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The role of technology in sustaining agriculture and the environment[1]

Joseph E. Aldy, James Hrubovcak, Utpal Vasavada *

Natural Resources and Environment Division, Economic Research Service, Washington DC 20005, USA

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Abstract

Visions of sustainable development often leave unanswered the question: What actions taken by the current generation will ensure that future generations can meet their economic and environmental needs? In this context, we assess the role of technology in steering agriculture along a more sustainable path. From the agricultural sector's perspective, this requires an optimal investment plan for a nation's stock of environmental assets that accounts for an intergenerational fulfillment of sustainability's dual goals: (1) satisfying food and fiber needs at reasonable costs to consumers; and (2) providing environmental service flows. In reviewing agricultural indicators to assess the nation's performance in meeting these goals, we find productivity growth has increased while rates of soil erosion, wetland conversion, and pesticide application have declined. However, individuals continue to demand more environmental services while private markets undersupply environmental services. The capacity of the agricultural sector to meet food and fiber and environmental service demands partially depends on the availability and adoption of new technology. Several market impediments explain the undersupply of sustainable technologies: (1) firms cannot fully appropriate rents from technology development; (2) success may vary with farm structure; (3) the heterogeneity of the resource base influences adoption; and (4) farmers cannot capture the benefits of environmental services. To address these market failures, sustainable agriculture policy should: (1) support research and development in sustainable technologies and provide incentives to encourage adoption; (2) ensure that conservation efforts reflect the efficient and sustainable allocation of environmental assets; and (3) legitimize markets for foods produced under more sustainable practices. © 1998 Elsevier Science B.V. All rights reserved.

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* Corresponding author. Present address: Economic Research Service, 1800 M. St., N.W., Washington, DC 20036, USA.

[1] The views of this paper do not necessarily represent those of the US Department of Agriculture.

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1. The role of technology in sustaining agriculture and the environment

A decade ago, the Brundtland Commission defined sustainable development as “meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on the Environment and Development, 1987 pp.8). Since that time, numerous attempts to operationalize this vision of sustainable development have been made. Some of this research has offered sets of sustainability indicators (Ayres, 1996), others have incorporated the environment into national income accounts (Solow, 1993; Hrubovcak et al., 1995; Repetto et al., 1989; Lutz and El Serafy, 1988) and still others have turned to assessing sustainability based on ecosystem resilience (Arrow et al., 1995).

The Brundtland Commission also called on governing institutions to better address sustainable development issues. To do so, a government must ask: What actions taken by the current generation will ensure that all future generations can meet their economic and environmental needs? Ostensibly, a sustainable development strategy would ensure that “...the present generation must leave the future with the wherewithal—the ‘social capital’ consisting of human, natural, and physical capital—to create the kind of life or a life of at least equal quality to ours” (Economic Report of the President, 1994 pp.188).

Public policy can play a positive role to steer an economy along a sustainable path of economic development. Specifically, public policy can ensure that society bequeaths an adequate endowment of environmental, human, and physical capital to posterity. As an implicit recognition of this vital role for public policy, a recent report pronounced that “our nation will protect its environment, its natural resource base, and the functions and viability of natural systems on which all life depends” (President’s Council on Sustainable Development, 1996, p. iv). Protecting natural resource and environmental asset endowments subsumes the broader strategy of bequeathing social capital in its diverse forms.

Some interesting questions follow from these broad vision statements about sustainability. Specifically, how does a general, economy-wide, vision apply to a single sector, such as agriculture? Which impediments to a freely functioning market economy can explain failure of the agricultural sector to move on a sustainable path of economic development? Which policies will steer the agricultural sector in a more sustainable direction? These three questions provide a natural foundation for analyzing the sustainability of US agriculture.

The plan of our paper follows. Section 2 casts the sustainability problem as one of optimally investing in diverse forms of capital. This optimal investment plan should achieve the dual goals of satisfying food and fiber needs at reasonable costs to consumers and of providing environmental services. Section 3 examines trends in natural resource and environmental capital use associated with US agricultural production. The availability of these assets relative to the future demand for food and fiber and environmental services is key to attaining sustainability. Section 4 assesses the potential of the US agricultural production sector in fulfilling the demand for food and fiber and environmental services. We also examine the potential role of green technologies as a panacea for satisfying these demands. This ‘technological quick fix’ in turn is linked to the supply and adoption of green technologies. We draw conclusions on policy implications in Section 5.

2. Investing in a more sustainable agriculture

A simple circular flow diagram powerfully illustrates the broad concept of sustainability (Fig. 1). The diagram divides the economy into stocks/endowments (physical capital and labor), and intermediate economic processes/technologies (agriculture, manufacturing, services) which are used to produce final goods and services (clothing, food, recreation), and savings/investment (changes in the stock of endowments over time). Returns to endowments (income) equal the value of consumption of final goods and services plus the value of net investment. Investment in physical capital and labor reduces current consumption of goods and services, although future consumption can increase.[2]

To account for sustainability, this economic framework must include the services provided by the environment and correct for the asymmetric treatment of natural capital and reproducible physical capital. Following the prescription of Solow (1993), we adjust our current economic framework by casting the environment as a set of natural capital assets (air quality, biodiversity, etc.). These natural capital assets provide flows of goods and services to economic processes (water for hydropower/commercial fishing) as well as consumers (birds to watch, landscape to view, etc.).[3]

Similar to our existing framework, the use of natural endowments should result in feedback effects. The depletion of stocks of natural endowments increases current consumption of goods and services. However, future consumption of goods and services can be lower if net investment in stocks is negative.[4]

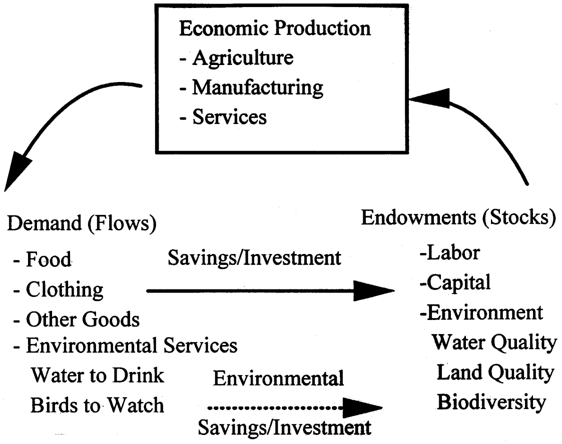

Fig. 1. Flow diagram with sustainability.

How does the general, economy-wide, concept of sustainability apply to a specific sector, such as agriculture? A formal definition of agricultural sustainability developed by the US Congress in the 1990 Farm Bill provides a context for examining this issue. Specifically, sustainable agriculture is an:

> "...integrated system of plant and animal production practices having a site specific application that will, over the long term: (a) satisfy human food and fiber needs; (b) enhance environmental quality; (c) make efficient use of non-renewable resources and on-farm resources and integrate appropriate natural biological cycles and controls; (d) sustain the economic viability of farm operations; and (e) enhance the quality of life for farmers and society as a whole" (Public Law 101–624, Title XVI, Subtitle A, Section 1603).

According to this definition, a sustainable system of agricultural production contributes to satisfying human food and fiber needs *and* generates environmental service flows. The Congressional perspective legitimizes the role of stewardship in formulating an optimal investment plan for a nation's stock of environmental and natural resource assets. The end goals of such an investment plan would be the intergenerational fulfillment of food and fiber needs and provision of environmental services.

It is important to note that the Congressional definition is unclear on two points. First, since supply always equals demand, food and fiber needs are always met in this sense. The crucial issue is at what market clearing price does supply equal demand? A sustainable path of economic development should ensure that food and fiber needs of a growing population are met at a reasonable cost to consumers. Second, a sustainable investment plan for environmental and natural resource assets must recognize that provision of additional environmental services entails an economic cost. Proper stewardship of environmental and natural resource assets must be based on an evaluation of the economic costs of providing these services and on providing compensation for any diminution in environmental service flows.

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[2] Future consumption levels depend on enhancements to stocks net of depreciation.

[3] As Harte (1995) points out, the natural capital concept has received significant support in sustainable development literature.

[4] Similar to reproducible capital, the current use of natural capital does not imply future consumption will be necessarily less than current consumption. In addition to current use, the rate of regeneration of stocks and depreciation will determine net investment.

3. The demand for environmental goods and services

How well has US agriculture performed in meeting the test of sustainability? To answer this question, we identify a set of environmental goods and services that are commonly associated with a more sustainable agriculture. Then, we review trends in their use and assess the economic demand for these goods and services. A review of trends in the use of these goods and services draws from Ayres' (1996) sustainability measures approach to develop a set of indicators of the sustainability of US agricultural production. To assess the demand for the environmental outputs of agriculture, we summarize the economic evidence from market data, the recreation demand literature, and the contingent valuation literature.

Agricultural production generates a set of outputs. These outputs include two major subsets: food and fiber outputs and environmental outputs. For US agriculture to achieve sustainability, production must balance availability of these two kinds of outputs to maximize social welfare. To determine the composition of the environmental set, we reviewed federal laws that address the environmental outputs of agriculture.[5] Inclusion to this set requires that federal laws target the environmental good or service for conservation or protection. Based on this criterion, we developed the following set of environmental indicators: surface water quality, ground water quality, ground water quantity, wetlands, and food safety.[6]

3.1. Surface water quality

Nonpoint source pollution from agricultural production can affect the quality of the nation's surface waters. According to the Environmental Protection Agency (USEPA, 1995), agriculture is the leading source of impairment in rivers (70%), lakes (affecting 50% of impaired lake acres, not including the Great Lakes), and the third leading source of impairment of estuaries (34%). Agriculture may serve as a significant cause of the overall decline in the quality of lakes and rivers (Fig.

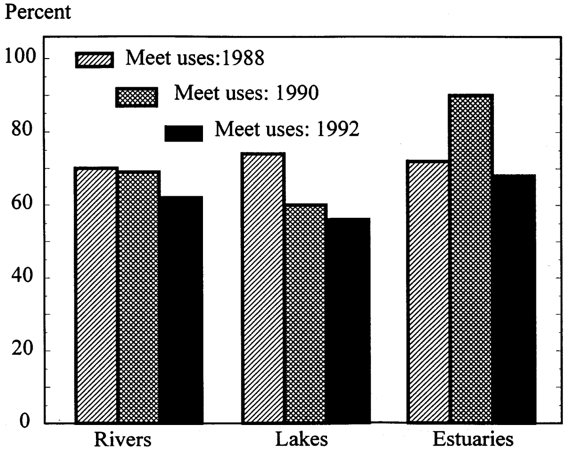

Fig. 2. Surface water quality: 1988, 1990, 1992. Source: USEPA (1995).

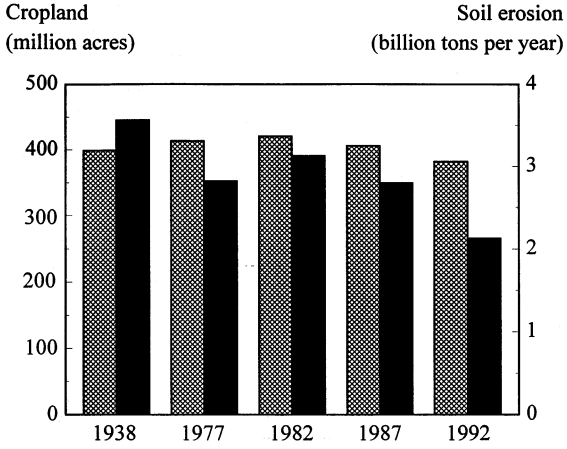

Fig. 3. Cropland stable but soil erosion declining. Source: Magleby et al. (1995).

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[5] Given the public good characteristics of most environmental goods and services, we assume that modern environmental and conservation law reflects, albeit imperfectly, the public's demand for environmental outputs and the failure of private markets to supply these outputs.

[6] In addition, surface water quantity is an important issue. Postel et al. (1996) and Gleick (1993) provide surveys of this issue. Data limitations prevent us from developing an accurate indicator of the effects of agricultural production on water quantity.

2). The share of rivers supporting designated uses fell from 70% in 1988 to 62% in 1992 and the share of lakes meeting designated uses fell from 74% to 56%. The share of estuarine waters supporting designated uses have fluctuated from 72% in 1988 to 90% in 1990 to 68% in 1992 (USEPA, 1995).

Impaired surface water quality results, in part, from soil erosion of agricultural land. Fig. 3 illustrates the pattern of cropland use and soil erosion in US agricultural production. Cropland use has remained remarkably stable at about 400 million acres since 1938. On this stable cropland base, the rate of soil erosion has declined. Since 1938, soil erosion from cropland has declined by an estimated 40% (Magleby et al., 1995). Most of this decline has occurred since 1982. This deceleration in the soil erosion trend resulted primarily from the 1985 Food Security Act, which established the Conservation Reserve Program and Conservation Compliance provisions. Earlier programs assumed, due to a lack of information, that farmers failed to protect soil productivity. However, recent studies have established that soil erosion provides minor threats to on-farm productivity (Alt et al., 1989; USDA, 1989; Crosson, 1995a,b).[7] New programs place greater emphasis on the off-site effects of soil erosion and act to minimize the off-site damages to rivers, lakes, and estuaries. Given the time lag in sediment transport, the benefits of a soil erosion control program may not start accruing until some time well after the implementation of the program (National Research Council, 1993, pp. 96–97).[8]

While agriculture still contributes to water pollution, evidence from economic analyses illustrates a significant demand for improving the quality of surface waters. Several studies have found that local improvements in water quality affected by agriculture can yield significant benefits for individuals (Piper et al., 1987; Crutchfield et al., 1995). Nationally, Ribaudo and Piper (1991) found that retiring 45 million acres of farmland through the Conservation Reserve Program would result in national recreational fishing benefits from reduced sediment pollution from soil erosion of $46 million.

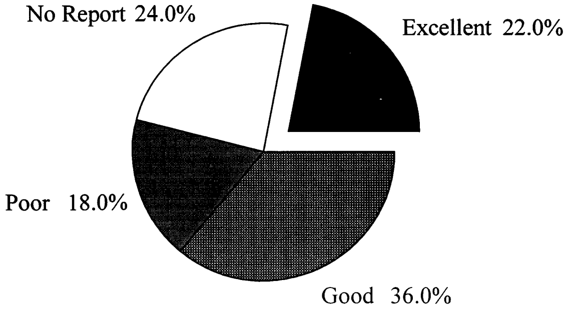

Fig. 4. Ground water quality: 1992. Source: USEPA (1993).

In addition to these recreation demand models, Carson and Mitchell (1993) conducted a contingent valuation study to assess the public's value for national water quality. They found that the mean annual willingness to pay to improve the nation's water quality from nonboatable to swimmable status is $280 per household.

3.2. Ground water quality

While the status of ground water quality in the US is not well known, of 38 States reporting overall ground water quality, 29 assessed their ground water as good or excellent (Fig. 4). 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 (Economic Research Service, 1994).

To estimate the demand for ground water quality, several researchers have conducted contingent valuation studies. Jordan and Elnagheeb (1993) 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 averaged between $120 and $148 per household for the different kinds of ground water

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[7] Refer to Pimentel et al. (1995) for an alternative perspective on soil erosion's on-farm impacts.

[8] For a survey on soil erosion, refer to Troeh et al. (1991).

users. Crutchfield et al. (1995) employed three contingent valuation studies for a benefits transfer application. They estimated household willingness to pay for ground water protection programs for four regions: central Nebraska, the lower Susquehanna basin (Pennsylvania and Maryland), the Mid-Columbia basin (Pacific Northwest), and the White River basin (Indiana), and found aggregate annual willingness to pay ranged between $197 and $730 million.

3.3. Ground water quantity

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) can provide an indication of the effect of irrigation on ground water level. This aquifer provides approximately one-third of the ground water withdrawn for agricultural irrigation in the US, and supports the agricultural activity in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (USGS, 1995). Fig. 5 illustrates the average drop in the water level of the aquifer in each of these states over two time periods. From 1940–1980, the region's average ground water level dropped 0.25 feet annually. Five of these states experienced declines in their ground water stocks while three experienced no change in their stocks over this period. From 1980–1994, the average ground water level for the high plains dropped 0.11 feet annually, with increases in ground water stocks reported in two states, and smaller annual declines reported in three other states (USGS, 1995).

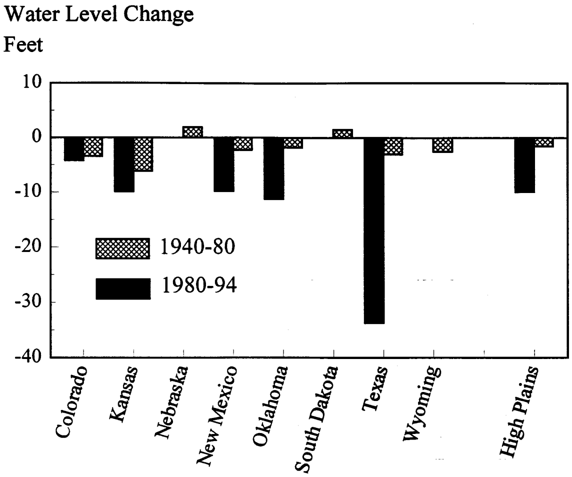

Fig. 5. Ground water quantity: change in the Ogallala, 1940–1980. Source: USGS (1995).

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

In the US, the energy costs of ground water extraction can range between $11 and $105 per acre annually, and sum in excess of $1 billion annually (Economic Research Service, 1994). However, a farmer's costs for water do not reflect the total social cost of the extraction, and therefore, their expenditures do not accurately reflect society's demand for ground water. Water suppliers treat a ground water stock as an open resource. By extracting water at a rate faster than recharge, water suppliers draw down the water level and decrease the aquifer's pressure. This requires water suppliers 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 events, with significant economic consequences (National Research Council, 1991).

3.4. Wetlands

The lower 48 states have lost almost one-half of all wetlands since 1780. Most of the original and remaining wetlands are in the Southeastern, Mississippi Delta, and Great Lake states. The Corn belt has lost nearly 90%, the Pacific states nearly 75%, and the Plains states approximately 50% of their original wetlands. However, available data suggest that while agriculture continues to contribute to wetland loss (Fig. 6), the rates of wetland loss in the 1980s are dramatically lower than

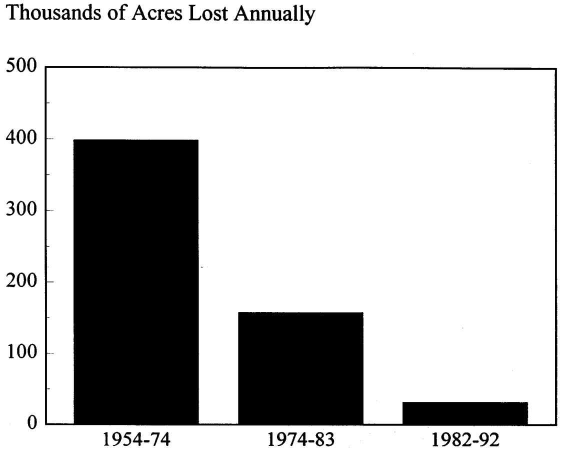

Fig. 6. Wetland losses caused by agricultural activity. Source: Natural Resources Conservation Service (1995).

in earlier decades (Natural Resources Conservation Service, 1995).

To address the economic benefits of conserving wetlands, Hoehn and Loomis (1993) assessed the demand for protection of wetlands and wildlife habitat in the San Joaquin Valley, California. The valuation of a wetlands improvement program averaged $166 per household annually.

3.5. Food safety

Consumers express concern over the potential that pesticide residues may increase the risks of illness from food consumption. Fig. 7 illustrates the trends in pesticide use between 1964 and 1992. Pesticide use more than doubled during this period, although a slight decline began after 1982 due to a decline in cropland acreage and an increase in the use of integrated pest management (Economic Research Service, 1994).[9]

The picture with regard to potential chemical toxicity is more complex. An index based on toxicity due to long-term exposure to small doses shows an 85% decline since 1964. An index based on acute exposure increased by about 25%, while pounds of active ingredients more than doubled (Lin et al., 1995). If a decline in chemical use eventually improves water quality, then these data can be consistent with long-term water quality improvement.

To assess the demand to avoid pesticide residues, Buzby et al. (1995) conducted a contingent valuation study on a hypothetical ban of a post-harvest pesticide. The authors estimated that survey respondents would, on average, pay 38% more for pesticide-free grapefruit than pesticide-treated grapefruit. They found that the aggregated national annual benefits for a ban on this fungicide exceeded $80 million.

The demand for pesticide residue free food is also reflected in premiums for organic produce. Organic farmers have received price premiums for more than 100 agricultural products, including corn, soybeans, wheat, oats, rice, and beef and most fruits and vegetables (Franco, 1989; National Research Council, 1989). An analysis of the California broccoli market illustrated that organic producers received price premiums in excess of 100% on several occasions during a calendar year, and the premium never fell below 10% (Franco, 1989). Hammitt (1986) compared the demand for conventional produce to the demand for organic produce in southern California. For 27 different foods, he found 16 foods had statistically significant price premiums which ranged from 25–172% of the conventional price for these goods. Additionally, surveys indicate consumers prefer or-

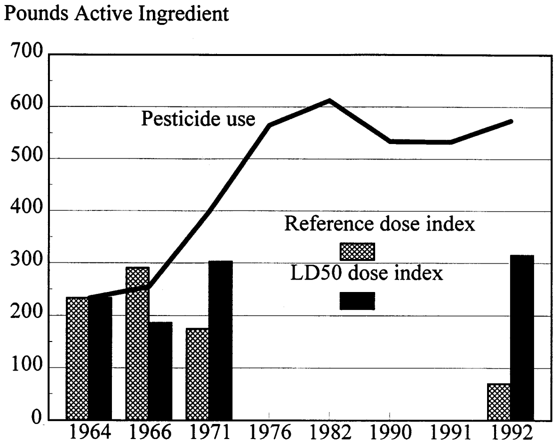

Fig. 7. Pesticide use, chronic and acute toxicity. Source: Economic Research Service (1994).

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[9] For a survey of agricultural pesticide issues, refer to Pimentel and Lehman (1993).

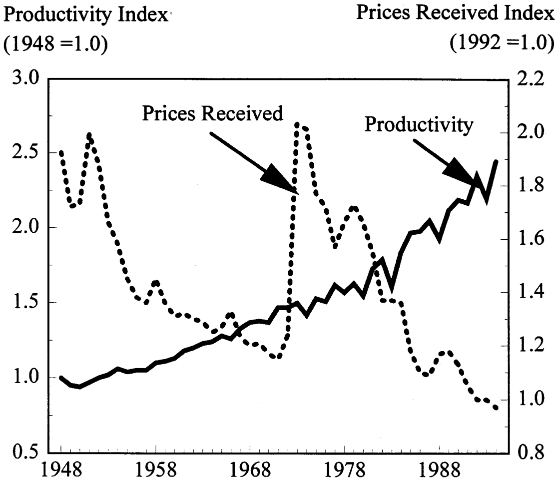

Fig. 8. US agriculture: productivity and prices received. Sources: Ball and Wehring (1996), Economic Report of the President (1997).

ganic, pesticide-residue free, or reduced input produce for health reasons as well as for concerns about pesticide effects on ground water, wildlife, and farm workers (Weaver et al., 1992).

3.6. Implications of environmental indicators

A review of these environmental assets indicates that agricultural production in the US has improved its environmental performance. Figs. 2–7 illustrate a reduction in the rate of soil erosion, potential long-term improvements in water quality, reductions in the rate of ground water depletion, and a reduction in the rate of disinvestment of wetlands. However, one may argue that the improved environmental performance of the sector has come at a cost in terms of current production of food and fiber. To assess the capacity of the US agricultural production sector to meet increasing demand for food and fiber, we present three interrelated indicators of performance: productivity growth; real commodity prices; and research and development.

Fig. 8 illustrates prices received and the pattern of input, output, and productivity growth in US agriculture (Ball and Nehring, 1996). Over the period 1948–1993, output in US agriculture grew at an annual average rate of 1.7%. A slight decline in input use accompanied this output growth, resulting in an annual productivity growth rate of 1.8%. The prices of agricultural products reflect this productivity growth. Over the same time period, the real prices farmers received for farm products dropped by about 50%.

For major field crops in US agriculture, yield growth parallels the observed pattern of productivity growth. Yields in major field crops (defined as output per acre) grew rapidly, ranging from 1–3%. Among field crops, corn, sorghum, and potatoes have exhibited the most rapid growth. Since 1939, corn yields have grown at an impressive 3% per year, wheat yields at approximately 1.8% annually, and soybean yields grew 1.25% per year.[10] The evidence for a plateau in the growth rates for yields is mixed. Some researchers have reported evidence suggesting that yield growth for major cereals has stagnated worldwide (Brown, 1994; Oram and Hojjati, 1995). This finding is challenged in a more recent paper, where evidence favoring the yield plateau hypothesis in the US is reportedly weak (Reilly and Fuglie, 1997).[11]

Comparing the productivity growth rates with the soil erosion rates over time indicates that productivity can continue with resource degradation, implying synthetic inputs (e.g. fertilizers) can substitute for natural resources (e.g. soil fertility). Technical change can mitigate some of the negative effects of resource degradation on agricultural productivity (Cleveland, 1995).

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[10] From 1939–1995, real prices for corn, sorghum, and potatoes dropped by about 50% while real prices for soybeans dropped by about 30% (market prices [National Agricultural Statistics Service, 1997] are deflated by the gross domestic product implicit price deflator [Economic Report of the President, 1997]). Productivity may provide a better indicator of the agricultural sector's performance because of the distorting effect of government programs on agricultural market prices.

[11] Evidently this is an unsettled research question and the answer depends in part on how one defines a plateau in yield growth. Reilly and Fuglie (1997) examine three competing models of yield growth (linear, logarithmic, and exponential). Out of 11 crops considered, five were consistent with the exponential model (increasing growth rate in yields per acre over time) and another five were consistent with the linear model (falling growth rate in yields per acre over time).

The most important factor contributing to the steady growth in US agricultural productivity is investment in agricultural research and development (R and D). Fig. 9 illustrates the pattern of R and D growth in US agriculture (Fuglie et al., 1996). Public research expenditures rose by 3–4% in real terms until approximately 1980, but since then, growth has slowed to 0.7% per year. While federal expenditures have remained relatively constant since 1976, the private sector has grown rapidly. Most of the post-1980 growth has resulted from increased contributions from the private sector, mainly for research conducted at land grant universities. The private sector now accounts for more than 50% of all agricultural research funds (Fuglie et al., 1996). If past patterns of R and D continue in the future, then it will be possible to maintain the rate of productivity growth in US agriculture. Ceteris paribus, maintaining this productivity growth rate will also contribute to an increased availability of food and fiber to future generations.

Continued growth in the demand for food as well as environmental goods and services will put additional pressure on protecting environmental and natural resource assets. The evidence pieced together from the demand studies reviewed above, coupled with continued increases in the US population suggest additional demands for goods and service flows may be forthcoming. Furthermore, research from public opinion surveys indicate that the public believes the nation should spend more for protection and conservation of environmental goods and services (Life Systems, 1994; see Fig. 10). This implies that the public perceives that the marginal benefits of environmental protection and resource conservation still outweigh the marginal costs.

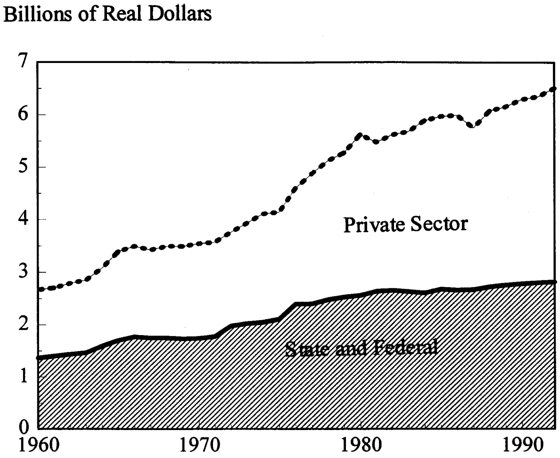

Fig. 9. Research spending. Source: Fuglie et al. (1996).

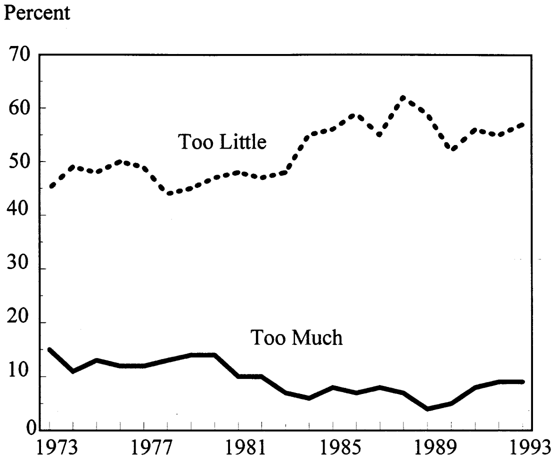

Fig. 10. Public opinion on environmental spending. Source: Life Systems (1994).

4. Green technologies for a more sustainable agriculture

In the previous section we have shown that the environmental performance of the agricultural sector was enhanced without a significant cost in terms of foregone output or higher real prices for agricultural commodities. What is less clear however, is if the sector has gone far enough from a society perspective in terms of adopting practices that can further mitigate the impact of agricultural production on the environment. In assessing the roles R and D, alternative practices, technology, and technological change can play in shaping sustainability, three questions become apparent. First, from a society perspective, is the supply of more 'sustainable' agricultural practices sufficient? Second, do the 'sustainable' practices under development reflect society's preferences for nutrition, health, and environmental goods and services? Finally, if more socially 'sustainable' practices were available, would the market encourage (or allow) farmers to adopt those practices? By addressing these questions, we can determine the role and limits of private markets in the development and adoption of more sustainable practices and identify opportunities for appropriate policy intervention.

4.1. What is technology?

It is important to differentiate between society's current ability to produce goods and services and how society's ability to produce goods and services changes over time. Fig. 11 illustrates these concepts through a production possibilities frontier. In Fig. 11, food represents the marketed goods and services produced by the economy and environmental services represents the non-marketed goods and services such as carbon dioxide sequestration and birds to watch.

The production possibilities frontier depicted by the curved line $A_{ES}A_F$ represents the technically efficient combination of food and environmental services that society can produce given its existing technology and endowments of labor, reproducible capital, and natural capital such as the stock of land and water quality at some time *t*. Over time the production possibilities frontier changes. As society produces food for current consumption, we use some amount of our endowments of natural and reproducible capital. If natural and reproducible capital used to produce current consumption goods is not replaced (i.e. negative net investment), the production possibilities frontier shifts inward to the dashed line $B_{ES}B_F$.

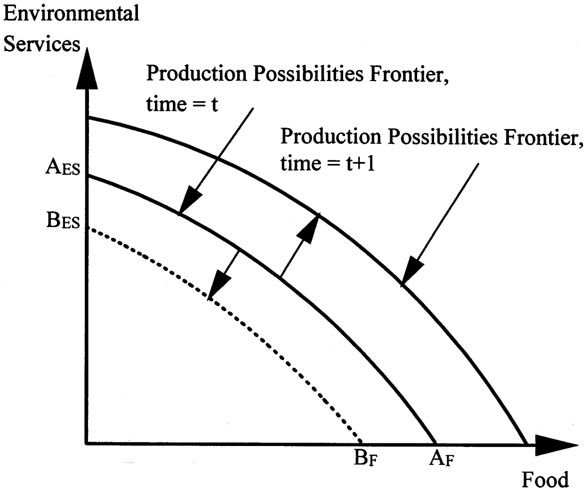

Fig. 11. Production possibilities frontier.

To prevent the production possibilities frontier from shifting inward, society can preserve its endowments for future generations by giving up some current consumption (i.e. take land out of production) and/or it can invest in R and D to develop more efficient production practices which conserve or even augment society's ability to produce goods and services over time. The importance of R and D for conservation and augmentation of society's natural and reproducible capital endowments becomes paramount as only investment can meet the increasing demands for goods and services of a growing population. In practice, however, impediments to the development and adoption of more sustainable practices exist. These serve as the focus for the remainder of this section.

4.2. Impediments to development of more sustainable practices—the supply-side

Market failure constrains the development of more sustainable practices. First, firms cannot fully appropriate the rents associated with developing and implementing a new technique due to the lack of complete property rights for information. Similarly, the lack of property rights associated with many of the attributes associated with more sustainable practices (e.g. environmental quality outputs) also discourages the development of new technologies.

Because competitors can often mimic a successful, new technology, the developers of new technologies cannot fully capture the benefits of their innovations. If developers could have complete property rights for their innovations, then they would optimally invest in R and D.

There are also rarely well-defined property rights associated with many of the attributes of

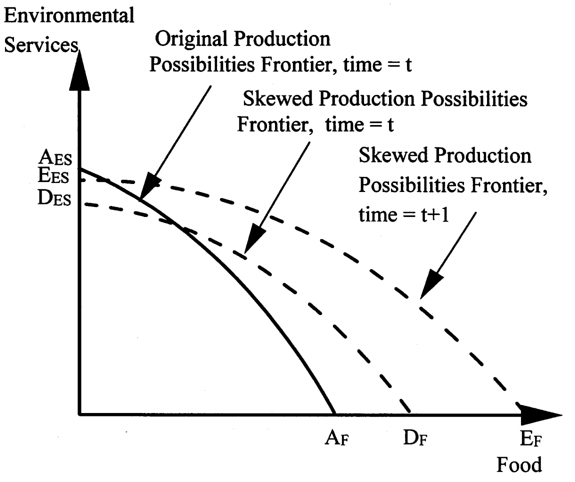

Fig. 12. Production possibilities frontier with skewed technology.

the more sustainable practices. For example, if a farmer adopts a more sustainable practice which provides better water quality, the farmer cannot exclude other individuals from the benefits. Markets for many of the attributes associated with more sustainable practices are incomplete. Theories associated with endogenous technological change suggest that private sector R and D focuses on practices that conserve or augment the limiting factor in production as reflected in the relative prices of factors of production. For example, because fertilizer is priced, the private sector has some incentive to conduct R and D on fertilizer-reducing, and therefore cost-reducing, practices. The private sector has no incentive for R and D on practices that produce improved habitat for wildlife or more scenic landscapes because these goods lack market prices. In addition, the private sector will limit R and D on the mitigation of natural resource stock depletion to marketed benefits. If complete property rights existed for environmental goods, then the private sector would optimally invest in R and D to supply them.

The implications of missing markets for environmental services and natural resource stocks are described in Fig. 12. First, the current supply of more sustainable practices is limited. Therefore, the current production possibilities frontier as represented by the curved line $D_{ES}D_F$ is skewed toward the more efficient production of food (marketed goods and services) than is the original production possibilities frontier ($A_{ES}A_F$). Second, the dynamic path as represented by the outward movement of the production possibilities frontier from $D_{ES}D_F$ to $E_{ES}E_F$ is also skewed toward the more efficient production of food rather than environmental services.

This result indicates that society underinvests in and undersupplies more sustainable agricultural practices. Furthermore, the sustainable practices that are being developed are not likely to reflect society's preferences for nutrition, health, and environmental goods and services. The direction of future R and D is important because, as stated, most of the recent growth in R and D has resulted from increased contributions from the private sector and there will be greater pressure to develop practices which conserve marketed inputs rather than practices which conserve natural resources.

4.3. Limits to adoption—the demand side

Limits to the adoption and implementation of more sustainable practices also exist. We highlight the importance of these limits to the adoption and implementation of four management practices considered as more sustainable. These practices include: integrated pest management (IPM); enhanced nutrient management; conservation tillage; and precision agriculture.

Each of these practices are ‘informational’. They require a farmer to have a more detailed understanding of how physical characteristics associated with a farm, such as soil type, rainfall, and temperature, interact with the use (management) of inputs, such as pesticides, nutrients, and soil, to affect the production of commodities. Each practice focuses on optimizing input use and has the potential for dramatic impacts on both farm profits and the environment. Finally, each practice faces somewhat different limits to adoption and implementation.

Our findings suggest that, for the four practices identified above, the most significant limits to adoption include: structural barriers to decision making; the heterogeneity of the natural resource base; the perception of risk associated with many new technologies; and the lack of clearly defined property rights associated with many of the attributes associated with more sustainable practices.

4.4. Structural barriers to decision making

Structural barriers are caused by the high fixed costs often associated with adopting a new practice. Just et al. (1980) show that given the transaction and information costs associated with innovations, a critical lower limit on farm size may exist, preventing smaller farms from adopting a new practice. As these costs increase, the critical size also increases. However, farm size may also serve as a surrogate for other factors, such as access to credit, scarce inputs, or information. Results for vegetable growers indicate that farm size affects IPM adoption, and confirm expectations that large farms are more likely to adopt IPM than smaller farms (Fernandez-Cornejo et al., 1994). In a similar manner, operators of larger farms are significantly more likely to adopt no-till, but that positive effect declines as size increases (Calvin and Brown, 1996).

Labor availability may also represent a serious impediment to the adoption of some practices. Farmers appear to more readily adopt labor-saving practices than labor-intensive practices. Results for vegetable growers generally illustrate that operator and unpaid family labor are significantly and positively associated with the adoption of IPM (Fernandez-Cornejo et al., 1994). This result also suggests that off-farm employment by the operator may present a constraint to IPM adoption, because it competes with on-farm managerial time. Alternatively, some consider less time spent on field operations as an advantage of no-till technology. As off-farm activities increase, a farmer has less time and flexibility for farm operations and the probability of adoption increases (Calvin and Brown, 1996).

4.5. Heterogeneity of the resource base

The limits to adoption and implementation associated with the heterogeneity of the resource base primarily involve locational factors such as soil characteristics and temperature. Results for vegetable growers indicate that the farm location, proxying for climate and soils, has a significant effect on pesticide demand, yields, and farm profits (Fernandez-Cornejo et al., 1994). Locational factors, such as soil fertility, rainfall, and temperature influence profitability differences among farms. The physical environment of the farm may affect profitability directly through increased fertility, and indirectly through its influence on pests. Ceteris paribus, a farm located in a dry, infertile area is less likely to adopt IPM than a farm located in an adequately wet, fertile area. Similarly, Crosson (1981) notes that no-till technology may not perform well in areas with poorly drained soils, short growing seasons, and high rainfall. As soil becomes finer and denser, adoption of no-till may decrease. Alternatively, farmers with well drained soils (those with high leaching potential), may be more likely to adopt no-till.

4.6. Risk

Different agricultural production technologies may have differing associated risks in production (i.e. potentially greater variance of returns due to a practice). How farmers address these risks depends on their risk behavior. A sustainable technology that carries higher risks than a conventional technology may not promote technical efficiency because of the actions of farmers to minimize these risks. In these cases, farmers may not realize the profit and environmental quality gains expected for a sustainable technology.

For example, Huang et al. (1996) found that a risk-neutral farmer may find it economically optimal to ‘over-apply’ nitrogen. This over-application increases as the probability that inclement weather will preclude access to the field for growing season application increases. In addition to ‘over-applying’ nitrogen, the probability of a farmer not having access to the field also affects the economically optimal timing of nitrogen application. When the probability of not being able to get into the field increases, it becomes economically optimal for the farmer to apply less nitrogen during the growing season and more nitrogen before the growing season starts, when it poses a more serious environmental threat.

4.7. Lack of clearly defined property rights

The lack of clearly defined property rights associated with many of the attributes of more sustainable practices differentiates sustainable practices from output enhancing or cost-reducing practices. The first three examples of impediments to the adoption and implementation of more sustainable practices can accompany any new practice. The lack of clearly defined property rights associated with many of the attributes of more sustainable practices prevents markets for environmental services from developing and affects the adoption and implementation of sustainable practices.

For the case of fresh market tomato growers and IPM adoption, farmers encounter a 'win–win' situation (Fernandez-Cornejo, 1996). Insecticide use is negatively and statistically significantly related to the adoption of IPM for insects. Similarly, fungicide use is negatively and significantly related to the adoption of IPM for diseases. Among fresh market and processed strawberry producers, however, adopters of IPM for diseases apply significantly more fungicides than non-adopters. Adopters of IPM for insects apply more insecticides than non-adopters for growers of processed strawberries but the effect of IPM for insects on insecticide use among fresh market strawberry producers is not significant.

Similarly, some have envisaged possible resource situations in which precision agriculture can both mitigate and exacerbate potential environmental problems associated with crop production (Heimlich, 1996). For example, a farmer could obtain increased soil cover on steeper slopes through variable rate technology (VRT) application, which 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 operate which reduce nitrogen uptake.

Each of the practices described has the potential for 'win–win' outcomes such as less pesticide or nitrogen use and higher farm profits. Until private agents can capture the non-market benefits of more sustainable practices, however, there is no assurance that the agricultural sector will provide a socially optimal mix of environmental services. The lack of private market incentives both for the development of more sustainable practices (the supply-side) and on the adoption of more sustainable practices (the demand-side) suggests a positive role for government. However, the availability of a practice does not assure the adoption of the practice and any governmental program must recognize the importance of addressing both the supply- as well as the demand-side of the issue.

5. Conclusions and implications for policy design

While it may never be possible to reduce sustainability to a simple rule, we know that sustainability requires incorporating non-market final 'goods' and 'bads' into our policy-making process. Sustainability also extends beyond current economic activity and accounts for future production possibilities. Government possesses several distinct, but not mutually exclusive, approaches to move the agricultural sector along a more sustainable path.

5.1. Technology policy

Our discussion of sustainable practices has demonstrated the impediments to the adoption and implementation of more sustainable practices and a role for government. From a policy perspective, it is critical that we carefully research and identify the correct limits to technology adoption and implementation (Ruttan, 1994). 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 (structural); geography (heterogeneity of the resource base); economic efficiency (profits, risk); or the lack of markets for the benefits of more sustainable practices (clearly defined property rights).

5.2. Conservation policy

Recent farm bills have mandated several natural resource conservation programs. The Conservation Reserve Program and the Wetlands Reserve Program conserve environmentally sensitive farmland by providing for the USDA to enter into long-term agreements with farm owners and operators. In return, the USDA pays the owners and operators cost sharing for establishing the plan and annual rental payments. The Clean Water Act stipulates a goal that all waters of the US should be “swimmable and fishable”. To achieve this goal, Congress mandated several mechanisms to address water pollution.

5.3. Marketing policy

The federal government has worked since the Progressive Era to ensure the quality and safety of the nation’s food supply. These efforts include food grading, food inspections, pesticide testing and registrations, and proper labeling of food products. The demand for foods grown under ‘more sustainable’ practices (e.g. organic) has stimulated an interest in producer certification and product labeling. Certification and labeling of organic, residue-free, and IPM-grown produce can provide consumers with reliable information about production techniques and legitimize price premiums. California began requiring certification of organic produce in the 1970s, and under the 1990 Farm Bill, the federal government required all organic producers to undergo annual certifications by independent state and local agencies (Jolly and Norris, 1991).

Clearly, each one of these approaches contributes towards a movement for more sustainable agriculture. In different ways, they work towards the same goal, i.e. ensuring that future generations have the social capital to meet their economic needs. Future research must examine the relative efficiency of these approaches. Policy evaluations should be benchmarked against an appropriate set of indicators of agricultural sustainability (Arrow et al., 1995, p. 93). It is also apparent that these approaches may not be mutually exclusive. Government may need to use these policy instruments concurrently to ensure that future generations satisfy their demand for environmental services and for food and fiber. What is the optimal mix of policy instruments? The question of policy design is also a potentially fruitful avenue for future research.

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