IV. Can Green Technologies Meet Sustainability Goals? Impediments to Overcome

In the United States, the agricultural sector has significantly increased its ability to produce food at a lower cost, implying that it takes fewer resources to produce a given amount of output. Increased use of machinery and equipment, the introduction of hybrid seeds, and improved management practices have all contributed to significant increases in agricultural output on essentially the same amount of cropland. In the livestock sector, improved management practices have also resulted in impressive gains in output growth.

This long-term view of technological evolution in the United States suggests that farmers continually adapt management practices to changing economic conditions. While production systems currently employed in the United States have evolved with the primary objective of maximizing profits, other objectives, such as improved environmental quality, have grown in importance. Current agricultural practices bear increasing criticism for compromising these objectives.

However, the private sector has little incentive to conduct research and development (R&D) on practices that produce habitat for wildlife, more scenic landscapes, or improved surface- or ground-water quality because these goods either lack market prices or the market prices that exist do not fully reflect societal values. Theories associated with endogenous technological change suggest private sector R&D will focus on increasing the output of relatively scarce goods and services, as reflected by market prices. Therefore, to the extent market prices do not fully reflect society's true scarcity value for environmental goods and services, there will be an under-investment in R&D on practices that produce those goods.

Similarly, private sector R&D will also focus on practices that conserve or augment the limiting factor in production as reflected in the relative prices of factors of production. This theory of induced innovation dates back to the work of Hicks (1932) and has been extended and applied to agriculture by Hayami and Ruttan (1985).[10] For example, if labor in agriculture is scarce, as reflected in relatively high or increasing wage rates, private sector R&D will focus on practices that save labor (e.g., R&D will focus on inputs such as machinery and equipment that can substitute for labor). Similarly, because land is priced, the private sector has some incentive to conduct R&D on land saving, and therefore cost-reducing, practices (e.g., R&D will focus on inputs that can substitute for land such as fertilizers). In addition, the private sector will limit R&D on conserving natural resource stocks.

If complete property rights existed for environmental goods, market prices would better reflect society's preferences and the private sector would optimally invest in R&D to supply them (Ervin and Schmitz, 1996). Also, the dynamic path (i.e., the evolution of technology) is skewed toward more efficient production of food rather than environmental services. This indicates that society under-invests in and undersupplies more sustainable agricultural practices (i.e., the practices that are developed do not fully capture society's preferences for environmental goods and services). The future direction of R&D is important because, as stated, most of the recent R&D growth has resulted from increased contributions from the private sector and there will be greater pressure to develop practices that increase marketed outputs or conserve marketed inputs rather than practices that increase nonmarketed outputs or conserve nonmarketed inputs.

Some production practices have the potential for win-win outcomes, with less environmental damage and higher farm profits. The results presented in table 6 suggest just such an outcome when fresh market tomato growers adopt IPM techniques. Insecticide use is negatively and significantly related to IPM use for insects. Similarly, fungicide use is negatively and significantly related to IPM use for diseases. An increase in the probability of IPM use for insects by 10 percent is estimated to decrease the number of insecticide applications by 4 percent. A 10-percent increase in the probability of IPM use for diseases is estimated to decrease the number of fungicide applications by 1 percent. The effect of IPM use on profits is positive but small. A 10-percent increase in the probability of IPM use for insects would increase variable farm profits by an estimated 0.1 percent, while a 10-percent increase in IPM use for diseases would increase variable profits by an estimated 2.7 percent. Similar results are obtained for grape grow-

[10] Olmstead and Rhode (1993) describe technological innovations in response to the rise in the relative price of one input as the "change variant" and technological innovation aimed at reducing the use of a relatively expensive input as the "level variant." For an alternative to the induced innovation hypothesis, see Olmstead and Rhode (1993).

Table 6—Impacts of IPM adoption on profits and on pesticide use

In some cases, IPM can potentially improve the environment and increase profits

Item	Fresh tomatoes	Fresh strawberries	Processed strawberries
Percentage change in pesticide use due to a 10-percent change in:			
IPM for insects	-4	ns	6.7
IPM for diseases	-1.1	4.6	11.5
Percent change in farm profits due to a 10-percent change in:			
IPM for insects	0.1	ns	ns
IPM for diseases	2.7	.3	-1.7

ns: not statistically significant from zero.
Source: Fernandez-Cornejo, 1996a and 1996b.

ers. IPM adopters reduced the use of insecticides and fungicides relative to nonadopters, and the impact on profits was positive albeit small (Fernandez-Cornejo, 1998).

Among fresh market and processed strawberry producers, however, adopters of IPM for diseases apply significantly more fungicides than nonadopters. Adopters of IPM for insects apply more insecticides than nonadopters for growers of processed strawberries but the effect of IPM for insects on insecticide use among fresh market strawberry producers is not significant. It is unclear if the added fungicides and insecticides represent any additional environmental risk. In some cases, operators may use less environmentally damaging pesticides but in greater quantities. Finally, no significant differences between adopters and nonadopters were observed for orange growers in California and Florida. Both groups exhibited similar yields, profits, and pesticide applications (Fernandez-Cornejo and Jans, 1996)

Similarly, conservation tillage has been widely adopted throughout U.S. agriculture and the onfarm productivity effects of soil erosion have largely been controlled. However, the off-site water quality impacts of soil erosion remain an area of concern. For example, Osborn and Konyar (1990) estimated the off-farm benefits of the CRP (improved surface-water quality, lower damages from windblown dust, and enhancements to wildlife) were five times greater than the onfarm benefits associated with preserving soil productivity. Similarly, the Conservation Compliance and Sodbuster provisions of the Food Security Act of 1985 have proved to be effective erosion control tools providing a social dividend of over $2 for every dollar of combined public and private expenditures required by the compliance provision (USDA, ERS, 1994). The positive net social benefit associated with Conservation Compliance suggests conservation tillage has been effective in reducing soil erosion. However, reducing soil erosion even more may be appropriate from society's perspective.

Lastly, much of the enthusiasm for precision agriculture is based on the belief that, environmentally it must make sense to match input application to plant needs. Precisely matching fertilizer and pesticide inputs to the capabilities and needs of the crop for small areas and exactly when the inputs are needed appears to be a logical way to limit the amounts of these materials that can escape to the environment. Unfortunately, there is little empirical evidence available that current implementation of precision agriculture actually reduces delivery of pollutants to ground and surface water and the atmosphere, relative to conventional techniques.

There is evidence that precision agriculture can reduce the amount of chemicals applied, and limited evidence that it can reduce the level of residual nitrogen. For example, comparisons between economic optimum nitrogen (EONR) fertilization rates using variable and conventional methods based on plot data from two soils in Minnesota showed reductions in average EONR of 34 to 54 percent using variable rates (Vetsch and others, 1995). Similarly, comparisons on Missouri soils show little difference in yield, but decreased unrecovered nitrogen on poorer soils with variable rate versus standard rate nitrogen application (Kitchen and others, 1995).

It is, however, possible to envision situations where precision agriculture can exacerbate potential environmental problems associated with crop production. For example, a farmer could obtain increased soil cover on steeper slopes through variable rate technology (VRT) application that could reduce soil erosion from parts of the field; however, increased nitrogen applied to these slopes could increase potential losses to the environment if other yield-limiting factors reduce nitrogen uptake. In another example, areas with droughty soils due to rapid percolation may have lower soil nitrogen levels due to greater leaching losses. VRT nitrogen application could exacerbate leach-

ing if additional nitrogen is applied to counteract losses on these soils. While these practices have the potential for win-win outcomes, such as less pesticide or nitrogen use and higher farm profits, farmers adopt and implement more sustainable practices based on private market incentives.

While complete property rights and market prices that reflect society's true values for environmental goods and services are necessary for ensuring a socially optimal amount of investment in R&D in more sustainable or green technologies, constraints on adopting and diffusing more sustainable or green technologies exist. These constraints are similar to those that slow the adoption and diffusion of any new practice. Experience with green technologies such as conservation tillage, integrated pest management, enhanced nutrient management, and precision agriculture demonstrates that in addition to profitability, three critical factors affect adoption. First, structural barriers, including farm size and labor availability, may deter adoption. Second, a diverse natural resource base, including varied soil, water, and climatic resources, makes it worthwhile to adopt these technologies only in some instances. Third, the economic risk of adopting new technologies may inhibit adoption. Correctly identifying constraints is important because these barriers can significantly (and perhaps unnecessarily) increase adoption costs, limit diffusion rates, and reduce the effectiveness of more sustainable or green technologies. Similarly, the efficacy of public policies aimed at encouraging the diffusion of more sustainable technologies will be limited if they are not designed to overcome the correct constraint. A policy aimed at increasing diffusion rates of sustainable practices among small farm operators by reducing the cost of acquiring information will not be as effective if the real constraint is limited access to credit or the inability to mitigate risk.

Farm Structure

The findings of Fernandez-Cornejo (1996b) and others (1994) reinforce the expectation that farm structure is an important element in adopting IPM (table 7). Farm size affects IPM adoption for vegetable growers in Florida and Texas. Large farms are more likely to adopt IPM than smaller farms. The availability of operator and unpaid family labor is also hypothesized to have a positive influence on IPM adoption.[11]

As McNamara and others (1991) argue, IPM requires a substantial amount of the operator's time that may compete with off-farm labor opportunities. The results in table 7 support this view. The availability of operator and unpaid family labor is significantly and positively associated with IPM adoption in Florida, Texas, and Michigan. Moreover, the significant and negative effect of livestock production on IPM adoption in all three States reinforces the hypothesis that the availability of managerial time is essential for IPM adoption. The managerial time constraint may be binding, especially for some livestock industries such as dairy and poultry. Because IPM does not require land-tied investments, land tenure is not expected to affect IPM adoption.[12]

Farm structure is also important in determining adoption of no-till technology. Unlike IPM, which requires a greater commitment of an operator's time, no-till technology requires a farmer to spend less time on field operations. According to one study, 24 percent of farmers adopted no-till to reduce time on field operations during critical seasons (Rahm and Huffman, 1984). Farmers with off-farm work view fewer field operations with time-critical components as an advantage of conservation tillage. As off-farm activities increase, a farmer has less time and flexibility for farm operations and the probability of adopting no-till technology increases.

Farm structure also affects the likelihood of farmers' adopting enhanced nutrient management practices. For example, timing nutrient applications for the growing season, when it is optimal for plant growth, may serve as a disincentive to farmers because a farmer's opportunity cost of labor and application logistics may be significantly higher during the late spring and growing season than during the fall. This may lead many farmers to apply nitrogen during the fall and spring rather than during the growing season. Amacher and Feather (1997), for example, found there was less chance of adopting enhanced nutrient

[11]Operator labor measures the amount of time that the operator dedicates to farm activities and is inversely related to off-farm labor of the operator.

[12]Landowners may influence the adoption decisions of their tenants.

Table 7—Factors affecting IPM adoption
Because IPM is labor intensive, greater labor availability increases the probability of adopting IPM

Explanatory variable	Florida	Texas	Michigan
Farm structure:			
Farm size	Increase	Increase	ns
Operator labor	Increase	Increase	Increase
Unpaid family labor	Increase	Increase	Increase
Livestock production	Decrease	Decrease	Decrease
Irrigation	Increase	Increase	Increase
Economic risk:			
Risk aversion[1]	Decrease	Decrease	Decrease
Resource heterogeneity:			
Regional proxy[2]	Decrease	ns	nc

Increase: An increase in an explanatory variable increases the probability of adoption. For example, an increase in farm size increases the probability of IPM adoption.
Decrease: An increase in an explanatory variable decreases the probability of adoption. An increase in risk aversion will decrease the probability of adoption.
ns: not statistically significant at the 10-percent level. nc: not included.
[1]Risk aversion is the combination of the effects of three explanatory variables: the debt-to-asset ratio, the decision to purchase crop insurance, and number of vegetable crops grown.
[2]A farm located in the southern part of Florida is less likely to adopt IPM.
Source: Fernandez-Cornejo and others, 1994.

management practices if farmers perceived them as more labor intensive, more expensive to use, or more difficult to use.[13]

While timing may act as a disincentive to adopt enhanced nutrient management practices for some farmers, improved placement may conserve time and energy by reducing trips across the field. By combining fertilizer placement with other field operations, such as cultivation, planting, and herbicide applications, a farmer can eliminate a trip across the field, thereby conserving energy. The per acre operation (both fixed and variable costs) of injection applications may cost more than the per acre operation of broadcast applications. However, by applying less fertilizer, the overall cost (operation and nitrogen fertilizer costs) is lower. Similarly, Amacher and Feather (1997) note that identifying and packaging certain enhanced nutrient management practices such as legume crediting and split nitrogen applications as bundles is more effective at increasing the adoption and diffusion of alternative practices than if the practices were introduced individually.

[13]Amacher and Feather (1997) define enhanced nutrient management as: manure crediting, legume crediting, and split nitrogen application.

Economic Risk

Economic risk is also critical in the farmer's decision to adopt a new technology for pest management. When farmers use a pest control strategy, the effects of this strategy on mitigating crop loss are uncertain (Greene and others, 1985). The results presented in table 7 support the idea that early adopters are more inclined to risk-taking than nonadopters. In table 7, risk aversion is measured as a combination of the effects of three variables: the debt-to-asset ratio, the decision to purchase crop insurance, and number of vegetable crops grown. Bultena and Hoiberg (1983) empirically support this view, finding that adopters are less risk-averse than nonadopters. Kovach and Tette (1988) found users of apple IPM indicate "a greater willingness to accept some economic risk to use all the scientific knowledge available to protect their crop." However, they reported a large percentage of non-IPM farmers preferred to spray on pesticides as insurance.

As with IPM, a new tillage technology involves an economic risk because the results vary substantially by site-specific conditions. The advantages of the various tillage systems depend on the soil and weather characteristics of a farmer's field. Many believe conservation tillage is profitable on light, well-drained soils. In semi-arid areas, farmers find the ability of conservation tillage to retain soil moisture attractive. A longer growing season may favor conservation tillage because the crop residue cover keeps the soil cooler in the spring and retards seed germination. Alternatively, a shorter growing season could favor no-till systems because these systems require less field work in a short period of time (Rahm and Huffman, 1984).

While fertilizer applications during the growing season can minimize nitrogen loss, such a strategy in some areas may conflict with a producer's risk considerations (Huang and others, 1996). For example, uncertain weather conditions may shorten the application window for growing season applications, increasing the economic risk of a yield loss from inadequate nitrogen availability. The impact of economic risk on adopting improved nutrient management practices will vary with farmers' risk attitudes, crop, climate, and other practices.

Huang and others (1996) have shown that a risk-neutral farmer may find it economically optimal to "over-

apply" nitrogen. The likelihood of over-application increases as the probability increases that inclement weather will keep the farmer out of the fields during the growing season. In a stylized example, Huang and others estimate that if the probability that a farmer cannot access the field during the growing season is 10 percent, it is economically optimal to over-apply nitrogen by 11 pounds per acre (table 8). However, if the probability of not being able to get into the field increases to 20 percent, it becomes economically optimal to over-apply nitrogen by 62 pounds per acre.

In addition to over-applying nitrogen, the probability of farmers' being unable to get into the field during the growing season to fertilize (e.g., because of rain) also affects the economically optimal timing of nitrogen. When the probability that a farmer cannot access the field during the growing season is only 10 percent, it is economically optimal for the farmer to apply 85 percent of the nitrogen (144 pounds per acre) during the growing season, when it is potentially less environmentally damaging, and only 15 percent of the nitrogen (25 pounds per acre) in the spring, when it is potentially more environmentally damaging (table 9). However, when the probability that a farmer cannot access the field during the growing season increases to 20 percent, it is economically optimal to apply only 33 percent of nitrogen (72 pounds per acre) during the growing season and 67 percent of the nitrogen (148 pounds per acre) in the spring.

The estimated environmental impacts are magnified if we assume a farmer is risk averse. In this case, not only does a risk-averse farmer apply greater amounts of nitrogen than a risk-neutral farmer, but the risk-averse farmer has a greater tendency to apply more nitrogen in the spring than during the growing season. The characterization of risk may be important in altering production practices because Bosch and others (1994) estimate that 45 percent of farmers can be characterized as risk averse.

The implications of economic risk are important for other practices as well. For example, farmers may undermine many of the benefits associated with precision agriculture if they are unable or unwilling to apply the changes in methods or rates at the most appropriate time.

Heterogeneity of the Resource Base

IPM adoption in the United States also varies significantly across States and crops. While it is difficult to compare IPM adoption in hot, humid climates, favoring the development of pests (e.g., Florida) to IPM used in more moderate climates (e.g., California), certain factors appear to affect the adoption decision similarly across regions of the country. Locational factors, such as soil fertility, rainfall, and temperature also influence the profitability of IPM. The physical environment of the farm may affect profitability directly through increased fertility, and indirectly through its influence on pests. The results for vegetable growers, presented in table 7, suggest farm location proxies (Regional Proxy) for weather and

Table 8—Economic risk and nitrogen application rates
As the probability that a farmer cannot access the field during the growing season increases, it is economically optimal for a farmer to apply greater amounts of nitrogen

Probability a farmer cannot access the field during the growing season	Optimal application rate	Revenue
Percent	lbs./acre	$/acre
0	158	$306
10	169	$280
20	220	$271

Source: Huang, Shank, and Hewitt, 1996.

Table 9—Economic risk and nitrogen application timing
As the probability that a farmer cannot access the field during the growing season increases, it is economically optimal for a farmer to apply greater amounts of nitrogen during the spring, when it is potentially more environmentally damaging

Probability a farmer cannot access the field during the growing season	Spring	Growing season
Percent	lbs./acre	lbs./acre
0	0	158
10	25	144
20	148	72

Source: Huang, Shank, and Hewitt, 1996.

soils do have a significant effect on pesticide demand, yields, and farm profits.[14]

As soil becomes finer and denser, the probability of corn farmers' adopting no-till decreases. Alternatively, farmers with well-drained soils (those with high leaching potential) are more likely to adopt no-till (Calvin and Brown, 1996). Conservation tillage generally improves soil quality by increasing soil biological activity and organic matter content. However, research on the effect of conservation tillage on yields has demonstrated no general trend, and the results depend on several farm variables in addition to the choice of tillage. A study of Indiana corn and soybean production showed yield potential varies with tillage, soil type, and rotation. No-till yields can exceed conventional yields in corn (after soybeans) on sloping, well-drained soils (Doster and others, 1983). Other research indicated that conventionally tilled corn yield exceeded no-till corn yields and that rotations can have more impact on yields than tillage (Martin and others, 1991).

Conservation tillage can also conserve soil moisture and, in semi-arid areas, farmers may consider this more important than erosion reduction considerations (Williams, 1988). Studies have generally found increased yields for crops in conservation tillage over conventional tillage in semi-arid areas, and the yield effect may result from higher soil moisture (Williams, 1988; Williams and others, 1990). A study of dryland wheat in Washington found yields with conservation tillage exceeded those with conventional tillage in dry years and equaled yields of conventional tillage in wet years (Young and others, 1993). Similarly, a study of spring wheat production in eastern Montana demonstrated no-till wheat had the highest yield and return to land, labor, and management of the various tillage and rotation systems examined (Aase and Schaefer, 1996).

The need for nutrient management varies with the location-specific characteristics of a farm. For example, the need for nitrification inhibitors varies with location. Potential economic benefits exist in areas where soils either drain poorly or drain excessively; farmers employ no-till cultivation; farmers apply nitrogen in the fall; crops grown (such as corn) require a large amount of nitrogen fertilizer; and excessively wet soil conditions prevent the application of nitrogen in the growing season (Hoeft, 1984; Nelson and Huber, 1987; Scharf and Alley, 1988). The greatest potential benefit occurs when farmers use nitrification inhibitors at or below the optimal nitrogen application rate. However, recent survey results reveal that corn growers in the Corn Belt likely apply more nitrogen fertilizer when they also use a nitrification inhibitor. Such a practice not only diminishes the economic benefit associated with using a nitrification inhibitor, but also increases the amount of residual nitrogen left on the field for leaching (Huang and Taylor, 1996).

Other Factors

Conservation tillage requires fewer trips across a field and saves the operator time and fuel. Farmers began adopting no-till during the energy crisis of the early 1980's to save fuel (Ladewig and Garibay, 1983). A 1981 survey showed that although Ohio farmers considered savings in fuel and labor the most important reasons for adopting conservation tillage, erosion and water quality issues were also very important (Ladewig and Garibay, 1983).[15] Another study found that 46 percent of farmers who adopted no-till considered both cost and time savings and conservation goals in their decision (Gadsby and others, 1987). Budgets prepared for an analysis of a wheat-fallow rotation in Kansas demonstrated labor costs and fuel and oil costs decreased by 32 and 35 percent, respectively, for conservation tillage relative to conventional tillage (Williams, 1988). Similarly, in Michigan, labor and fuel and oil costs decreased by 47 and 64 percent, respectively for corn grown with conservation compared to conventional tillage (Krause and Black, 1995).

Conservation tillage may also involve a decline in machinery costs. Initially, adopting any new technology may require new or modified machinery. Eventually, costs would likely decline because conservation tillage requires a smaller machinery complement (USDA, ERS, 1994). However, for some farmers an initial investment in machinery could pose an

[14]While weather, soil type, and other locational variables may affect the adoption decision, statistical considerations often limit their use. Dummy variables for States or regions within a State serve as locational proxies to account for the effect of environmental factors on adoption.

[15]Surface residue can slow runoff and filter out sediment and sediment-adsorbed chemicals that can reduce the pollutant concentrations and quantity of runoff.

obstacle to adopting conservation tillage (Doster and others, 1983; Epplin and Tice, 1986; Krause and Black, 1995).

According to conventional wisdom, pesticide use increases with the adoption of conservation tillage to compensate for a reduction in tillage operations that controlled weeds. Empirical evidence on the link between adoption of conservation tillage technology and herbicide use contradicts this conventional wisdom. Duffy and Hanthorn (1984) found little difference in herbicide use between conventional and conservation tillage for corn and soybeans. Baker and others (1987) rejected the hypothesis that pesticide use increases with conservation tillage. Lin and others (1993) also investigated pesticide use under a range of tillage options. They looked at a continuum of tillage operations including no-till, ridge-till, mulch-till, conventional tillage without a moldboard plow, and conventional tillage with a moldboard plow. They found herbicide use increased when they compared the most extreme change from conventional tillage with a moldboard plow to no-till. However, among some of the more intermediate tillage categories, pesticide use did not significantly change. A study of herbicide use by tillage system by Bull and others (1993) also proved inconclusive.

Some farmers may also employ crop rotations with leguminous crops to supply nitrogen to the field. While such rotations increase nitrogen to crops and decrease susceptibility to pests and diseases, farmers generally earn greater profits through monocultures of crops. For example, corn that received deficiency payments and was in rotation with soybeans generally was less profitable than continuous corn production in Iowa (Huang and Lantin, 1993) and Nebraska (Huang and Daberkow, 1996). The relative profitability of monoculture may be partially attributed to deficiency payments received by participation in a commodity program. With the phase-out of crop subsidies (elimination of deficiency payments), rotations may become more competitive.

While animal waste could serve as an inexpensive and significant supply of nitrogen, the economic benefits of manure for crop production appear limited by available storage and the transportation distance (Bouldin and others, 1984). The effects of storage and transportation distance vary by crop production region. Numerous studies have shown the economic benefits of use of manure in crop production. For example, farmers in Iowa have found application of manure in corn production to be profitable (Chase and others, 1991). Transfer of poultry litter from the litter-surplus areas to litter-deficiency areas in Virginia is economically viable (Bosch and Napit, 1992).

Precision agriculture will be more valuable in situations where farmers work with more variable resource conditions than in situations with relatively uniform resource conditions. While operators know the current costs of equipment associated with precision agriculture, the rapid adoption and evolution of the technology will cause future costs to fall. We know much less about the labor required, the amount of time needed to integrate the systems and keep them running, and the costs of true custom rates if "unbundled" from other services provided by farm chemical and input dealers.

The costs presented in table 10 have been developed from the literature by adjusting assumptions about useful life, repair costs, amortization, soil sample grid size, and the number of acres. A difference exists between what these practices will cost farmers who might spread the costs over 1,000 acres and, hypothetically, have much higher opportunity costs for labor, and the costs from a dealer who can spread the cost over more acres and hire labor at relatively low rates. Most of the costs a farmer would bear accrue from acquiring information about soils, yields, and pest problems. Grid soil sampling costs $3 to $7 per acre on a 3-acre grid at plow depths, but can increase 3 to 5 times if rooting depths for the crop (such as sugar beets) are sensitive to fertilizer concentrations at greater depth. Yield monitors for common field crops like corn and soybeans cost $1.45 to $1.66 per acre, assuming 1,000 acres are farmed. A global positioning system (GPS) receiver for precise location information adds another $0.75 to $1.45 per acre, depending on whether a farmer needs a differential correction. Weekly scouting during the cropping season costs a minimum of $4 per acre for common field crops. To take advantage of the precision information obtained, farmers need to add variable rate controllers to sprayers and applicators (VRT), adding $1 to $5 per acre for retrofitting existing equipment. Variable

Table 10—Summary of precision agriculture costs

Item	Cost range (per acre)	Sources[1]
Farmer cost:[2]		
Grid soil sampling (plow depth, 3-acre grid)	$3-$7	1,2
Grid soil sampling (4-foot depth, 3-acre grid)	$16-$22	3
Yield monitor	$1.45-$1.66	1
GPS receiver	$0.75-$1.45	1
Scouting package, weekly	$4	2
VRT controllers, various applicators	$1-$5	1
Variable rate fertilizer application (difference)	$3-$7	1,2
Dealer cost:[3]		
DGPS receiver	$0.23-$0.79	4
Grid soil sampling unit	$0.62-$1.60	4
Yield mapping computer and software	$0.33-$1.16	4
Liming application unit	$1.09	4
VRT fertilizer unit	$0.22-$10	4

[1]Source: 1 = Lowenborg-DeBoer and Swinton, 1995; 2 = Giacchetti, 1996; 3 = Berglund and Freeburg, 1995; 4 = Kohls.

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

[3]Assumes 3-year useful life for equipment (except 5 and 10 years for liming, soil sampling, and VRT equipment), 6% interest rate, 3% repair cost, and 5,000 acres.

fertilizer application from a dealer, where available, adds an additional $3 to $7 per acre.[16]

Chemical dealers will more likely make the major investments in precision agricultural equipment because they can spread the costs over many farmers' fields, reducing the cost per acre. Assuming a dealer will treat a total of 5,000 acres, compared to 1,000 acres for an individual farmer, the costs for differential GPS receivers and the differential correction systems needed range from $0.23 to $0.79 per acre, about half of what the farmer would incur. The ATV or pickup-mounted grid sampling system would cost $0.62 to $1.60 per acre, assuming a 5-year useful life. This does not consider the labor costs of collecting the samples or the laboratory costs of analyzing them. Equipment for variable rate lime application by dealers costs about $1 per acre. Variable rate equipment for fertilizer application varies from $0.22 per acre for retrofitting variable controls on anhydrous ammonia applicators to more than $10 per acre for the largest Soilteq truck-based applicator designed for on-the-go mixing and variable rate application.

Despite the unsettled economic questions, some farmers have assessed their own values of precision agriculture. A survey of farmers about precision agriculture's prospects found that 75 percent of respondents would pay $5 per acre for the benefits of precision agriculture, while 50 percent would pay $10 per acre. However, no respondents valued precision agriculture at $20 per acre (Giacchetti, 1996). A survey of 200 corn growers by Mike Buckley and Associates found that 46 percent thought precision agriculture would reduce inputs and 42 percent thought it would improve profits (Whipker and Akridge, 1996). However, 48 percent expressed concern about the cost of new equipment and 38 percent expressed uncertainty about the drawbacks associated with precision agriculture. A survey of 44 farm managers in Indiana found, on average, that respondents valued information from yield monitors at $3.06 per acre (Lowenberg-DeBoer, 1996). The 11 respondents that managed farms with yield monitors in 1995 valued the information less highly ($2.31 per acre) than the 33 respondents that did not manage farms with yield monitors ($3.44 per acre). While these surveys are certainly not definitive, they indicate the interest and enthusiasm with which farmers consider precision agriculture.

[16]Remote sensing technology for precision agriculture has entirely different costs than GPS/GIS/VRT technologies (Corbley, 1996; DeQuattro, 1996). Imagery from airborne sensors, such as those used in the prototype system developed by NASA and now managed by a consortia called Resource 21, and from satellites such as the LANDSAT Thematic Mapper or SPOT. However, no individual farmer would find it economical to purchase raw data. Data providers acquire imagery in near real-time over the season, process it, and print images for a farmer's fields (Lamb, 1996).