Agriculture's Portfolio for an Uncertain Future: Preparing for Global Warming

By Mark Drabenstott

To help prepare U.S. delegates to the upcoming United Nations Conference on Environment and Development, the U.S. Department of Agriculture in 1991 commissioned the Council for Agricultural Science and Technology (CAST) to determine how U.S. agriculture can prepare for global warming. CAST assembled a panel of 11 national experts, including eight biological and physical scientists and three economists. Their report, *Preparing U.S. Agriculture for Global Climate Change*, is being published by CAST. Copies are available from CAST, 137 Lynn Avenue, Ames, IA 50010-7197, telephone (515) 292-2125. This article summarizes the report's major findings and recommendations.

On June 3, world leaders will convene in Rio de Janeiro for the United Nations Conference on Environment and Development—or what people around the world are calling "Earth Summit." Earth Summit will draw legions of official delegates and perhaps up to 50,000 observers, all anxious to see whether nations can agree on a strategy for maintaining economic progress while coping with mounting concerns about the environment. Recognizing that lofty aim, some are calling this conference the ecological equivalent of Bretton Woods, the 1944 New Hampshire summit that set the global financial framework for a generation of postwar economic growth.[1]

The conference will take up many issues, but the central topic will be global warming. The burning of fossil fuels and a host of other human activities are putting more greenhouse gases like carbon dioxide in the atmosphere, threatening a warmer climate in the future. Like other industries, agriculture emits greenhouse gases, but it

Mark Drabenstott is a vice president and economist at the Federal Reserve Bank of Kansas City and is a member of the CAST panel on Preparing U.S. Agriculture for Global Climate Change. The other members of the panel are: Paul Waggoner, Chairman, Connecticut Agricultural Experiment Station; R. Lee Baldwin, University of California-Davis; Pierre Crosson, Resources for the Future; Donald Duvick, Pioneer Hi-Bred International—retired; Ronald Follett, Agricultural Research Service; Marvin Jensen, Colorado State University; Greg Marland, Oak Ridge National Laboratory; Robert Peart, University of Florida; Norman Rosenberg, Resources for the Future; and Vernon Ruttan, University of Minnesota.

is unique in that it also absorbs them through photosynthesis. Delegates at the conference will consider ways to cut emissions of greenhouse gases, store the gases that are emitted, and help the global economy adapt to a different climate.

Global warming poses a bigger threat to agriculture than to any other industry. Agriculture is conducted mostly outdoors, and changes in climate affect where, when, and how food and timber are produced. But climate is always changing, and for centuries farmers and foresters have been discovering ways to adapt to climate change. In the twentieth century, dramatic advances in technology have made agriculture even more adaptable. Thus, while global warming may pose a very real threat, U.S. agriculture will have many tools with which to respond and adapt.

Many attempts have been made to predict how global warming would affect U.S. agriculture, but these predictions remain inconclusive because tomorrow's climate is so uncertain. To decide how public policy should prepare for the threat of global warming, the following questions must be answered.

First, does U.S. agriculture play a big role in emitting greenhouse gases, and can it emit less and store more? The first section of this article describes the greenhouse effect and shows that U.S. agriculture contributes only fractionally to global greenhouse gases. Still, agriculture could store substantial amounts of the gases in forests and soil, if necessary.

And second, what can U.S. agriculture do to adapt successfully to future climate change? The second section concludes that the nation should manage a diverse portfolio of agricultural assets to adapt to an uncertain future climate. The nation has a strong base portfolio of ten assets—each of which can help agriculture adapt. A crucial asset will be the world market that facilitates trade flows among countries. But if agriculture is to adapt successfully, steps must be taken now both to strengthen those assets—including world trade channels—and to increase the flexibility in using them.

U.S. AGRICULTURE AND THE GREENHOUSE EFFECT

The greenhouse effect, although widely discussed, is still widely misunderstood. Part of the confusion is that the greenhouse effect is both natural and induced. *The natural greenhouse effect* results from gases like carbon dioxide and water vapor forming an atmospheric thermal blanket around the earth, trapping the warmth of sunlight and making the earth habitable. It has been estimated that without that natural blanket of greenhouse gases, sunlight would simply be reflected back into space and the earth's temperature would be colder by 33 degrees Celsius (C), or 59 degrees Fahrenheit (F). *The induced greenhouse effect*, or what scientists call climate forcing, is the result of additional greenhouse gases put into the atmosphere through human activities, such as the release of carbon dioxide when fossil fuels are burned. The induced greenhouse effect is well understood, and the rise in greenhouse gases from human activity is well documented. What remains unclear is how and when the increase will affect the earth's climate.

Agriculture has three vital links to the greenhouse effect. First, agriculture is made possible only through the natural greenhouse effect, and any changes to the current climate will change agriculture itself. Second, agriculture contributes to the induced greenhouse effect; burning fossil fuel to power tractors, for example, releases carbon dioxide. Finally, agriculture can reduce the amount of greenhouse gases in the atmosphere because trees and plants absorb carbon dioxide from the atmosphere and store carbon in wood or soil. This section examines these three links.

The greenhouse effect and global warming

The root issue in the global debate over climate change is whether an observed increase in greenhouse gases will change the climate in the future, and if so, how. Unfortunately, scientists have not made a conclusive link between rising atmospheric concentrations of the major greenhouse gases and future changes in climate. Notwithstanding the scientific loose ends, the consensus view today is that more greenhouse gases will mean a significant change in climate tomorrow.[2]

Without doubt, the atmosphere contains more of the major greenhouse gases than it did a century or two ago. Table 1 lists the four main greenhouse gases: carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). The table describes the sources of emission for the gases and then compares the concentrations of the gases before the industrial revolution and today, along with their current rate of increase. Carbon dioxide is the biggest culprit in climate forcing, or the induced greenhouse effect. From 1980 to 1990, carbon dioxide accounted for an estimated 55 percent of climate forcing. To stabilize the concentration of carbon dioxide at current levels, emissions from human activities—largely the burning of fossil fuels—would have to drop more than 60 percent, a highly unlikely prospect.[3]

The more important issue is how these rising concentrations of greenhouse gases will change tomorrow's climate. To answer that question, climatologists and physicists have constructed ambitious computer models called General Circulation Models (GCMs).[4] GCMs quantify the complex processes of the global climate system and are so massive that they can be solved only by running the biggest supercomputers for weeks or months on end. Once constructed, model parameters can be changed to examine the effects of rising concentrations of greenhouse gases. Nearly all projections are based on carbon dioxide concentrations doubling from pre-industrial revolution levels, an outcome that might happen by 2050 if the current rate of greenhouse gas emissions continues.

The United Nation's Intergovernmental Panel on Climate Change (IPCC) is widely regarded as issuing the benchmark prediction of future change (IPCC 1990). Drawing on GCM projections, the panel's 1990 report predicted that a doubling of carbon dioxide would ultimately raise the earth's mean temperature 1.5° to 4.5°C (2.7° to 8.1°F), with 2.5°C (4.5°F) the best guess. They also estimated that the earth will warm 1°C (1.8°F) by 2030. Along with a rise in temperature, global precipitation would increase 3 to 15 percent.

The IPCC estimated that changes in temperature and precipitation would not be distributed uniformly around the globe, but they placed less confidence in their regional projections than their global ones. For central North America (including the United States), the IPCC estimated that by 2030 temperatures would increase 1° to 3°C (1.8 to 5.4°F) in winter and 1 to 2°C (1.8° to 3.6°F) in summer. Precipitation would increase 0 to 15 percent in winter but decline 5 to 10 percent in summer. Overall, the climate would be more adverse for agriculture, particularly due to a drop in soil moisture and more days of extreme heat in the summer.

All of the IPCC projections must be tempered, however, by the many shortcomings of the GCMs that lie behind the projections (Rosenberg; National Academy of Sciences 1991a; Solow). The models divide the world into segments roughly the size of Colorado—a scale too big to capture important regional effects. And for agriculture, the regional effects are far more important than global averages. The models do not capture the dynamic interaction between temperature, evaporation, and cloud cover. That is, the models cannot predict whether global warming means more or fewer clouds, a key point in deciding how much sunlight is reflected and how much is trapped. Most important of all, the models do not effectively couple the atmosphere and the oceans, a crucial link in the earth's climate system.

The future climate cannot be predicted with a lot of certainty, but if the IPCC scenario proved true, the change in climate would have a major impact on U.S. agriculture. Higher temperatures might cut crop yields, especially if temperatures were significantly higher during critical periods such as corn pollination. Shifting temperature and

Table 1

The Principal Greenhouse Gases

	Carbon dioxide	Methane	Nitrous Oxide	CFC11	CFC12
Source of emission	Fossil fuels, deforestation	Rice cultivation, ruminants, biomass burning, coal mining	Fossil fuels, biomass burning, agricultural practices	Refrigerants, propellants solvents	Refrigerants propellants solvents
Atmospheric concentration	parts per million	parts per million	parts per billion	parts per trillion	parts per trillion
Pre-industrial (1750-1800)	280	.8	288	0	0
Present day (1990)	353	1.72	310	280	484
Current rate of change per year	1.8	.015	.8	9.5	17
	.5%	.9%	.25%	4%	4%
Reduction in human-made emissions required to stabilize concentration at present-day levels	more than 60%	15-20%	70-80%	70-75%	75-85%
Contribution to global climate forcing from 1980 to 1990	55%	15%	6%	17%	

Source: Compiled from a number of tables and figures in the Policymakers Summary and Part I of IPCC (1990), Lemon et al. (1992), and Solow (1991).

precipitation patterns might force regional shifts in production—a northward drift of the corn belt, for example. Increased rates of evaporation would make irrigation more costly and perhaps impractical in many parts of the country, including the Great Plains. But these negative impacts would be counterbalanced by the positive impact of more carbon dioxide available for photosynthesis and new technologies and production practices enabling plants and animals to adapt to the new climate.

In sum, no one can be sure that climate forcing will warm the future climate at all, but scientists generally agree that it will. A benchmark report recently issued by the National Academy of Sciences offers some helpful insights (National Academy of Sciences 1991a). The Academy's panel of experts concluded the following: At least a decade or more may be needed before atmospheric scientists refine their predictions. In the meantime, there is a "reasonable chance" (they do not put a numerical probability on reasonable chance) that greenhouse gas concentrations may double by the middle of the next century. There is also a reasonable chance that global temperatures will rise from 1° to 5°C

(1.8° and 9°F), although increases of less than 1° or more than 5°C cannot be strictly eliminated. Such a rise will have several troublesome effects on agriculture and other industries. Offering no claim that any of their projections are imminent, the Academy panel of experts also concluded that "none are precluded" (p. 26).

The CAST panel began its work with the premise that the steady enrichment of the atmosphere by greenhouse gases makes warming likely. Whether the global climate will change inconsequentially, change differently among regions, or warm even more in the future, only time will tell. But the responsible course today is to examine how agriculture might adapt to a degree or two of warming.

U.S. agriculture's contribution to the greenhouse effect

The emission of greenhouse gases is a by-product of agricultural production: carbon dioxide is released when fossil fuel is burned to power tractors. Methane is released by rice paddies and by cattle and other ruminants—animals that have more than one stomach enabling them to digest grass. And nitrous oxide is released when fertilizer decomposes in the soil. Contrary to perception, agriculture's emissions of greenhouse gases are small. The CAST panel found that emissions of carbon dioxide, methane, and nitrous oxide from U.S. agriculture comprise only 0.8 percent of global climate forcing by these three greenhouse gases (Chart 1).[5] While cattle and other ruminants are often viewed as major contributors to global warming, in fact, emissions from U.S. ruminants are a very small portion of total climate forcing from methane. Thus, it is clear that strategies aimed at reducing emissions from U.S. agriculture will have very minor impact on total global warming.

Agriculture's potential contribution in reducing greenhouse gases

Although ways could be found to cut the industry's emissions of greenhouses gases, the greater opportunity for U.S. agriculture to help mitigate climate change lies in "stashing" carbon in soil and trees and displacing fossil fuel. Stashing is a term for any process that stores or sequesters carbon out of the atmosphere and keeps it out. Agriculture is a unique industry in that it not only emits greenhouse gases, it also stashes carbon. Through photosynthesis, plants and trees use carbon dioxide and in the process store carbon in crops and trees. The consumption or decay of crops and trees returns some carbon to the air as carbon dioxide, but much is stored in timber or as organic matter in the soil. (A molecule of carbon stored in a tree that becomes a piece of furniture can be kept out of the atmosphere for a very long time.)

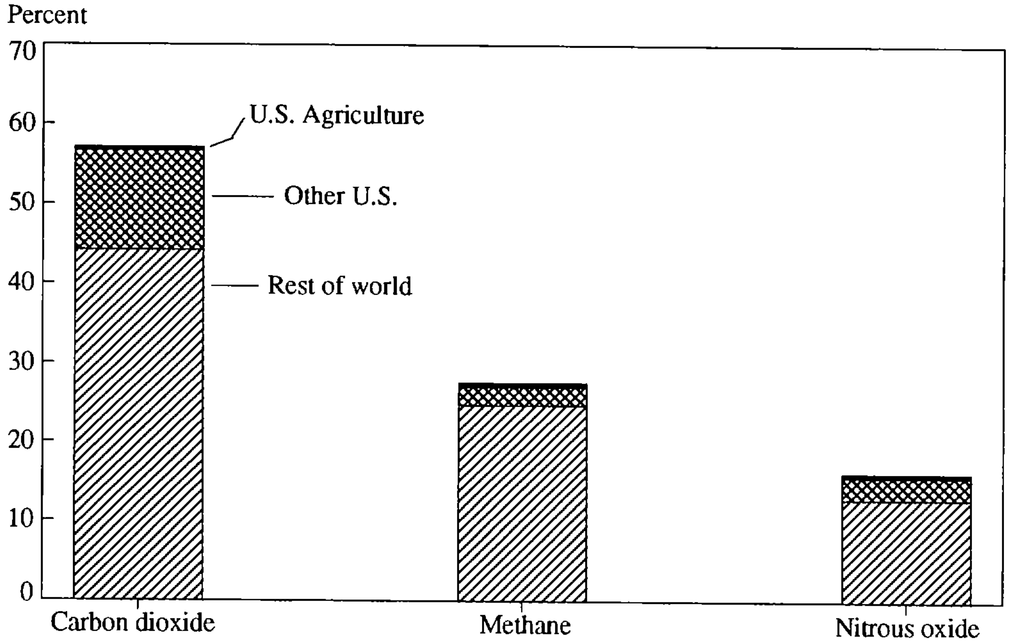
Agriculture can also produce biofuels, fossil fuel substitutes made from renewable crops, such as trees or corn. Ethanol, for example, can be produced from either wood or corn. The advantage of biofuels is that the carbon in them comes from the atmosphere. That is, photosynthesis uses carbon dioxide to produce the corn or trees that yields the biofuel. The carbon in fossil fuels, on the other hand, has been stored in the earth for millennia. When biofuels are burned, therefore, they simply recycle the carbon already in the atmosphere, unlike fossil fuels which release new amounts of carbon into the atmosphere.

Many strategies are available, but biofuels appear to offer agriculture's biggest potential to store more carbon.[6] Scientists and economists estimate that renewable crops could supply 8 percent of current U.S. energy needs. Displacing fossil fuels, the renewable crops would reduce U.S. total emissions of greenhouse gases fully 10 percent. Moreover, the biofuels would turn U.S. agriculture into a net absorber of greenhouse gases rather than a net source of their emission.

The biofuels approach to reducing atmospheric carbon dioxide, however, is not economical today. Under some circumstances, biofuels are economically competitive, but displacing more fossil fuels will require more incentives than cur-

Chart 1

Sources of Global Climate Forcing Based on 1990 Emissions



rent markets provide. To become more feasible, either the price of fossil fuels must rise or the public must be willing to tax their use.

ENCOURAGING SUCCESSFUL ADAPTATION: A PORTFOLIO APPROACH

Scientific predictions notwithstanding, agriculture faces an uncertain future climate. And in a world where population and incomes will continue to rise, agriculture's ability to adapt to climate change is crucial. Thus, the CAST panel devoted most of its attention to the question, "How well might agriculture adapt to global warming in a world with more people and more trade?"

U.S. agriculture has great inherent ability to adapt—what agricultural scientists term autonomous adaptation. The adaptations are called autonomous because they take place without policy encouragement.[7] Global temperatures have risen about 0.5°C (0.9°F) this century, but that change in climate has had virtually no impact on U.S. agriculture. The change in climate coincided with rising concentrations of carbon dioxide that are good for plants. Any impact of the slight warming was swamped by the shift from horses to tractors, from open-pollinated to hybrid corn, and the arrival of soybeans and agricultural chemicals (National Academy of Sciences 1991b).

Looking ahead, the CAST panel believes that autonomous adaptations plus improved photosynthesis from more carbon dioxide will ease much of the harmful impact of climate change on U.S. agriculture.[8] The industry will be able to draw on many resources as it adapts, including a vast land base and an extensive array of technology. Water may be the most constraining resource in adaptation, since less of this vital resource will be available to agriculture as more is reallocated to other uses whether the climate changes or not.

Yet while the nation's resilient farmers can adapt in many ways, successful adaptation will depend on the social costs that accompany autonomous adaptation. Some adaptations will cost farmers and the rest of society more than others. Social costs include adverse impacts on humans, the economy, and the environment. If the climate changes severely, farmers in some regions could be forced from business, food prices could rise, and some cropland could be lost. And those costs could mount even with a number of autonomous adaptations.

To reduce the social costs of climate change to acceptable levels, further adaptation will need to be encouraged through a series of policy steps, both now and in the future. Therein lies the goal for policymakers: pursuing policies that encourage adaptation to a range of possible future climates at minimum social cost.[9] But how can policymakers prepare now for a future climate that is so uncertain?

A portfolio strategy for encouraging adaptation

Portfolio theory suits the climate problem well because it is "concerned with decisions involving outcomes that cannot be predicted with complete certainty" (Sharpe). Moreover, U.S. agriculture has many "assets," each a unique and valuable resource for responding to climate change. The nation's extensive land base is one such asset, its agricultural research capacity yet another.

With so much uncertainty ahead, policymakers should assemble a portfolio of agricultural assets that is both diverse and flexible. Diversity is key because no one knows today which agricultural resources will provide the best opportunity for successful adaptation in the future. As in the investment world, "a good portfolio is more than a long list of [assets]. It is a balanced whole, providing the [policymaker] with protections and opportunities with respect to a wide range of contingencies" (Markowitz). To illustrate: climate change may make some U.S. farm land unproductive (effectively reducing the amount of our land asset), while greater investment in research (a net addition to our research capacity asset) could enhance productivity on the remaining land base. Alternatively, some land may become less productive, while other parts of the U.S. land base could become more productive.

Assets are valuable, but they do not help adaptation if they are frozen. Thus, flexibility is a second critical attribute of the effective portfolio. Flexibility brings the assets into play, gradually if climate change is gradual, or rapidly if an extreme drought heralds sudden change. A quick change in regional weather patterns, for instance, may mean idling land in one region while expanding plantings in another. Or it may mean using less land and more water. Flexibility will be necessary, therefore, both within an asset category, such as land, and *across* assets.

Adopting a portfolio strategy not only enables U.S. agriculture to adapt to future climates, it also measures the industry's current preparedness to adapt. Two weak spots appear immediately. First, many agricultural resources are not currently viewed as "climate change assets." Climate change assets are the unique resources that will be the basic elements in agriculture's adaptation to climate change. Responding to climate change, for example, may require agriculture to draw on the fullest reaches of its genetic diversity, placing new value on an overlooked national asset. Second, agriculture's current mix of assets is bound by several institutional barriers that prevent full use of some assets or make it difficult to switch from one asset to another. To cite but one example, numerous farm trade barriers around the world stifle the very trade flows that would mitigate climate-caused shifts in farm production.

A portfolio of flexible climate change assets

U.S. agriculture has ten assets for adapting to climate change (Table 2). Other assets might be added to the portfolio, but these ten form what will be the backbone for successful adaptation. The table describes their value as a climate change asset and summarizes the policy steps needed to make the asset stronger and more flexible in adaptation. The list of assets is not intended to initiate a quantitative assessment of all options available, but "to uncover the elements necessary for intelligent policy choices" (Nordhaus 1990). These ten assets provide options for adaptation, acknowledging that each may not be appropriate to a given situation. Collectively, however, they provide a diversity of response and thus a maximum probability that U.S. agriculture can adapt at acceptable social cost.

The United States holds a strong portfolio of climate change assets, especially compared with many other nations. The United States can lay claim to all ten assets, and it has a rich endowment of many of them. Given such strength, U.S. agriculture can play a lead role in developing the global strategy for adapting to changes in climate. Notwithstanding the portfolio's overall strength, however, the nation will have to make new efforts to both strengthen some assets and allow greater flexibility in using them. The ten assets and the CAST panel's recommended policy steps are discussed below.

Land. Land is agriculture's cornerstone asset. Compared with other sectors of the economy, agriculture uses wide expanses of land. This is no surprise because agriculture is in the business of capturing sunlight and converting it into food, fiber, and timber. Fortunately, the nation has a large base of cropland for agricultural purposes, currently about 188 million hectares (465 million acres). The nation has another 239 million hectares of pasture and range (591 million acres) and 262 million hectares of forest land (647 million acres). The wide expanse of U.S. agricultural land ranges across a diversity of climates, offering some built-in insurance against whatever climate changes might occur.

The United States could thus pursue several land options in responding to climate change. It could convert additional land to cropland. It could shift crop and animal production from one region to others. And it could devote more land to the production of biomass for fuels or to forests for stashing carbon dioxide.

Reform agricultural policy to encourage flexible land use. While the nation has an extensive land asset, policy changes are needed to fully utilize that asset as the climate changes. Current farm programs discourage farmers from shifting to alternative crops and they also discourage production shifts from one region to another. With the future climate uncertain, farm policy should encourage farmers to switch land uses freely in response to changing market signals.

Water. The nation can draw on a substantial water asset in responding to changing climate. Ground water reserves and surface water supplies are considerable in many parts of the country. Nevertheless, the competition between agriculture and other uses is already cutting the irrigated acreage in most regions. That growing competition would be heightened by any change to a drier climate.

Several water options are available for responding to climate change. Farmers can more fully adopt proven technologies that improve water use efficiency, or the quantity of farm output per unit of water input. Scientists can search for crops, production methods, and irrigation systems that increase water use efficiency. Water markets could be improved and expanded to facilitate transfers to the most valuable uses. Better weather information systems could be combined with

Table 2

Portfolio of Assets to Prepare for Climate Change

Asset	Value for adapting to climate change	Policy steps to increase flexibility
1. *Land*	Extensive cropland across diverse climates provides diversity for adaptation.	• Reform agricultural policy to encourage flexible land use.
2. *Water*	Water, which already limits farming in some regions, is crucial for adaptation if climate becomes more dry.	• Reform water markets to encourage more prudent use of water. • Raise the value of crop per volume of water used.
3. *Energy*	Reliable energy supply is essential for many adaptations to new climate.	• Improve the efficiency of energy in food production. • Explore new biological fuels and ways to stash more carbon in trees and soil.
4. *Physical infrastructure*	Facilitates trade and input flows when market signals change.	• Maintain and improve input supply and export delivery infrastructure.
5. *Genetic diversity*	Provides source of genes to adapt crops and animals to new climates.	• Assemble, preserve, and characterize plant and animal genes. • Conduct research on alternative crops and animals.
6. *Research capacity*	Provides source of knowledge and technology for adapting to climate change.	• Broaden research agenda to encompass adaptation to climate change. • Encourage private research on adaptation. • Find farming systems that can be sustained in new climates. • Develop alternative food systems.
7. *Informtion systems*	Provide information needed to track climate change and adapt to it.	• Enhance the nation's systems that exchange information. • Encourage the exchange of agricultural research information.
8. *Human resources*	Provide pool of skills enabling farmers and researchers to adapt to climate change.	• Make flexible skills the hallmark of agriculture's human resources. • Strengthen rural education systems, particularly continuing education.
9. *Political institutions*	Determine the policies and rules that facilitate or hinder adaptation to new climates.	• Harmonize agricultural institutions and policies.
10. *World market*	Enables trade to mediate shifts in farm production and sends price signals that eventually adjust production to new climates.	• Promote freer trade and avoid protectionism.

regional operation of water facilities to better manage scarce water supplies.

Reform water markets to encourage more prudent use of water. With a climate that seems likely to make water more scarce in the United States, water policies will need to be overhauled so that water prices reflect true social costs. That step will encourage better market allocation of water supplies, both within agriculture and between agriculture and other parts of the economy. Policies and institutions that govern water transfers also need careful review and investment. Efficient water markets are now found in some places, but more such markets are needed. Agriculture needs both the incentive and the mechanism to move water from low-value use to high-value use.

Raise the value of crop per volume of water used. Another high priority is to develop and introduce technologies and management systems that enhance water use efficiency. Some technologies or practices will decrease the amount of water consumed per area of cropland. Others will raise the yield of crop per area and even substitute more valuable species of crop for less valuable ones. Still others will discover and use crops for drier land and even saline water.

Energy. Although agriculture consumes less than 3 percent of the nation's total energy demand, a reliable supply of energy will be an important asset as agriculture adapts to climate change. Agriculture uses energy as tractor fuel and in the guise of fertilizers. Low energy prices in the future will help agriculture adapt, but may also encourage more emissions as agriculture consumes fossil fuels. Higher energy prices, of course, would discourage emissions but could make adaptation more difficult. Whether prices rise or fall, finding ways to increase efficiency will strengthen farmers capacity to adapt.

Improve the efficiency of energy in food production. So long as agriculture uses fossil fuels, getting more food from each unit of energy will lessen emission of a greenhouse gas. Moreover, if energy prices rise—due to reduced supplies or taxes to limit emissions—energy would be a more limiting factor in food production, forcing farmers to use it more efficiently.

Explore new biofuels and ways to stash more carbon in trees and soil. Agriculture has a second connection to energy. In addition to its traditional production of food and fiber, agriculture and forestry can produce renewable energy from solar energy by photosynthesis and the yield of biomass. The same processes can also stash away carbon from the atmosphere in trees or soil.

Physical infrastructure. One climate change asset that should not be overlooked is the nation's physical infrastructure, which supports agricultural production and trade. The Soviet Union lacked efficient systems for distributing inputs, storing and handling output, and processing food, and thus could not move its deficient supplies to consumers. By contrast, these systems mark a real strength of U.S. agriculture.

Infrastructure will play a critical supporting role in adaptation. The nation's efficient grain transportation system will facilitate new flows of trade. Irrigation systems may become even more important if the climate becomes hotter and drier. But, to be used effectively for adaptation, the nation's infrastructure cannot be taken for granted. Some grain-handling infrastructure, for example, may need to be relocated if the Corn Belt moves north.

Maintain and improve input supply and export delivery infrastructure. Due to a global consolidation of the grain industry, some segments of the U.S. grain handling and transportation system are being eliminated—elevators and rail lines, for example. Although difficult to predict now, some of the pieces now being lost could prove useful to the nation under a different climate. This suggests a thorough review of transportation infrastructure as a climate change asset. Meanwhile, enhancing water storage and distribution systems will allow easier transfer of water across uses and regions in response to changing economic conditions. In addition, adding more water storage capacity would make it easier to adapt successfully under some climate scenarios.

Genetic diversity. A diverse portfolio of genes is clearly an asset for adapting to change. One action is needed to strengthen the asset and another to bring it into play.

Assemble, preserve, and characterize plant and animal genes. A major constraint in developing a cost-effective strategy for collecting, preserving, and using genetic resources is an adequate characterization of the nation's genetic materials. A thorough description and cataloging of plant and animal genetic resources is essential if the United States is to make effective use of the plant and animal breeding techniques—including genetic engineering—that are available now and that will become available in the future. Moreover, maintaining the genetic richness of our forests and less managed ecosystems will be key to their adaptation.

Conduct research on alternative crops and animals. On a local or regional basis, developing and incorporating minor crops and animal species into mainstream production could contribute significantly to adaptation. Nevertheless, it is unlikely that alternative crops or animals will soon emerge to substantially replace existing crops or animal species now in production.

Research capacity. The nation's research capacity offers the most versatile, and perhaps most enduring, asset in the nation's portfolio of climate change assets. In many respects, research is the gilt-edge investment that will be asked to do much of the work of adaptation. With an uncertain climate ahead, the traditional focus of agricultural research on production in stable circumstances must be changed to a new mission: preparing for an uncertain climate ahead while expanding production to meet the demands of growing population and trade.[10] From this new mission flow four recommended actions.

Broaden the nation's agricultural research agenda to encompass climate change. Global warming will impose new demands on the nation's agricultural research system. In short, that system must carry out today's research agenda while at the same time preparing agriculture for an uncertain future climate. To meet that challenge, multidisciplinary research will be critical to finding technologies that will enable the nation's farmers and foresters to adapt to climate change.

Broadening the research agenda will require more funding. Part of the funding will come from the private sector, and part can be achieved through improved efficiency in public research efforts. But much of agriculture's research agenda that relates to global warming will be conducted only by publicly funded researchers.

With the extent and speed of future climate change largely unknown now, the nation's agricultural research system will need to become more flexible. If climate change is rapid, social costs of the change could mount quickly before agricultural researchers can provide technological adaptations. Thus, ways need to be found to shorten the time between the discovery of agricultural technology and its applications.

Encourage private research on adaptation. Changes in the regulations that govern agricultural production and practices often hobble the research plans of the private sector. Private sector agricultural research is quite sensitive to uncertainty about changes in regulatory regimes and how regulations are administered. Regulations that restrict the use of technology discourage new investments in research and limit the returns of previous research. Consumers, for example, may press for regulation for aesthetic reasons. If public funding for agricultural research remains limited, regulations that hobble private research will be even more debilitating in preventing successful adaptation.

Find farming systems that can be sustained in new climates. Climate change may lead to sharp impacts on the quality of the U.S. environment, intensifying the attention paid to agriculture's effect on the environment. Many technical and institutional innovations are possible to make agriculture more environmentally friendly. Among the technical possibilities are the design of new "third" of "fourth" generation chemical and biological pest management technologies and practices that enhance agriculture's ability to stash carbon.

Develop alternative food systems. If the climate change is severe, the United States may need to consider entirely new food systems. A food-system perspective should become the organizing principle for improving existing systems and for designing new systems. Many of these alternatives will include the use of plants other than current grain crops. Some of the alternatives may involve radical changes in food sources. Rogoff and Rawlins, for instance, have suggested one such system based on cellulose—both for animal production and human consumption.[11]

Information systems. Agriculture, like nearly all other industries, has been swept along as technology carries the economy into an "information age." The information asset is vital to managing modern production agriculture. It is also the lifeblood of the world market, which sends the many price signals that bring forth the supply of food that consumers are demanding. Information becomes even more important in a world where climate may change considerably. Information will be needed about climate and weather as well as about progress in adaptation.

Enhance the nation's systems that exchange information. One of the major reasons that scientists have difficulty predicting climate change is a paucity of meteorological data. Weather data for developing countries are especially weak, and because weather patterns know no borders, the threat of climate change is a strong motivation for improving weather monitoring systems globally. Using additional weather data to forecast weather for a whole season will be especially valuable to farmers who must choose their crop before a season begins and who must ration water over a whole season of irrigation. Although private weather services will continue to innovate, providing weather data will remain largely the responsibility of government.

In a changing climate, animal and plant pests and diseases will move to new regions. "Smart" systems will be required to support extension agents, consultants, and producers in identifying new problems and selecting optimum and environmentally sound control strategies. New information technology and less expensive electronic hardware provide opportunities for upgrading existing information systems.

Encourage the exchange of agricultural research information. Historically, the public sector has conducted much of the nation's agricultural research and thus maintained much of agriculture's research data. Today, private sector institutions are developing more and more new technologies for their own needs, especially in fields such as biotechnology and plant breeding. Increasingly, proprietary claims are attached to new technologies, whether the research institution is public or private. These proprietary claims (generically known as "intellectual property rights," and including such things as patents, plant variety protection, and trade secrets) are actually new ways of stimulating the development and exchange of new biological information and materials.

All mechanisms for developing and exchanging research information and materials become increasingly important as researchers—both public and private—attempt to respond quickly to climate change. It therefore behooves public and private research institutions to work together. The two groups must learn how to build on the growth in intellectual property rights and develop additional beneficial mechanisms for developing and exchanging information and materials in biological research.

Human resources. People manage the farms and invent the technology that will adapt to climate change. Agriculture's people clearly need to be well-trained. But the uncertainty surrounding the future climate calls for additional care in training this important asset.

Make flexible skills the hallmark of agriculture's human resources. Farmers and researchers have proved they can adapt to changing climatic circumstances. History is replete with examples. But the uncertain climate ahead suggests even greater need for improving general and technical skills. While it is difficult to gauge the overall skill levels of agriculture's human resources, climate change will place new and different demands on them. With so many different climates possible in the future, those that manage the farms and do the research must be able to switch production practices or research strategies with elan.

Strengthen rural education systems, particularly continuing education. Continuing education will be particularly important in helping rural communities cope with climate change. If the Corn Belt migrates north, for example, many rural communities in the southern Corn Belt face a difficult transition.

Political institutions. The institutions we create become the conduits of change. When well conceived, institutions allow agriculture to adapt to changing circumstances. When poorly conceived, institutions can hobble the inventiveness and resourcefulness that might otherwise mitigate a change in climate.

Institutions take many forms. A major institution affecting U.S. agriculture is the array of programs that constitute the nation's agricultural, natural resource, and trade policies. The rules that govern world trade in agriculture shape the trade flows that try to offset variations in agricultural production around the world.

Climate change will demand that our institutions become more flexible. For example, the water policy that settled the West in the late nineteenth century must obviously change if it is to cope with the potential climate of the twenty-first century. A number of the institutional changes needed have been mentioned for each asset, but to these we add one overriding recommendation.

Harmonize agricultural institutions and policies. The disharmony that now exists in some agricultural policies and institutions will hobble successful adaptation in the future. To cite but one example, U.S. commodity programs encourage producers to maintain production in one particular crop. The result is a rigid planting pattern across the nation, where crops become tied to one region and where alternative crops are discouraged.

The disharmonies must be identified and then corrected. There is a great need to better understand the design of institutions that encourage compatible behavior across individuals, organizations, and society at large. Policy changes will be needed in many areas, but more flexible commodity programs and improved water allocation are likely to be priorities.

World market. Perhaps the most overlooked asset in the U.S. portfolio is the world market. Today, the world market allows U.S. agriculture to sell its abundant production abroad, earning foreign exchange for the nation. The market also puts U.S. consumers in touch with foreign foods that are lower priced or more available than from domestic sources. But as the climate changes, the world market will provide even bigger benefits. It will signal U.S. producers where climate change is creating new markets for them. Its prices will encourage U.S. producers to shift production into alternative crops for society's benefit. The flow of trade will relieve food shortages, whether in the United States or elsewhere. As the grand invisible hand that coordinates adaptation, therefore, the world market is a particularly valuable climate change asset.

Promote freer trade and avoid protectionism. The world market will be a key asset to encourage successful adaptation in the future. Today, the world market is beset by a battery of trade barriers and subsidies that distort world prices. If producers respond to the wrong price signals, consumers may suffer. That is, as the climate changes farmers may produce a surplus of products that consumers do not need and a scarcity of products they want. In short, trade barriers and distortive subsidies lead to wayward adaptations that are wide of the target society intended to hit. The only way to prevent these wayward adaptations is to reduce protectionism and promote free trade through such efforts as the Uruguay Round of GATT negotiations.

CONCLUSIONS

Farmers and foresters will adapt as the climate changes, but the attendant social costs call for policy steps now to encourage even more adaptation. The challenge to policymakers can be viewed as building a balanced portfolio of climate change assets and then managing it effectively. The nation already has a rich allocation of agricultural resources, but these resources must be improved if they will be effective adapting agents in the future. With climate change highly uncertain, the portfolio must be diverse, providing several options for future adaptation. The portfolio must also be flexible, allowing ready substitution both across assets and within an asset category.

Assembling such a portfolio will not be free. As in the financial world, building the portfolio will require investment. One of the most difficult decisions facing policymakers is deciding how much to invest, and in which assets to invest. Ideally, today's investment would be weighed against the social costs imposed by climate change tomorrow. The problem, of course, is that those costs cannot be calculated.

Does this policy dilemma have a solution? There are partial solutions. First, many of the actions outlined above represent only small public investments. It is obviously in society's interest to make investments or policy changes that cost little today while substantially enhancing adaptation tomorrow. Second, most of the actions outlined above will pay economic and social dividends even if the climate does not change at all. For example, consumers will reap steady benefits from a freer world market, the grand invisible hand that coordinates adaptation. Building the physical structures and adopting policies to move water from use to use as market forces change will help the nation with its current climate and needs and certainly will speed adaptation to new climate and needs. Thus, society gains from the investment while it also prepares itself for an uncertain climate ahead.

Put simply, investing in a diverse portfolio of agricultural assets must be viewed as prudent policy. The climate seems likely to change; how much and how soon, we do not know. If the climate changes, there will be social costs to the nation, and the costs could be large. A prudent way to hedge the risk of those costs is to hold a diverse portfolio of assets and assure the flexibility to use them. Such a portfolio offers the best chance for agriculture to adapt successfully to whatever climate unfolds. And even if the climate stays the same, investing in such a flexible portfolio will surely pay dividends in the stream of other changes bound to come.

ENDNOTES

1 "Bush Caught in Earth Summit Crossfire," *Wall Street Journal*, April 7, 1992.

2 This section is based largely on Rosenberg, with supplemental information from Solow and Schneider and others.

3 Human activity accounts for only a part of the earth's total emissions of carbon dioxide. Therefore, to stabilize the amount of the gas in the atmosphere, emissions from human activity would have to be curtailed sharply.

4 A good explanation of GCMs is found in Lawrence Livermore National Laboratory (LLNL): "GCMs divide the global atmosphere into tens of thousands of discrete boxes and use the dynamical equations of motion, energy, and mass to predict the changes in winds, pressure, and water vapor mixing ratio (humidity). The vertical domain of GCMs typically extends from the Earth's surface to about 35 kilometers; this distance is divided from 2 to 20 computational levels. The horizontal domain covers the globe with grid cells, each of which is several hundreds of kilometers on a side."

5 Chart 1 is a simplification. It includes only carbon dioxide, methane, and nitrous oxide because those are the three greenhouse gases agriculture emits. As a result, the share of climate forcing attributed to the three gases is somewhat different than listed in Table 1. If other greenhouse gases are included, agriculture would have an even smaller share of total emissions.

6 Other strategies for sequestering carbon include conservation tillage practices in row crop production, preserving

natural wetlands, minimizing dryland fallowing, and reforestation. For a discussion of these and other approaches, see chapter 6 of the CAST report.

7 The process of autonomous adaptation can be illustrated as follows. When weather changes—the onset of a drought, for example—market prices change, setting in train a sequence of responses that ultimately serves to offset the initial impacts of the drought. In the case of drought, farmers unaffected by the drought plant more, lured by the higher prices. The rise in prices also encourages consumers to use less or buy more from foreign growers. The rise in prices, if sustained, also induces scientists to develop drought-resistant crops. Over time, all of these actions serve to dampen the initial rise in prices and, if the drought is mild or the production capacity elsewhere is great, mitigate it altogether.

8 A warmer climate may adversely affect U.S. agriculture, but an increase in carbon dioxide increases photosynthesis and thus makes plants more productive. A doubling of carbon dioxide from pre-industrial revolution levels, for example, is estimated to increase corn yields 10 percent and soybeans yields 30 percent (Acock and others; Jones and others; and Kimball).

9 This article focuses on the policy issues confronting agriculture. For a discussion of broader issues for economic policymakers, see Nordhaus 1991 and Schelling.

10 More than 15 years ago, Goeller and Weinberg demonstrated the right response to an uncertain future. Technical change must be directed toward widening the possibilities of substitution among natural resources and between natural resources and technology (Goeller and Weinberg).

11 Their unconventional approach suggests that some foods now produced by cereal grains and oilseeds could be produced from plants, such as trees, that contain cellulose. By means of fermentation processes, they contend, food could be engineered out of wood pulp. The advantage of the approach would be that trees are much more efficient plants than most cereals and oilseeds.

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