage, irrigation, land levelling, fences and other investments. Mapping records the spatial distribution of yield while the crop is being harvested. Systems have been used mostly for grains, and use mass flow and moisture sensors to determine grain mass and GPS receivers to record position. Yield maps can also help farmers make decisions such as how much to bid, or whether to bid, on renting a field. Precision agriculture data generated for sub-field management may have additional value when combined with similar material from other fields and farms.

Some PA technologies are development-specific, relying on computer models to predict crop growth, pasture growth, animal digestion and growth, or pest damage. They mostly take the form of decision support tools that predict crop or animal response to management actions. Examples are integrated pest management (IPM) threshold programmes that predict how crop yield and net revenues would respond to control of weeds, insects or diseases. IPM threshold programmes for insects and weeds typically simulate pest demographics, cumulative crop damage projected from rising populations and response to alternative pest control practices (Pedigo *et al.*, 1986; Cousens *et al.*, 1987). IPM thresholds for diseases typically focus on predicting disease spread based upon weather prediction and length of opportunity for disease control, since many diseases are devastating once they spread (Travis and Latin, 1991). Other DS software predict livestock weight gain under alternative feeding regimes at different life cycle stages (for example, Rotz *et al.*, 1989). Because site-specific technologies are relatively new, we will focus primarily on them rather than on the development-specific technologies.

ADOPTION: WHAT TO EXPECT

A conceptual model can assist in forecasting the settings in which adoption of PA information technologies is likely to occur. Consider the dynamic problem of choosing a stream of inputs over time that will maximize a farmer's discounted net revenue stream. In particular, the problem is to choose those capital inputs (both information technologies, k_I, and conventional technologies, k_x and the annual variable inputs (custom PA services, cs_I, and conventional inputs, x) whose costs depend in part on the level of capital investment in related technologies:

$$\underset{k_I, cs_I, k_x, x}{Max} \int_{t=1}^{T} \delta^t E(\pi_t)dt \qquad (1)$$

subject to:

$$
\begin{aligned}
&\pi = r(p, A, y[x,z]) - c(w_x, x, w_I, cs_I[K_I, CS_I]) - k_I - k_x - FC \\
&k_j = k_j(K_{jt-1}, L_f, \int \delta^t \pi_t dt, WK(Y^{nf}, credit[K_{jt-1}, i, A]) \quad \forall j = I, x \\
&K_{jt} = K_{jt-1} + k_{jt} \\
&K_{I0} = 0; K_{x0} = K_0
\end{aligned}
\tag{2}
$$

In this model, $E(\cdot)$ is the expectations operator, δ is a discount factor, and π_t is net revenue in period t, with integration covering all periods up to time horizon T. In the constraint set, the time subscript is suppressed for simplicity. Annual net revenue, π_t, depends upon revenue ($r(\cdot)$), variable costs ($c(\cdot)$), and capital costs (k_j, FC). The revenue function, $r(\cdot)$, depends upon product price, p, land operated, A, and productivity, y. Productivity, in turn, depends upon conventional inputs, x (including seed, fertilizers, pesticides, hired labour) and conditioning factors, z (such as human capital, management ability and land quality). The variable cost function, $c(\cdot)$, depends on input levels and unit input prices, w_x, for conventional input x and w_I for information custom services, cs_I. The demand for custom services will depend on both the level of existing farm investment in information technologies, K_I, and the existing set of custom services available in the local economy, CS_I. The annual capital costs for information technologies (k_I) and conventional technologies (k_x) also figure in net revenue, along with other fixed costs, FC. Annual investment costs of either technology, k_j, depend upon prior capital stocks, K_{jt-1}, the availability of family labour (L_f), expected future net revenues from changes in capital level (the second term) and the availability of working capital, WK. WK, in turn, depends upon non-farm income, Y^{nf}, and credit, which is a function of current ownership of capital (K_{jt-1}), interest rate (I), and land (A). The final two constraint equations specify the dynamics of motion and initial conditions.

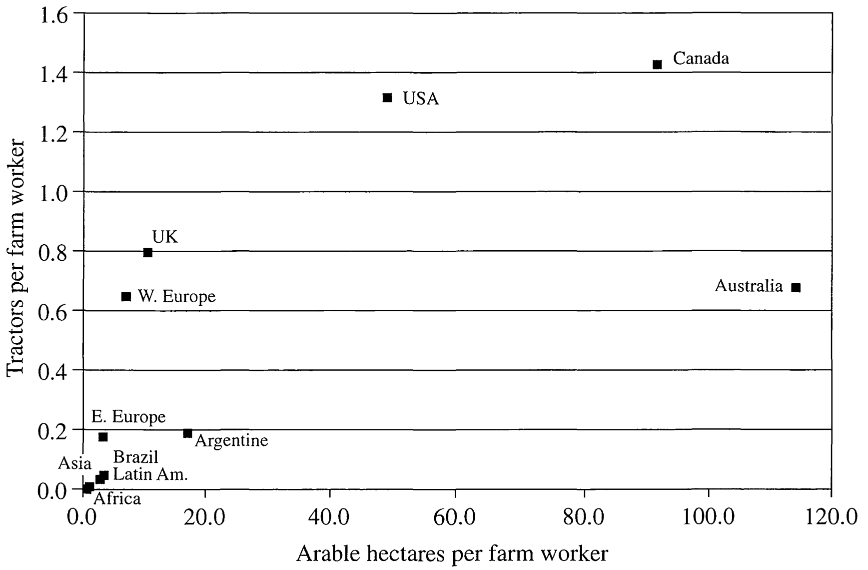
Creating a Hamiltonian from (1) and (2) and differentiating with respect to k_I or cs_I leads to a reduced-form input demand function that highlights the expected determinants of adoption for PA technologies:

$$k_I = k_I(p, w_I, w_x, i, K_0, Y^{nf}, CS_I, A, z) \tag{3}$$

Equation (3) suggests that, apart from input and output prices, SS PA technology adoption depends on the farm's access to investment capital, be it from an initial endowment, off-farm income or land. Because PA technologies can enhance land productivity, land also matters for its role in the revenue function. Embedded in the z variable are management quality elements, including human capital, suggesting that more rapid adoption of PA technologies occurs where education levels are higher. The model also points to the importance of an agribusiness infrastructure that makes available PA custom services.

This conceptual model provides a starting point for a critical assessment of PA technology adoption. If the model is extended, further attributes can enter. For example, if risk is included in the utility function of the decision maker, then the determinants of yield variability may enter the adoption function. Likewise, where governments enact policies to reduce non-point source water pollution from agricultural chemicals, policy parameters may also enter the adoption function. In such nations, adoption may be more advanced for environmental policy reasons, other things being equal.

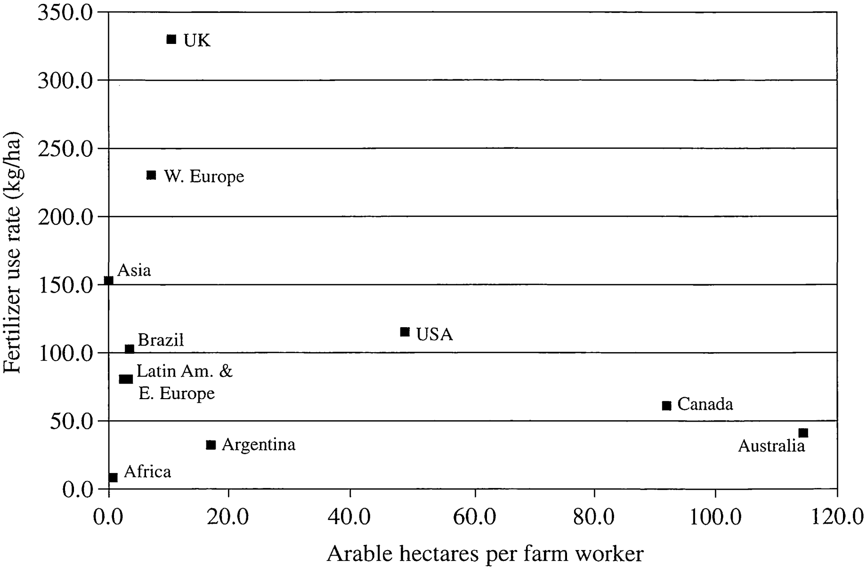
The model suggests we might expect earliest adoption of PA technologies among farms and in countries where agricultural land and capital are abundant. After all, site-specific technologies automate management decisions for mechanized agriculture. They can be thought of as another wave of technological innovation induced by factor prices that enhance the productivity of labour in regions where it is relatively most scarce (Hayami and Ruttan, 1985). Focusing on complementary inputs per worker, Figure 1 compares existing levels of agricultural land and capital (as tractors) per worker in major agricultural regions of the world. The relative abundance of land and capital relative to labour (or conversely, the relative scarcity of labour) suggests that Canada, the United States and Australia would be prime candidates for site-specific technology adoption.



Notes: Africa = sub-saharan Africa; Asia excludes Japan and Israel; population data refer to 1990.

Source: FAOSTAT databases on land, fertilizers and economically active agricultural population (*http://apps.fao.org/lim500/agri_db.pl*).

FIGURE 1 *Tractors and arable land per farm worker: selected nations and regions, 1997*



Notes: Africa = sub-Saharan Africa; Asia excludes Japan and Israel; population data refer to 1990.

Source: FAOSTAT databases on land, machinery and economically active agricultural population.

FIGURE 2 *Fertilizer rates and arable land per worker: selected nations and regions, 1997*

To the extent that SS PA technologies offer agrochemical input cost savings, Figure 2 suggests that a second category of PA adopter countries could be those land-abundant nations where fertilizer use is high (especially if environmental regulations discourage non-point source water pollution from agricultural chemicals). Figure 2 reveals that no countries combine both land abundance and heavy fertilizer use rates. However, in Western Europe, fertilizer use is quite high. So if input cost saving and environmental protection are major adoption determinants, these may be areas for willing adoption of PA technologies.

ADOPTION: WHAT WE OBSERVE

Where PA adoption is occurring

At present, there exist no inter-country data with which to test formally the hypothesis that adoption of PA technologies would occur where land and capital are abundant compared to labour. However, fragmentary survey data bolstered by anecdotal evidence are highly supportive. Adoption of site-specific technologies appears to be highest in the USA, followed by Canada and then, probably, Australia and/or Great Britain. But farm-level adoption of site-specific technologies is still concentrated in certain crops and regions, even in these countries.[3] What data are available focus on the two practices that are easiest to measure: the use of yield monitors and VRA controllers.

In the USA, results from the 1996 national Agricultural Resource Management Survey (ARMS) indicate that approximately 9 per cent of US corn growers had adopted site-specific PA technologies, representing about 19 per cent of the corn acreage (Daberkow and McBride, 1998a, 1998b). Soil sampling, using a grid or map approach, was the most adopted practice with 15.8 per cent of corn acreage, followed by yield monitoring with 15.6 per cent. In the corn, soybean and wheat country of the Midwestern USA, where SS technology adoption is most widespread, Khanna *et al.* (1999) found that nearly 14 per cent of farmers were grid sampling their soils in 1997. Eleven per cent of the farmers used VRA for fertilizer application, 2.5 per cent used VRA for pesticide application and 2.4 per cent used it for seed application.

More than 18 per cent of US corn and soybean acreage was under yield monitors in 1998 (Table 1), according to the ARMS studies. Khanna *et al.* (1999) found similarly that in 1997 almost 10 per cent of farmers surveyed in Illinois, Iowa, Wisconsin and Indiana had adopted yield monitors for use on farms covering more than 17 per cent of the cropped acreage surveyed.

TABLE 1 *Percentage of US corn, soybean and wheat acreage under yield monitors, 1996–8*

	Corn	Soybeans	Wheat
1996	15.6	13.0	5.0
1997	17.3	12.2	6.0
1998	18.5	18.6	7.9

Source: USDA/ERS agricultural resource management surveys (ARMS).

Data on adoption of site-specific technologies are spotty elsewhere. In Canada and Australia, wheat growers have begun adopting yield monitoring, but low crop prices and yields have limited the level of investment in nutrient management technologies such as spatial soil sampling and VRA fertilizer application (East, 1999). Likewise, a recent account of PA adoption in Argentina indicates that roughly 1–2 per cent of combines are equipped with yield monitors, but that adoption of VRA for fertilizer application is slow (Lowenberg-DeBoer, 1999). Anecdotal information suggests a similar pattern among large farms in Mexico and Brazil,[4] where in the latter 50 combines were reportedly equipped with yield monitors in early 2000.[5]

Adoption in Europe has been highest in Germany and the UK, and concentrated among larger producers. A 1997 mail survey of 90 crop farmers in the UK found 15 per cent using some form of site-specific technology, including 6 per cent using cereal yield mapping, 7 per cent using VRA for fertilizer application and 12 per cent doing spatially referenced soil sampling and mapping (Fountas, 1998). Eastern Europe lags far behind. In Asia, adoption of site-specific technologies was virtually non-existent by 1998 (Srinivasan, 1998). Emerging Asian use of SS PA technologies appears principally to be applied to perennial plantation crops.[6] In sub-Saharan Africa, expe-imentation with yield monitors and VRA fertilizer has been reported in South Africa,[7] with anecdotal reports of use in Zimbabwe.

Why PA adoption is occurring

Expected profitability is the mostly widely touted reason for adoption of site-specific technologies. More precise information offers the promise of increasing yields (where nutrients were deficient or pests excessive) and decreasing input use (where nutrients were overabundant or pests sparse) (Lowenberg-DeBoer and Boehlje, 1996). Yield risk reduction may also result from VRA fertilization (Lowenberg-DeBoer and Aghib, 1999). Environmental benefits from the reduction of unnecessary agrochemical applications is another potential benefit that farmers could find desirable. Apart from the appeal of site-specific technologies, the feasibility of adoption is another matter, as implied in the conceptual model presented in equations (1) and (2). What is the evidence?

The results of 17 studies that assessed the profitability of SSM are presented in Lowenberg-DeBoer and Swinton (1997). Most of the studies focus on only a single PA practice, but it is clear that the profitability of SSM practices varies significantly by crop, location and year. Five studies found SSM not profitable, six had mixed or inconclusive results, and six showed potential profitability. Upon applying standard cost assumptions to the nine studies based on field (rather than simulated) data, Swinton and Lowenberg-DeBoer (1998) found that profitability correlated closely with crop value. This result supports inclusion of output price in the adoption function above (equation 3). Recent evidence suggests that site-specific management is beginning to see use on fruits, vegetables and other high-value crops (Tisseyre *et al.*, 1999; Chan *et al.*, 1999).

If crop value is so important, why has adoption of site-specific technologies been greatest to date on lower value crops such as corn, wheat and soybeans? One reason may be the ease of adapting existing machinery to the technologies such as yield monitors, and the importance of large field size. McBride *et al.* (1999) conducted a logit analysis of factors influencing corn producers' attitudes toward site-specific farming. Among other things, they found that producers with a favourable attitude farmed more corn land (80–100 acres).

But human capital also favours PA adoption, perhaps because better educated farmers are able to wring higher profit out of complicated site-specific technologies. Khanna (1999) found that education and innovativeness favoured adoption of VRA fertilizer application. Likewise, McBride *et al.* (1999) found farmers favourably inclined towards site-specific technologies were younger (by 4–6 years), had more formal education (by one year), and were more likely to use crop consultants.

This last point highlights the importance of agribusiness infrastructure. The USA has an exceptionally high number of agricultural input dealers who make PA services available to farmers. In 1999–2000, 38–45 per cent of fertilizer dealers in the USA offered soil sampling with GPS, 23–29 per cent offered yield monitoring, and 32–40 per cent offered agronomic analysis of GPS data (Whipker and Akridge, 1999, 2000). Contracting for services with dealers allows producers to test the technology without making a long-term investment. The technically simpler and less expensive technologies such as grid soil fertility testing and pest scouting are used by a larger fraction of the farmers than are the more sophisticated technologies. Interestingly, adoption of SS PA services among US input dealers is beginning to stabilize, perhaps in response to low crop commodity prices. In each case above, the smaller adoption figure in the range given refers to the year 2000, the larger to 1999.

Larger farms are more likely to adopt site-specific methods. As suggested by equations (1) and (2), this occurs because of both the revenue effect from added yield and the fixed cost effect of being able to spread capital costs over a larger output. As illustrated by Thirkawala *et al.* (1999), the profitability of VRA increases with farm size and field variability. Apart from technical economies of scale, large farms may also obtain pecuniary gains in the form of quantity discounts for consulting and custom hire services. The empirical evidence contradicts the assertion that there 'does not appear to be an unambiguous size bias in precision agriculture or similar technologies' (NRC, 1997, p.81). Khanna *et al.* (1999) found that farms adopting PA technologies were 1.6 times larger than non-adopters.

The adoption appeal of potential environmental benefits from site-specific technologies seems to be negligible. Khanna *et al.* (1999) found that only 8 per cent of the Midwestern US farmers surveyed indicated that their first or second most important reason for adopting PA would be its environmental benefits.

Global prospects for adoption of site-specific technologies

While it is not known which technologies will prove to be the most practical and standard PA practices in the long term, evidence to date suggests that PA adoption is likely to increase slowly, but will be concentrated primarily in certain regions in developed countries.

For crop production in the USA, Khanna *et al.* (1999) predict that adoption of VRA for fertilizer application and yield monitors may rise from their 1997 levels of 10–11 per cent to be adopted by about 40 per cent of Midwest farmers by 2001. PA adoption elsewhere in the USA is likely to be lower as profitability is mixed (Swinton and Lowenberg-DeBoer, 1998). The larger and more educated crop farmers in the Midwest have adopted PA quite rapidly. As the technologies are adapted to other crops (for example, yield monitors for cotton) continued spreading among larger farmers in other regions of the country can be expected.

PA adoption for livestock management is yet to begin, but remote sensing is likely to become attractive for range-fed livestock production in land- and capital-abundant areas. Remote sensing of vegetative vigour provides a low-cost means of locating good pastures. Such technologies may see adoption by ranchers not only in areas like the western prairies of North America, but also in other semi-arid regions where livestock are grazed extensively, such as Argentina, Brazil and Australia.

Despite the high rates of agrochemical input use in Western Europe (Figure 2), less land per farm worker is likely to make adoption of site-specific crop technologies less urgent. In selected countries, such as the Netherlands, environmental regulations provide an incentive to reduce fertilizer use, but it is unclear whether costly PA site-specific technologies are the best way to achieve this when fields are small. While the large fields of Eastern Europe are technically suited to site-specific technologies, a shortage of capital will likely continue to hinder adoption of these technologies.[8]

What about developing countries? First, it is likely that SS PA adoption will remain low in developing countries for the foreseeable future. A recent literature review ascribes low fertilizer adoption in sub-Saharan Africa to reliance on subsistence crops and shortages of financial, human and physical capital (Reardon *et al.*, 1999). Such barriers are infinitely more formidable for costly site-specific PA technologies. Indeed, where fields are small and operators know them intimately, PA technologies offer few advantages. The absence of a supporting agribusiness infrastructure is another major deterrent to the diffusion of site-specific technologies in those areas of Africa, Asia (Srinivasan, 1998), and Latin America dominated by peasant agriculture.

Plantation agriculture is the likely exception to the general prediction that SS PA is unlikely to be adopted in developing countries. Plantations growing perennial crops such as coffee, tea, bananas and rubber have the land and capital to take advantage of the potential variable input savings and yield benefits from precision agriculture. Indeed, incipient adoption of PA technologies for plantation crops has been reported in Latin America and Asia.[9]

In certain areas of middle-income developing countries, conditions exist that will favour the adoption of site-specific farming methods. Brazil, Argentina and Mexico include regions with very large farms, despite the fact that the average land per agricultural worker does not stand out on a national scale (Figure 1). In all three countries, farm supply dealers have recently expressed growing interest in site-specific technologies.[10] As noted above, Argentina is seeing the beginnings of yield monitor adoption (Lowenberg-DeBoer, 1999). For similar reasons, there may be spotty adoption of site-specific technologies in South Africa.

Second, the relatively slow adoption in developed countries means that aggregate cost effects and therefore effects of the technologies on world output prices are also likely to be small for the next few years. Adjustments within developed countries are likely to be significantly greater than impacts on developing countries. The relatively small price effects imply that most of the economic benefits of PA technologies are likely to accrue to producers rather than consumers.

Although private adoption of site-specific technologies is unlikely to be widespread in developing countries, there are several public uses of site-specific technologies that may see significant adoption. Remote sensing technologies have been used for 20 years for national crop inventory statistical estimates (Srinivasan, 1998) and yield estimates for early warning of famine risk (Unganai and Kogan, 1998). Remote sensing has other public natural resource management applications, such as monitoring the health of forests and public range land.

ENVIRONMENTAL IMPLICATIONS OF PRECISION AGRICULTURE

The resource conserving/environmental benefits of PA will depend on the potential of the practices to reduce environmental costs if adopted and on incentives for their adoption. Although farmers may include environmental benefits in their utility functions, it cannot necessarily be assumed that the effects of all PA practices are positive for the environment, or that farmers value those benefits enough to adopt the practices if they are only marginally or not profitable.

Part of the enthusiasm for PA off the farm is due to a belief that there will be environmental benefits from more precisely matching inputs such as fertilizers and pesticides to the needs of a crop in small areas and from applying these chemicals exactly when needed (NRC, 1997). Khanna and Zilberman (1997) argue that the root cause of agricultural pollution is not modem technology, input use, or production per se, but inefficient utilization of inputs in the production process. Agricultural pollution comes from inputs that do not reach their target. Residuals from inputs such as irrigation water, fertilizers and pesticides are a major source of mineralization and salinization of soil and chemical contamination of ground and surface water (ibid.). And controlling pollution at the source is likely to be cheaper than cleaning it up afterwards. Indeed, field-level agronomic studies indicate that PA may permit large reductions in input use without sacrificing yields.

Evidence suggests, however, that PA may result in less environmental improvement than indicated by field-level agronomic studies (NRC, 1997; Kitchen *et al.*, 1995; Redulla *et al.*, 1996). One reason is that a major source of nutrient loss from agricultural production systems arises from leaching that occurs during the part of the year when the plants are not in the field (Groffman, 1997). Nutrients lost in the autumn, winter and spring are not so much 'left-over' fertilizer from growing season applications as nutrients lost owing to a lack of a plant 'sink' when the ground is bare (Groffman, 1997; Shipley *et al.*, 1992). Therefore winter catch crops, buffer zones or reduced autumn tillage may have a greater effect than PA, at least for control of nitrogen leaching in temperate climates. Shipley *et al.* (1992) found that only about 20 per cent of total nitrogen in a field of maize in Maryland was derived from fertilizer applications. Second, field-level effects often do not scale up to ambient effects as the latter correlate most closely with factors such the location of the field where PA is being applied in relation to streams or lakes. Third, PA technologies do not always imply lower total input use *per unit of land* even though they would generally not have been applied if they did not reduce inputs *per unit of output*. More precise measurements may suggest lower input use in some parts of the field, but greater use in other parts.

The NRC study speculates that PA might also make it attractive to expand production on certain marginal and heterogeneous fields, possibly creating new environmental problems (NRC, 1997). The marginal lands factor might work the other way, if PA increases yields and total production, thereby reducing pressures to keep marginal areas in production.

The potential clearly exists for environmental improvements as a result of specific PA technologies for certain crops, regions and environmental categories (Larson *et al.*, 1997). Schmerler and Jurschik (1997) found nitrogen fertilizer savings of 5 to 15 per cent and higher yields for site-specific fertilization compared to uniform fertilization on winter wheat and spring barley in Germany. In a four-year study of site-specific weed control in Germany, Gerhards *et al.* (1999) found significant herbicide reductions on maize, sugar beets and wheat. Leiva *et al.* (1997) estimate that PA might save up to 40 per cent in herbicide costs and reduce nitrogen applications by 10 per cent on a farm producing cereals in the UK. Lu and Watkins (1997) found that conventional production was more profitable than three alternative variable-rate nitrogen practices on potatoes in Idaho, and VRA-reduced nitrogen loss only marginally. Thirkawala *et al.* (1999) found that VRA technology on corn in Ontario, Canada has the potential to reduce nitrogen leaching by 4 to 36 per cent, with the variation depending on the natural level of fertility and variability in the fields.

Many studies to date of the environmental impacts of SS management have been based on simulation as opposed to measurement of actual impacts. Hoskinson *et al.* (1999) applied an expert system to model variable rate fertilizer application to wheat and potatoes in Idaho, USA and found a 30 to 40 per cent fertilizer cost decrease on wheat, although they found a significant increase on potatoes. Weiss (1997) found precision application of phosphorus on an Illinois cornfield to be uneconomical, although it did reduce excess residual phosphorus.

Apart from nutrient management, some promising results have been reported for pesticides as well. Weisz *et al.* (1996) report reducing insecticide use by 60 to 95 per cent for control of Colorado potato beetle. Khakural, Robert and Koskinen (1995, cited in Larson *et al.*, 1997) reported reductions in concentrations of alachlor herbicide in runoff water and sediments from SS applications compared with uniform ones. Heisel *et al.* (1999) found that using site-specific weed management reduced herbicide use on winter wheat and barley in Denmark by 47 to 62 per cent compared to label recommendations.

In summary, these and other studies indicate significant *potential* for environmental gains from PA, but those gains will be far from uniform across commodities and locations. In addition, limited profitability may constrain adoption even though environmental gains might be great. Where societal benefits exceed private profitability, there may be a need for public policies to encourage adoption. As illustrated in Figure 3, if there is a negative externality associated with crop production, perhaps due to residuals from agricultural

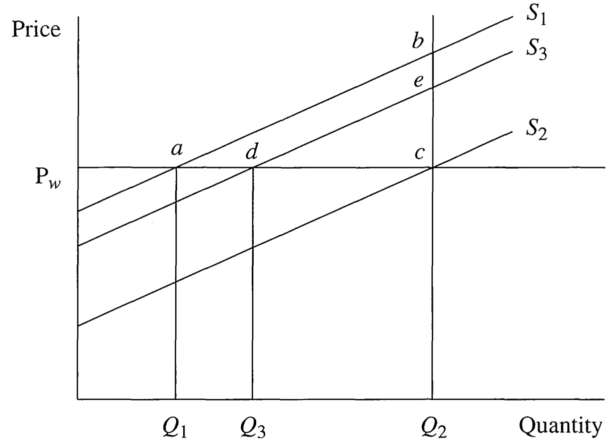


FIGURE 3 *Benefits of precision agriculture with no price effect, but a production externality*

chemicals, the marginal social cost curve S_1 may lie above the private supply curve, S_2. The optimal private quantity, Q_2 is produced rather than the quantity that is optimal from society's point of view, Q_1. The net social cost due to the externality is area *abc*. If adoption of PA technologies reduces the environmental externality, and therefore shifts the marginal social cost curve down to Q_3, the net social cost is reduced, to *dec* in our example. Of course the technology may shift the private supply curve down as well, and the net savings in marginal social cost depend on whether the distance between the old and new private and social cost curves has narrowed.

If there is potential for environmental gains and yet profitability constrains PA adoption for at least some commodities and regions, several policy options exist as discussed by Khanna and Zilberman (1997) and Casey *et al.* (1999). A few are input taxes, technology taxes or subsidies, uniform technology standards, and tax-free quotas for inputs such as nitrogen with taxes on additional input purchase. Regardless of the approach chosen, the cost effectiveness or opportunity cost of devoting resources to encouraging PA adoption as opposed to other means of improving the environment must be considered.

Input taxes, differentiated by PA versus non-PA technology, might be appropriate if there were means to observe how the inputs were being applied. However, less efficient uniform input taxes are likely to be more practical owing to prohibitive monitoring costs. Even these taxes may not be effective in influencing behaviour, however, since fertilizer and pesticide demand appears to be relatively inelastic. Water demand may be more elastic and therefore a better candidate for a tax solution.

Technology subsidy schemes can be used where it is more difficult to monitor inputs such as fertilizer, water and pesticides. Influencing the relative fixed costs of conventional versus PA technologies should influence incentives to adopt the technology, assuming the savings are passed on to farmers by the dealers who are often the ones purchasing and renting out their services to farmers. Of course, one way to get around the 'middleman' effect is to grant farmers direct payments or tax deductions. In a survey conducted by Khanna *et al.* (1999) in 1997, 61 per cent of farmers said they would be willing to adopt advanced PA technologies if a cost-share subsidy of up to 50 per cent were offered.

Uniform technology standards such as mandated equipment are less flexible than the tax or subsidy schemes. While they have worked for certain other cases such as pesticide restrictions and regulations on spraying equipment standards, they may be difficult to enforce with PA technologies.

Dubgaard (1990) advocates a policy that includes a tax-free quota of nitrogen combined with taxes on additional nitrogen purchases. PA could greatly aid such a system. Setting quota levels that differ by farm size, location and so on, however, would involve significant transactions costs and might spur unproductive rent-seeking activity, depending on rules for allocating the quotas.

Batie and Ervin (1999) propose other policy approaches. Marketable pollution permits, for example, would reward producers who could reduce their pollution to levels below permit thresholds (perhaps by using PA). Such successful containment of pollution would permit sales of surplus permits to other growers. Eco-labels represent another potential approach. Product labels that certify responsible environmental stewardship during the production process can attract consumers to pay a premium for environmental attributes in the product. Though primarily a private sector strategy, eco-labelling may require government bodies to establish or monitor certification standards (van Ravenswaay and Blend, 1999).

In the USA, farmers are encouraged to adopt practices that reduce environmental and resource problems through a programme called the Environmental Quality Incentives Programme (EQIP). Producers who enter into contracts are offered technical assistance, education, cost-sharing and incentive payments. Cost sharing and incentive payments go directly to the farmer, thereby avoiding uncertainties about whether a dealer will pass them along. The EQIP programme may be the preferred mechanism to implement a PA adoption incentives programme for that country. The programme works primarily in watersheds or areas where significant natural resource problems exist. Priority areas are identified through a locally led process. The advantage of working through the EQIP programme is that environmental benefits of PA would be judged against the benefits of spending public resources on other environmentally friendly practices.

CONCLUSION

The set of information-intensive technologies collectively known as site-specific precision agriculture have experienced significant growth over the past decade, with potentially favourable implications for the environment in regions where they can be profitably adopted. Although adoption should continue to increase in developed countries, there is likely to be little immediate impact in, or on, developing countries. One exception is the use by the public sector of remote sensing for early warning of famine dangers in parts of Africa and Asia. Environmental benefits are not well documented as yet, and they will vary with the crop, production environment and specific PA technologies. To the extent that the technologies have favourable environmental impacts, developed countries may want to consider encouraging their adoption through public policies. Whether and when policy incentives are needed to induce the adoption of PA technologies remain empirical questions. Their answers will be context-, technology- and site-specific.

NOTES

[1]Remote sensing also has the potential to contribute to PA, as the possibility of frequent acquisition of remote sensing data by satellites seems likely in the future. Several additional earth-observing satellites are scheduled for launch over the next few years, and some companies are concentrating their marketing and sales efforts on PA (NRC, 1997). Growth in the use of remote sensing for crop management will require an expanded set of people who understand the relationship between crop-soil properties and remote sensing (ibid.).

[2]Map-based VRT systems are most common for high-volume application of fertilizers and lime. However, these systems are available for farm tractor use with liquid fertilizers, anhydrous ammonia, herbicides and seeds. They are also available for water and fertilizer application through centre-pivot irrigation systems (NRC, 1997). Sensor-based VRT is employed to vary anhydrous ammonia in response to soil types, seeding rates in response to soil cation exchange capacity and topsoil depth, herbicide rates in response to organic matter, starter fertilizer in response to soil cation exchange capacity, and side-dress nitrogen fertilizer in response to soil cation exchange capacity, topsoil and soil nitrate levels (ibid.).

[3]The only exception to this generalization would be selected development-specific technologies, which have seen widespread adoption, especially in North America and Europe. Among IPM practices, the use of scouting to predict crop pest damage thresholds had spread to 78 per cent of US corn growers and 84 per cent of apple growers by 1996 (Fernandez-Cornejo and Jans, 1999).

[4]Harold Reetz, Midwest Director, Phosphate and Potash Institute, Monticello, IL, personal communication to Precision Agriculture e-mail List, 4 October 1999.

[5]José P. Molin, ESALQ/USP Piracicaba, personal communication to Agriculture e-mail list, 17 May 2000.

[6]Ancha Srinivasan, senior researcher, Regional Science Institute, Kita-ku, Sapporor, Japan, personal communication to Agriculture e-mail list, 16 May 2000.

[7]Jess M. Lowenberg-DeBoer, Purdue University, W. Lafayette, IN, USA, personal communication to Agriculture e-mail list, 15 May 2000.

[8]John K. Schueller, Department of Mechanical Engineering, University of Florida, personal communication to Precision Agriculture e-mail list, 4 October 1999.

[9]Ancha Srinivasan, Regional Science Institute, Kita-ku, Sapporo, Japan, personal communication to Precision Agriculture e-mail list, 16 May 1999.

[10]Harold Reetz, Midwest Director, Phosphate and Potash Institute, Monticello, IL, personal communication to Precision Agriculture e-mail list, 4 October 1999.

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