Green Technologies for a More Sustainable Agriculture. By James Hrubovcak, Utpal Vasavada, and Joseph E. Aldy, with contributions from Linda Calvin, Jorge Fernandez-Cornejo, Dwight Gadsby, Ralph Heimlich, Wen Huang, Paul Johnston, and Dale Leuck. Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, Agriculture Information Bulletin No. 752.

Abstract

For U.S. agriculture to continue along a sustainable path of economic development, further production increases must be generated by technologies that are both profitable and more environmentally benign. In this context, we assess the role of these "green" or sustainable technologies in steering agriculture along a more sustainable path. However, the lack of markets for the environmental attributes associated with green technologies can limit their development. In addition, simply making a technology available does not mean it will be adopted. Experience with green technologies such as conservation tillage, integrated pest management, enhanced nutrient management, and precision agriculture demonstrates that even when technologies are profitable, barriers to adopting new practices can limit their effectiveness.

Keywords: Sustainable agriculture, natural capital, nonrenewable resources, renewable resources, environmental services, green technology, integrated pest management, conservation tillage, enhanced nutrient management, precision agriculture

Acknowledgments

The authors thank Margot Anderson, William Anderson, Pierre Crosson, Dave Ervin, George Frisvold, and Michael Toman for their comments and participants of the ERS-Farm Foundation sponsored workshop for their insights on sustainable agriculture. Linda Calvin, Jorge Fernandez-Cornejo, Ralph Heimlich, Wen Huang provided the material on conservation tillage, integrated pest management, enhanced nutrient management, and precision agriculture. Paul Johnston and Dale Leuck provided the material for Appendix 1. Errors in interpretation are those of the authors.

1800 M Street, NW
Washington, DC 20036-5831 June 1999

Contents

Summary iii

Introduction 1

I. The Sustainability Issue—Background 2

II. The Case for a More Sustainable Agriculture 4
Agricultural Productivity 4
Soil Erosion 5
Ground-Water Quantity 6
Surface-Water Quality 7
Ground-Water Quality 8
Wetland Conversion Rates 9
An Aggregate Assessment for U.S. Agriculture 10

III. Steering Agriculture in a More Sustainable Direction—The Role of Green Technologies 12
Integrated Pest Management 13
Conservation Tillage 13
Enhanced Nutrient Management 14
Precision Agriculture 16

IV. Can Green Technologies Meet Sustainability Goals? Impediments to Overcome 18
Farm Structure 20
Economic Risk 21
Heterogeneity of the Resource Base 22
Other Factors 23

V. Conclusions 26

References 27

Appendix 1—Farm Level Case Studies on Profitability-Environment Tradeoffs 34

Appendix 2—Workshop on the Economics of Sustainable Agriculture 37

Summary

For U.S. agriculture to continue along a sustainable path of economic development, further production increases must be generated by technologies that are both profitable and more environmentally benign. In this context, we assess the role of these "green" or sustainable technologies in steering agriculture along a more sustainable path. However, the lack of markets for the environmental attributes associated with green technologies can limit their development. In addition, simply making a technology available does not mean it will be adopted. Experience with green technologies such as conservation tillage, integrated pest management, enhanced nutrient management, and precision agriculture demonstrates that even when technologies are profitable, barriers to adopting new practices can limit their effectiveness.

Sustainability extends beyond the economic well-being of the current generation and reflects the ability of future generations to meet their needs. Sustainability recognizes that economic well-being relies on goods and services (like food and clothing) bought and sold in well-functioning markets, as well as goods and services (like those provided by the environment—e.g., recreation, safe drinking water, and scenery) not necessarily bought and sold in markets. Sustainability also requires investing in diverse forms of capital including both human-made capital (e.g., buildings and machinery) and natural capital (e.g., farmland, aquifers, lakes, rivers, estuaries, and wetlands).

Agriculture has a unique role to play in sustainability. Agriculture produces food and relies on natural capital for producing food. Agriculture also accounts for a majority of land and water use and is a major source of impairment of rivers, lakes, and estuarine waters. Because both food and natural capital are necessary for current and future generations, moving along a more sustainable path of economic development requires effective stewardship in agricultural production.

Because there is no single indicator of agricultural sustainability, we review trends in some existing indicators that are linked to sustainability. These indicators include: agricultural productivity, soil erosion, ground-water quantity, surface-water quality, ground-water quality, and wetland conversion rates. While there is overlap between the services these indicators represent, one can think of agricultural productivity, soil erosion, and ground-water quantity as indicators of our ability to provide food to current and future generations at reasonable costs to consumers. Surface-water quality, ground-water quality, and wetland conversion rates can be thought of as indicators of the environmental impacts associated with agricultural production. When taken as a whole, these indicators are consistent with a view of agricultural production in the United States where environmental problems exist, but where many of these problems can be addressed by thoughtful programs and policies.

Historically, the government has tried to correct many of the environmental problems associated with agricultural production through various conservation programs. For example, within USDA, the Conservation Reserve Program makes payments to farmers to remove highly erodible or environmentally sensitive land from production. Similarly, the Wetlands Reserve Program provides payments and cost-shares to landowners who permanently return prior convert-

ed or farmed wetlands to wetland conditions. These payments, albeit imperfectly, take the place of market prices and provide incentives for resource conservation.

Recently, “green” or more sustainable technologies are receiving a great deal of attention because they can potentially improve the environmental performance of agricultural production without reducing farm production or profits. However, the lack of markets for the environmental attributes associated with green technologies can limit their development. Market prices provide a signal about the scarcity of a resource. In general, research and development and the adoption and diffusion of new technologies will be directed to conserve those resources that are most scarce or highest priced; the so-called induced innovation hypothesis. Because the market prices of many environmental services and natural resources are less than their true value to society, there is less of an economic incentive to develop or adopt technologies that conserve those resources.

In addition, simply making a technology available does not mean it will be adopted. The adoption and diffusion of green technologies may be slow and gradual. 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 the lack of financial capital and limits on labor availability, may deter adoption. Second, a diverse natural resource base, including varied soil, water, and climatic resources, make it worthwhile to adopt these technologies only in some instances. Third, the economic risk of adopting new technologies may inhibit adoption. Barriers to the adoption and diffusion of green technologies have additional implications. Because the economic and environmental implications of green technologies vary by crop and region, there is no one technology that will be sustainable for every farmer in every part of the country. Because these barriers differ across the country, there is a premium on knowledge about regional adoption and diffusion constraints and an advantage to a decentralized approach to research and development and technology transfer.

Green Technologies for a More Sustainable Agriculture

James Hrubovcak
Utpal Vasavada
Joseph E. Aldy*

Introduction

Agriculture plays a unique role in sustainability, providing food at a reasonable cost to current and future generations. To assess whether U.S. agriculture is sustainable, all the costs of agricultural production to current and future generations must be considered. These costs include the impact of agricultural production on the environment and stocks of natural capital (e.g., farmland, aquifers, lakes, rivers, estuaries, and wetlands). This view of agricultural sustainability is consistent with the USDA policy on sustainable development:[1]

> *USDA will balance goals of improved production and profitability, stewardship of the natural resource base and ecological system, and enhancement of the vitality of rural communities.*— From USDA Secretary's Memorandum on Sustainable Development (SM 9500-6).

This report highlights the role of agriculture in the sustainability debate. However, due in large part to data constraints, no universally accepted indicator of agricultural sustainability has been developed. For example, adjusting current measures of farm income for the environmental impacts of agricultural production cannot be done completely because many environmental services lack market prices, and data regarding changes in the physical amount of many types of natural capital is limited (Hrubovcak, LeBlanc, and Eakin, 1995). Therefore, to evaluate the sustainability of U.S. agriculture, we review trends in several indicators (productivity, soil erosion, ground-water quantity, surface- and ground-water quality, and wetland conversion rates).

We use these trends to assess the contribution of technological change in furthering the sustainability of agriculture. For example, historically, to meet the growing demand for food, new technologies developed through agricultural research and development were employed in agriculture. These technologies have contributed to a tremendous surge in agricultural productivity and output. The empirical accounting framework used to measure productivity and output, however, accounts only for conventionally measured agricultural inputs and outputs. Services from the environment and the use of natural resources are currently treated as gifts of nature. In addition, any off-farm economic costs attributed to agricultural production are not taken into consideration. For U.S. agriculture to continue along a sustainable path of economic development, further increases in output must be generated by technologies that add to both the profitability and the environmental performance of agricultural production.

To assess the potential for research and development to contribute to sustainability, we highlight four practices that are considered more sustainable and have the potential for widespread diffusion in the agricultural sector. These practices include: integrated pest management, conservation tillage, enhanced nutrient management, and precision agriculture. From our experiences with these practices, we draw lessons regarding potential impediments to the adoption and diffusion of more sustainable technologies.

---

*With contributions from Linda Calvin, Jorge Fernandez-Cornejo, Dwight Gadsby, Ralph Heimlich, Wen Huang, Paul Johnston, and Dale Leuck.

[1]The impact of agricultural production on the vitality of rural economies is outside the scope of this report.

I. The Sustainability Issue—Background

More than a decade has passed since the Brundtland Commission focused public attention on concerns regarding sustainability and sustainable development. According to this Commission's report, a sustainable path of economic development will "...meet the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

Since that time, the sustainability issue has appealed to a diverse, and often unrelated, collection of interest groups. According to Graham-Tomasi (1991), ".... just about everyone is on the sustainability bandwagon, and sustainability has come to mean all things to all riders on this bandwagon" (p. 82). For example, Murcott (1997) has identified 57 definitions of sustainable development since 1979. The Brundtland Commission's vision of sustainability continues to provide a useful point of departure for public debates on sustainability (President's Council on Sustainable Development, 1996).

Similar to the Brundtland Commission's vision of sustainability, we view an economy to be sustainable when the economic well-being of both the present and future generations is maximized. Economic well-being, however, goes beyond the traditional view of economic goods and services, such as food and clothing, to include goods and services often not bought and sold in markets, such as the services provided by the environment (e.g., recreation, safe drinking water, and scenery).

Sustainability also extends beyond the economic well-being of the current generation and reflects the ability of future generations to meet their needs. The well-being of current and future generations is linked by extending the traditional view of capital (e.g., buildings and machinery) to include farmland, forests, lakes, rivers, estuaries, and wetlands (natural capital) (Aldy, Hrubovcak, and Vasavada, 1998). From an economywide perspective, this definition of sustainability requires investing in an appropriate amount and mix of human-made and natural capital to ensure that both market and nonmarket goods and services are available to society. This includes not only direct investment in different types of capital but also investment in research and development (R&D) on technologies that can increase the production of goods and services at a lower cost.

Opinions diverge on whether the actual performance of many economies is consistent with this vision of sustainable economic development. For example, in the *Limits to Growth*, the current generation's (over)use of nonrenewable natural resources such as oil and coal adds pressures to those caused by a fixed land base to create a bleak outlook for future generations (Meadows and others, 1972). Specifically, according to this study:

> *If present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years.*

Simon, Weinrauch, and Moore (1994) provide a contrasting view on the availability of natural resources. They argue that the relevant measure of resource scarcity is price, where the highest priced resources are the most scarce. Based on an evaluation of trends in the real (inflation adjusted) price of key nonrenewable natural resources, they conclude that these prices exhibit a declining trend, casting doubt on the conclusions reached in the *Limits to Growth*. Similarly, Nordhaus (1992) concluded that price data for real resources did not indicate a major turn toward scarcity.

More recently, the broader concept of the "carrying capacity" of the environment has been added to the list of sustainability concerns. Carrying capacity represents a biological limit on the environment's ability to support human activities. For example, many of the services the environment provides are regenerative or renewable but may be exhausted from over-use if the use rate exceeds the natural regenerative rate. In effect, carrying capacity represents the limits to growth caused by society's reliance on and (over)use of both nonrenewable and renewable resources.

Some have argued that the Earth's capacity to carry populations may be hindered. For example, Pimentel and Giampietro (1994) have argued that agricultural productivity in the United States is already unsustainable "given current depletion rates of land, water, and energy resources." In addition, nitrates and pesticides were detected in surface and ground water in agricultural regions including the Corn Belt, New York, Pennsylvania, Florida, and in at least 23 other States (National Research Council, 1989). This finding has contributed to concerns that current agricultural production practices have exceeded the environment's capacity to act as a buffer and assimilate fertilizers and pesticides before they leach into ground and surface water.

This divergence of opinions regarding the actual performance of economies as well as the requirements for an economy to be considered sustainable are shaped, in large part, by differences in perceptions regarding the substitutability between inputs, now and in the future. For example, Christensen (1989) argues that, in most cases, human-made and natural capital cannot substitute for one another. That is, an increase in output requires more of both human-made and natural capital. Along this line of reasoning, Daly (1990) argues that sustainability requires that: (1) harvest rates of renewable resources (e.g., fish, trees) not exceed regeneration rates, (2) use rates of nonrenewable resources (e.g., coal, gas, oil) not exceed rates of development of renewable substitutes, and (3) rates of pollution not exceed the assimilative capacities of the environment.

Solow (1992) argues that it is not possible to preserve every type of capital and suggests a weaker definition of sustainability where human-made and natural capital are allowed to substitute for one another. Under this definition of sustainability, traditional measures of income can be extended to account for environmental goods and services and the value of changes in the stock of natural capital. Weitzman (1997) has shown that this extended measure of income can be considered an indicator of sustainability. Because human-made and natural capital are allowed to substitute for one another, the only requirement for sustainability is that the overall stock of capital, rather than each type of capital, is not decreasing over time.[2]

[2]This requirement abstracts from population growth. A more precise sustainability requirement is that the overall rate of net investment plus the rate of technological change is at least equal to the growth rate of population.

II. The Case for a More Sustainable Agriculture

To evaluate the sustainability of U.S. agriculture we review trends in the following indicators: agricultural productivity, soil erosion, ground-water quantity, surface-water quality, ground-water quality, and wetland conversion rates. While there is overlap between the services these indicators represent, one can think of agricultural productivity, soil erosion, and ground-water quantity as indicators of our ability to provide food to current and future generations. Surface-water quality, ground-water quality, and wetland conversion rates can be thought of as indicators of the environmental impacts associated with agricultural production.

Agricultural Productivity

Productivity measures the difference between output growth and input growth rates. If productivity growth is positive, then the same output can be produced with fewer inputs. Figure 1 illustrates the pattern of productivity growth in U.S. agriculture (Ahearn, Ball, Yee, and Nehring, 1998). From 1948 to 1994, output in U.S. agriculture grew at an annual average rate of 1.9 percent. A slight decline in input use accompanied this output growth, resulting in an annual productivity growth rate of 1.9 percent compared with 1.1 percent for the nonfarm sector. The prices of agricultural products reflect this productivity growth. Over the same period, the real prices farmers received for farm products dropped about 50 percent.

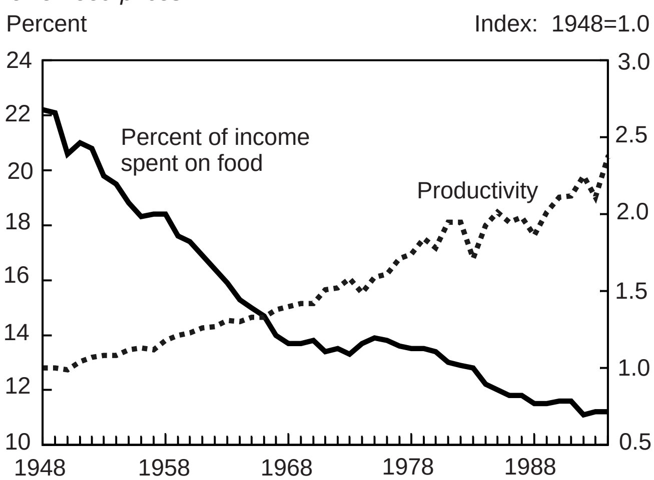
For major field crops in U.S. agriculture, yield growth parallels the observed pattern of productivity growth. Yields in major field crops grew rapidly, ranging from 1 to 3 percent per year. Among field crops, yields of corn, sorghum, and potatoes have grown the most rapidly. Since 1939, corn yields grew at an impressive 3 percent per year while wheat yields grew at around 1.8 percent. Over the same period, the real prices (market prices adjusted for inflation) for corn, sorghum, and potatoes dropped about 50 percent while the real price for soybeans dropped about 30 percent (USDA, National Agricultural Statistics Service, 1997).

Greater agricultural productivity growth, higher yields, and lower farm prices have benefited consumers.[3] As also captured in figure 1, in 1948, consumers spent 22 percent of their disposable personal income on food. By 1996, the share of disposable personal income spent on food had fallen to 11 percent (Manchester and Allshouse, 1997). These data suggest that, relative to the performance of the economy in general, agriculture has met a part of the sustainability challenge by supplying food to consumers at a reasonable cost.

Investment in agricultural research and development (R&D) contributes significantly to productivity growth. Figure 2 illustrates the pattern of R&D growth in U.S. agriculture (Fuglie and others, 1996).

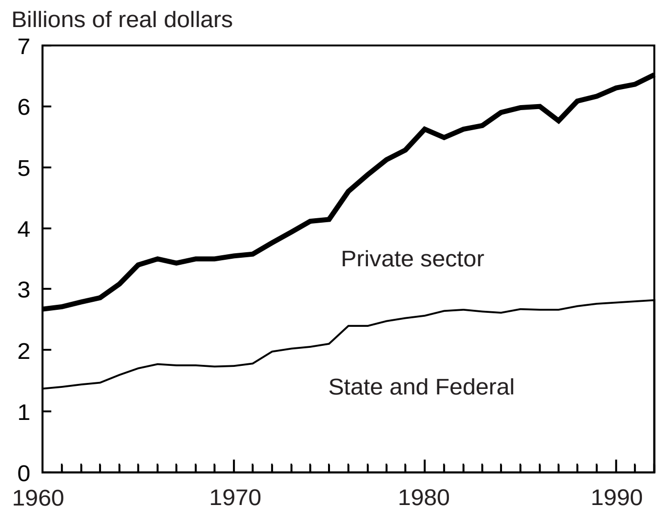
[3] Productivity is a better indicator of agriculture's performance than prices because farm programs distort agricultural prices.

Figure 1
Income spent on food and agricultural productivity
Increases in agricultural productivity have resulted in lower food prices



Sources: Economic Research Service, USDA; Ahearn, Ball, Yee, and Nehring, 1998; Manchester and Allshouse, 1997.

Figure 2
Research spending
Real private sector spending on R&D has outpaced State and Federal spending



Source: Economic Research Service, USDA; Fuglie and others, 1996.

Beginning in 1960, public research expenditures rose by 3 to 4 percent per year in real terms up to around 1980, but since then, growth has slowed to 0.7 percent per year. Although Federal expenditures have remained flat since 1976, growth of private sector research has been rapid. Most of the post-1980 growth has come from increased contributions by the private sector. The private sector now accounts for more than 50 percent of all agricultural research funds. If past patterns of R&D persist in the future, then it may be possible to maintain productivity growth rates in U.S. agriculture. Maintaining a productivity growth rate greater than the growth rate of food demand will contribute to the availability of food at a reasonable cost to future generations.

Soil Erosion

The link between agricultural production practices, soil erosion, and farmland's ability to produce output has been studied extensively. Recent studies have established that soil erosion does not threaten agricultural output (Alt and others, 1989; Crosson, 1995; USDA, 1989). For example, as part of the Second Resources Conservation Act (RCA) Appraisal, the U.S. Department of Agriculture (1989) estimated a 3-percent loss in overall agricultural output over the next 100 years if farming/management practices remained as they were in 1982. Similarly, Alt and others (1989) found that the output effects of soil erosion are small.[4]

One reason for the lack of an overall effect on output is that soil management practices have improved considerably in the last 50-60 years. For example, while cropland use has remained remarkably stable at about 400 million acres since 1938, soil erosion has declined by an estimated 40 percent (fig. 3) (Magleby and others, 1995). Most of this decline has occurred since 1982. In 1982, total erosion from cropland was estimated at 3.1 billion tons per year or 7.4 tons per acre per year. By 1992, total erosion from cropland had declined to 2.1 billion tons per year or 5.6 tons per acre per year. The post-1982 decline results from government programs aimed at mitigating the environmental impacts of agricultural production practices such as the Conservation Reserve Program (CRP) and the Conservation Compliance provisions of the Food Security Act of 1985.

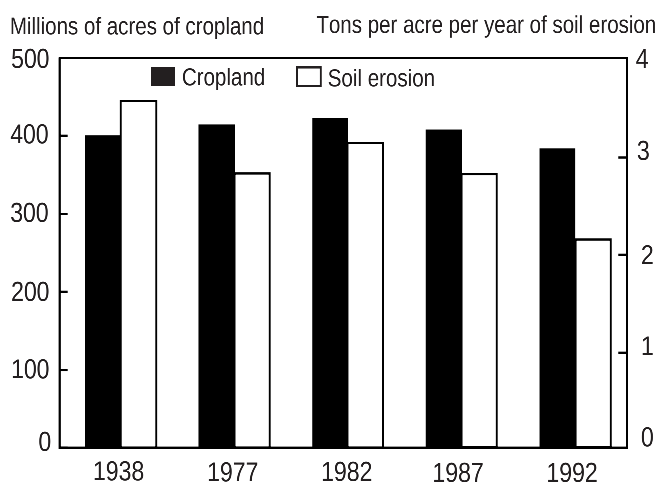
[4]Both studies employ a crop production model, Erosion Productivity Impact Calculator (EPIC), that links production practices, erosion rates, and productivity.

Comparing the productivity growth rates with soil erosion rates over time indicates that productivity can continue to grow with natural resource degradation. This is because chemical inputs (e.g., fertilizer) can substitute for natural resources (e.g., soil fertility), and technological change can mitigate the negative agricultural productivity effects of resource degradation on most soils (Cleveland, 1995). However, a failure to consider off-site effects can affect the supply of environmental services. For example, soil erosion can affect surface-water quality with repercussions for recreational services that depend on this natural capital asset.

While the estimated costs of erosion in terms of lost output are not nationally significant, they may be significant at the regional or State level. For example, Faeth (1993) shows negative net economic value per acre after accounting for soil depreciation and off-site costs for Pennsylvania's best corn-soybean rotation over 5 years. This work demonstrates there may be significant regional variation in resource depreciation and off-site costs of agricultural production.

While the impact of erosion on loss of soil productivity is relatively straightforward, it is more difficult to assess a more comprehensive view of soil quality over time. For example, overall soil quality can be degraded physically (erosion, compaction), chemically (salinization, acidification), and biologically (declines

Figure 3
Cropland and soil erosion
The amount of cropland has remained stable over time while soil erosion rates have fallen considerably



Source: Economic Research Service, USDA; Magleby and others, 1995.

in organic matter or soil carbon) (National Research Council, 1993). Chambers and Lichtenberg (1995) found the incremental value of organic matter in soil to be quite high when the initial stock of organic matter is low, but the value diminishes rapidly. For example, for a conventional farming system, a 1-percentage-point increase in organic matter increased the value of land by $285 per acre when initial organic matter was 0.8 percent, but by only $60 per acre when initial organic matter was 1.9 percent. When organic matter was greater than about 2 percent, an increase in organic matter no longer increased land values.

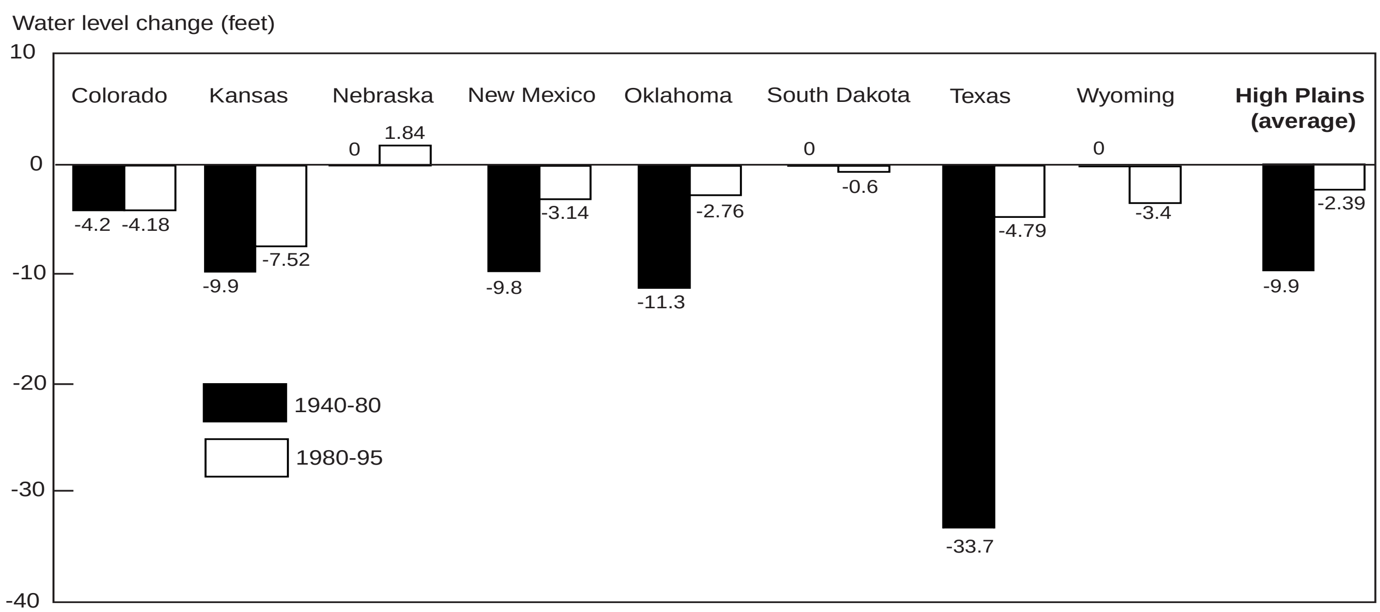
Ground-Water Quantity

In the longrun, an equilibrium is generally reached in terms of recharges (precipitation, imports from other regions) and discharges (natural evapotranspiration, exports to other regions, consumptive use, and natural outflow) from any ground-water system. However, in some water resource regions, discharge rates have consistently been greater than recharge rates, leading to a decline in the stock of ground water (U.S. Geological Survey-USGS, 1995). While long-term trend data for most of the Nation's ground-water stocks do not exist, measurements of change in the water level of the High Plains Aquifer (Ogallala) may indicate the effect of irrigation on ground-water levels. This aquifer provides approximately one-third of the ground water withdrawn for agricultural irrigation in the United States, and supports the agricultural activity in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (USGS, 1995).

Figure 4 illustrates the average drop in the water level of the aquifer in each of these States over two time periods. For 1940-80, the region's average ground-water level dropped 0.25 foot annually or a total of about 10 feet. Five of these States experienced declines in their ground-water stocks while three experienced no change in their stocks over this period. From 1980 to 1995, the average ground-water level for the High Plains dropped 0.16 foot annually or about 2.4 feet in total. An increase in ground-water stocks was reported in one State and smaller declines compared with 1940-80 were reported in four States (USGS, 1995).

While the total ground-water stock has declined from 1980 to 1995, the stock increased in 1993 and 1994. The average ground-water level rose 0.21 foot in 1993, and another 0.56 foot in 1994. The reductions in the rate of decline of the ground-water stock result from technological advances in irrigation development to increase the efficiency of water delivery and above normal precipitation in the region (USGS, 1995).

Figure 4
Change in ground-water level in the High Plains
While the ground-water level in the High Plains continued to fall, the current rate of decline is less than in prior years



Source: USGS, 1995.

The data on ground-water levels in the High Plains indicate that while ground-water mining contributed to significant drawdowns in the past, in recent years the Ogallala has experienced slower withdrawal rates. The ground-water withdrawals in this region primarily support irrigated agriculture. The private economic costs of extracting ground water and the social costs of ground-water drawdowns are significant. In the United States, the energy costs of extracting ground water can range between $11 and $74 per acre annually, and amount to more than $1 billion annually (USDA, ERS, 1997). These increases in energy costs are reflected in farm profitability. For example, Aillery (1995) estimated the returns to irrigation including the returns to water, fixed capital, and management above variable water costs and net of returns to dryland alternatives at $33 per acre-foot of water used in agricultural production.[5]

However, farmers' water costs do not reflect the total social cost of the extraction, and therefore, their expenditures on water do not accurately reflect society's demand for ground water. Water suppliers and farmers treat ground-water stocks as an open resource. By extracting water at a rate faster than recharge, water suppliers and farmers draw down the water level and decrease the aquifer's pressure. This requires water suppliers and farmers to use more energy per unit of water extracted than under a steady-state or increasing water level scenario. In addition, ground-water withdrawals can cause land subsidence, with significant economic consequences (National Research Council, 1991a).

Surface-Water Quality

Surface-water quality has generally improved since 1974, when monitoring began. In a 1974 survey, the Environmental Protection Agency (EPA) found that only about 40 percent of the largest rivers in the United States were safe enough for fishing and swimming (USEPA). In 1994, 60 percent of the Nation's surveyed rivers, lakes, and estuaries were safe enough for fishing and swimming. While surface-water quality has improved over the long term, the EPA has identified agriculture as an important contributor to the surface-water quality problems that do exist.

[5]An acre-foot of water is the volume of water required to cover 1 acre of land to a depth of 1 foot of water; also equal to 325,851 gallons (USGS, 1985).

According to the EPA's 1996 *National Water Quality Inventory*, agriculture is the leading source of impairment in rivers (contributing to impairment of 25 percent of the surveyed river miles), lakes (contributing to impairment of 19 percent of the surveyed lake acres, not including the Great Lakes), and the fifth leading source of impairment to estuaries (contributing to impairment of 10 percent of the surveyed estuary acres) (table 1).[6] Primary agricultural pollutants

[6]EPA defines impaired waters as waterbodies either partially supporting uses or not supporting uses (USEPA, 1998).

Table 1—Major sources of impairment to rivers, lakes, and estuaries
Agriculture is the leading source of impairment in rivers and lakes and is the fifth leading source in estuaries

Item[1]	Percent
River miles:	
Agriculture	25
Municipal	5
Hydrologic modification	5
Habitat modification	5
Resource extraction	5
Urban runoff	5
Lake acres:	
Agriculture	19
Unspecified nonpoint	9
Atmospheric deposition	8
Urban runoff	8
Municipal point sources	7
Hydrologic modification	5
Estuaries (acres):	
Industrial	21
Urban runoff	18
Municipal	17
Upstream sources	11
Agriculture	10
CSO's	8

[1]Examples of sources:
Agriculture—Crop production, pastures, rangeland, feedlots, animal operations.
Construction—Land development, road construction.
CSO's—Combined sewer overflows—Facilities that treat storm water and sanitary sewage.
Habitat modification—Removal of riparian vegetation, streambank modification.
Hydrologic modification—Channelization, dredging, dam construction, flow regulation.
Industrial—Pulp and paper mills, chemical manufacturers, steel plants.
Land disposal—Leachate or discharge from septic tanks, landfills.
Municipal—Publicly owned sewage treatment plants.
Resource extraction—Mining, petroleum drilling, runoff from mine tailing sites.
Urban runoff—Runoff from streets, parking lots, buildings.
Source: USEPA, 1998.

contributing to surface-water quality problems are sediment and siltation, nutrients, pesticides, salinity, and potential pathogens. For example, sediment and siltation affect 18 percent of surveyed river miles and 10 percent of lake acres (table 2). Similarly, nutrients affect 14, 20, and 22 percent of surveyed river miles, lake acres, and estuaries, respectively.

Maintaining surface-water quality is key to supplying recreational services that both current and future generations demand. For example, sediment and siltation affect water quality by harming fish, reducing water clarity, and filling in waterbodies. Ribaudo (1989) identified the following damages from sediment and siltation: reduced opportunities for freshwater and marine recreation and commercial fishing; increased cost for maintaining roadside and irrigation ditches, municipal water treatment, and steam power cooling; and greater chances of flooding. Similarly, nutrients in waterbodies (from lawn and crop fertilizer use, sewage, manure) can overstimulate the growth of aquatic weeds and algae, which then clog waterways, interfere with boating and swimming, and lead to oxygen depletion (USEPA, 1998).

Table 2—Major sources of pollution to rivers, lakes, and estuaries
Sediment and siltation affect 18 percent of surveyed river miles and 10 percent of lake acres

Item[1]	Percent
River miles:	
Sedimentation and siltation	18
Nutrients	14
Bacteria	12
Oxygen-depleting	10
Pesticides	7
Habitat alterations	7
Suspended solids	7
Lake acres:	
Nutrients	20
Metals	20
Sedimentation and siltation	10
Oxygen-depleting	8
Noxious plants	6
Suspended solids	5
Total toxics	5
Estuaries: (acres)	
Nutrients	22
Bacteria	16
Toxics	15
Oxygen-depleting	12
Oil and grease	8
Salinity	7
Habitat alterations	6

Source: USEPA, 1998.

When prices fail to convey information about the value placed on these services, feedback effects will likely be observed on the availability of this asset. The off-farm economic costs of agricultural pollution to surface waters appear substantial. Several studies have found improvements in water quality can yield significant benefits for individuals (Crutchfield, Feather, and Hellerstein, 1995). At the national level, Ribaudo (1989) found that retiring 40 to 45 million acres of highly erodible farmland through the CRP would result in national benefits (net present value) from reduced sediment pollution of $46 million per year. Comprehensive estimates of the damages from agricultural pollution are lacking, but soil erosion alone is estimated to cost water users $2-$8 billion annually (Ribaudo, 1989). Similarly, Hrubovcak, LeBlanc, and Eakin (1995) estimated the damages to surface-water quality from erosion on cropland at about $4 billion per year. Carson and Mitchell (1993) conducted a contingent valuation study to assess the public's value for national water quality. They provided survey respondents with water-quality improvement programs to meet the boatable, fishable, and swimmable goals of the Clean Water Act. The authors found that the mean annual willingness to pay to improve the Nation's water quality from nonboatable to swimmable status is $280 per household or about $29 billion per year.

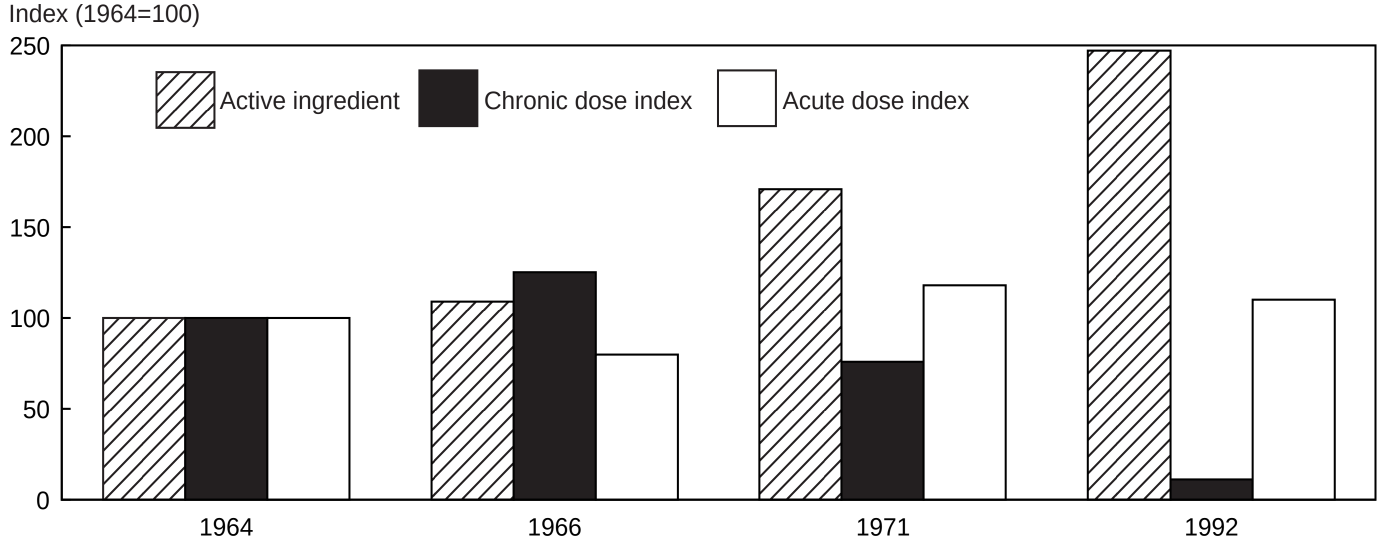
Ground-Water Quality

The infrastructure that monitors the Nation's environment cannot accurately depict trends in U.S. ground-water quality. Of 38 States reporting overall ground-water quality, 29 judged their ground water to be good or excellent. When degradation of ground-water quality does occur, it typically remains a localized problem and agriculture is often the source. Of 49 States reporting sources of ground-water contamination, 44 cited agriculture as a source (USDA, ERS, 1997).

Recent chemical use trends suggest that long-term improvements in ground-water quality may occur. After pesticide use more than doubled between 1964 and 1982, it declined slightly beginning in 1982 due to a decline in cropland acreage and the introduction of new pesticides that reduced application rates (fig. 5). The picture with regard to potential chemical toxicity is more complex. An index based on toxicity due

Figure 5
Pesticide use, chronic and acute risks

Although the total amount of pesticides based on the amount of active ingredients has increased since 1964, an index based on chronic risk has fallen while an index based on acute risk has remained relatively flat



Note: The chronic risk index combines Reference Dose (indicator of chronic toxicity) and soil half life (indicator of potential exposure). The acute risk index combines an oral LD50 (dose of a toxicant or microbe that will kill 50 percent of the test organisms within a designated period) with the soil half life measure. Source: Economic Research Service, USDA, 1997.

to long-term exposure to small doses shows an 89-percent decline since 1964. An index based on acute exposure increased by about 10 percent, and pounds of active ingredients more than doubled (USDA, ERS, 1997). Maintaining ground-water quality is important because it affects the supply of safe drinking water for many communities. Here again, a failure of markets to convey information about the value that communities place on the quality of a resource can affect the availability of a resource (safe drinking water) for future generations.

The evidence of ground-water quality impairment from agriculture paints an uncertain picture. While continued monitoring of ground water will clarify the Nation's understanding of pesticide and nutrient leaching, the risk of ground-water pollution carries significant economic costs.[7] Results from contingent valuation studies indicate a very large willingness by consumers to pay to avoid contamination of drinking water supplies. For example, Sun and others (1992) and Jordan and Elnagheeb (1993) evaluated the demand for ground-water protection from agricultural nitrate and pesticide leaching. Sun and others asked respondents for their willingness to pay for a protection program that would keep the ground-water quality below EPA health advisory levels in southwestern Georgia. The annual willingness to pay for this program averaged $641 per household. Jordan and Elnagheeb assessed the demand for protection from nitrate contamination of ground-water serving wells and drinking water utilities in Georgia. The authors estimated the annual willingness to pay for protection to average $120 to $150 per household for the different kinds of ground-water users.

Wetland Conversion Rates

Wetlands are an important asset for supplying environmental services. Wetlands provide opportunities for popular activities such as hiking, fishing, and boating. Similarly, wetlands provide fish and wildlife habitat, flood retention, and water filtration. Conversion of wetlands into cropland may increase the availability of food for the current generation but can affect the supply of environmental services, for both current and future generations. Because market prices may not convey information about the environmental services supplied by wetlands, there is a propensity to deplete this resource faster than would be justified by opportunity cost considerations.

The lower 48 States have lost about half of their wetlands since 1780. In 1780, wetlands in the lower 48

[7]Monitoring costs for agricultural chemicals have been estimated at $890 million to $2.2 billion for private wells (Nielsen and Lee, 1987).

States totaled slightly over 220 million acres compared with about 124 million acres in 1992 (USDA, ERS, 1997). Most of the original and remaining wetlands are in the Southeast, Delta, and Lake States. The Corn Belt has lost nearly 90 percent of its original wetlands, the Pacific States have lost nearly 75 percent, and the Plains States have lost approximately 50 percent. Between 1954-92, 64 percent of all converted wetland acreage supported agriculture.

Available data suggest that the rates of wetland loss in the 1980's are dramatically lower than in earlier decades (table 3). For example, from 1954 to 1974 and 1974 to 1983, the net rate of wetland losses in the lower 48 States was 458,000 and 290,000 acres per year. However, from 1982 to 1992, the net rate of wetland losses in the lower 48 States slowed to about 80,000 acres per year. From 1982 to 1992, almost 11,000 acres per year moved out of agricultural production and into wetlands.

Several studies have addressed the effects of agricultural production on the economic values of wetlands. In perhaps the most comprehensive evaluation of the economic values associated with wetlands, Heimlich and others (1998) assessed and classified 33 studies as to the function of wetlands, the goods they provide, and the economic value of those goods. Examples of the goods provided by wetlands include: marketed fish and fur (goods sold in markets by commercial fishermen and trappers such as blue crabs, fish, oysters, fur trapping); nonmarketed fish and wildlife habitat; nonmarketed recreation, fishing, and hunting opportunities; and nonmarketed ecological functions (nutrient filtering, storm damage). Heimlich and others then estimated the economic losses associated with the loss in wetlands from 1952 to 1992. Their estimates of the total direct economic damages range from $421 million for commercial fisheries to $135 billion for recreation and noncommercial fishing and waterfowl hunting. Based on total wetland losses of 12.9 million acres over that period, they estimate an imputed average value of $10,558 per acre of lost wetlands.

An Aggregate Assessment for U.S. Agriculture

Conclusions regarding the overall sustainability of U.S. agriculture depend on the vision of sustainability a researcher adopts. Aside from agricultural productivity, the remaining indicators are not consistent with a strong vision of sustainability (table 4). Soil continues to erode even though its impact on future agricultural output is small. Ground-water stocks continue to be depleted, although at slower rates than in the past. While data are not available to assess changes in the quality of surface and ground water over time, agriculture is likely the major contributor to impairments.

Agriculture made significant progress toward meeting the goals of sustainability in the 1980's. The growth rate of agricultural productivity was 3.3 percent per year from 1980 to 1994 compared with only 1.4 percent per year from 1948 to 1980. Interestingly, while productivity was increasing, soil erosion was declining from 3 to 2 billion tons per year, ground-water depletion rates were falling, and agriculture became a net supplier of wetlands, helping reduce net wetland conversion rates over time.

Recent research has integrated environmental and natural resource indicators in a consistent economic framework. For example, Smith (1992) compared the

Table 3—Wetlands conversions per year, 1954-74, 1974-83, and 1982-92
Wetland loss in 1980's are dramatically lower than in earlier decades

	1954-74			1974-83			1982-92		
Item	From wetlands	To wetlands	Net	From wetlands	To wetlands	Net	From wetlands	To wetlands	Net
				1,000 acres per year					
Agriculture	-592.8			-234.8	81.5	-153.3	-30.9	41.8	10.9
Development	-54.5			-14.0	0.4	-13.6	-88.6	1.5	-87.1
Other	-35.3			-168.1	53.4	-114.7	-16.4	28.8	12.4
Subtotal	-682.6	247.8	-434.8	-416.9	135.3	-281.6	-135.9	72.1	-63.8
Deepwater	-47.6	24.7	-22.9	-29.0	20.4	-8.6	-20.2	4.8	-15.4
Total	-730.2	272.5	-457.7	-445.9	155.7	-290.2	-156.1	76.9	-79.2

Source: USDA, ERS, 1997.

Table 4—Physical indicators of agricultural sustainability
Indicators give mixed signals with respect to agricultural sustainability

Indicator	Year	Physical change
		Growth rate per year (percent)
Agricultural productivity	1948-80	+1.4
	1980-94	+3.3
	1948-95	+1.9
		Billion tons per year
Soil erosion	1938	3.56
	1982	3.13
	1987	2.80
	1992	2.13
		Feet per year
Ground-water depletion	1940-80	0.25
	1980-95	0.16
Surface-water quality		Agriculture is leading source of impairment but less erosion has likely reduced damages from sediment
Ground-water quality		Of 49 States reporting sources of ground-water contamination, 44 cited agriculture as a source
		Acres per year
Net loss of wetlands*	1974-83	153,300
	1982-92	-10,900

* Attributed to agriculture. Sources: USDA/ERS, NRCS; USGS; and EPA.

effects of damages associated with soil erosion, wetland conversions, and ground-water contamination to the value of crops in 1984. His estimates of damages range from less than 1 to 7.5 percent of the value of crops grown in the Mountain region to 3.5 to 40 percent of the value of crops grown in the Northeast. Damages in the Corn Belt range from 6 to 7 percent of the value of crop output. According to his results, agriculture's contribution to social welfare far exceeds the environmental damages and deterioration of the stock of natural capital resulting from food production.

Similarly, Faeth (1996) paints a picture of an agricultural sector that is improving over time with respect to environmental damages. Faeth adjusts the agricultural productivity estimates presented in figure 1 for the off-site damages associated with soil erosion. From 1977 to 1992, agricultural productivity increased from 2.3 to 2.4 percent per year, reflecting the dramatic decline in soil erosion over that time.

Lastly, Hrubovcak, LeBlanc, and Eakin (1995) estimate that total farm income should be reduced by about $4 billion per year when adjustments are made for agriculture's contribution to the impairments in surface-water quality and draw-downs in the stock of ground water. Their adjustments to net farm income range from 6 to 8 percent and have decreased from 1987 to 1992.[8] They note one possible explanation for the decrease is that policies and programs for controlling soil erosion were effective during this period. In particular, removing nearly 22 million acres of highly erodible land from production through the CRP contributed to a nearly 21-percent decrease in estimated soil erosion on cropland even though planted acreage for grains increased by 6 percent. Conservation compliance requirements promulgated under the Food Security Act of 1985 provided additional incentives for reducing erosion.

These estimates are consistent with a view of U.S. agriculture where environmental problems exist and the resource base is depreciating, but the extent of the effects is in the range that can adequately be addressed by thoughtful policy.

[8]These estimated adjustments represent average costs of environmental damages. Marginal costs are likely to be higher.

III. Steering Agriculture in a More Sustainable Direction—The Role of Green Technologies

Generations can share resources in numerous ways. This study distinguishes between two broad approaches. The first approach directly conserves natural resources for future generations. This approach has been, and will continue to be, widely used in government programs. Numerous programs have been instituted to limit environmental degradation and to conserve natural resources. For example, the Food Quality Protection Act (FQPA) of 1996, Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), and the Federal Food, Drug, and Cosmetic Act (FFDCA) allow the EPA and the Food and Drug Administration (FDA) to restrict the use of certain pesticides based on their risks to human health, wildlife, ground-water quality, and other environmental effects. Similarly, the Endangered Species Act (ESA) was enacted as a way to preserve/conserve plant and animal species that are in danger of extinction (endangered species) or that may become so in the foreseeable future (threatened species).

With respect to agriculture, USDA offers landowners financial, technical, and educational assistance to implement conservation practices on privately owned land and thereby directly invests in natural resources. Using this help, farmers and ranchers apply practices that reduce soil erosion, improve water quality, and enhance forest land, wetlands, grazing lands, and wildlife habitat. For example, the CRP was established to reduce soil erosion on highly erodible land and to achieve other secondary objectives. Similarly, the Wetland Reserve Program (WRP) provides easement payments and restoration cost-shares to landowners who permanently return previously converted or farmed wetlands to wetland condition. Most recently, the 1996 Farm Bill also expanded the Department's conservation programs with the Wildlife Habitat Incentives Program (WHIP) and the Farmland Protection Program. WHIP allows for technical and cost-share assistance to landowners to develop improved wildlife habitat. Under the Farmland Protection Program, USDA leverages Federal funds with State and local funds to protect farmland.

A second approach, and the focus of this report, operates through a farmer's choice of technologies. This approach encourages research and development (R&D) and adoption and diffusion of more sustainable farming practices.[9] Investment in these "green technologies" is currently receiving a great deal of attention because they promise to augment farm profitability while reducing environmental degradation and conserving natural resources.

There is a wealth of information in the form of case studies suggesting that green technologies can be both economically profitable and environmentally sustainable (see Appendix 1). However, simply because a practice is available does not mean that farmers will adopt it. In the long run, the adoption and diffusion of alternative practices will depend on profitability. Other factors, such as differences in farm structure (e.g., crops grown, diversity of output, farm size), economic risk, and geographic location, will also affect adoption and diffusion rates of green technologies.

To assess what may be the most significant impediments to the adoption and diffusion of alternative production practices, we highlight four practices that are often considered more sustainable and have been researched. These practices are: integrated pest management (IPM), conservation tillage, enhanced nutrient management, and precision agriculture. These practices have either been broadly adopted or have the potential for wide-scale adoption in agricultural production. For example, farmers have used IPM in the United States for more than 20 years, and scouting is used on almost two-thirds of surveyed fruit and nut acreage and nearly 75 percent of vegetable acres (USDA, ERS, 1994). Wide-scale adoption of conservation tillage has a more recent history, with farmers employing mulch-till, ridge-till, or no-till systems on over 36 percent of planted acres in 1995; up from less than 18 percent in 1988 (USDA, ERS, 1997). Farmers also have considerable experience with enhanced nutrient management practices, although wide-scale adoption has not occurred. Among the most recent is an emerging suite of management practices known as precision agriculture.

Each of these practices is "information and management intensive," because a farmer is required to understand much more than in the past how the physical characteristics associated with farming, such as

[9] Adoption refers to the use or intensity of use of a practice at the farm level. Diffusion refers to the intensity or rate of adoption at the sector level.

soil type, rainfall, and temperature, interact with managing inputs, such as pesticides, nutrients, and soil, to affect the production of commodities. Each practice uses inputs efficiently and may dramatically affect farm profits, the quality of the environment, and the pattern of natural resource use. These practices may improve our indicators of agricultural sustainability by both increasing food production and mitigating the impact of current agricultural production practices on the environment. For example, sediment and siltation are the primary pollutants of rivers in the United States (USEPA, 1998). Conservation tillage has significantly reduced soil erosion from farmland and therefore can potentially improve surface-water quality. Similarly, nutrients are the leading pollutant associated with lakes and estuaries and the second leading pollutant associated with rivers. Enhanced nutrient management can reduce the leaching of fertilizers and manures and can further improve surface- and ground-water quality. IPM can reduce the need for pesticides, which also improves surface and ground-water quality. Lastly, precision agriculture can improve all facets of the environmental performance of U.S. agriculture.

Integrated Pest Management

IPM includes various techniques that maintain pest infestation at an economically acceptable level rather than attempting to completely eradicate all pests. The USDA uses the following definition: "IPM is a management approach that encourages natural control of pest populations by anticipating pest problems and preventing pests from reaching economically damaging levels. All appropriate techniques are used such as enhancing natural enemies, planting pest-resistant crops, adapting cultural management, and using pesticides judiciously" (USDA, Agricultural Research Service, 1993). IPM monitoring methods include scouting by regular and systematic field sampling, soil testing for pests, such as nematodes, using pheromone odors and visual stimuli to attract target pests to traps, and recording environmental data, e.g., temperature and rainfall, associated with the development of some pests. Pest management practices used in IPM include biological controls such as natural enemies or "beneficial" semiochemicals (including pheromones and feeding attractants) and biopesticides; cultural controls such as hand hoeing, mulching, and crop rotation; strategic controls such as planting dates and location; and plants resistant to some pests.

While IPM does not exclude the use of synthetic pesticides, the pesticides used in IPM often differ from those used on a preventive or routine schedule. Where possible, IPM uses pesticides that target specific pests and decrease toxic exposure to beneficial organisms. To the extent that IPM decreases pesticide use, gains in environmental benefits can occur in terms of improved water quality, decreased probability of wildlife poisonings, and decreased probability of negative health effects for applicators.

The following provides an operational definition of IPM to manage insects (diseases). A farmer uses IPM to manage insects (diseases) if: scouting for insects (diseases) and economic thresholds are used in making insecticide (fungicide) treatment decisions, and one or more additional insect (disease) management practices among those commonly considered to be IPM techniques are employed (Vandeman and others, 1994).

While many of the techniques under the umbrella term “IPM” have been around for some time, and unifying these practices into a cohesive group occurred about 25 years ago, large-scale adoption of some IPM techniques on U.S. farms is a fairly recent phenomenon. If current conditions prevail, adopting IPM techniques will reach 75 percent of the vegetable acreage nationally between 2008-36, except for scouting, which attains the 75-percent level in the present decade (Fernandez-Cornejo and Kackmeister, 1996). For fruit acres, the 75-percent IPM adoption goal will likely be achieved between 1995 and 2005, except for scouting which has already achieved this goal (Fernandez-Cornejo and Castaldo, 1998).

Conservation Tillage

Conservation tillage involves maintaining adequate soil cover to decrease soil erosion by wind and water. The following definitions for a set of systems that manage crop residue may help one better understand the distinctions between various approaches to conventional and conservation tillage (USDA, ERS, 1994):

Conventional tillage with moldboard plow: Any tillage system that includes the use of a moldboard plow.

Conventional tillage without moldboard plow: Any tillage system that has less than 30 percent remaining residue and does not use a moldboard plow.

Conservation tillage: Any tillage and planting system that maintains at least 30 percent of the soil surface covered by residue after planting to reduce soil erosion by water; or maintains at least 1,000 pounds per acre of flat, small grain residue equivalent on the surface during the critical wind erosion period where soil erosion by wind is the primary concern.

Two key factors influence crop residue: the previous crop, which establishes the initial residue amount and determines its fragility, and the type of tillage operations prior to and including planting.

Conservation tillage practices include:

Mulch till. The soil is disturbed prior to planting. Operators use tillage tools such as chisels, field cultivators, disks, sweeps, or blades.

Ridge till. The soil is left undisturbed from harvest to planting except for nutrient injection. Farmers complete planting in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges.

No-till. The soil is left undisturbed from harvest to planting except for nutrient injection. Planting or drilling is accomplished in a narrow seedbed or slot created by coulters, row cleaners, disk openers, inrow chisels, or rototillers.

Farmers have adopted conservation tillage partly in response to incentive effects associated with Conservation Compliance and, in many cases, on a voluntary basis. As depicted in table 5, adoption rates have generally increased since 1988. For example, in 1995, only 11 percent or less of acres were tilled using conventional tillage with a moldboard plow in corn, northern soybean, southern soybean, or winter wheat production; compared with as much as 28 percent for northern soybeans in 1988.

Clearly, some individual farmers perceive that the benefits of adopting conservation tillage outweigh the costs. Potential private benefits of conservation tillage include: increased profits, greater convenience, decreased economic risk, and the potential for reducing erosion. However, all farmers will not find conservation tillage equally attractive because, as was the case for IPM, the costs and benefits will vary by farm. For example, studies comparing profitability of conservation and conventional tillage systems provide mixed results. Several studies have found net returns do not significantly differ between reduced tillage and conventional tillage (Duffy and Hanthorn, 1984; Jolly and others, 1983). Other studies have found conventional tillage has higher returns (Klemme, 1985; Martin and others, 1991) and yet other studies have found conservation tillage has higher returns (Williams and others, 1989).

Enhanced Nutrient Management

Enhanced nutrient management involves efficiently using nutrients from commercial fertilizers and animal and municipal wastes. The primary goal of nutrient management is to sustain an increase in agricultural production and minimize the environmental damage from unused nutrients. Enhanced nutrient management practices include altering existing practices by assessing nutrient needs, timing applications, placing fertilizer closer to the seed, using alternative products, changing crop and irrigation management, and using manure and organic wastes.

Assessing Needs

Soil tests and plant analyses play an integral part in balancing the supply of nutrients and the need for nutrients by crops. Soil tests can reveal the level of a nutrient present in the soil profile available for plant uptake before the application of commercial fertilizer. With a soil test, the farmer, in matching the crop's need for nutrients, can determine whether and how much additional nutrient should be supplied.

Timing

Timing nitrogen applications to meet the crop's biological needs can reduce application rates. Effectively timed applications match the biological needs of a crop resulting in less nitrogen available for leaching, runoff, denitrification, and other losses.

Placement

Farmers can employ a variety of improved nitrogen application practices to place nitrogen fertilizer closer to the seed or plant for increased crop uptake (Achorn and Broder, 1991). These include the use of injection, knifed-in, and side dressing applications. These application practices can increase the efficiency of plant uptake of nitrogen fertilizer.

Table 5—Adoption of alternative tillage practices, percent of acres, 1988-95
Adoption rates of alternative tillage practices have increased since 1988

Crop	Year	Conventional tillage with moldboard plow	Conventional tillage without moldboard plow	Mulch till	Ridge till	No till
			Percent of acres			
Corn	1988	20	60	14	*	7
	1995	8	49	23	3	17
Northern soybeans	1988	28	55	14	*	3
	1995	8	37	24	1	30
Southern soybeans	1988	3	85	5	*	7
	1995	1	67	7	--	25
Winter wheat	1988	15	67	16	--	1
	1995	11	67	15	--	7
Spring durum wheat	1988	14	63	22	--	1
	1995	6	67	22	--	5
Total	1988	19	63	13	*	5
	1995	8	56	19	1	16

* = included with no till.
Source: USDA, ERS, *Agricultural Resources and Environmental Indicators* (1997).

Alternative Products

A farmer can choose a variety of products that differ in their potential to leach and denitrify. Several researchers have ranked the chemical stability, ranging from least stable to most stable, for nitrogen products: ammonium nitrate, nitrogen solutions, anhydrous ammonia, urea, and ammonia-based fertilizer with an added nitrification inhibitor (Aldrich, 1984). Ammonia-based fertilizer can minimize nitrogen loss for land vulnerable to leaching. A nitrate-based fertilizer can best address areas vulnerable to ammonia volatilization.

Crop Management

Crops in rotation with a nitrogen-fixing legume crop can reduce nitrogen application needs and use. In addition, crops in rotation reduce soil insects, improve plant health, and increase nitrogen uptake efficiency. Legume crops at an early stage of growth absorb residual nitrogen in the soil and minimize leaching. Planting "scavenging" crops between crop seasons can prevent residual nitrogen buildup during land dormant seasons. Some nitrogen-scavenging cover crops include hairy vetch and small grain crops.

Irrigation Management

The quantity of water in the soil affects the nutrient concentration in soils and the rate of nutrient movement to the root zone (Rhoades). Too much water can promote nitrogen leaching, reduce nutrient concentration in soils, and lower plant uptake. Too little water can result in water stress with respect to plant growth. Water stress stunts plant growth and reduces crop yields. Farmers can improve irrigation efficiency, for example, by switching from gravity irrigation to sprinkler irrigation, by scheduling and applying irrigation water according to plant need, and by using improved gravity irrigation practices.

Using Manure and Organic Wastes

Manure is a source of nutrients and an important source of organic matter. Organic matter in soil provides nutrients to crops and acts as a soil conditioner enabling crops to achieve high yields. Managing nutrients in animal manure for better use requires testing the manure to ascertain its nutrient content.

Precision Agriculture

Precision agriculture encompasses a range of management practices that attempt to achieve optimal crop, livestock, or forestry output by using information to adjust inputs to expected soil, weather, and environmental conditions (National Research Council, 1997). Precision agriculture is simply a more disaggregated version of the kinds of best management practices already recommended at the field scale (Ogg, 1995). Furthermore, precisely matching fertilizer and pesticide inputs to the capabilities and needs of the crop for small areas and exactly when the crop needs the inputs limits the amounts of these materials that can escape to the environment. Some evidence suggests precision agriculture can reduce the amount of chemicals applied and can reduce the level of residual nitrogen (Kitchen and others, 1995). Information technologies used in precision agriculture cover the three aspects of production: data collection or information input, analysis or processing of the precision information, and recommendations or application of the information.

Data Collection

Data collection consists of two major components: data collected in advance of crop production, and data collected in "real time" as production activities occur.

To collect data at precise locations, a farmer can use the global positioning system (GPS) satellite data alone, or use differentially corrected for positional error with supplemental data (DGPS). GPS/DGPS location information enhances the spatial accuracy of the data (National Research Council, 1995).

Data collection technologies operating in advance of crop production include grid soil sampling (Goering, 1993), yield monitoring, remote sensing (Jackson, 1984; Moran and others, 1997), and crop scouting (Johnson and others, 1997). These provide basic information on the conditions under which production occurs or will occur. A farmer can apply each to crop, forage, or tree production, although the frequency, timing, and density of sampling will likely vary between production systems.

Other data collection, known as "local" sensing, takes place nearly simultaneously with management (Morgan and Ess, 1996; Sudduth and others, 1994). For example, probes thrust into the soil on the front of fertilizer spreaders continuously monitor electrical conductivity, soil moisture, and other variables and predict soil nutrient concentrations to instantaneously adjust fertilizer application at the rear of the spreader (Birrell, 1995; Colburn, 1991). Other examples include optical scanners that detect soil organic matter, or "recognize" weeds to instantaneously alter the amount of herbicides applied (Gaultney and Shonk, 1988; McGrath and others, 1990). These "local" sensors do not need GPS location capability, but a farmer may use them in association with a GPS for entry into a field geographic information system (GIS). In livestock production, electronic ear tags can trigger automated feeding bins that provide (or withhold) a precise ration for specific animals (*AgWeek*, 1996).

Analysis or Processing

The precise data can improve productivity only if a farmer can analyze or process the information to adjust management. The principal technology used to integrate spatial data coming from various sources is the GIS. This is primarily an intermediate step, because data collected at different times on the basis of different sampling regimes and different scales must be combined in space (and time) for use with subsequent decision technologies (Usery and others, 1995). Decision technologies take three forms: process models, artificial intelligence systems, and expert systems (National Research Council, 1989, 1996). Process models use frequent time-steps to simulate the processes of crop, livestock, or forest growth, or generation and movement of potential pollutants through the environment. Artificial intelligence systems use more heuristic or empirical decision rules (rather than the theoretically based relationships in most process models) to reach conclusions about appropriate management techniques. Expert systems incorporate the "rules of thumb" used by human experts that match the conditions reflected in the input data to reach recommendations (McGrath and others, 1995).

Application

Ideally, a farmer can adjust production inputs for each corn plant, animal, or tree to optimize production according to physical, economic, and environmental goals. In practice, technology limits how small an area can be addressed and how finely calibrated input applications can be controlled (Chaplin and others, 1995). Variable rate application is used to describe precise control of inputs, which can include fertilizer and micronutrient application, liming, seed variety and rate, pesticides, irrigation water and drainage, and livestock feed. Also, a farmer may use selective harvest, expressed in the timing of crop harvest to optimize quality aspects, as rotational grazing in livestock systems, or by selective thinning in forestry.

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 leaching 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).

V. Conclusions

For an economy to move along a more sustainable path of economic development, the economic needs of a growing population must be satisfied. A more sustainable path of economic development for agriculture is one that meets the growing demands for food at reasonable costs to consumers. These costs include any environmental damages to current and future generations caused by agricultural production. An important lesson learned in this report is that no institutional mechanism exists to steer the agricultural sector along a more sustainable path of economic development. Historically, government programs have tried to correct such market failures by directly conserving natural resources. For example, programs such as the Conservation Reserve Program, albeit imperfectly, take the place of market prices and provide incentives for resource conservation. Recently, investment in green technologies has received a great deal of attention because of their potential to increase farm profits and improve the environmental performance of agricultural production. However, simply making a technology available does not necessarily mean it will be adopted. Until markets are developed for the environmental attributes associated with green technologies, farmers will under-use these technologies.

Several conclusions emerge from this report. First, the environmental and natural resource effects of a technology are location-specific. A given technology may be profitable for one farm but not for others within the same region. This limits the power of inferences that can be drawn from individual case studies such as those reviewed in Appendix 1. This is equally true of the environmental benefits of a green technology, which may also exhibit significant spatial variation.

Second, even when a green technology is profitable, there are many impediments to adoption and diffusion such as structural barriers, risk, and heterogeneity of the farm resource base. As a result, a number of policy instruments must be used to encourage adoption of green technologies. Economic incentives alone may not be enough, as policymakers may need to consider risk management strategies, for example, to deal with the risk associated with adoption of a green technology. Historically, increased adoption has been achieved through two approaches: regulations (e.g., pesticide registration) and incentives (e.g., cost sharing). Our findings indicate that these approaches can be complemented with other approaches.[17]

Third, the heterogeneity of the resource base implies that technology transfer programs must be tailored to regional conditions. This follows because the environmental benefits-profitability nexus exhibits spatial variation. A green technology may work in one region but may be totally inappropriate for another region. The empirical findings of this report caution against adopting a "one size fits all" approach to adoption of green technologies.

Finally, there can be environmental trade-offs associated with the technologies examined (e.g., controlling one type of problem might exacerbate another). For example, it is possible that conservation tillage may increase herbicide use while reducing soil erosion. It is necessary to consider such tradeoffs between environmental problems while formulating policy approaches.

The in-depth study of four green technologies has provided information on the potential tradeoffs between environmental quality, natural resource conservation, and the choice of technology. This information provides some background for developing policy implications to move agriculture in a more sustainable direction.

[17]These findings were reinforced by participants at a workshop co-sponsored by ERS. Workshop participants suggested a number of policies that could be adopted to steer agriculture in a more sustainable direction (see Appendix 2 and Vasavada, Hrubovcak, and Aldy, 1997).

References

Aase, J., and G. Schaefer. 1996. "Economics of Tillage Practices and Spring Wheat and Barley Crop Sequences in the Northern Great Plains," *Journal of Soil and Water Conservation.* 15: pp. 167-70.

Achorn, F., and M. Broder. 1991. "Mechanics of Applying Nitrogen Fertilizer," *Managing Nitrogen for Groundwater Quality and Farm Profitability*. Madison, WI: Soil Science Society of America.

AgWeek Magazine. February 1996.

Ahearn, M., E. Ball, J. Yee, and R. Nehring. 1998. *Agricultural Productivity in the United States*. AIB-740. U.S. Dept. Agr., Econ. Res. Serv.

Aillery, M. 1995. *Federal Commodity Programs and Returns to Irrigation in the West*. ERS Staff Paper 9502. U.S. Dept. Agr., Econ. Res. Serv.

Aldrich, S. 1984. "Nitrogen Management to Minimize Adverse Effects on the Environment," *Nitrogen in Crop Production*. Madison, WI: Soil Science Society of America.

Aldy, J., J. Hrubovcak, and U. Vasavada. 1998. "The Role of Technology in Sustaining Agriculture and the Environment," *Ecological Economics*. 26: pp. 81-96.

Alt, K., C. Osborn, and D. Colacicco. 1989. *Soil Erosion: What Effect on Agricultural Productivity?* AIB-556. U.S. Dept. Agr., Econ. Res. Serv.

Amacher, G., and P. Feather. 1997. "Testing Producer Perceptions of Jointly Beneficial Best Management Practices for Improved Water Quality,"*Applied Economics*. 29: pp. 153-9.

Babcock, B., and A. Blackmer. 1994. "The Ex Post Relationship Between Growing Conditions and Optimal Fertilizer Levels," *Review of Agricultural Economics*. 16 (September).

Baker, J., T. Logan, J. Davidson, and M. Overcash. 1987. "Summary and Conclusions," in T. Logan, J. Davidson, J. Baker, and M. Overcash, eds., *Effects of Conservation Tillage on Groundwater Quality: Nitrates and Pesticides*. Chelsea, MI: Lewis Publishers.

Berglund, D., and M. Freeburg. 1995. “Grid Sampling and Precision Agriculture in the Red River Valley.” CENTROL Crop Consulting, Twin Valley, MN. July 19. 6 pp.

Birrell, S. 1995. "Multi-ISFET Sensor System for Soil Analysis." Ph.D dissertation, University of Illinois, Urbana.

Bock, B., K. Kelley, and J. Meisinger. 1992. "Predicting N Fertilizer Needs in Humid Regions: Summary and Future Directions," in *Predicting N Fertilizer Needs for Corn in Humid Regions*. Bulletin Y-226, National Fertilizer and Environmental Research Center. Tennessee Valley Authority, Muscle Shoals, Alabama.

Bosch D., and K. Napit. 1992. "Economics of Transferring Poultry Litter to Achieve More Effective Use as Fertilizer," *Journal of Soil and Water Conservation*. 47 (July-August).

Bosch, D., K. Fuglie, and R. Keim. 1994. *Economic and Environmental Effects of Nitrogen Testing for Fertilizer Management*. Staff Report. U.S. Dept. Agr., Econ. Res. Serv.

Bouldin, D., S. Klausner, and W. Reid. 1984. "Use of Nitrogen from Manure." *Nitrogen in Crop Production*. Soil Science Society of America, Madison, Wisconsin.

Bull, L., H. Delvo, C. Sandretto, and B. Lindamood. 1993. "Analysis of Pesticide Use by Tillage Systems in 1990, 1991, and 1992 Corn and Soybeans," *Agricultural Resources: Inputs, Situation and Outlook Report*. AR-32. U.S. Dept. Agr., Econ. Res. Serv.

Bultena, G., and E. Hoiberg. 1983. "Factors Affecting Farmers' Adoption of Conservation Tillage," *Journal of Soil and Water Conservation*. (May-June): pp. 281-84.

Calvin, L., and C. Brown. 1996. "Conservation Tillage." Paper presented at the ERS/Farm Foundation Sustainability Workshop. October.

Carson, R., and R. Mitchell. 1993. "The Value of Clean Water: The Public's Willingness to Pay for Boatable, Fishable, and Swimmable Quality Water," *Water Resources Research*. 29: pp. 2445-54.

Chambers R., and E. Lichtenberg. 1995. "Economics of Sustainable Farming in the Mid-Atlantic." Final Report to the USDA/EPA Ace Program.

Chaplin, J., E. Roytburg, and J. Kaplan. 1995. "Measuring the Spatial Performance of Chemical Applicators," in P. Robert, R. Rust, and W. Larson, eds. *Site-Specific Management for Agricultural Systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Chase, C., and M. Duffy. 1991. "An Economic Comparison of Conventional and Reduced-Chemical Farming Systems in Iowa," *American Journal of Alternative Agriculture*. 6: pp. 168-73.

Chase, C., M. Duffy, and W. Lotz. 1991. "Economic Impact of Varying Swine Manure Application Rates on Continuous Corn," *Journal of Soil and Water Conservation*. 46.

Christensen, P. 1989. "Historical Roots for Ecological Economics--Biophysical Versus Allocative Approaches," *Ecological Economics*. 1(1): pp. 17-36.

Cleveland, C. 1995. "Resource Degradation, Technical Change, and the Productivity of Energy Use in U.S. Agriculture," *Ecological Economics*. 13: pp. 185-201.

Colburn, J. 1991. Soil Chemical Sensor and Precision Agricultural Chemical Delivery System and Method. U.S. Patent 5,033,397.

Corbley, K. 1996. "Remote Sensing, GIS, GPS Transforming Data into Information," in *Convergence of Geotechnologies Enhancing Precision Farming* @griculture Online, @gInnovator online at <http://www.agriculture.com/contents/agii/agrispot.htm>.

Crosson, P. 1995. "Soil Erosion and Its On-Farm Productivity Consequences: What Do We Know?" Discussion Paper 95-29. Resources for the Future, Washington, DC.

Crutchfield, S., P. Feather, and D. Hellerstein. 1995. *The Benefits of Protecting Rural Water Quality: An Empirical Analysis*. AER-701. U.S. Dept. Agr., Econ. Res. Serv.

Daly, J. 1990. "Toward Some Operational Principles of Sustainable Development," *Ecological Economics*. 2: pp. 1-6.

DeQuattro, J. 1996. "Orbiting Eye Will See Where Crops Need Help," *Agricultural Research*. 44: pp. 12-4.

Doster, D., D. Griffith, J. Mannering, and S. Parsons. 1983. "Economic Returns for Alternative Corn and Soybean Tillage Systems in Indiana," *Journal of Soil and Water Conservation*. 38: pp. 504-9.

Duffy, M., and M. Hanthorn. 1984. *Returns to Corn and Soybean Tillage Practices*. AER-508. U.S. Dept. Agr., Econ. Res. Serv.

Economic Report of the President. 1994. Washington, DC: U.S. Government Printing Office.

___________. 1997. Washington, DC: U.S. Government Printing Office.

Epplin, F., and T. Tice. 1986. "Influence of Crop and Farm Size on Adoption of Conservation Tillage," *Journal of Soil and Water Conservation*. 41: pp. 424-27.

Ervin, D., and A. Schmitz. 1996. "A New Era of Environmental Management in Agriculture?" *American Journal of Agricultural Economics*. 78: pp. 1198-1206.

Faeth, P. 1993. "Evaluating Agricultural Policy and the Sustainability of Production Systems: An Economic Framework," *Journal of Soil and Water Conservation*. March/April: pp. 94-9.

___________. 1996. "Environment and Productivity in Agriculture." In *Has Environmental Protection Really Reduced Productivity Growth: We Need Unbiased Measures*. Washington, DC: World Resources Institute.

Fernandez-Cornejo, J. 1996a. "The Microeconomic Consequences of IPM Adoption: Theory and Application," *Agricultural and Resource Economic Review*. 25: pp. 149-60.

___________. 1996b. "IPM Adoption by Growers of Selected Fruits and Vegetables." Paper presented at ERS Sustainability Workshop. August.

___________. 1998. "Environmental and Economic Consequences of Technology Adoption: IPM in Viticulture," *Agricultural Economics*. 18: pp. 145-55.

Fernandez-Cornejo, J., and C. Castaldo. 1998. "The Diffusion of IPM Techniques Among Fruit Growers in the USA," *Journal of Production Agriculture*. October-December.

Fernandez-Cornejo, J., and S. Jans 1996. "The Economic Impact of IPM Adoption For Orange Producers in California and Florida," *Acta Horticulturae*. 429: pp. 325-34.

Fernandez-Cornejo, J., and A. Kackmeister. 1996. "The Diffusion of Integrated Pest Management Techniques," *Journal of Sustainable Agriculture*. 7: pp. 71-102.

Fernandez-Cornejo, J., E. Beach, and W. Huang. 1994. "The Adoption of IPM Techniques By Vegetable Growers in Florida, Michigan, and Texas," *Journal of Agricultural and Applied Economics*. 1: pp. 158-72.

Fuglie, K., N. Ballenger, K. Day, C. Klotz, M. Ollinger, J. Reilly, U. Vasavada, and J. Yee, with contributions from J. Fisher and S. Payson. 1996. *Agricultural Research and Development: Public and Private Investments Under Alternative Markets and Institutions.* AER-735. U.S. Dept. Agr., Econ. Res. Serv.

Gadsby, D., R. Magleby, and C. Sandretto. 1987. "Why Practice Conservation?" *Soil and Water Conservation News*. December.

Gaultney, L., and J. Shonk. 1988. "Spectroscopic sensing for the determination of organic matter content." ASAE Paper No. 887-2142. St. Joseph, Mich.: Amer. Soc. Agric. Eng.

Giacchetti, N. 1996. "The Pricing Paradox: Here's How One Dealership Puts a Price Tag on Precision Agricultural Services," *Farm Chemicals*. 159: p. 38.

Goering, C. 1993. "Recycling a Concept," *Agricultural Engineering Magazine*. November. St. Joseph, Mich: Amer. Soc. Agric. Eng.

Graham-Tomasi, T. 1991. "Sustainability: Concepts and Implications for Agricultural Research Policy," in P. Pardey, J. Roseboom, and J. Anderson, eds., *Agricultural Research Policy: International Quantitative Perspectives*. New York, NY: Cambridge University Press.

Greene, C., R. Kramer, G. Norton, E. Rajotte, and R. McPherson. 1985. "An Economic Analysis of Soybean Integrated Pest Management," *American Journal of Agricultural Economics*. 67: pp. 567-72.

Hayami, Y., and V. Ruttan. 1985. *Agricultural Development: An International Perspective*. Baltimore, MD: The Johns Hopkins University Press.

Heimlich, R., K. Wiebe, D. Gadsby, R. House, and R. Claasen. 1998. *Wetlands and Agriculture: Private Interests and Public Benefits*. AER-765. U.S. Dept. Agr., Econ. Res. Serv.

Hicks, J. 1932. *The Theory of Wages*. London: Macmillan and Co.

Hoeft, R. 1984. "Current Status of Nitrification Inhibitor Use in U.S. Agriculture," *Nitrogen in Crop Production*. Soil Science Society of America Madison, Wisconsin.

Hrubovcak, J., M. LeBlanc, and B. Eakin. 1995. *Accounting for the Environment in Agriculture*. TB-1847. U.S. Dept. Agr., Econ. Res. Serv.

Huang, W., and S. Daberkow. 1996. "The Role of Planting Flexibility and the ARP in Encouraging Sustainable Agricultural Practices," *Journal of Sustainable Agriculture*. 7: 163-179.

Huang, W., and R. Lantin. 1993. "A Comparison of Farmers' Compliance Costs to Reduce Excess Nitrogen Fertilizer Use Under Alternative Policy Options," *Review of Agricultural Economics*. 15.

Huang, W., and H. Taylor. 1996. "Use of Nitrogen Stabilizers in U.S. Crop Production and Economic and Environmental Effects." Paper presented in 1996 Annual Meeting of Southern Agricultural Economics Association. Greensboro, North Carolina, February.

Huang, W., D. Shank, and T. Irwin Hewitt. 1996. "On-Farm Costs of Reducing Nitrogen on Cropland Vulnerable to Nitrate Leaching," *Review of Agricultural Economics*. 18: pp. 325-39.

Jackson, R. 1984. "Remote Sensing of Vegetation Characteristics for Farm Management." Proceedings. SPIE (The International Society for Optical Engineers) 475: pp. 81-96.

Johnson, G., J. Cardina, and D. Mortensen. 1997. "Site-Specific Weed Management: Current and Future Directions," in F. Pierce, and E. Sadler, eds., *The State of Site-Specific Management in Agriculture*. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Jolly, R., W. Edwards, and D. Ehrbach. 1983. "An Economic Analysis of Conservation Tillage in Iowa," *Journal of Soil and Water Conservation*. 38: pp. 291-4.

Jordan, J., and A. Elnagheeb. 1993. "Willingness to Pay for Improvements in Drinking Water Quality," *Water Resources Research*. 29: pp. 237-45.

Kitchen, N., D. Hughes, K. Sudduth, and S. Birrell. 1995. "Comparison of Variable Rate to Single Rate Nitrogen Fertilizer Application: Corn Production and Residual NO3-N," in P. Robert, R. Rust, and W. Larson, eds., *Site-Specific Management for Agricultural Systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Klemme, R. 1985. "A Stochastic Dominance Comparison of Reduced Tillage Systems in Corn and Soybean Production Under Risk," *American Journal of Agricultural Economics*. 67: pp. 550-7.

Kohls, C. 1996. "Costs of Precision: Here's a Sampling of Equipment Costs to Aid in Your Precision Planning," *Farm Chemicals*. 159(4): pp. 21-6.

Kovach, J., and J. Tette. 1988. "A Survey of the Use of IPM by New York Apple Producers," *Agricultural Ecosystems and Environment*. 20: pp. 101-8.

Krause, M., and J. Black. 1995. "Optimal Adoption Strategies for No-till Technology in Michigan," *Review of Agricultural Economics*. 17: pp. 299-310.

Ladewig, H., and R. Garibay. 1983. "Reasons Why Ohio Farmers Decide For or Against Conservation Tillage," *Journal of Soil and Water Conservation*. pp. 487-88.

Lamb, F. 1996. Cropix, Inc. Irrigon, Oregon (personal communication).

Leopold Center for Sustainable Agriculture. 1996. Progress Report: Summaries of 15 Research and Education Projects. Ames, IA: Iowa State University Press.

Lin, B., H. Taylor, H. Delvo, and L. Bull. 1993. "Factors Influencing Herbicide Use in Corn Production," *Agricultural Resources: Inputs, Situation and Outlook Report*. AER-32. U.S. Dept. Agr., Econ. Res. Serv.

Lowenborg-DeBoer, J. 1996 "Value of Yield Monitors to Farm Managers in Indiana," Special Report, <@griculture Online, @gInnovator online at http://www.agri-culture.com/contents/aginn/sr04pur6.html>.

Lowenborg-DeBoer, J., and S. Swinton. 1995. "Economics of Site-Specific Management in Agronomic Crops," Staff Paper 95-14. Department of Agricultural Economics, Purdue University, West Lafayette, IN.

Luna, J., V. Allen, J. Fontenot, L. Daniels, D. Vaughan, S. Hagood, D. Taylor, and C. Laub. 1994. "Whole Farm Systems Research: An Integrated Crop and Livestock Systems Comparison Study," *American Journal of Alternative Agriculture*. 9: pp. 57-63.

Lynch, S., C. Greene, and C. Kramer-LeBlanc, editors. 1997. *Proceedings of the Third National IPM Symposium/Workshop*. Miscellaneous Publication 1542. U.S. Dept. Agr., Econ. Res. Serv.

Magleby, R., C. Sandretto, W. Crosswhite, and C. Osborn. 1995. *Soil Erosion and Conservation in the United States*. AER-718. U.S. Dept. Agr., Econ. Res. Serv.

Manchester, A., and J. Allshouse. 1997. *U.S. Food Expenditures*. Data Product ERS-91003. U.S. Dept. Agr., Econ. Res. Serv.

Martin, M., M. Schreiber, J. Riepe, and J. Bahr. 1991. "The Economics of Alternative Tillage Systems, Crop Rotations, and Herbicide Use on Three Representative East-Central Corn Belt Farms," *Weed Science*. 39: pp. 299-307.

McGrath D., J. Ellington, and A. Leedahl. 1990. *Variable application rates based on soil organic matter*. Pap. Amer. Soc. Agric. Eng. Winter 1990. Paper 901598. St. Joseph, Mich.: Amer. Soc. Agric. Eng.

McGrath, D., A. Skotnikov, and V. Bobrov. 1995. "A Site-Specific Expert System with Supporting Equipment for Crop Management, in P. Robert, R. Rust, and W. Larson, eds., *Site-Specific Management for Agricultural Systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

McNamara, K., M. Wetzstein, and G. Douce. 1991. "Factors Affecting Peanut Producer Adoption of Integrated Pest Management," *Review of Agricultural Economics*. 13: pp. 129-39.

Meadows, D.H., D.L. Meadows, J. Randers, and W. Behrens III. 1972. *The Limits to Growth*. New York: Universe Books.

Moran, M., Y. Inoue, and E. Barnes. 1997. "Opportunities and Limitations for Image-Based Remote Sensing in Precision Crop Management," *Remote Sensing of Environment*. 61: pp. 319-XX.

Morgan, M., and D. Ess. 1996. "Sensors for Tomorrow's Precision Agriculture," in *New Trends in Farm Machinery Development and Agriculture*. SAE Special Publication, SP-1194, SAE.

Murcott, S. 1997. "Sustainable Systems: Definitions, Principles, Criteria, and Indicators." Paper presented at the 1997 American Association for the Advancement of Science, Seattle, Washington.

National Agricultural Pesticide Impact Assessment Program. "Biological and Economic Assessment of Pesticide Use on Corn and Soybeans," NAPIAP Report No. 1-CA-95.

National Research Council. 1989. *Alternative Agriculture*. Washington, DC: National Academy Press.

__________. 1991a. *Mitigating Losses from Land Subsidence in the United States*. Washington, DC: National Academy Press.

__________. 1991b. *Sustainable Agriculture Research and Education in the Field, A Proceedings*. Washington, DC: National Academy Press.

__________. 1993. *Soil and Water Quality: An Agenda for Agriculture*. Washington, DC: National Academy Press.

__________. 1995. *The Global Positioning System: A Shared National Asset, Recommendations for Technical Improvements and Enhancements*. Washington, DC: National Academy Press.

__________. 1996. *Ecologically Based Pest Management: New Solutions for A New Century*. Washington, DC: National Academy Press.

__________. 1997. *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management.* Washington, DC: National Academy Press.

Nelson, D., and D. Huber. 1987. "Nitrification Inhibitors for Corn Production," National Corn Handbook 55. Purdue University Cooperative Extension Service.

Nielsen, E., and L. Lee. 1987. *The Magnitude and Costs of Groundwater Contamination from Agricultural Chemicals*. AER-576. U.S. Dept. Agr., Econ. Res. Serv.

Nordhaus, W. 1992. "Lethal Model 2: The Limits to Growth Revisited," in W. Brainard and G. Perry, eds., *Brookings Papers on Economic Activity 2,* Washington, DC: Brookings Institution.

Northwest Area Foundation. 1994. *A Better Row to Hoe: The Economic, Environmental, and Social Impact of Sustainable Agriculture*. Minneapolis, MN.

Office of Technology Assessment. 1995. *Challenges for U.S. Agricultural Research Policy*. Report OTA-ENV-639. Washington, DC: Government Printing Office.

Ogg, C. 1995. "Roles for Site-Specific Research in U.S. Pollution Prevention Initiatives," in P. Robert, R. Rust, and W. Larson, eds., *Site-Specific Management for Agricultural Systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Olmstead, A., and P. Rhode. 1993. "Induced Innovation and American Agriculture: A Reconsideration," *Journal of Political Economy*. 101: pp. 100-18.

Osborn, C., and K. Konyar. 1990. *A Fresh Look at the CRP*. AO-166. U.S. Dept. Agr., Econ. Res. Serv.

Pimentel D., and M. Giampietro. 1994. "Food, Land, Population and the U.S. Economy." <http://dieoff.org/page40.htm>.

President's Council on Sustainable Development. 1996. *Sustainable America: A New Consensus*. Washington, DC: Government Printing Office.

Rahm, M., and W. Huffman. 1984. "The Adoption of Reduced Tillage: The Role of Human Capital and Other Variables," *American Journal of Agricultural Economics*. 66: pp. 405-13.

Rhoades, F. 1991. "Nitrogen or Water Stress: Their Interrelationships," *Managing Nitrogen for Groundwater Quality and Farm Profitability*. Madison, WI: Soil Science Society of America.

Ribaudo, M. 1989. *Water Quality Benefits from the Conservation Reserve Program*. AER-606. U.S. Dept. Agr., Econ. Res. Serv.

Scharf, P., and M. Alley. 1988. "Nitrogen Loss Pathways and Nitrogen Loss Inhibitors: A Review," *Journal of Fertilizer Issues*. 5 (Oct.-Dec.).

Shortle, J., W. Musser, W. Huang, B. Roach, K. Kreahling, D. Beegle, and R. Fox. 1993. *Economics of Environmental Potential of the Pre-side-dressing Soil Nitrate Test*. Final Report to the Environmental Protection Agency. The Department of Agricultural Economics and Rural Sociology, The Pennsylvania State University.

Simon, J., G. Weinrauch, and S. Moore. 1994. "The Reserves of Extracted Resources: Historical Data," *Non-Renewable Resources*, pp. 325-40.

Smith, V. 1992. "Environmental Costing for Agriculture: Will It Be Standard Fare in the Farm Bill of 2000?" *American Journal of Agricultural Economics*. 74: pp. 1076-88.

Solow, R. 1992. "An Almost Practical Step Toward Sustainability," *Resources Policy*. 19(3): pp. 162-72.

Sudduth, K., S. Borgelt, S. Birrell, and N. Kitchen. 1994. "Within-Field Location and Sensing Technology," ACSM/ASPRS Annual Convention & Exposition. Baltimore: ACSM/ASPRS. 1: pp. 624-33.

Sun, H., J. Bergstrom, and J. Dorfman. 1992. "Estimating the Benefits of Groundwater Contamination Control," *Southern Journal of Agricultural Economics*. 24: pp. 63-71.

U.S. Department of Agriculture. 1989. *The Second RCA Appraisal: Soil, Water, and Related Resources on Nonfederal Land in the United States, Analysis of Conditions and Trends*. Miscellaneous Publication 1482.

___________, Agricultural Research Service. 1993. "USDA Programs Related to Integrated Pest Management," USDA Program Aid 1506, Washington, DC.

___________, Economic Research Service. 1994. *Agricultural Resources and Environmental Indicators*. AH-705.

___________, Economic Research Service. 1997. *Agricultural Resources and Environmental Indicators, 1996-97*. AH-712.

___________, National Agricultural Statistics Service. 1997. *Historic Data Information*. <http://www.usda.gov/nass/pubs/histdata.htm>.

___________, Sustainable Agriculture Research and Education Program. 1995. *SARE 1995 Project Highlights*.

U.S. Environmental Protection Agency (USEPA). <http://www.epa.gov./25year/water/water.html>.

___________, Office of Water. 1998. *National Water Quality Inventory: 1996 Report to Congress*.

U.S. Geological Survey (USGS), U.S. Dept. of the Interior. 1985. *National Water Summary 1984-Hydrological Events Selected Water-Quality Trends and Ground-Water Resources*. Water-Supply Paper 2275.

___________. 1995. *Water-Level Changes in the High Plains Aquifer, Predevelopment to 1994*. <http://water.usgs.gov/public/wid/FS_215-95/FS_215-95.html>.

Usery, E., S. Pocknee, and B. Boydell. 1995. "Precision Farming Data Management Using Geographical Information Systems," *Photogrammetric Engineering & Remote Sensing*. 61: pp. 1383-91.

Vandeman, A., J. Fernandez-Cornejo, S. Jans, and B. Lin. 1994. *Adoption of Integrated Pest Management in U.S. Agriculture*. AIB-707. U.S. Dept. Agr., Econ. Res. Serv.

Vasavada, U., J. Hrubovcak, and J. Aldy. 1997. "Incentives for Sustainable Agriculture," *Agricultural Outlook*. AO-238. March: pp. 21-4.

Vetsch, J., G. Malzer, P. Robert, and D. Huggins. 1995. "Nitrogen Specific Management by Soil Condition: Managing Fertilizer Nitrogen in Corn," in P. Robert, R. Rust, and W. Larson, eds., *Site-Specific Management for Agricultural Systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Vision News. 1996. "Agronomist predicts geo-referencing will change business of agriculture," volume 2 (Spring). Rockwell Agricultural Systems, Cedar Rapids, IA. 12 pp.

Weitzman, M. 1997. "Sustainability and Technical Progress," *Scandinavian Journal of Economics*. 99(1), pp. 1-13.

Whipker, L., and J. Akridge. 1996. "Precision Ag and Your Customer Base," *Farm Chemicals*. 159: pp. 12-14.

Williams, J. 1988. "A Stochastic Dominance Analysis of Tillage and Crop Insurance Practices in a Semi-arid Region," *American Journal of Agricultural Economics*. 70: pp. 112-20.

Williams, J., R. Llewelyn, and G. Barnaby. 1990. "Risk Analysis of Tillage Alternatives with Government Programs," *American Journal of Agricultural Economics*. 1: pp. 172-81.

Williams, J., R. Llewelyn, and C. Mikesell. 1989. "An Economic Risk Analysis of Conservation Tillage Systems for Wheat, Grain Sorghum, and Soybeans in the Great Plains," *Journal of Soil and Water Conservation*. 44: pp. 234-9.

World Commission on Environment and Development. 1987. *Our Common Future*. Oxford: Oxford University Press.

Young, D., T. Kwon, and F. Young. 1993. "Profit and Risk for Integrated Conservation Farming Systems in the Palouse," Washington State University, Unpublished paper, June.

Appendix 1—Farm Level Case Studies on Profitability-Environment Tradeoffs

There are many sustainable agriculture success stories. Typically, these stories detail how shifting from a conventional to an alternative production system can provide economic and environmental benefits. Several institutions have developed research programs in sustainable agriculture. In general, these institutions have targeted research projects that would otherwise be ignored by traditional institutions of agricultural research. We review some case study evidence on economic and environmental trade-offs developed by these institutions below.

National Research Council Interviews with Sustainable Farm Operators

The National Research Council conducted interviews with farm operators who adopted sustainable production practices. Anecdotal evidence obtained from those interviewed was then collated and published (National Research Council, 1989). We abstract some examples of National Research Council interviews below.

The Spray brothers' 720-acre Ohio farm includes 400 acres of cropland: 100 acres of corn, 88 acres of soybeans, 12 acres of adzuki beans, 100 acres of wheat and oats, and 100 acres of red clover, some of which receives premium prices as seed. The farm controls weeds with rotations, frequent cultivation, and by hand. Over half of the corn is fed to 32 dairy cows and 40 to 50 head of beef cattle. The farm does not participate in the feed grain program, but receives premium prices for oats, soybeans, and adzuki beans from health food stores because of its organic certification. No lime, fertilizer, or pesticides have been purchased since 1971.

The Kutztown farm in eastern Pennsylvania is 305 acres, with slopes reaching 25 percent. The farm finishes 250 to 290 beef cattle and 50 to 250 hogs, annually. Except for a small amount of starter fertilizer, fertilizer needs are satisfied with the livestock manure. The farm controls weeds with cultivation and crop rotation, with occasional herbicide applications on about half of the acreage. Most of the fields are contour-farmed in strips 100 to 200 feet wide. Although erosion exceeds the level needed for soil replacement, it is below the State average.

The Rodale Institute

The Rodale Institute began one of the earliest long-term studies in 1981 for examining the process of converting to low-input cropping systems (National Research Council, 1991b). The Institute compared a conventional rotation of corn and soybeans using typical levels of purchased inputs with two low-input systems. One of the alternative systems incorporated a 5-year rotation of corn, soybeans, small grains, legume hay and corn silage combined with cattle, and the other included a low-input cash grain system. During the transition period of 1981-84, a change in the equilibrium between plant growth and soil microorganisms was manifested in lower corn yields for both alternative systems. All systems have had similar yields since that time.

The Institute also found a higher level of microbiological activity and more microarthropods in the alternative systems, and attributed these to the variety of crops in the rotation, rather than simply the absence of pesticides (National Research Council, 1991b). A comparison of 9 years of data revealed that the cash grain rotation would have earned about 8 percent more profits than the conventional system, in the absence of government support payments. In addition, larger profits were subject to less annual variation.

Northwest Area Foundation

The Northwest Area Foundation (1994) reported on a 6-year $4.5-million research project it funded to investigate the economic, environmental, and social impacts of sustainable agricultural systems in seven States. The report characterizes sustainable farms as: more diversified in crops and livestock than conventional farms; maintaining soil productivity with soil-building crop rotations, nutrient cycling, and tillage practices; and using a greater amount of labor, but in ways that spread it out over the year. Sustainable farms had fewer assets, although they tended to own more of their land. As a group, they tended to be less competitive than conventional farms, but the upper one-third performed competitively with conventional farms. Management appears to be the key to being competitive. Sustainable farmers were also younger than their conventional counterparts and adopted sustainable practices early in their careers, suggesting that education may encourage sustainable farming.

The Leopold Center

The Leopold Center funds studies on the feasibility and effectiveness of new resource management techniques for cattle and crops. Most of the studies are focused on specific aspects of the farm, rather than the total farm. The Center has funded research on the scale of swine operations in a loose housing arrangement, rotational grazing on highly erodible land, a simulation model of farm decisionmaking, manure management, reaction of a desired predator to a natural fertilizer, and educational videos about managed grazing. Some of the findings of these studies are: 1) small swine farmers can be more competitive with larger producers by using a computerized feeding, loose housing operation; 2) paddocks for cattle and interseeding grassy pastures are feasible alternatives to row cropping on land after removal from the Conservation Reserve Program (CRP); 3) late spring testing of soil, corn stalks, and manure provides more accurate information on the needs of crops at crucial times; 4) manure management reduces fertilizer costs; and 5) urea and fresh manure inhibit the effectiveness of biological control agents on black cutworms (Leopold Center for Sustainable Agriculture, 1996).

Long-Term Trials

Long-term crop trials attempt to measure the effect of selected treatments on a small number of variables such as crop yield or profitability. Chase and Duffy (1991) reported on a 12-year comparison of crop rotations carried out at the Northeast Research Center of Iowa State University. The three rotations were continuous corn (C-C), corn-soybeans (C-Sb), and corn-oats-meadow (C-O-M). Chase and Duffy noted that monoculture and limited rotations are viewed as increasing soil erosion and reducing soil productivity that must be made up by increases in fertilization. Conventional pesticide and fertilizer applications were made on the C-C and C-Sb rotations. For the C-O-M system, manure was used as the nutrient source and pesticides were applied only as pests exceeded threshold levels, as determined by the farm manager. The meadow was an alfalfa hay with oats as a companion crop. The alfalfa was harvested in the year after the oats and was plowed under after the last cutting in preparation for the following year's corn crop. Labor costs were the highest for the C-O-M rotation because labor was used as a substitute for machinery, chemicals, and other nonfarm inputs. Excluding labor, the C-O-M rotation had average production costs of $96 per acre, compared with $159 per acre for C-Sb and $207 per acre for C-C. Returns to land, labor, and management were similar for the C-C rotation and the C-O-M rotation, but nearly 60 percent higher for the C-Sb rotation. No assessment of the effects on environmental quality was made, but appropriate pricing of reduced chemical residues would raise the relative return to C-O-M.

Luna and others (1994) reported on a systems-wide trial begun in 1987 by a team of seven researchers representing six departments at Virginia Polytechnic Institute and State University, intended to last 10 years. The object was to compare a crop-livestock system using integrated pest management (IPM) with an alternative system intended to maintain or improve profitability and soil productivity while reducing soil erosion and chemical use. Preliminary conclusions suggest that similar levels of productivity can be achieved on both systems, and the need for nitrogen fertilizer and pesticides can be decreased by using managed grazing and an alfalfa rotation. Manure from feeding of corn silage provides most of the nutrients for the following year's corn crop. Luna and others noted it is difficult to draw inferences that can be extended much beyond the specific systems compared, and even those inferences are location specific as well. Furthermore, it is difficult to assign cause and effect in such trials because many factors are operating simultaneously and over time.

In the livestock sector, operators have also employed more environmentally benign practices. Rotational grazing, for example, involves managing livestock on a series of pastures. Farmers effectively rotate herds across this series of pastures through the year to maximize profits. A key component to the success of rotational grazing is the planting of forage crops that mature at different times through the year. This allows for farmers to rotate their herds to pastures with sufficient forage throughout the year. Both dairy and beef cattle farmers have used rotational grazing.

Through rotational grazing, some farmers have gained significant cost savings by reducing the amount of supplemental feed necessary for their herds. By moving herds to fields with forage at its optimal growth stage, farmers can ensure their herds consume both high-quality and high-quantity forage. In some cases, dairy cattle have been found to graze 50 percent more forage on productive fields than expected. In addition, rotational grazing can decrease labor requirements for herd management. These economic benefits have yielded substantial profit increases for dairy farmers in Vermont and South Carolina and beef farmers in Iowa.

A well-managed rotational pasture system allows a farmer to substitute natural resource inputs (forage) for capital inputs (feed). Given that the farmer moves the herd from field to field, this substitution is sustainable because grazing does not exceed a field's rate of regrowth. Several researchers have experimented with rotational grazing as an alternative to row crop agriculture on environmentally sensitive lands covered by soon-to-expire Conservation Reserve Program (CRP) contracts. They have found that rotational grazing ensures soil cover and yields, and in some locations, greater profits than row crops. In these cases, CRP land can return to active agricultural productivity without losing the environmental benefits associated with the program (USDA, Sustainable Agriculture Research and Education Program, 1995). Similar economic considerations apply for explaining the barriers to the adoption and availability of more environmentally benign production practices in the livestock sector.

The literature reviewed above indicates there may be some potential for achieving sustainability goals by increasing the availability of green technologies. This, however, may be easier said than done because the success of these technologies on a particular farm may not be easily replicated to all farm resource situations. Significant impediments may exist in replicating the success of a particular technology on a large scale.

Appendix 2—Workshop on the Economics of Sustainable Agriculture

The workshop "Economics of Sustainable Agriculture" was held in Washington, DC, on October 21-22, 1996. USDA's Economic Research Service/Resource Economics Division (ERS/RED) and the Farm Foundation co-sponsored this workshop.

Workshop Goals

The goals of this workshop were:

- to solicit input on the complex issue of sustainable agriculture from a diverse group of individuals including farmers, public interest groups, academic and government economists, and former and current policymakers within the government.

- to present a preliminary draft of the Resource Economics Division's sustainability research report and to invite critical feedback on improving this report.

A broad cross section of stakeholders was invited to this workshop, including farmers (both conventional and sustainable), public interest groups, academic and government economists, and policymakers in government. A list of participants attending this workshop is provided below.

Policy Recommendations

Are existing policy instruments adequate to steer agriculture along a more sustainable path of economic development? The workshop considered this question and sought to identify policies that could effectively steer agriculture in a more sustainable direction.

Some of these ideas are extensions of ideas reflected in the 1996 Farm Bill. For example, the idea of program flexibility was determined to be critical in program implementation. The idea of flexibility is clearly evident in the Environmental Quality Incentives Program (EQIP) and Wildlife Habitat Incentives Program (WHIP). Under EQIP and WHIP, USDA's Natural Resources Conservation Service (NRCS) has leadership for the program. To advise NRCS, local conservation districts will convene local work groups, comprised of the districts, NRCS, USDA's Farm Service Agency (FSA), FSA county committees, USDA's Cooperative State, Research, Education, and Extension Service, tribes, and others interested in natural resource conservation.

Other ideas presented at the workshop include the following:

Policy goals for a more sustainable agriculture must be well articulated. The sustainable agriculture community, and others involved in policy design, must provide well-defined goals to be achieved to move along a more sustainable path of economic development. Achievement of goals should be defined in terms of outputs and not inputs. For example, achievements should be measured in terms of soil erosion reduced or improvements in surface- and groundwater quality, and not be the number of farmers that adopt conservation tillage or IPM.

Flexibility in implementing Federal programs is essential because of the diversity of our natural resource base and the need to target specific issues related to sustainability. For example, for farmers with shallow soils, wind erosion may be a significant obstacle to sustainability in the Northern Plains while sheet and rill erosion pose a more serious threat to sustainability in the Corn Belt. A "one size fits all" approach to sustainability will not work because there is a need to customize programs to match local needs. The 1996 Farm Bill approach, which allowed greater planting flexibility to farmers, is an appropriate model to tailor future sustainability programs. The Swampbuster provisions of the 1996 Farm Bill also made it easier for landowners to mitigate wetland conversions by restoring other wetlands.

In addition to allowing local flexibility in targeting issues related to sustainability, policies must also allow for flexibility in solving problems. There is a role for the government to make more sustainable technologies available, but the government should not prescribe specific technologies to achieve sustainability. Prescribing specific technologies does not provide adequate incentives to develop or adopt less costly alternatives.

Identifying the limits to adoption and implementation of alternative technologies is also critical in implementing policy. It is important to determine if the adoption and implementation of a practice is limited by farm size, labor availability, access to credit, access to information (structure); geography (resource heterogeneity); economic efficiency (profits, risk); or if the private benefits from implementation are significantly different from the social benefits from implementation (lack of markets).

Market development for more environmentally friendly crops is also a key to moving toward a more sustainable agriculture. The creation of organic standards is an example of market development. By developing markets, especially for high-value products, producers who use sustainable production practices can obtain a premium for choosing to exercise environmental stewardship.

The government should provide insurance as a way to encourage the adoption of sustainable practices. Impeding adoption of more sustainable practices is the risk associated with switching from the time-tested conventional mode of production. Further analysis of the feasibility of providing insurance against such risks is needed.

Access to credit can also impede adoption of sustainable production practices. To encourage adoption, policy can be restructured so that farmers who wish to adopt can finance the costs of switching to a new technology regime.

Rural development policies should focus on mitigating the shock of changing economic and social realities. Rather than attempting to isolate rural communities from change, such policies should ease the pain of rural adjustment due to changing economic and social realities.

Research and development should focus on the problems faced by producers who adopt sustainable technologies. Greater emphasis should be placed on interdisciplinary research and on evaluating the tradeoffs between environmental quality and profitability for both conventional and sustainable technologies. It is also imperative that researchers focus on tightening the definition of "sustainable" technologies.

List of Workshop Participants

Academic Economists:
Darrell Bosch, Virginia Polytechnic Institute and State University
George Frisvold, University of Arizona
Randall Kramer, Duke University
Timothy Phipps, West Virginia University
John Reilly, Massachusetts Institute of Technology
Vernon Ruttan, University of Minnesota
Kathleen Segerson, University of Connecticut
James Shortle, The Pennsylvania State University
David Sunding, University of California
David Zilberman, University of California-Berkeley

Environmental and Non-Profit Organizations:
Norman Berg, Soil and Water Conservation Society
Pierre Crosson, Resources for the Future
David Ervin, Henry Wallace Institute of Alternative Agriculture
Ferd Hoefner, Sustainable Agriculture Coalition
Robbin Marks, Natural Resources Defense Council
Megan Moynihan, W.K. Kellogg Foundation

Industry:
Thomas Gilding, American Crop Protection Association
Janis McFarland, Ciba-Geigy, Inc.

Farmers:
Varel Bailey, Bailey Farms, Inc.
Fred Kirschenman, Kirschenman Farms, Inc.
William Richards, Richards Farms, Inc.
Thomas Trantham, Trantham Farms, Inc.

Government:
Mary Ahearn, USDA/ERS
William Anderson, USDA/ERS
Joe Aldy, Council of Economic Advisors
Margot Anderson, USDA/Office of Chief Economist
Linda Calvin,USDA/ERS
Jorge Fernandez-Cornejo, USDA/ERS
Ralph Heimlich, USDA/ERS
Robert House, USDA/ERS
James Hrubovcak, USDA/ERS
Wen Huang, USDA/ERS
Bengt Hyberg, USDA/Natural Resources Conservation Service
Carol Kramer-LeBlanc, USDA/Center for Nutrition Policy and Promotion
Barbara Meister, USDA/Research, Education, and Economics
Parveen Setia, USDA/Office of Civil Rights
Robbin Shoemaker, USDA/ERS
Utpal Vasavada, USDA/ERS