The Australian Journal of Agricultural and Resource Economics, 41:1, pp. 63–80

Economics of new technologies for sustainable agriculture†

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Sustainable agriculture is prescribed as a policy approach that maximizes economic benefits while maintaining environmental quality. It is argued that this approach is human capital-intensive and encourages new scientific developments. To attain sustainability, economic incentives for the development and adoption of precision technologies (with minimal residues that cause environmental damage) have to be developed. Taxation and tradeable permits are desirable policies to attain first-best solutions; however, when heterogeneity and lack-of-information problems are significant, alternative institutions have to be developed. The paper presents and discusses such institutions.

Modern agriculture has been to a large extent a major success story. In the last few decades increases in agricultural production have resulted in the ability to feed the entire world, despite rapid population increases over the same period. World per capita supplies of food for direct human consumption are approximately 18 per cent higher than they were 30 years ago (Alexandratos 1995). However, this unprecedented achievement has had its negative side. The capacity to access food supplies varies widely among countries, with the problem of overeating as a major health problem in rich countries occurring alongside malnutrition from food deprivation in poor countries. Additionally, increases in agricultural production have been associated with significant environmental problems. These include soil erosion, deforestation for agricultural land clearing, contamination of groundwater, and a severe reduction in wildlife populations. In many areas, it has been recognized that current production patterns cannot last forever because they depend on exhaustible resources. The recognition of

†Invited paper presented at the Australian Agricultural Economics Society Conference, University of Melbourne, 11–16 February 1996.

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these problems and their potential impacts on future production capacity has led to the quest for sustainable agricultural systems.

The cause of sustainable agriculture is embodied in the larger cause of sustainable development. This phrase is embraced by a diverse group of people and has many and sometimes contradictory interpretations. Everyone would like to see a greener future, better quality of life, and a healthy environment, but disagreements are common about how to get there and what exactly such a future would look like.

In this paper, we will present a personal interpretation of sustainable agriculture and sustainable development and argue that economic thinking and analysis are crucial for the interpretation and pursuit of these objectives. We also argue that the practice of economics will be enriched by the incorporation of sustainability concerns in the research agenda, as such research will facilitate dialogues with other disciplines, resulting in a more comprehensive and relevant field.

The first part of the paper will discuss the mechanics through which science, technology, and entrepreneurship impact on the attainment of sustainable agriculture. The second section will rely on the economics of exhaustible resources to identify situations where government intervention and incentives are needed to attain sustainable agricultural development. In this section we will argue that the development of new precision technologies is an important avenue for pursuing agricultural sustainability under many circumstances found in the world today. This section will identify the difficulties associated with enacting policies addressing environmental and resource problems in agriculture. Based on this analysis, we recommend the development of interdisciplinary research capabilities which will capture the heterogeneity of economic and ecological systems and allow for better policy-making. In the following subsection we discuss the equity implications of policies to promote sustainability and some possible transfer mechanisms to mitigate the distributional impacts. The paper concludes with a section on directions for future research.

1. Sustainable agriculture, science, and technology

The pursuit of sustainability is motivated by dissatisfaction with the existing state of affairs. While many economists are concerned at the degradation of environmental quality associated with modern agriculture, others are concerned with the destructive impact that science-based technologies and modernization have had on lifestyle and culture (Batie 1989). There is a sharp division in the assessment of the role of modern technologies in the pursuit of sustainable agriculture. Some may take the extreme position that science-based agriculture and the technologies it has engendered — such as chemical fertilizers, pesticides, and monoculture cropping systems — are inherently detrimental to the environment. They may argue that the only path to sustainable development requires discarding these modern technologies and building new agricultural systems on native practices and traditional knowledge (National Research Council 1989).

While organic farming and traditional crop rotations may have a significant role in a sustainable future, we do not believe that the keys to sustainability are in the technologies of the past. The drastic changes in agricultural practices during the past 100 years have come about in response to social needs, and we cannot turn the clock back and still feed the current human population. We do not believe that science and technology are inherently anti-environment. The work of scholars such as Hayami and Ruttan (1985) and Griliches (1957) have shown that technologies have evolved and been adopted in response to incentives. In cases where technological changes have caused severe environmental damage, it is often because of the lack of incentives to prevent this damage. Many of our environmental problems are not the result of 'bad' science but, rather, inadequate policies, institutions, and management systems.

The case of drip irrigation can be used to illustrate the above point. Drip irrigation is a technology that conserves water and reduces drainage. This technology was developed in response to the incentives present in Israel, a country that suffers from a severe water scarcity problem, and which made a concerted effort to develop water-conserving technologies. While this technology is available to all growers in California, it has been adopted mostly by growers who face high water costs and have low quality lands (Caswell 1991). Shah, Zilberman, and Chakravorty (1993) argue that the institutional environment is a major factor working against the adoption of drip technology — even in water-scarce California. Traditional water rights regimes based on the principle of 'use it or lose it', and which restrict trading, encourage farmers to use traditional, water-wasting surface irrigation technologies. With institutional innovation and the introduction of water trading, farmers gain from reducing the irrigation water they apply (they can sell the extra water); thus, one would expect to see an increase in the use of water-conserving technologies.

Modern scientific research has played a crucial role in identifying and mitigating many of the negative externalities associated with modern agriculture. Concern with environmental problems has led to technological developments aimed both at remedying them and preventing their future occurrence. One example is new technologies which allow for targeted pesticide applications, which are less likely to result in spillovers and negative environmental side effects than past technologies.[1] One has to remember that, not long ago, farmers were spraying arsenic and other human toxins for pest control, without any protective clothing.

Some of the environmentally objectionable characteristics of modern technologies are the result of too little scientific knowledge, not too much. Modern science is relatively young and there is room for much improvement in science-based agriculture. We have developed monocultural cropping technologies not because they are inherently the most efficient ones, but because monocultural systems are much easier to analyse systematically. We are only now starting to understand the dynamics of multispecies systems. The development of multi-crop, interdependent food production systems which are economically and environmentally viable is an incredible scientific challenge. But such systems are already being developed, and we believe that more will follow in time.

Some of the distrust of modern science by proponents of sustainable development is understandable. Science is not the only source of technologies and, until recently, most innovations were originated by people in the field, rather than people in the lab. There has been a tendency among scientists to discount indigenous knowledge and new techniques and innovations that cannot fully be explained by the existing state of scientific knowledge. We were surprised to learn, when we studied the origin of drip irrigation in Israel, that it was successfully practised in the field in the mid-1960s, at which time it was scorned by the scientific establishment.

One reason why scientists dismiss the knowledge and practices developed by farmers is a difference in perspective between researchers and economic agents (farmers). The scientist is aiming to discover the absolute truth and provides his or her seal of approval only to solutions that can be proven superior with a very high degree of statistical significance. The degree of statistical significance that will make an economic agent consider a practice superior may be much lower, as they are maximizing expected utility or profit. Furthermore, scientists are usually not as familiar with the physical, social, and economic constraints faced by farmers, and underestimate the practical difficulties associated with scientifically prescribed solutions. This leads to alienation between scientists and farmers and many missed opportunities.

The scientific tendency to generalize and the human desire to simplify have led to pursuit of uniform solutions to production problems, but heterogeneity of both physical and socio-economic conditions suggests that optimal solutions will be differentiated across space and time and calls for

[1] J.E. Casida, personal communication, January 1996.

the development of technologies that are appropriate to specific circumstances. Getting farmers involved in the process of technology development is an important avenue for recognizing and incorporating heterogeneity of production conditions.

The development of new technologies must be a two-way process: some technologies may develop from the bottom up, and others will be the product of cutting-edge scientific knowledge. The scientific establishment has to recognize this complementarity and develop mechanisms to incorporate local and indigenous knowledge into scientific knowledge. The recognition and incorporation of indigenous knowledge are especially important in the developing nations, where the development of new technologies relevant to farmers' needs is critical to achieve the increase in agricultural productivity necessary to maintain even a subsistence income for their rapidly growing populations. It is also in these countries that some of the richest sources of indigenous knowledge exist and the linkages between the scientific research establishment and local farmers have been weakest. A key challenge facing researchers, policy-makers, and local leaders is to devise strategies which would promote initiative and entrepreneurship among farmers to facilitate the bottom-up portion of the technology development process, as well as to encourage researchers to recognize and integrate local knowledge in their research agenda. Strategies which accomplish these goals will result in the development of superior technologies.

Continued support for research and more attention to indigenous knowledge will provide a tremendous base for attaining efficient and environmentally sound agricultural production systems, but a bigger challenge may be the development of institutions that will enable us to take advantage of the technological capabilities we possess. The land-grant college system in the United States has been essential in providing technologies that increase the productivity of agriculture immensely and in maintaining a competitive structure. This system emphasizes the development of biological and agronomic innovations while the private sector has been active mostly in initiating mechanical innovations. As science and technology become more complex, the interaction between the university and industry is increasing. In the case of medical biotechnology, we have seen the institution of technology transfers where the universities sell their patents to private companies who develop and sell the products based on university-developed knowledge. To some extent this model may work in agriculture, but the heterogeneity of the agricultural sector and the need to adapt varieties and practices to local conditions will require modification and perhaps even expanding the extension system (Postlewait, Parker and Zilberman 1993). Again, the need for mechanisms to facilitate and promote the inclusion of local level knowledge in the development and spread of new technologies is apparent.

In addition, many agricultural technologies have a public good nature and cannot be embodied in new machinery or equipment that are profit-generators. Furthermore, developing an understanding of the environmental impact of agricultural activities is an ever-growing research challenge. Therefore, the public research establishment has to be maintained and directed to the areas that may not be addressed by the private sector.

2. Precision technology and sustainable agriculture

Ideally, the objective of sustainable agricultural systems is the maximization of a joint benefit of economic production and environmental amenities over the long term. However, due to the difficulties in evaluating environmental amenities, it may be useful to simplify (as in Baumol and Oates 1974) and define the objective of sustainable agriculture to be the maximization of net economic benefits from a given set of resources, subject to a set of environmental quality constraints. The sustainable management of agricultural resources can be modelled in a dynamic framework as an exhaustible resource problem where some cumulative measure of environmental quality is an exhaustible resource. The problem of water logging provides a good example. Water logging occurs where impenetrable underground layers prevent the downward movement of percolating water. This water accumulates, reaches the root zone, and eventually makes production impossible. The accumulated stock of percolating water is a negative measure of environmental quality. Policy-makers should design measures such that producers incorporate the impacts of their production decisions on the groundwater accumulation process (for an economic framework of this model, see Shah, Zilberman, and Lichtenberg 1995) while maximizing the net benefits from production. Other water quality problems, such as the concentration of nitrates in groundwater and the disposal of toxic agricultural chemicals, can be similarly modelled. Environmental quality constraints may enter the model as limits on the aggregate level of waste or concentration of chemicals in the water. Hueth and Regev (1974) show pesticide resistance problems can also be modelled as dynamic exhaustible resource problems and McConnell (1983) presents similar arguments for soil erosion problems.

2.1 Modelling the effect of precision technologies

A major source of environmental quality deterioration is the accumulation of residue material. An important element of an optimal policy solution is the introduction and adoption of precision technologies which would limit these accumulations. Heuristically, we will define precision technologies as input application or harvesting technologies which can respond to varying environmental conditions, resulting in the reduction of wastes relative to traditional technologies. To formally model the choice of these technologies and their impacts, it is necessary to distinguish between applied inputs which are the quantities applied in the field, and effective input — the quantity which is actually consumed by the crop or other production activity.

Assuming a constant returns-to-scale technology for convenience, let a_i denote input use under technology i, where i can assume a value of 0 for traditional technology and 1 for precision technology. Let e_i denote effective input use per acre. It is useful to write

$$e_i = h_i(\alpha)a_i$$

where $h_i(\alpha)$ is input use efficiency, a function of technology and α which is an indicator of environmental quality, assuming values from 0 to 1.

This formulation has been used by Caswell and Zilberman (1986) to model irrigation technology. The traditional technology may be furrow irrigation, and precision technology can be more advanced technologies such as sprinkler or drip. Effective water is the water which actually is used by the crop. This type of model can be used to analyse other technologies as well. For example, in pesticide application technology, the less precise technology ($i = 0$) may be aerial spraying while the more precise technology ($i = 1$) may be ground spraying. For fertilizer applications, precision technologies adjust the applied volume based on information obtained from satellite data and from laser monitoring of environmental conditions and topography, increasing substantially the effectiveness of the fertilizer used. In each of these cases, the precision technology tends to improve the effectiveness of variable input use, but it also entails a higher application cost. That is, if k_i denotes application cost per acre, then $k_1 > k_0$. Precision technologies may entail not only higher application costs per acre but also higher application costs per unit input because input application is more time- and skill-intensive. Thus, if w_i denotes per unit variable input cost, then $w_1 > w_0$.

Khanna and Zilberman (1996) use the notion of input effectiveness in the formulation of the following production function:

$$y_i = \beta_i f(e_i) = \beta_i f[a_i h_i(\alpha)]$$

where

y_i = output per acre

f = output, a function of effective input
β_i = scale coefficient that represents the contribution of technology i into productivity above and beyond its contribution to input use effectiveness. β_i may represent the contribution of the precision technology to productivity by improved timing.

This specification recognizes that the production system may result in residuals that will not contribute to the production process but which may be the cause of environmental damage. For simplicity, let us define the residual generated per acre as z_i where:

$$z_i = a_i - e_i = a_i(1 - h_i(\alpha))$$

Using this notation, Khanna and Zilberman (1996) demonstrate that the socially optimal levels of input use and technology for a given α are determined by solving:

$$(1) \quad \max_{i,a_i}\{P\beta_i f(a_i h_i(\alpha)) - w_i a_i - v a_i[1 - h_i(\alpha)] - k_i\}$$

where P is the output price and v is the per-unit social cost of the pollutant (residue). The optimization problem is solved in two stages: first, the optimal input use under technology i is selected, and then profits under each technology are compared, such that the optimal technology is selected. A comparison of input use and output among technologies indicates that precision technologies will result in higher output at lower pollution levels than the traditional technologies. In addition, precision technologies will save on input use in most cases. However, while these technologies increase variable profit, they require higher fixed costs, and if the yield-increasing and pollution-decreasing effects are insufficient to overcome these additional costs, precision technologies may not be selected.

Comparing the profitability of various technologies, Khanna and Zilberman (1996) showed that precision technologies have the potential to provide higher revenues, lower variable input costs, and lower environmental pollution. Increases in output price, pollution costs, and a proportional increase in the input costs, w_0 and w_1, increase the likelihood of adoption of precision technology. Nevertheless, these technologies are not adopted as widely as is socially optimal. One reason for this is that in most cases the damage associated with residues does not directly affect the farm or production unit that generates it. Therefore, without government intervention, the private choice of technology level is determined by solving:

$$(2) \quad \max_{i,a_i}\{P\beta_i f(a_i h_i(\alpha)) - w_i a_i - k_i\}.$$

When pollution is not regulated, (v = 0), there will be a smaller diffusion of precision technologies and higher use of variable inputs, leading to a more rapid accumulation of the pollutant.

The value of v, the marginal cost of pollution, may be computed within a static framework, when the input is a chemical causing worker safety costs or environmental safety problems with immediate effects. Optimal taxation may be derived from a dynamic framework, as the optimization problem presented in equations (1) and (2) can be viewed as the Hamiltonian of the dynamic optimization problem. The work of Shah, Zilberman, and Chakravorty (1995) suggests that, when the environmental quality constraints are associated with accumulated residual stocks, the optimal price of pollution will increase over time, which will trigger a gradual diffusion of the precision technology. As time goes by, the adoption of this technology will become widespread, resulting in a decline in input use and pollution per acre, and a decline in aggregate pollution.

The major cause of environmental problems in agriculture is that producers do not pay the social costs associated with their production choices. Rarely, if ever, are agricultural spillovers taxed, which leads to severe under-investment and under-adoption of precision technologies, as well as over-use of the variable inputs with existing technologies. Examples of this phenomena abound: the over-use of irrigation water and the under-investment in technologies like drip irrigation as well as under-use of irrigation scheduling, the excessive aerial spraying of pesticides, the excessive use of fertilizers (without taking into account their effects on water quality), and the excessive problems of soil erosion. We see some adoption of precision technologies, but it occurs primarily because of their impact on yields and profitability. Throughout the world, we have not seen much adoption of such technologies, in spite of the contributions they can make to sustainability.

2.2 Intervention measures and issues of implementation

Despite the potential environmental and economic benefits, the introduction of optimal taxation to deal with issues of environmental quality associated with agricultural production is not very easy. Several obstacles have to be overcome. First, monitoring of residues is very difficult. There is no simple way to trace individual sources of aggregate waste materials. Agricultural pollution problems are viewed as non-point source problems that are sometimes much more difficult to address than point sources because of the difficulty in assigning liability to individual users. But the distinction between source and non-source problems depends on monitoring technology, and new research over time will lead to the development of technologies which will trace and monitor residues at low cost and allow easier regulation of agricultural residues.

In the meantime, we need to replace the taxation of residues with second-best policies. One obvious candidate policy is the taxation of inputs. For example, a pesticide should be taxed according to the value of the marginal damage caused by its residues. Similarly, one can derive a tax on fertilizers, water, etc. While in principle this seems to be simple, in practice, computation of such taxation is extremely difficult. First, the tax has to be adjusted by application technology. For example, a tax on pesticide applied aerially should be much higher than the tax on pesticides applied with precision technology. Similarly, the taxation at times has to vary by location. In the case of pesticides, they cause problems of food safety, worker safety, and contamination and damage to wildlife and the environment. The residues of a farm located close to a body of water are much more likely to cause damage than those of a farm located further away from the body of water. The input tax imposed on the two farms should reflect this differential damage. Thus, we can see that the design of an input tax is tricky, and it has to be differentiated according to several criteria, making the imposition of such a tax very difficult.

In many cases, input use is difficult to monitor. One of the challenges that agricultural regulators and society are faced with is developing an effective means of monitoring input use, taking advantage of existing and developing computer technology. We still have a long way to go to reach this goal. In many cases, the only observable information policy-makers may have available is the type of technology farmers have used for chemical applications — be it modern irrigation technology or other precision application technology. We may need to design discriminatory payment schemes that are based on observable technologies. Such taxes will obviously be less efficient and effective than input taxes or pollution taxes. Still, they will provide the correct incentives to promote the adoption of precision technology.

In developing taxation schemes for agricultural residues, we also encounter problems of incomplete information. Policy analysts may need to take advantage of the literature on incentive compatibility (Laffont 1988) to design the best instrument, given the information at hand. The design of this instrument has to take into account both uncertainty about individual behaviour as well as uncertainty about the biological relationships present. Knowledge concerning agricultural technologies, the basic physical relationships governing residues, and the relationship between applied and effective inputs will be very useful in providing an initial framework for the design of second-best policies which will provide appropriate incentives for achieving agricultural sustainability.

It may be that the use of taxation *per se* is difficult to implement for political and economic reasons as well as practical ones. Policies must be designed so as to ensure they will be politically acceptable, easy to implement, and economically sound. Good policy design is an art which requires experience and imagination. The Conservation Reserve Program in the United States is an example of useful policy in addressing some of the environmental side effects of pesticide and chemical use and the issues associated with soil erosion and groundwater contamination. Under this policy, the government provides a fund for the purchase of environmentally sensitive lands to divert them away from activities which may be especially harmful to the environment. The purchase by the public sector of riparian lands in many areas may prevent many of the run-off problems and water contamination and provide wildlife protection. Thus, the development of environmental amenity purchasing funds which will be used to modify land-use and production patterns in sensitive areas may be a very useful policy to achieve sustainability, given that the design of first-best policies is virtually impossible in many cases.

Sometimes taxation and the working of the market system may not be the optimal means of achieving sustainability and regulations may work better. For example, in addressing problems of the human side effects associated with pesticide use or other agricultural chemicals, the best solutions may include the introduction of worker safety regulations, including protective clothing, re-entry regulation, etc. A trick in making these policies work is flexibility. In many cases it may be beneficial to use monitoring technologies to determine the most appropriate local conditions and safety devices. In other cases it may be better to design policies with liability rules so that local decision-makers will have some freedom in choosing safety devices but with a clear understanding that misbehaviour on their part will result in penalties.

It is also important to recognize that some aspects of reduced chemical use in agriculture are not justified by environmental and health concerns *per se* but reflect individual preferences. Some of the desire for pesticide-free foods may represent aesthetic preferences. Individuals may vary in their objections to the use of pesticides or pesticide-sprayed foods. In this situation, it is useful to use markets to discriminate between different types of consumers and increase the range of foods available, so consumers can choose between fruits and vegetables that are sprayed with chemicals, ones that are organic, and those that were grown with fertilizers but not pesticides.

Indications are that the use of taxation is most advantageous in situations where the environmental side effects associated with the use of agricultural inputs or agricultural production do not differ very much across locations. This is the case when we have a global externality, e.g., emission of chemicals that contribute to global warming. In these cases, one can design uniform taxation policies that may be imposed on input use or pollution. However, even in these cases, taxation schemes may be objectionable for political economic reasons (Buchanan and Tullock 1975), so a mechanism of tradeable permits and the right to pollute may be more feasible. Under this type of scheme, permits will be distributed to users and then trade allowed. These trading schemes will result in a distribution of tax revenues back to the polluters (e.g., farmers) rather than extraction by the government, thus making this policy more politically attractive to such groups.

In the United States, with the widespread diffusion of computers and the spread of data networks throughout the country, it seems reasonable to require reporting of chemical applications by farmers so that a base for monitoring the regulation of pesticide use can be constructed. Another possibility that should be considered is limiting the prescription of pesticide applications to trained professionals who will be liable professionally for their decisions and who will take into account both the economics as well as the environmental consequences of their choices. Growing ranks of independent agricultural consultants provide a bank of individuals who can play the role of advisors in determining pesticide use. The problem is that at present consultants mainly determine application levels based solely on agronomic needs, while prescriptions which take into account both environmental as well as agronomic considerations are necessary. Policymakers will have to develop specific guidelines and decision rules which will simplify the determination of application levels, as well as monitoring and enforcement. Of course, one problem with this proposed solution is the high cost that this extra bureaucracy may impose. Further consideration of the advantages and disadvantages of such a policy needs to be considered.

Thus far, we have discussed the importance of the role of correct economic incentives to induce the adoption of precision technologies which primarily improve input applications and reduce input residues. Some precision technologies improve the harvesting of output. One example is improved harvesting technologies in fisheries which will reduce by-catch. By-catch is seen as one of the most severe problems in implementing single-species quota systems in fisheries, and its reduction can improve the quality of fisheries throughout the world.

Another area where precision harvesting is crucial is in the management of forests. In many cases an acre of land may be destroyed in a tropical forest in order to harvest only a small number of trees. Thus, precision technologies induced by the correct incentives may play a role in reducing damage not only because of their impact on input waste but also on wasteful harvesting processes.

While most of the precision technologies discussed above are high tech and require new capital, precision technology does not always necessarily require investment in capital. In some cases, it may be labour-intensive. Scouting of pests prior to spraying (an important element of integrated pest management) is a labour-intensive activity. The types of precision technologies that are relevant in different countries will depend on the relative prices of inputs. All the precision technologies are typified by the requirement of better knowledge and understanding of systems and the substitution of human knowledge for excessive inputs. Human capital is required both for the design of the technology and, at times, for the implementation. However, it is clear that there is one input that is not polluting the environment and which is most desirable in the development of the sustainable strategies — the human brain. Therefore, one resource, the accumulation of which we need to greatly encourage as part of a sustainable future, is knowledge.

The analysis thus far argues for the development of policies to improve environmental quality and sustain production capacity which involve the development of new precision technologies, and the provision of incentives for adoption of these technologies. In most cases, these activities will require extra expenditure on research and development in both the private and public sectors. At least in the early stages, much of the expenditure will be in the public sector because much more basic knowledge is needed to develop a wider range of precision technologies that can address many of the environmental problems with which we are very concerned today.

The promotion of incentives to adopt these technologies will raise the cost of certain agricultural production activities, in spite of the fact that precision technologies have a yield-enhancing effect. Thus, having a more sustainable future may require increased government expenditure, on the one hand, and more taxation, on the other hand. Furthermore, this taxation will be discriminating, aimed at producers who use environmentally degrading technologies, while encouraging producers who operate with green technologies. Obviously, this set of strategies will require considerable education and much convincing and, given today's political climate, will present a Herculean challenge. In an atmosphere where the main concern is with government expenditure, and there is much effort to simplify taxes at any price, policies which tend to increase public sector activities and lead to more complex financial schemes will require more education of both the public and policy-makers as to their benefit.

One of the biggest problems preventing the implementation of economic incentives, which may lead to a sustainable future, is the lack of economic knowledge on the part of many biologists. Because our curricula do not emphasize economics, natural sciences, and engineering, and because of the simplistic introduction and presentation of economic models to non-economists, many biologists view efficiency and economic incentives as irrelevant or even hostile to their cause. They may be the first to object to introducing economic incentives to address environmental problems. Many non-economists who are concerned about the environment naturally tend to use command and control mechanisms to address environmental problems, not recognizing the inefficiency of such policies, nor the political objections that they raise. One of our main challenges is to educate biologists at all levels and to introduce more economic reasoning within environmental movements.

On the other hand, much of the economic analysis of environmental issues is devoid of any recognition of the complex biological relationships which affect the environment, as well as any technological options or considerations. Economic theories that address environmental and agricultural problems must incorporate some basic natural relationships that affect production processes and environmental pollution relationships, recognize some of the basic biological and physical rules affecting the generation and management of agricultural technology, and be much more specific and relevant to agricultural and environmental situations. Greater familiarity on the part of economists with the specificity of agriculture and the problems of the environment will make them much more effective participants in the debate on environmental resource management issues. Thus, much in the same way that we require a better economic education of the general populace, and of environmentalists and biologists in particular, it is essential that agricultural and environmental economists be better educated about biological systems.

Additionally, it is important to educate farmers and the public at large about the economic value of preserving environmental quality. One reason for sustaining environmental amenities is the benefits they provide to society. One challenge that is faced by environmental organizations is how to increase environmental awareness and environmental education. Support for sustainability will increase as more people appreciate the beauty and options that environmental amenities provide.

2.3 Equity implications of precision technology adoption

The development and adoption of precision technologies which will reduce the environmental side effects of agriculture and which will promote sustainable agricultural systems may have significant equity effects. While precision technologies tend to increase yields, which may mitigate the impact of the increased costs associated with them, in many cases, and especially in the short term, the combined effect of the adoption of these technologies and the taxation that environmental regulation entails will increase the net cost of agricultural production and reduce supply. A study by Zilberman, Schmitz, Casterline, Lichtenberg and Siebert (1991) has shown that, while the overall cost of pesticide cancellation may not be very significant to consumers, the relative impact on low-income consumers may be greater because of the larger share of their income that is spent on food products. In poorer countries, with large sections of the population spending a major proportion of their income on food products, the impact of such sustainability-promotion policies can be expected to be quite significant.

In some cases precision technologies will have an element of increasing returns to scale and require extra human capital and physical capital. The introduction of such technologies may lead to structural shifts in the agricultural sector, resulting in an increased concentration of landholdings and wealth. Since the concentration of agricultural production is undesirable for social and, to some extent, economic reasons, it will be important to increase extension efforts and public education activities which will allow smaller farms to overcome possible deficiencies in human capital and adopt precision technologies that are appropriate for them. Research on policies which will enhance broad-based adoption of such technologies is also important.

Governments need to recognize the extra burden that the introduction of green policies places on the farm sector. In particular, in developing countries it will be quite important to reduce the burden of taxation imposed on agriculture. If pollution or input taxes are substituted for agricultural output taxes which are currently widely used in many developing countries, poor agricultural producers may stand to gain, as they will have the incentives to protect the resource base on which they critically depend for survival. By promoting environmentally friendly production practices, sustainability-promotion policies will enhance the long-term productivity of agricultural systems, thus contributing to poor producers' welfare.

Solow (1992) has argued that the policies which promote environmental sustainability and increase intergenerational equity may often sharpen intra-generational inequity between the 'haves' and the 'have nots'. Our analysis confirms his perspective. It may be that certain transfer policies have to be introduced to mitigate the impact of the increased costs of supply restrictions associated with achieving environmental objectives. In particular, if policies that aim to increase global sustainability require extra sacrifices from farmers in less-developing countries, they should be compensated through transfer mechanisms. Some work in this area is already being started through the Global Environmental Facility — looking at compensation schemes for reducing tropical deforestation and other global environmental issues.

3. Directions for future research

Our analysis thus far argues that the key to sustainability is the use of new incentives to develop improved technologies and to promote the use of precision technologies that are available and under-utilized. Another important issue is increased interdisciplinary knowledge and the mutual education of economics and environmental studies among environmentalists, biologists, and economists.

We have not mentioned uncertainty problems. In all of the issues raised in this paper, uncertainty considerations are important. Technological change and adoption are activities which are done under significant uncertainty. The ability to develop mechanisms to reduce risk, and shift it away from farmers, who are risk-averse, towards government agencies and private organizations, which are less risk-averse, will be critical in order to accelerate processes of technological change and adoption. Thus, the risks and uncertainties that are associated with new precision technologies should be investigated and studied, and their implications for policy design must be explicitly recognized.

Similarly, one has to recognize the immense uncertainty associated with the environmental side effects of agricultural activities and with biological phenomena. The recent models of Dixit and Pindyck (1994) present some very practical tools that can be introduced into simulations in order to incorporate some of the natural uncertainties into environmental models. Uncertainties regarding the future of benefits may lead to delayed investment as decision-makers wait until more information is available. The uncertainty associated with environmental consequences and the irreversibility effects of interventions in some natural systems should induce decision-makers to take extra caution and develop more strict environmental regulations in situations where uncertainty is more significant. Therefore, more effort should be given to both the quantification of estimates of environmental uncertainties and the modelling of policies that take into account these uncertainties.

Finally, we are challenged to continue studying both time preferences and preferences towards non-market amenities. Indications are that discount rates may change over time, and time preferences may have some interesting and unique features. Also, individuals and societies may have different time preferences regarding the preservation of environmental amenities and financial assets. Research on this issue is still in its infancy and, as it progresses, will make development of environmental and sustainable policies more sound and acceptable. Furthermore, our lack of ability to reach a consensus regarding the value of some amenities makes it difficult to develop quantitative criteria for environmental regulation and to develop priorities between different environmental objectives. Nevertheless, in spite of the difficulties, it is clear that we are not happy with the current environmental side effects associated with agricultural activities. Even setting some basic standards for the maintenance or improvement of environmental quality can be used as a starting point towards a sustainable policy. Our big challenge will be to promote incentives which will lead to the development and adoption of new precision technologies, as well as other beneficial practices, thus promoting sustainable agricultural systems.

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