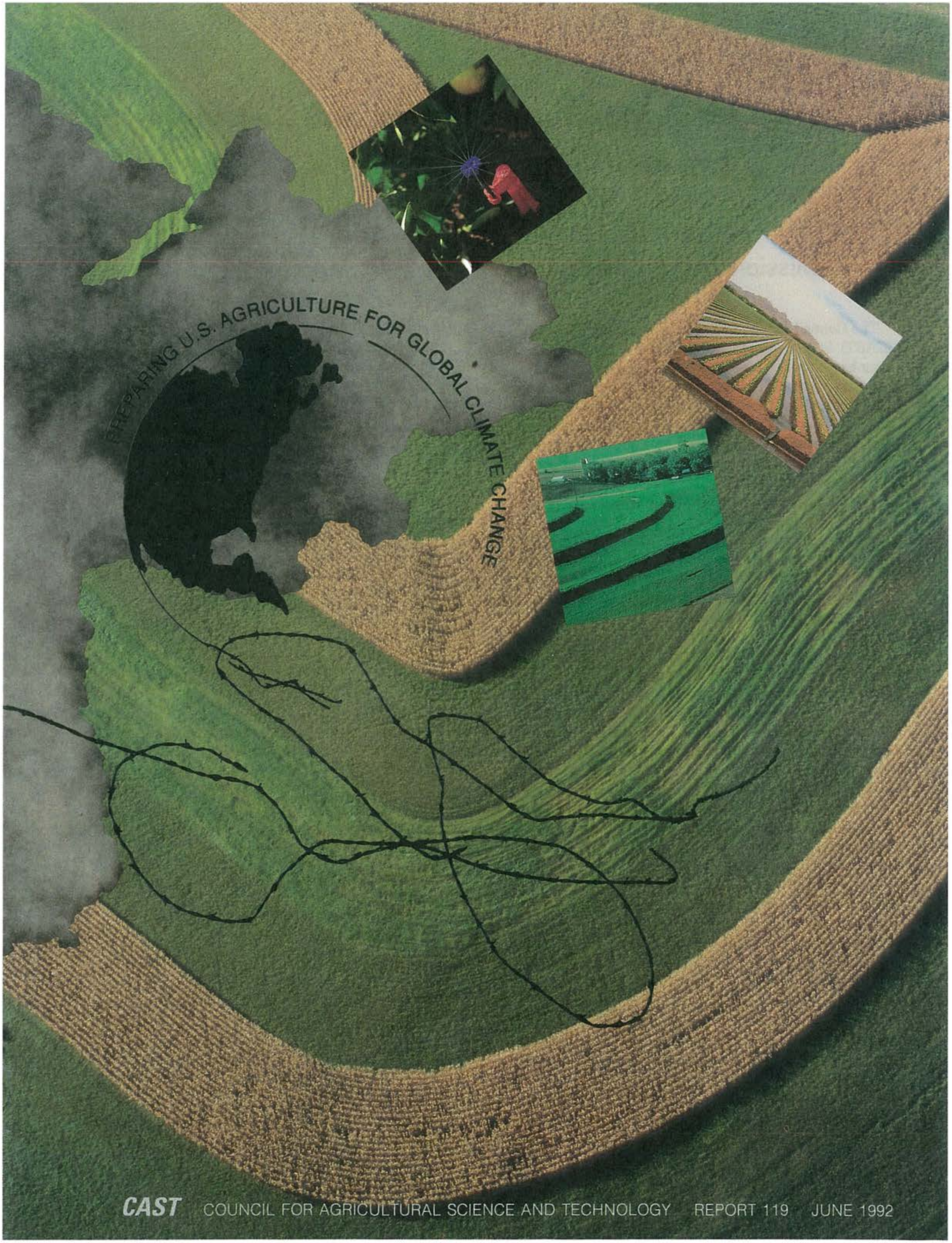

PREPARING U.S. AGRICULTURE FOR GLOBAL CLIMATE CHANGE

CAST COUNCIL FOR AGRICULTURAL SCIENCE AND TECHNOLOGY REPORT 119 JUNE 1992

Council for Agricultural Science and Technology

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    Left, Farmer raising his fence to keep pace with the soil drifts, Oklahoma, 1930s, Arthur Rothstein (Library of Congress)
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Foreword

Even more than the rest of humanity, farmers and foresters worry about the weather. All of their trees, almost all of their crops, and many of their animals stand exposed outdoors. So they worry when someone computes that greenhouse gases may change climate. They worry even more when they read that gases rising from farming or forestry may contribute to a climatic change.

Accordingly, in the spring of 1990, Assistant Secretary of Agriculture, Charles E. Hess, turned to the Council for Agricultural Science and Technology (CAST), asking on behalf of the U.S. farmers and foresters

- What role does agriculture play in having adverse effects upon the climate?
- What should agriculture do to adapt to possible climate change?
- What can agriculture do from a positive standpoint to reduce emissions of greenhouse gases?

Later in 1990, Deputy Assistant Secretary Harry C. Mussman emphasized that the analysis conducted to provide answers to those questions should be visionary and amplified them with

- Does (any proposed) strategy make sense if global warming is not realized?
- Will the net social benefits exceed the net social costs?
- What are the impacts on other resources and are they acceptable?

CAST impaneled eleven experts for this task force, including Dr. Paul E. Waggoner, Connecticut Agricultural Experimental Station, New Haven, as chair. Some had studied the emission of greenhouse gases and the impact of climate change. Others brought to the task force experience and expert knowledge of the many facets of agriculture. These facets include the underlying resources, banking and finance, the soils and fertilizers that nourish crops, breeding and husbandry of crops and animals, and the irrigation that supports crops in dry places. The facets ranged from inducing research for adaptation all the way to trade in farm products.

The task force refined the questions that amplify the charge from the U.S. Department of Agriculture (USDA) and formed the outline of the analysis and report. They searched the literature of climatology and agriculture for answers and wrote the answers. The CAST staff provided logistical support and necessary editing of the manuscript for printing. The CAST Executive and Editorial Review committees reviewed the final draft. The task force, however, is responsible for the answers.

On behalf of CAST, we thank the authors who gave of their time and expertise to prepare this report as a contribution of the scientific community to public understanding. Also, we thank the employers of the authors who made the time of the authors available at no cost to CAST. This study was supported by Grant Agreement No. 59-0700-1-107, U.S. Department of Agriculture.

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In the end, the task force and CAST hope the answers to the questions will help farmers and foresters sustain humanity in a current of changes that now includes uncertainty about the climate. The task force and CAST hope the answers will guide leaders to encourage farmers and foresters as they swim in the current of changes they will surely encounter.

Paul E. Waggoner
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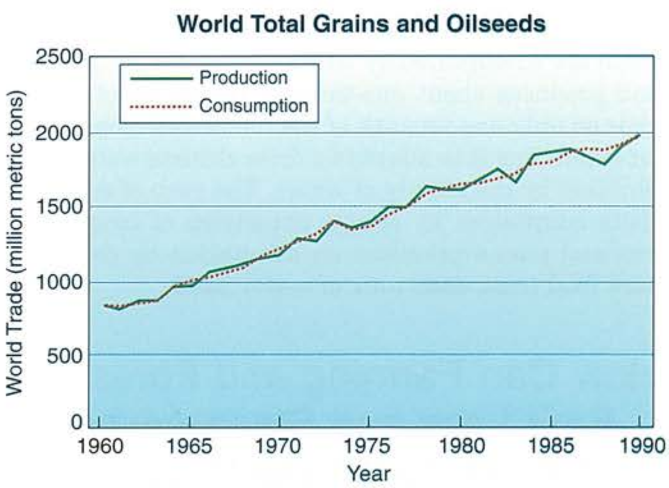
Summary

If climate changes substantially during the next half century, meeting the demands from rising population may be more difficult. On a globe with scarce resources, sustaining the required rate of growth of food production will become harder. Expanding knowledge and technology for improving agricultural production, resource husbandry, and environmental quality can, however, expand the capacity for meeting the future demands on the globe's scarce resources. This report is largely about U.S. farming and forestry—but they are connected with other nations and sectors, which also will be changed continually by the same factors affecting U.S. agriculture.

Population Growth and Grain Consumption



World Total Grains and Oilseeds

If the planet grows warmer during coming decades, climate change will join other changes foreshadowed by the growth in world production of grains and oilseeds during the generation from 1960 to 1990. As population and incomes grew during that generation, both production and trade expanded sharply, allowing diets to improve somewhat. For several decades to come, population and incomes will surely continue rising, increasing demand for food in the world market. So, the farmers of the world confront the challenge of a rising, changing population of consumers and more trade as well as likely climate change. The source of information is shown in Section 5.1.

Faced by these uncertainties, this report answers The Question:

> For a warmer planet with more people, more trade, and more CO_2 in the air, can U.S. farming and forestry prepare within a few decades to sustain more production while emitting less and stashing away more greenhouse gases?

Gases such as CO_2, methane, and nitrous oxide are called greenhouse gases because they absorb the long-wave, invisible radiation as glass absorbs radiation in a greenhouse, rather than allowing the heat to be radiated away from the earth. The steady enrichment of the atmosphere by greenhouse gases makes warming likely. So, whether the global climate will change inconsequentially, change differently among regions, or warm even more in the distant future, examining whether farming might adapt to a degree or two warming or might slow warming is the responsible course.

United States agriculture is a minor source of the gases that might change the global climate. But because farming is mostly outdoors, agriculture is more sensitive to climate than any other sector of the U.S. economy. Agriculture could, however, slow global climate change through somewhat lessened emissions and, especially, by stashing away carbon or displacing fossil fuels. If the climate changes, farmers will autonomously, without outside encouragement, adapt considerably. The human, economic, and environmental costs, which we lump together as social costs, can be reduced by encouragements that give farmers flexibility, knowledge, and technology. The public response should be to provide a wider and more flexible portfolio of assets for adaptation.

To analyze adaptation to all the changes agriculture will encounter during coming decades, we first envision a future without climate change. Without climate change, the prospects for U.S. agriculture accommodating the demand for its products at acceptable social costs appear reasonably good—if enough is invested in new knowledge to overcome emerging scarcities of resources, especially that of water.

Now we add climate to the changes agriculture will likely encounter. The history of technical change in U.S. agriculture, which shows its great capacity to meet emerging scarcities of resources, offers promise of comparable adjustments to climate change if agricultural research and the adoption of technology are encouraged. Studies show that adaptation plus the improved photosynthesis and water-use efficiency from more CO_2 would offset much harm of moderate climate change. The prolonged drought of the 1930s, the severest on record and cause of the Dust Bowl, provides an analog of a harmful climate change. Combined with the Great Depression, it harmed farming severely and disrupted communities. Since then, rising agricultural production, government programs, and a strong national economy have tempered the harm of later droughts, although none have been as severe as that of the 1930s.

During the intervening years, plant and animal breeding, irrigation, fertilizer, and accompanying husbandry contributed much to the higher agricultural productivity and exemplify the tools for adaptation. Although scarcity of water will inhibit irrigation, advances in genetics and husbandry appear at least, and possibly more, promising in the future than in the past.

Because emissions of CO_2, methane, and nitrous oxide from U.S. agriculture comprise only 1% of the global forcing of climate change by these three greenhouse gases, diminishing their emission from U.S. agriculture can mitigate the change little. Nevertheless, the emission per unit of U.S. farm product can be economically and justifiably diminished somewhat and carbon stashed away.

Autonomous Adaptation

Autonomously, without outside encouragement, farmers will adapt to ease the impact of climate change. Just how they adapt will depend on the nature and severity of impacts and the technical and managerial options open to them. Some adaptations will cost farmers and the rest of society more than others will. Generally, the lower the social cost of an adaptation, the more successful it will be. The success of adaptation thus depends upon its costs. Flexibility of the system of world trade will promote successful adaptation. Present trade policies of the United States and other countries make the existing system less flexible than it could be.

Autonomous adaptation by farmers requires sustained research to develop adapted crops, animals, and management. Many scenarios of climate change, some exceeding the analog of the Dust Bowl, have been submitted to farm simulators. When the accompanying rise in CO_2 is incorporated, the simulators show production can be maintained if new technologies are forthcoming and water is available. Much uncertainty in foreseeing adaptation arises from the uncertainty of regional climate change. Autonomous adaptations to climate change, such as minimum tillage and forestry, and adaptations to fuel costs, such as conservation of energy and fertilizers, seem more likely to mitigate or even stash away carbon than to raise emissions of greenhouse gases.

Generally, the land resources supporting agriculture will not be depleted by the autonomous adaptations if the knowledge required for raising the productivity of the land is available. The exception is water, a resource that will become less available to farming as more is re-allocated to other uses whether climate changes or not. The external effects of autonomous adaptations may be either helpful or harmful. For example, more efficient use of fertilizer and more minimum tillage will mitigate or store emissions of nitrous oxide and CO_2, whereas less irrigated land will harm some farm communities and income.

While meeting most of the challenge posed by The Question, the difficulty and cost of autonomous adaptation are exemplified by irrigation. Today irrigated land produces about one-third of the value of U.S. crops on only one-seventh of the harvested cropland, but expanding it to adapt to a drier climate would be inhibited by the supply of water. The curb of supply limits adaptation by simple expansion of irrigated area and puts a premium on adaptation by getting more food from each unit of water used.

How Can Farming and Forestry Emit Less and Stash Away More Greenhouse Gases?

Burning less fuel when fuel prices are higher and so emitting less CO_2 illustrates autonomous adaptation. Programs that remove marginal land from tillage and enrich the organic carbon in the soil illustrate encouraged adaptation. The small present emission from agriculture plus the requirement for nitrogen for crops or carbohydrate for cows, however, set boundaries of acceptable cost around the climate forcing that can be mitigated by agriculture (Figure S.1).

Despite recent reductions in fuel per unit of agricultural production, some more can likely be saved. Although U.S. cropland today emits more carbon than it absorbs, changed but still economical husbandry could cause a net absorption of carbon equal to one-third of all emissions from farming. Continuing the steady improvements in animal breeding and husbandry, the adoption of biotechnologies, and the current declining trend in consumption of milk and red meat could cut methane emissions from farming by one-fifth. Also, husbanding fertilizer could cut emission of nitrous oxide.

The great opportunity for U.S. agriculture, to help mitigate climate change lies in stashing carbon in soil and trees and displacing fossil fuel.

Through photosynthesis, farming and forestry take in much CO_2 and store the carbon in crops and trees. Although consumption and decay of food and plants return much carbon as CO_2, still, much is stored as in timber, cotton, or organic matter in the soil. When wood is burned as fuel, it displaces fossil fuel. A plausible future is displacing some 8% of U.S. energy source with biomass fuel, thus reducing U.S. emissions of CO_2 from all sources by 10%. Because this is 2 to 3 times the amount of energy used by U.S. agriculture, it would make U.S. agriculture effectively a net storer of carbon.

Happily, many of the strategies that reduce emission, sequester carbon, or yield more food from less land or fewer animals are good agricultural husbandry that should be implemented anyway.

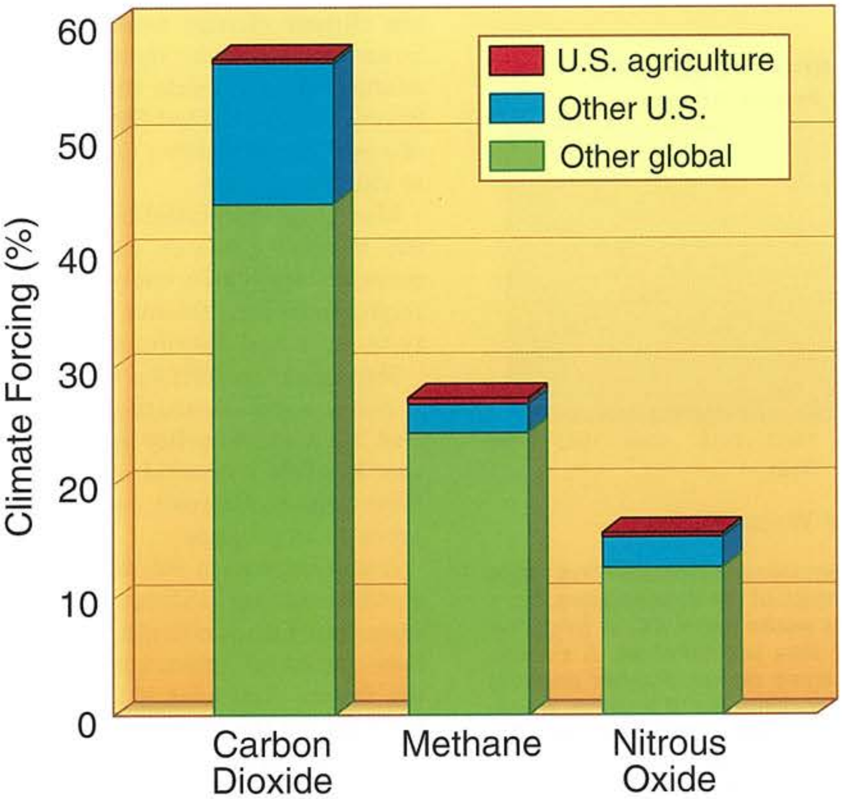


Figure S.1. The climate forcing by U.S. agriculture related to that by other activities on the globe. To compare the contribution of different activities to climate change requires a single measure called climate forcing. It combines estimates of emissions of the various greenhouse gases by each activity with the absorption of long-wave radiation from the earth and the estimated lifetime in the atmosphere of each gas. In this figure, climate forcing is expressed as the percentage of the forcing during the next 100 years by the 1990 global emission of three gases. For example, emissions of methane from the globe are 27% of all forcing, and methane from U.S. farming is 0.4% of all forcing. U.S. agriculture's emissions of all the three gases is 0.8% of the global forcing from the three gases. The sources of information are shown in Section 4.1.

How Can the Nation Encourage More Successful Adaptation?

United States agriculture faces an uncertain future climate, and changes in climate across regions are even harder to predict. Although resilient farmers and foresters can adapt in many ways, autonomous adaptation will likely leave some social costs too high. Leaders must, therefore, prepare the nation by encouraging adaptations that cut the costs of climate change to acceptable levels.

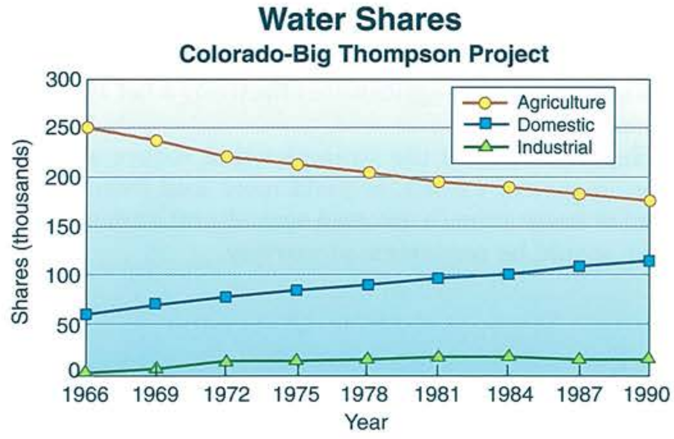
A prudent way to hedge the risk of future costs is to assemble a diverse portfolio of agricultural assets. These assets are the nation's means that will enable agriculture to adapt to climate change. Diversity is key because no one knows which asset will be needed most in tomorrow's climate. Flexibility is needed to shift from one asset to another as the climate changes.

United States agriculture has a strong portfolio of ten climate change assets (Table S.1). The nation, however, must take steps both to strengthen these assets and to increase the flexibility in using them. Success by the United States could make the concept of a portfolio attractive to other nations as a response to climate change.

Managing the portfolio will not be free. Enhancing the nation's research capacity and broadening its research agenda to encompass climate change will require new investments. So will enhancing the ability to store and distribute water more efficiently.

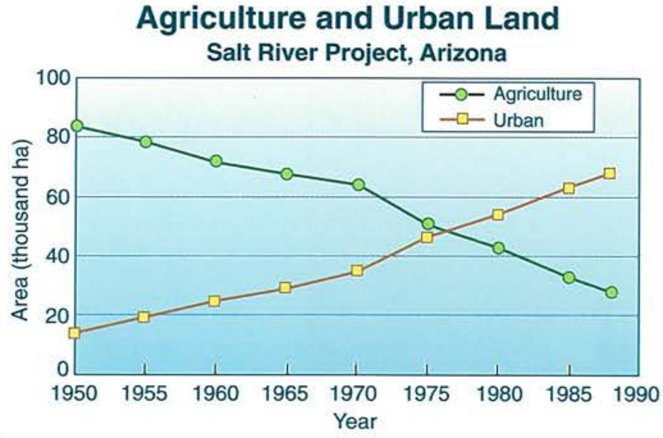
Managing the portfolio will also require innovations in public policy. To use the nation's extensive land base best, agricultural policy must allow more flexible land use. To allow the world market to coordinate adaptations here and abroad, farm and trade policies must promote freer trade.

A prudent nation will develop a diverse and flexible portfolio of agricultural assets to prepare for an uncertain future climate. Such a portfolio offers the best chance for agriculture to adapt to the climate of the future. And even if the climate stays the same, investing in the portfolio surely will pay dividends in the stream of other changes certain to occur.



Water Shares

Colorado-Big Thompson Project



Agriculture and Urban Land

Salt River Project, Arizona

Transfer of Water Rights

If climate changes, the preeminent factor affecting crops will be water supply. Over much of the United States, more water would help and less would harm yields. Irrigation could offset the harm of less precipitation. A climate change would, however, come amidst another ongoing change, the transfer of water rights out of farming. Transfers of water rights to growing cities and industries in the West are already reducing the area of land irrigated. The upper panel of the figure shows transfers that have been occurring in Colorado. Just east of the Rocky Mountains during the past 25 years, shares in the Colorado-Big Thompson project have been transferred from farming to cities for domestic and industrial use. The lower panel, marked Arizona, shows land and the accompanying rights to water that have been transferred from farming to urban use during the past 38 years. These two examples illustrate the growing competition among environmental, fishery, urban, recreational, power, and agricultural uses. The sources of information are shown in Section 3.4.

Table S.1. Portfolio of assets to prepare for climate change

Asset	Value for adapting to climate change	Policy steps to increase flexibility
Land	Extensive cropland across diverse climates provides diversity for adaptation.	Reform agricultural policy to encourage flexible land use.
Water	Water, which already limits farming in some regions, is crucial for adaptation if climate becomes more dry.	Change institutions to encourage more prudent use of water. Raise the value of crop produced per volume of water consumed.
Energy	Reliable energy supply 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.
Physical infrastructure	Facilitates trade and input flows when market signals change.	Maintain and improve input supply and export delivery infrastructure.
Genetic diversity	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.
Research capacity	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.
Information 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.
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.
Political institutions	Determine the policies and rules that facilitate or hinder adaptation to new climates.	Harmonize agricultural institutions and policies.
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.

Introduction

The likelihood of a global warming of several degrees within a century caused by humanity's enrichment of the atmosphere with greenhouse gases awakens our fear about future food (Adams et al., 1990).

Valuable to humanity and sensitive to weather, agriculture levers the projected impact of climate change. Although our report places U.S. agriculture in its global setting, our report does emphasize the farming and forestry of the United States. Sometimes we abbreviate the phrases 'the practices of foresters' or of farmers by simply writing forestry and farming. Conservatively putting aside pleading about the essentiality of food and reckoning only in dollars, one still calculates the value of U.S. agriculture and fisheries as $97 billion or 2.2% of the total national income (*Survey of Current Business*, 1992). Because most agriculture is exposed outdoors—and even irrigated crops in the end depend on precipitation and sheltered chickens expire during heat waves, agriculture is sensitive to climate. The product of this combined value and sensitivity is an anticipated harm or benefit of climate change to agriculture eclipsing the impact on any other sector (Nordhaus, 1991).

Trees and soils store carbon from the greenhouse gas, carbon dioxide (CO_2), cows and rice paddies give off another greenhouse gas, methane, and nitrogen in fertilizer can become still another greenhouse gas, nitrous oxide. Nevertheless, agriculture is largely a receiver rather than maker of climate change. Mitigation measures to forestall the accumulation of greenhouse gases would mainly affect the burning of fossil fuel. The likelihood of greenhouse warming and the possibility of harm to valuable agriculture as well as to other valued things from seaports to landscapes might seem simply to demand mitigation of our emission of greenhouse gases. Then we could put impacts and adaptations to climate change out of our mind.

But mitigation is not simple. Climate change is in the future, but the convenience and power from burning fossil fuel is now. No nation controls even a quarter of the emissions of greenhouse gases[1] (Marland, 1992). And because all nations have added a quarter to the atmospheric concentration of CO_2 since 1800 and because global temperature lags behind the concentration, humanity may already have committed the globe to some yet unseen change[2] (Keeling and Whorf, 1990; Neftel et al., 1990). So, after all, agriculturalists must think about impacts and adaptations.

Warming of the global average temperature is only a proxy for a spectrum of changes. To agriculture the potent changes would be in the level of water in streams and soil, the extremes of heat and cold, and the calendar of seasons. Since crops and forests grow in localities rather than the global average, farmers and foresters can only act on local predictions, which are still unreliable. The units of measurement and acronyms we shall employ are defined in the Appendix.

If we concentrated too much on climate change, we could overlook the flood of other changes ahead. Since the airborne CO_2 that forces climate change also feeds the photosynthesis of crops, its rise will raise crop yields, other things being equal. The global population rises inexorably, multiplying demand for food and wood. Trade moves more goods, faster and further. And, to mitigate climate change, farmers might be commanded to restrict emissions of methane and nitrous oxide, and foresters might be told to store more carbon in wood.

Farmers and foresters are in a stream of events, turbulent and variable now and uncertain and unclear in the future. As they swim, they are learning, adjusting, and adapting. Looking ahead should help them navigate this stream and thus care for humanity, which depends upon agriculture staying afloat.

So, on behalf of American agriculture, the Assistant Secretary of Agriculture for Science and Education asked CAST to answer the Big Question:

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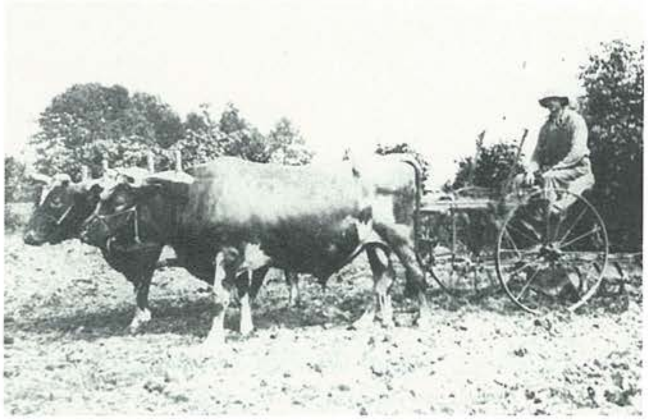
[1] In 1988 the United States emitted 1,310 million metric tons of carbon, the world 5,893.

[2] 284 ppm for 1814–1836 at Siple station to 351 ppm for 1988 at Mauna Loa is a 23.6% rise.



The speed of past adaptations encourages hope for future ones. Seven decades past is a period of time similar to that for the likely change of climate in the future. About seven decades ago in 1918 Donald F. Jones of The Connecticut Agricultural Experiment Station invented the double-cross method for producing hybrid corn. In 1920 on a farm on the Connecticut coast, farmer George Carter produced the first commercial hybrid seed. Finding it impossible to use horses to plow the rocky fields and cultivate crops in the rocky soil, Carter used a team of Guernsey bulls. In the ensuing seven decades the adaptation called hybrid corn transformed the crop. The adaptation from Carter's bulls to modern herbicides makes the transformation of the corn crop pictorial (Crabb, 1947). Credits: The Connecticut Agricultural Experiment, New Haven (left) and Pioneer Hi-Bred International, Inc. (right).

For a warmer planet with more people, more trade, and more CO_2 in the air, can U.S. farming and forestry prepare within a few decades to sustain more production while emitting less and stashing away more greenhouse gases?

The steady enrichment of the atmosphere by greenhouse gases makes warming likely. It makes the chance of a cooler climate unlikely. So, whether the global climate will change inconsequentially, change differently among regions, or warm even more in the distant future, examining whether farming might slow warming or, especially, might adapt to a degree or two warming is the responsible course.

A United Nations conference about the winners and losers from global warming concluded, "Some nations, sectors, and groups may have the ability to respond or adapt to climate change, turning this to their future advantage" (Glantz et al., 1990). Instead of suffering the impacts of the stream of climate and other changes it shall receive, and to the benefit of all who eat and use its products, American agriculture in this report prepares to adapt, emulating the ancient folk who invented farming by growing cereal in the Near East.

1 The Backdrop for Farming, Including Climate Scenarios

Foresight helps adaptation. Just reading and reacting to newspapers day by day, people may adjust to new circumstances and now and then turn them to advantage. Their adaptations will be less wasteful and frustrating, however, if they can foresee what circumstances they must adjust to tomorrow. So, without complex computation or minute detail that might impart an illusion of precision, we sketch the backdrop of affairs and environment that farming and forestry will encounter. The backdrop is suggested in the introductory phrase of the Big Question, "For a warmer planet with more people, more trade, and more CO_2 in the air."

1.1 For A.D. 2030 and without climate change, what is the most likely state or scenario of the demand for U.S. agricultural products and state of the land, water, and other resources to meet the demand? What surprises might change that scenario?

We sketch two scenarios of the future of U.S. agriculture over the next 40 years, a period that might encompass a climate change.

The first scenario, which we call a baseline, depicts a "most likely" future with respect both to domestic and foreign demand for U.S. agricultural output and to the adequacy of the land, water, and other resources needed to meet the demand. This scenario is based on study of current trends in agricultural demand and supply factors and on conjectures about how these trends are most likely to change over the next several decades. The second, "surprise scenario" sketches what, in our judgment, is a less likely future but one still sufficiently probable to be taken seriously.

The Baseline Scenario

Domestic and Global Demand for Agricultural Output

Recent History

Throughout most of U.S. history, except perhaps for cotton in the 19th century, the greater part of the demand for the nation's farm output was from domestic consumers, and the growth of demand reflected both domestic population and per capita income growth. In the last several decades, however, export demand grew faster than domestic demand, reflecting a decline in the rate of domestic population growth and a declining percentage of additional income spent on food; rapid population and per capita income growth in the rest of the world, particularly in the less developed countries (LDCs); and the strong competitive position of U.S. farmers in rising world agricultural markets.

Figure 1.1.1 shows the growth of U.S. production, consumption, and exports of grains and soybeans over the last three decades. The figure features these crops because they regularly account for two-thirds to three-quarters of the nation's land in crops, most of the herbicides and insecticides used on farms, a significant part of irrigation water applied, and, most importantly, as will be shown, because over the next several decades changes in U.S. agricultural production will be dominated by changes in export demand for these crops.

The Future

Most Americans are now sufficiently well nourished that they spend little if any increase in income on food. Thus population growth will be the main driver in the growth of domestic demand for grains and soybeans over the four decades to 2030, the period of reference taken here. Census Bureau and United Nation's baseline projections concur in showing a 20 to 25% increase in U.S. population over that period.

In the rest of the world, population is expected to grow much faster than in the United States because of relatively rapid growth in the LDCs. Bulatao et al. (1990) project an 80% increase in global population

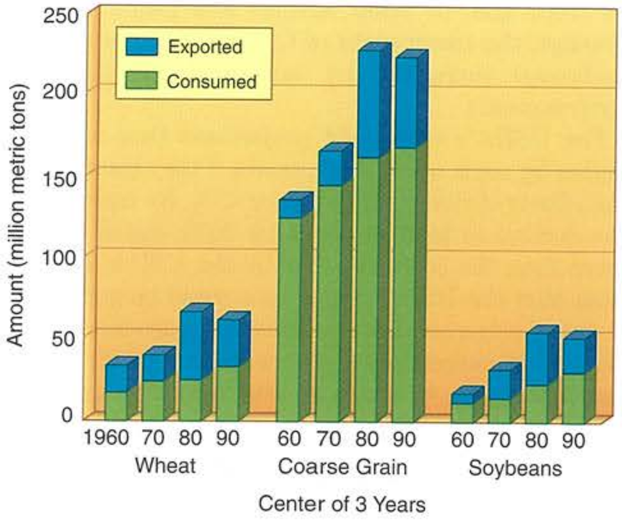


Figure 1.1.1. **U.S. production, consumption, and exportation of wheat, coarse grain, and soybeans. Consumed is the annual average million metric tons for the three years identified by the middle year and includes changes in stocks, and exported is the annual average for the same years. The sum of the two is production. Coarse grain is corn, sorghum, barley, and oats. The exports of soybeans are the beans themselves plus oil and meal in amounts equivalent to beans. U.S. Department of Agriculture. Various years. Agricultural statistics.**

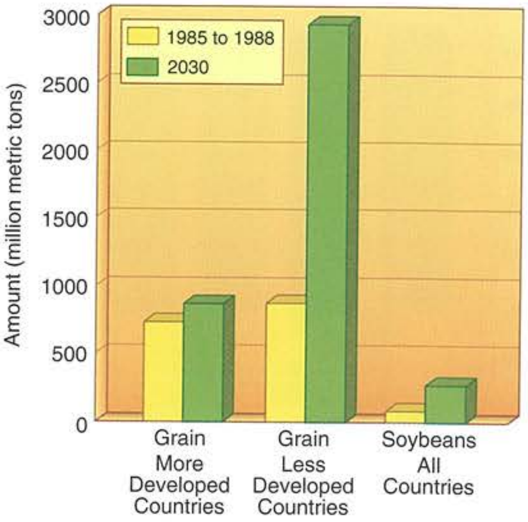


Figure 1.1.2. **The global demand for grains by rich or more developed countries and by poor or less developed countries during 1985/1988 and projected for 2030. The demand for soybeans by all countries for the same years (Crosson and Katz, 1991).**

from about 5 billion in 1990 to about 9 billion in 2030. Over 90% of the increase will be in the LDCs.

Hundreds of millions of people in the LDCs are malnourished, and as their income increases they spend some portion of the increase on food. The record suggests that they will increase their demand for meat, which will stimulate demand for feed grains (primarily corn and sorghum) and soybeans (a high protein animal feed supplement). The upgrading of LDC diets also will stimulate the demand for wheat, increasingly seen as a superior food to rice, even in Asia.

Pulling these various population and per capita income factors together, Crosson and Katz (1991) produced the scenario of global demand for grains and soybeans in Figure 1.1.2. The scenario is here taken to represent the global baseline agricultural demand environment that U.S. farmers will respond to in 2030.

The U.S. Supply Response

The ability of American farmers to respond to the demand scenario sketched in Figure 1.1.2 will depend on the quantity and quality of the land, water, technological and other resources they have available to them, including their own management skills. Figure 1.1.1 shows that the nation's capacity to produce grains and soybeans far exceeds domestic demand for these crops. In fact, Figure 1.1.1 understates the excess capacity over domestic demand because it does not reflect the fact that in 1990 the nation had some 25 million hectares of cropland in the Conservation Reserve and other land retirement programs.

Although the future as always is uncertain, there can be no serious doubt that over the next four decades U.S. agriculture will have no difficulty meeting a population driven increase in domestic demand of some 20 to 25%. The critical question concerning the future scale of the nation's agriculture is the extent to which its natural and human resources will permit it to compete in the rising global market depicted in Figure 1.1.2.

Land Resources

Figure 1.1.3 shows land in crops, forest and grassland pasture and range in selected years since 1950. The increase in forest land from 1950 to 1969 reflects inclusion of Alaska as a state, and the decline in such land from 1969 to 1987 is in large part the result of federal legislation designating several million hectares of forest land as wilderness. The stability of cropland over the entire period is owed to shifts of land in forests, grassland pasture and range to compensate for losses of cropland to urban and built-up uses. Cropland harvested is more volatile than cropland because

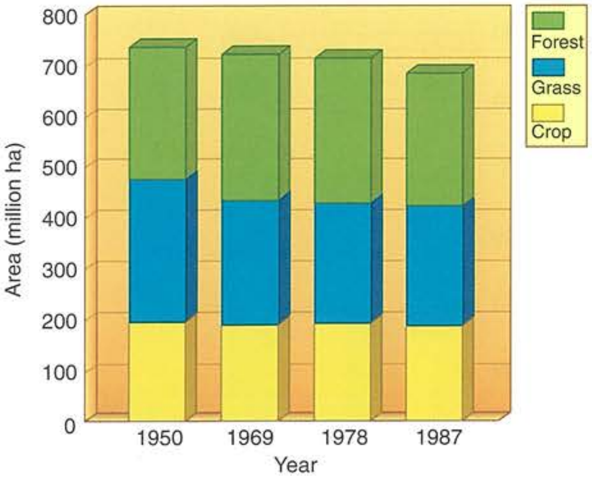


Figure 1.1.3. **The U.S. land in crops, forest, and grassland pasture and range in millions of hectares (Daugherty, 1991).**

farmers plant and harvest varying amounts of their cropland, depending on market conditions and government programs. It is noteworthy that in 1986/88, average annual crop production in the country was 72% higher than the 1949/51 average even though the amount of cropland in 1987 was slightly less than in 1950 (U.S. Department of Agriculture, 1991a).

In 1987, over 50 million hectares of land in forests, grassland pasture and range had high-to-medium potential for conversion to crop production under late 1980s economic conditions (U.S. Department of Agriculture, 1990). Projections by the USDA (1990) of land in crops in 2030 suggest, however, that the potential cropland will not be needed over that period. The USDA projections show a 30% decline in cropland from 1990 to 2030 even though production of grains and soybeans would increase about 50%. This happens because in the USDA scenario, demand for crops rises more slowly than crop yields, which technology raises as discussed below.

The yield growth contemplated by the USDA does not reflect the effects of rising atmospheric CO_2 on yields. Whether or not the CO_2 increase forces changes in climate, we know that it will affect plant growth. The question is how much under field conditions. Most plants, including many grains and tree seedlings, grow faster or larger in elevated CO_2 environments. Photosynthesis is stimulated, and there is some indication of reduced plant respiration rates as well (Wullschleger et al., 1992). Also, a CO_2-enriched environment increases water use efficiency in many plants, and this may lessen the impact of droughts. B. Kimball (1986) reviewed over 700 agronomic observations of yields of 38 crops and 18 other species and found that, on average, the mean yield of C_3 crops (e.g., wheat and soybeans) increased by one-third in high CO_2 environments.

The USDA's crop yield projections thus would be higher by some uncertain amount if they incorporated the effects of rising atmospheric CO_2. By implication, the decline in land in crops by 2030 would be even more than the 30% projected by the USDA. It seems clear that the USDA projections could be generously in error, either in underestimating future increases in demand or overestimating increases in yield, and the nation's supply of cropland still would be ample.

Irrigated Land

In 1982, the nation had irrigation systems in place on about 24 million hectares and actually irrigated about 20 million hectares (U.S. Department of Agriculture, 1990). The areas irrigated declined somewhat in the 1980s because of weaker crop prices, rising costs of pumping groundwater (higher energy prices and declining water tables in the Great Plains), and increasing opportunity costs of water in urban and industrial uses (Figure 1.1.4).

The U.S. Department of Agriculture (1990) projects continuing declines in irrigated area such that in 2030 little more than 12 million hectares would be irrigated, a 40% decline from the 1980s. Other experienced observers agree that irrigated land likely will decline, but not by the 40% projected by the USDA (Jensen, pers. com., 1992). The USDA's projected reduction is

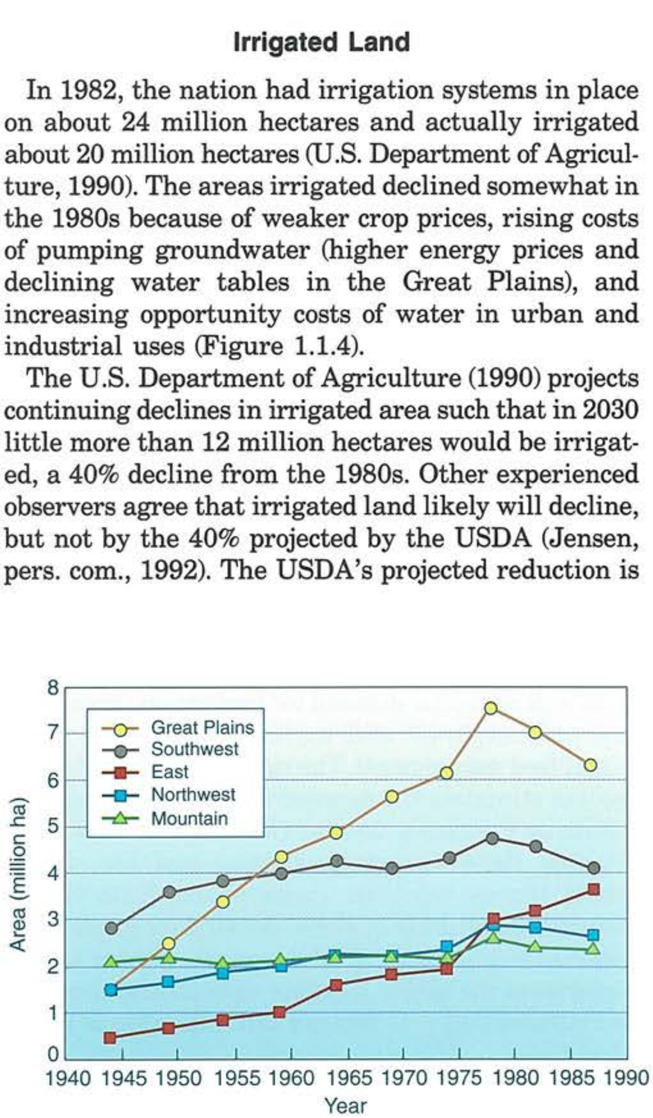


Figure 1.1.4. **The expansion of irrigated area in the five regions of the United States, and in four of the regions, its contraction (U.S. Department of Agriculture, Agric. Stat., 1983; U.S. Department of Commerce, 1989).**

owed to continuing declines in crop prices and rising water costs in the semi-arid and arid west. The higher costs would continue the trends evident in the 1980s: higher energy prices, lower water tables, and increasing competition from nonagricultural uses of water. Frederick (1991) argues that these trends will result in a relative westward to eastward shift in the location of agricultural production in the country.

In this scenario increasing water scarcity clearly is an ever tighter constraint on agricultural production over the next four decades. The constraint is confined to the West, however. On a national scale, opportunities for expansion of nonirrigated production in subhumid and humid regions more than offset the constraint.

Technology

The U.S. Department of Agriculture (1990) expects advances in technology to double yields of feedgrains, wheat, and soybeans from the 1980s to 2030 and to increase animal productivity 60 to 70%. The yield increases would average about 1.5% annually, less than the 1.8% achieved over the last 40 years. (As noted, these yield projections do not include the effects of rising atmospheric CO_2).

The USDA yield projections were developed from the deliberations of a group of experts actively engaged in agricultural research who were assembled by the Department in the early 1980s. The group assessed the then status of research on the various crops, weighing the factors tending to impede progress against those promoting it. Potential developments in biotechnology and in information technologies were prominent in the group's assessment. Explicit note was taken of the importance of maintaining federal government investments in research and development for the projected rate of technical advance to occur. We add the importance of restrictions not inhibiting the introduction of new and use of present technologies that raise yields and productivity.

Some of the expert group's thinking may now be obsolescent, if not obsolete—e.g., corn yields in the 1980s lagged considerably behind the 1.5% annual growth projected by the group, and the fruit of biotechnological research on crops continues to recede—but by and large the projections of yields continue to look plausible enough. Even if actual yield experience falls somewhat short of the projections, the abundance of land in the country suggests that land supply would not seriously impede achievement of the Department's production projections.

People, Institutions, and Infrastructure

The capacity of American farmers to adopt new technology and respond to rising domestic and foreign markets has been amply illustrated over the last 40 years. By and large, farmers were well served in this by a highly developed set of institutions for providing the information and capital needed for the farmer response and by a transport infrastructure that facilitated the movement of inputs to farmers where and when they needed them and of outputs to both domestic and foreign markets.

Although there is continuing concern about the levels of investment in rural people and infrastructure, and about current stress in financial institutions, there is no reason to expect weakness in these areas to significantly inhibit the capacity of American farmers to respond to the demand projections developed by the USDA.

This brief assessment suggests that the land, water, and other resources available to American farmers over the next 40 years and without climate change will be sufficient for them to respond at acceptable social costs to the increases in domestic and foreign demand in the baseline scenario.

The Surprise Scenario

The baseline scenario is a plausible extension of where present trends in demand and supply factors may take American agriculture over the next 40 years, given current understanding of the demographic, economic and policy conditions underlying the trends. Put briefly, the baseline scenario is an expression of the "conventional wisdom" about the future of American agriculture.

But, as everyone knows, the conventional wisdom is often wrong. Unexpected developments, or misreadings of the longer term implications of current developments, may create some "surprises" that cause significant differences between the actual future and that sketched in the baseline scenario.

We here discuss some of these possible "surprises," that is to say, events which on present understanding have low probability of occurrence but, should they occur, have high potential for creating a significantly different future for U.S. agriculture than that depicted in the baseline scenario. We leave out cataclysmic events, such as nuclear war or collision with a large asteroid, that would have consequences for the whole world system, not just agriculture.

Demand Surprise Factors

World Population Growth

Long term population projections can be wildly inaccurate, e.g., demographers in the United States in the 1940s and early 1950s completely missed the "baby boom" because they relied heavily on trends in fertility rates in the economically depressed 1930s.

The great uncertainty about present population projections is in the LDCs. The United Nations' (1989) high and low projections for those countries in 2030 differ by 1.6 billion people—from 7.9 billion to 6.3 billion. We would consider any outcome within this range as consistent with the baseline scenario. Anything outside the range we would consider a surprise. A slower rate of growth, in our judgment, is more likely than a higher one, for two reasons. Conceivably the "demographic transition"—the move from a regime of low death rates and high birth rates to one of both low death and birth rates—could occur faster in the LDCs than reflected in the World Bank's low projection. Changing attitudes in those countries toward optimum family size, advances in birth control technologies, and increased investment in family planning policies could produce such a result.

Deadlier spread of the acquired immune deficiency syndrome (AIDS) virus is the second reason for a scenario of slower global population growth than the baseline case. Some recent speculation suggests that AIDS mortality in subSaharan Africa over the next several decades could produce this result (International Service for National Agricultural Research, 1991). Asia so far has been relatively unaffected by AIDS, but there is no guarantee that the virus will not spread widely there also.

"Surprisingly" low population growth in the LDCs would cause a significant less buoyant global market for U.S. exports of food and fiber than sketched in the baseline scenario.

Production in Other Countries

The USDA data show that from the mid-1960s to the late 1980s grain production in the LDCs grew at 3.2% annually. Our baseline scenario assumes slower growth over the next 40 years, reflecting increasing natural resource and environmental constraints and greater difficulty in developing new technology. If, however, these obstacles were easily overcome and the 3.2% rate of production growth maintained, the LDCs as a group would be essentially self-sufficient in food by 2030, drastically depressing the demand for U.S. agricultural output below that assumed in the baseline scenario.

The reform of agriculture in Eastern Europe and the area of the former USSR could have a similar effect. The agricultural potential of those regions is vastly greater than performance over the last 70 years would indicate. The success of reform would significantly reduce their imports below the levels implicit in the baseline scenario. Indeed, they would emerge as net exporters, directly competitive with U.S. farmers in world markets.

Political Upheaval

The experience in Eastern Europe and the Soviet Union indicates the potential importance of radical political change as a factor affecting U.S. agriculture. As late as 1987 no one seriously expected the complete overthrow of the communist system in those areas, the subsequent emergence of popularly elected governments, and the beginnings of market economies. The events of 1989 to 1991 thus were genuinely surprising.

Changing Diets in the United States

The baseline scenario assumes that demand for grains in the United States will grow with population. Underlying this projection is the assumption that people will continue eating about the same diet. As we wrote above, most Americans are sufficiently well nourished that, individually, they will not likely consume more food, in total. On the other hand, if they changed the quality of their diet, they could consume a different amount of agricultural product. A fanciful change would be to a diet synthesized from fossil fuel, which would use no agricultural product. A more likely change, however, would be to a diet with less red meat. In fact, per capita red meat consumption has been declining for some time, by some 20% from the peak in 1971 to 1988. At the same time per capita consumption of poultry rose almost two-thirds. Concern about the health effects of red meat consumption appears to be one of the reasons for the decline, although rising red meat prices relative to poultry prices likely were also significant.

Cattle and hogs consume more grain per pound of meat produced than poultry, so continuation of these trends would in time tend to depress the demand for grain. Should the health concern about red meat consumption strengthen, the decline in demand could accelerate.

Nonfood Uses of Grain

Some corn now is used to produce ethanol, which is mixed with gasoline to make gasohol. Gasohol is not presently economically competitive with gasoline without high federal, and in some cases state, subsidies. Gasohol produces less carbon monoxide than gasoline and possibly fewer hydrocarbon emissions, although evidence on this is mixed. Should a major national policy be launched to capture these perceived environmental advantages of gasohol, it would stimulate demand for grain beyond the levels in the baseline scenario. So would greater than expected increases in petroleum prices and breakthroughs in the technology of ethanol production from grain.

Present thinking is that this set of events stimulating growth of domestic demand for grain has low probability. In addition, studies by the Solar Energy Research Institute suggest that if the nation adopts a policy of substituting biomass for fossil fuels the most likely feedstocks would be trees and several varieties of nongrain grasses, not corn or sorghum. Consequently, emergence of strong demand for grain for energy would be genuinely "surprising." But it could happen, in which case demand would grow faster than depicted in the baseline scenario.

Supply Surprise Factors

Technology

The baseline scenario assumes that technological advances in U.S. agriculture, as measured by crop yields, will be at a somewhat slower pace than in the last 40 years. The assumption could be invalidated by either upside or downside factors. On the upside, increased investments in both public and private agricultural research could produce quicker results in development of biotechnologies than now seems likely. The unexpected emergence of some "great idea" for translating a basic science finding into practical technology could have a similar effect.

These "surprisingly" rapid advances in U.S. technology, if not replicated in other countries, would increase the U.S. competitive position in world markets and stimulate more export demand than assumed in the baseline scenario. Although other countries probably would catch up with the United States in time, the export advantage could endure long enough to make a positive difference in U.S. agricultural production. (The yield-enhancing effects of rising atmospheric CO_2 would be felt worldwide, so would convey no competitive advantage on the United States).

The reverse of the factors affecting technological advance could have a comparable downside effect on the growth of agricultural supply. So could the strengthening and spread of an already evident public fear of new technology in general and of biotechnology in particular. If sufficiently strong and pervasive to shape public policies, such a fear could affect both the level and direction of agricultural technology research in ways that would slow the growth of supply significantly below the rate assumed in the baseline scenario.

Natural Resource and Environmental Constraints

Present evidence indicates that soil erosion is now not a serious threat to the long-run productivity of the nation's land resources (Crosson, 1991). Should this evidence prove misleading, erosion-induced loss of soil productivity could constrain the supply of land much more than is assumed in the baseline scenario.

Increasing concern about the environmental consequences of agriculture, e.g., sediment-polluted waters and perceived threats of agricultural chemicals to human health and ecological systems, could have a similar effect on supply. These concerns are reflected to an extent in the baseline scenario, that is the scenario assumes continuation, and probably some strengthening, of current environmental policies. But the concerns could strengthen to a level not now expected, with consequent constraints on farm management practices that would significantly limit the nation's supply response to rising domestic and foreign demand.

In Brief

The baseline scenario from now until A.D. 2030, assuming no climate change, suggests that the land, water, and other resources plus the skill of U.S. farmers and their support in research and commerce will be sufficient for them to meet domestic and foreign demand at acceptable economic and environmental costs. Among the surprises that might confound this scenario, we believe two are most plausible. On the side of demand for U.S. farm products, the growth in production in other countries could exceed expectations. On the side of supply in the United States, the likelihoods of slower practical realization of technological advances and stronger resource and environmental restrictions than expected seem more plausible than faster realization of technology and weaker restrictions.

1.2 In broad terms and for a world warmer on average, what changes of annual precipitation and, hence, water resources are likely in several major farm regions in the United States?

Rising Greenhouse Gases, Especially CO_2

Sketching the backdrop suggested in the introductory phrase of the Big Question, "For a warmer planet with more people, more trade, and more CO_2 in the air," we have completed the portions about where people seem headed and how they seem almost sure to change their direction. We come now to how the climate around them will *likely* change.

Climate change is not new. Temperature changes some 30°C from summer to winter in Minnesota, and annual precipitation changes some 2,000 mm from Forks, Washington to Indio, California. The global average temperature is 10 to 15°C cooler now than during a warm period millions of years ago and about 5°C warmer than during the Ice Age thousands of years ago. The change we write about is likely, but it is a different kind of change.

Greenhouse gases underlie the present likelihood of warming. The globe's atmosphere forms a greenhouse, tempering its warming and cooling by radiation. Much of the short-wave radiation from the sun penetrates the atmosphere, strikes the earth, and warms it. Although clouds and dust in the air absorb some of the incoming radiation, the gases are highly transparent to solar radiation as our eyes testify. The globe would, of course, become hot indeed if the incoming solar radiation were not offset by another, outgoing stream of radiation. Although some of the outgoing stream is reflected sunlight, much of it is invisible long-wave radiation emitted by the earth according to its temperature. Being much longer waves than the incoming sunlight, the longer, outgoing waves are absorbed in considerable part by peculiar gases in the atmosphere. Called greenhouse gases because they act like the glass in a greenhouse, the peculiar gases transmit sunlight but absorb outgoing radiation, are warmed by it, and in turn emit some back, warming the earth.

An effective greenhouse gas is transparent to the short-wave solar radiation and absorbs wavelengths of the long-wave earth radiation that are not absorbed by other gases. Common, abundant water vapor is an effective greenhouse gas. Three other gases concern us particularly: large quantities of CO_2 added by burning of fossil fuel and decaying organic matter, smaller quantities of methane from wet land and ruminant animals, and nitrous oxide from fertilizer. In Chapter 4 we report the quantities of the three emitted from agriculture and other sources, and we relate the emissions to global warming.

Because the greenhouse principle is enduring and not something new, its existence alone is not a reason to write now that climate is likely to change. The reason change is likely is humanity's enrichment of the atmosphere with greenhouse gases. The gas in today's atmosphere is richer in methane and nitrous oxide than bubbles trapped in glaciers centuries ago. A similar comparison shows the enrichment of the atmosphere with CO_2. Since the beginning of the industrial revolution in the 19th century, its concentration has risen from about 280 to about 353 parts

Dust storms during the Dust Bowl era of the 1930s encouraged planting of shelter belts. Credits: Soil Conservation Service, U.S. Department of Agriculture.

per million (ppm) and is projected to reach 600 during the 21st century (Houghton et al., 1990).

Scientists compute the likelihood of climate change from the greenhouse principle and the enrichment of the atmosphere with these and other greenhouse gases. We shall report some of their computations, especially of precipitation, the climatic factor with special agricultural force.

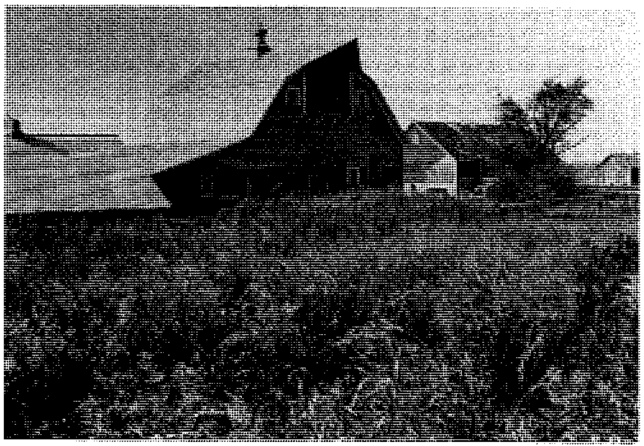
Before that report, however, we must mention a second effect of the greenhouse gas, CO_2. While CO_2 is a greenhouse gas, it also is the raw material for plant growth and narrows foliar pores, giving it a dual effect in agriculture. While CO_2 may affect agriculture indirectly by eventually changing climate, it directly affects crops now by fertilizing photosynthesis and slowing evaporation of water from plant foliage.

Computations

Whether climate change will matter demands going above the firm foundation to less firm estimation of how big or small the change might be. For more than a century scientists have been reckoning and even calculating how much greenhouse gases might warm the earth (Ausubel, 1983). The warm global average temperatures during the 1980s (Hansen and Lebedeff, 1987; Jones et al., 1986a; Jones et al., 1986b) do not prove the prediction that rising greenhouse gases will in the end warm the planet, but they are consistent with the prediction. In the computer age, scientists have progressed beyond simple calculations to computing the effect of greenhouse gases with global circulation models (GCMs). GCMs are complex mathematical simulators of the circulation of the global atmosphere, which incorporate many principles of meteorology and oceanography. They compute simulated climates of regions from specifications, including the concentration of greenhouse gases in the atmosphere.[3]

Although the direct effect of the gases is warming, warming means increased evaporation from water surfaces, and more evaporation means more water in the air and more precipitation. The loss by evaporation and gain by rain may not, of course, happen in the same place. Since water is the preeminent climatic factor for agriculture, the central question is, "Where and by how much will the demand for and supply of water change?"

While most GCMs predict more precipitation worldwide, a sampling of recent computations for a concentration of CO_2 twice the preindustrial one suggests that large regions of the conterminous 48 states of the United States will be drier. For all seasons in four regions, three GCMs all computed warming, 2 to 7°C (Figure 1.2.1). But while nearly all GCMs predict more precipitation globally, the regional and seasonal predictions for the United States are for decreases, generally deeper in the summer growing season than in the winter. One GCM in the graph predicts a decrease as deep as 0.5 mm/day during the summer. During the summer, warmer temperature would also cause faster evaporation, exacerbating shortages of soil moisture and runoff from less precipitation unless offsetting climate changes such as more clouds or less



A photo on the back cover of this report shows a barn in Beadle County, South Dakota surrounded by drifting soil and tumbling weeds. In the photos on this page, sorghum and sudan grass are shown reclaiming the soil in September 1937. Credit: National Archives.

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[3] Among many places, the principles and uncertainties of computing climate can be found in Schneider et al., 1990. A national evaluation of GCMs and their results is in Committee on Science, Engineering and Public Policy, 1991c.

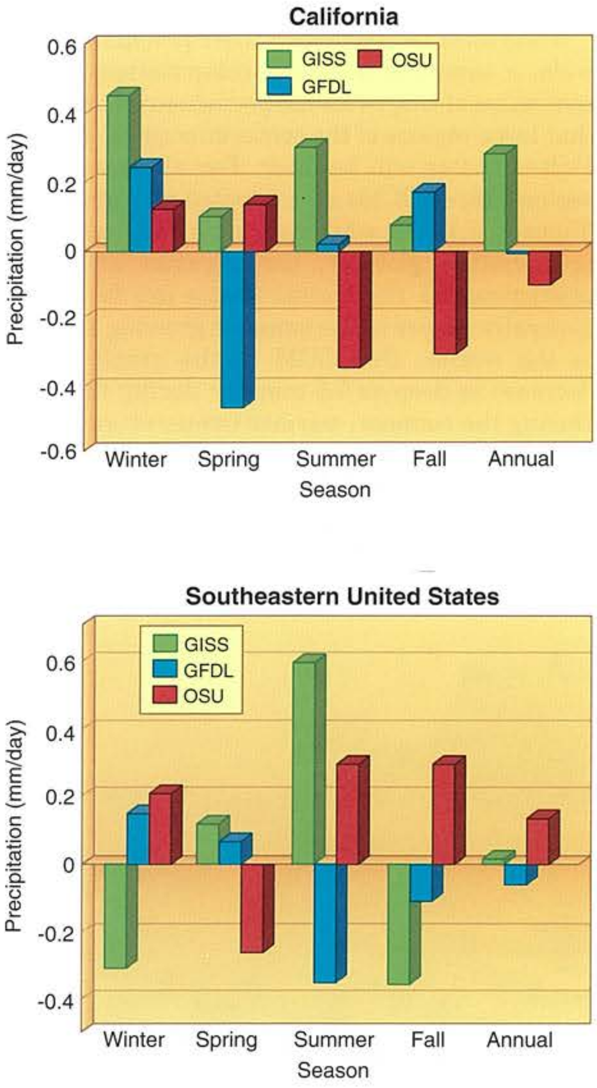

Figure 1.2.1. **Changes in seasonal precipitation predicted for California and the southeastern United States for CO_2 concentrations twice the preindustrial ones. The changes are in mm/day, and for scale, note that the July normal in Chicago is 3 mm/day. The predictions were made by three global circulation models (GCMs): Goddard Institute of Space Science (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU) (Smith and Tirpak, 1989).**

wind also occur (Martin et al., 1989).

To anticipate the effect of climate on agriculture, however, the climate of a specific region, not an imaginary average one, must be predicted. For corn production, the climate of the Corn Belt matters, and for fruits and nuts, the water supply in California's Central Valley matters especially. Reliable regional predictions will not soon be made for several reasons. First, an enormous volume of specifications and then calculations are required for regional forecasts. The present grid for calculation uses boxes roughly the size of Colorado, and even for regions of several of these large boxes, the present GCMs compute different outcomes (Figure 1.2.1). So, while most GCMs agree about the climate change likely in broad latitudinal belts, they disagree significantly about the future climate of regions and even continents (Grotch, 1988).

The second reason reliable regional predictions will not soon be made is the imperfect understanding of some important processes affecting climate. The most important of these processes seem to be the dynamics of oceanic storage and transfer of heat and the effects of clouds from increased atmospheric water vapor as well as its action as a greenhouse gas (Committee on Science, Engineering and Public Policy, 1991c). These uncertainties in turn call forth uncertainties as great as changes in ocean currents that affect regional climate (Broeker, 1987).

Unfortunately, the computations of GCMs are not generally presented as the indices that matter most to agriculture (Committee on Science, Engineering and Public Policy, 1991a): stream flow and soil moisture, changes in the timing of seasons, and untoward extremes of heat and cold. Although GCMs can compute climatic variability, their indications are not yet reliable (Mearns et al., 1990). This is a particular hindrance since climate variability determines how crops grow and animals behave.

Analogs

Analogs are an alternative to using the computations of GCMs as the backdrop for assessing impacts of regional climate change on agriculture. The analogs of climate change are periods selected from the past that are generally consistent with the warming computed by GCMs. The analog is the actual weather experienced in the past and hence has spatial and time variability on a regional scale that GCMs cannot provide. Further, the impacts on affairs and the adjustments of people during the analog period are real. One obvious analog consistent with the GCMs is the unusually hot and dry "Dust-Bowl" decade of the 1930s. During the decade, weather was not uniformly droughty in all portions of the region. For the full decade, however, average warming ranged from 0.7°C in Missouri to 1.0°C in Nebraska. Annual deficiencies in precipitation relative to later decades ranged from 28 mm in Missouri to 102 mm in Kansas. (The average precipitation declines from about 900 mm in Missouri to 400 mm in western Kansas.) The climate of the decade is generally consistent with GCM prediction for the region called MINK, Missouri-Iowa-Nebraska-Kansas. It served as the analog for a study of the impacts of climate change on MINK (Rosenberg and Crosson, 1991a, 1991b).

In Brief

For now, the backdrop of climate envisioned in the question by the phrases, "More CO_2 in the air" and "A warmer planet," must remain as sketchy as its foundation, an extrapolation of the recent rise in CO_2 in the air and its interpretation by the computations of GCMs. The extrapolation carries the concentration to 600 ppm during the next century. Given the computations of 1 to 5°C from various GCMs, the wise course is to explore adaptation to a couple of degrees warming and accompanying changes in other factors like rain that are consistent with the couple of degrees warming. If climate does not change, we will, nevertheless, have acted responsibly in our attempts to prepare for the future. And if it changes more than 2°C, we prepared for the first part of the warming. To foresee the real changes that could happen within a few years and among localities, a study of such analogs of a warmer climate as the 0.7 to 1.0°C warming of the Dust Bowl of the 1930s and in the MINK region can be instructive.

2 The Climate of Tomorrow Imposed on the World of Today

2.1 What sort of changes in crop yield and animal growth have been computed for the imposition on A.D. 1990 farming of a changed A.D. 2030 climate and CO_2 concentration? That is, what would be the impact of A.D. 2030 atmosphere and water supply on farmers suffering and never changing after 1990?

Although people and agriculture will change while the climate is changing and farmers will not suffer any harm from a new climate, we begin by assessing the impact of a future climate on the affairs of today. After all, the need for adaptation is revealed by answering what would happen without them, without change. Impact assessments of this sort have been made for more than a decade.

Animals

Before considering the impact on plants, which are exposed outdoors to the weather, we must examine the impact on animals even though they are often sheltered. After all, the $79 billion cash received for livestock in 1988 exceeded the $73 billion for crops and $7 billion for lumber[4]. Two of the interlocking factors that would affect the region and type of animal agriculture will be (1) changes in crops and (2) direct effects on productivities of the animals.

If the southwestern United States becomes more arid, the land suitable only for extensive grazing would expand and in turn increase the use of the heat tolerant cattle already found in arid, hot parts of the Southwest. Similarly, if a warmer climate moved corn production northward and present acres growing corn were planted to sorghum, the feedlots for finishing cattle would move northward to cut the cost of feed transport. Although the production of pork and broilers might also move northward with the feed crops, their movement would be driven more by the direct effect of climate on productivity because their production is intensive and highly capitalized, making the cost of transporting feed a lesser consideration. Because milk and eggs are perishable and expensive to move, their production will not move away from consumers unless climate cuts productivity significantly.

The direct harm of warmer weather to animal productivity is a mix of humidity, ventilation, housing or fencing, sun and shade, and crowding. When the temperature exceeds 29 to 30°C for long periods, feed intakes usually fall 5 to 10% and productivity, 15 to 25%. Decreasing crowding, fencing with wire, and shading the animals can significantly reduce this heat stress on cattle in arid environments (Garrett et al., 1960; Schmidtman and Miller, 1989; Stem et al., 1989).

These measures are much less effective in humid regions. Where poultry and swine are already shaded by housing, the stress can be managed somewhat by ventilation. In swine the stress can also be reduced by wetting floors or pens.

The harm of warming seems most likely in the humid South where much broiler and egg production is concentrated. Above 35°C, birds are killed, and because evaporative cooling through wet filters and ventilation is as hard in the humid South as it is through the animals' respiration, shade and ventilation are the only practical remedies. Obviously, with the warming of climate, animal pests now common in warm regions could move north, while heat in the South held other pests in check.

Overall and without effects on feed, the harm of the foreseen warming on U.S. livestock production would likely be occasional higher egg and broiler prices during and after heat waves in the southeastern poultry belt (Emmans and Charles, 1989).

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[4] The value of crops and livestock is tabulated in the Statistical Abstract (U.S. Bureau of the Census, 1990) and the value of lumber was calculated by multiplying the 45 billion board feet produced by $150 per 1,000 board feet (U.S. Department of Agriculture, 1989).

Computed Impacts of Climate Change on Crops

Luckily for the assessment of climate impacts on present crops and husbandry, mathematical models of crops and their yields have been composed, tested, and refined for many years. These models incorporate knowledge of physiological processes and field and laboratory experiments on photosynthesis, crop and soil moisture, soil properties, and CO_2 concentration. Because they mimic processes within the crop they are often called 'simulators.' Generally, the simulators require specifications of soils, plant variety, planting date, and irrigation plus daily or even hourly weather. Then they compute hourly changes in soil and plant moisture as well as the growth of foliage, roots, seeds, and so forth (Jones et al., 1988; Williams et al., 1984). Tests show the simulators can simulate crop yields within 10% of actual yields in field plots, and for example, a soybean simulator has been tested fully 36 times in the United States, Venezuela, Taiwan, Costa Rica, Thailand, and France. The simulators are ideal for comparing climates because they respond to climatic variables, and no confounding conditions are present in these tests (Hoogenboom et al., 1990; Jones and Ritchie, 1991).

Although the impact of weather on crops can be detected in historical records (Thompson, 1969), the simulators incorporating physiology have the virtue of accommodating the impact of the rising CO_2 that will accompany climate change. CO_2 concentration directly affects photosynthesis, and this effect and its difference among crops have been incorporated in simulators, showing improvements by doubled CO_2 ranging from 10% in maize and wheat to 30% in soybeans (Acock and Allen, 1985; Jones et al., 1985; Kimball, 1983). Also, CO_2 concentration narrows leaf pores through which transpired water escapes. The consequent reduction of transpiration even in a warmer climate has been computed by crop simulators (Idso et al., 1987; Jones et al., 1985; Rosenberg et al., 1989).

Simulators were important in the EPA assessment of the potential effects of climate change for U.S. agriculture (Smith and Tirpak, 1989) . The climate change scenarios produced by three GCMs for doubled greenhouse gases along with higher CO_2 concentrations were specified to simulators of several crops. The general findings were that the benefits of more CO_2 offset some or all of the harm of climate change. In many areas the moderate change predicted by one GCM raised simulated yields, while the hotter and drier prediction of the others cut them.

The foregoing generalities obscure the fact that the climate scenarios computed by the three GCMs differed and led to predicted yields ranging from mild gains to severe losses (Figure 2.1.1). All scenarios called for warming but they specified precipitation during the growing season that was different from the historical record and from each other. Hence, different yields followed, emphasizing the uncertainty of the impacts of climate change.

Historical Analog of a Warmer, Drier Climate

Because climate scenarios are uncertain, the realism of the Dust Bowl years was used as an analog of a climate change (Easterling et al., 1990). Yields on some fifty representative farms in Missouri-Iowa-Nebraska-Kansas (the MINK region) were simulated for the actual hot, dry weather of the 1930s as an analog or scenario of climate change. Different soil, crops, and husbandry made yields vary realistically from place to place (Figure 2.1.2). Further, during the 1930s, the weather was not uniformly droughty

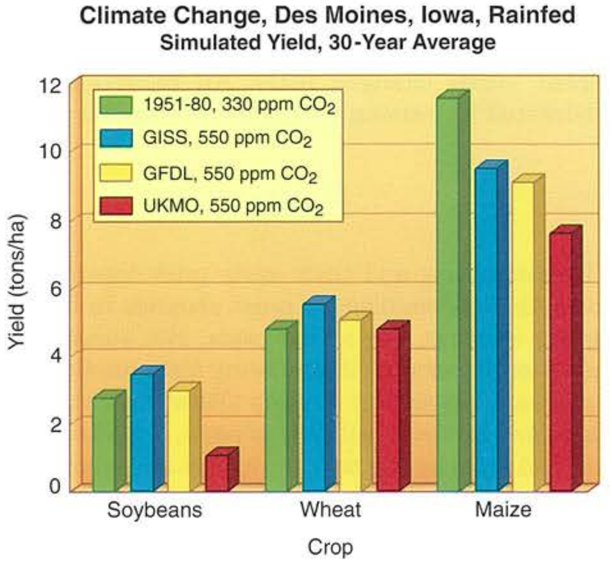

Figure 2.1.1. **The different yields of three crops computed for four climate scenarios for Des Moines, Iowa. Different global circulation models (GCMs) computed a change to a warmer climate in Des Moines, from 3.8°C for Goddard Institute of Space Science (GISS) to 8.1°C for United Kingdom Meteorological Office (UKMO) during the growing season, but they computed different precipitation climates. Annual precipitation changes computed ranged from + 3.3% for GISS to + 17% for Geophysical Fluid Dynamics Laboratory (GFDL) (Rosenzweig et al., 1992).**

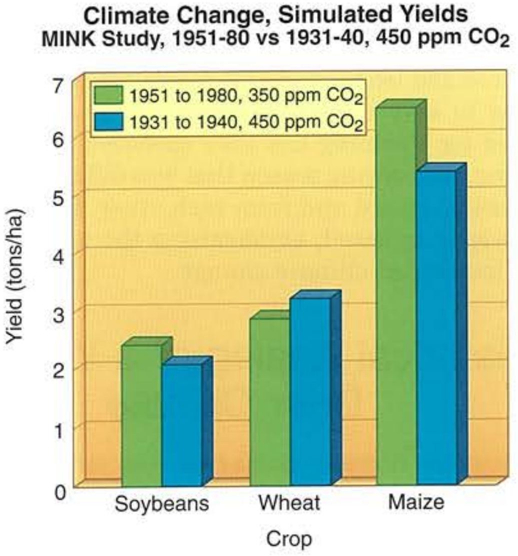

Figure 2.1.2. **The yields of modern varieties of three crops computed for the weather of 1951 to 1980 and the Dust Bowl years, 1930 to 1939. The yields were computed for 19 locations in Missouri-Iowa-Nebraska-Kansas (MINK) for corn and soybeans and 11 for wheat (Easterling et al., 1990).**

throughout the region. Generally, though, yields of summer crops fell, on average, between 18 and 25%. Wheat yields changed little. All reductions were moderated by raising CO_2 from 350 to 450 ppm.

Pests

Because crops and their pests grow together outdoors, the epidemiology of crops abounds in linkages among weather, crops, and pests. Not surprisingly, scenarios of warmer climate bring forth predictions of northward movement of pests (Stinner et al., 1989). There are, however, all sorts of pests, some favored by cool and some by warm, some by wet and some by dry weather. If climate change places a crop in a climate favorable to a pest, that pest may be expected there sooner or later (Zadoks, 1989). So, the certain outcome of a climate change is not more nor less plant pests, but rather different ones. Without new controls, the different pests will surely damage yields.

Forests

The impact of changed climates on today's forests must also be examined. Forests have the sensitivity to CO_2 and weather, especially moisture, that crops have. But longevity, diverse species, and less management distinguish forests from crops. Simulations (Botkin and Nisbet, 1989; Solomon and Tharp, 1985; Solomon and Webb, 1985; Urban and Shugart, 1989) of the impact of climate change on forests can be summarized: If the forest includes some species that are suited to a warmer climate, then the mass of timber can increase despite the decline or death of some trees. The increase may be rather rapid if the favored species are dominant species, or be slower if they are low in the canopy. Certainly, if none of the plants in the forest can adapt to the warmer climate, the total mass of the forest will decline, possibly rapidly until, perhaps by chance, a species favored by the warmer climate appears. More is written about changes in forest in answering Question 4.3 about storing more carbon in trees.

In Brief

In the end, the scenarios of the future climate that greenhouse gases are likely to bring are uncertain, the impacts of scenarios vary from harm to benefit, crop to crop, and place to place, and harm is tempered by more CO_2 fertilizing photosynthesis. In the absence of adaptation, the outlook for the impact of A.D. 2030 weather on A.D. 1990 crops is not bright. The outlook for the present forests is also affected by the uncertainty of the future climate, and in addition, one must consider whether species favored by warmer climate are already present, whether they can or will be moved in, and how long they will take to replace the unfavored ones.

3 Lessons Taught by Experience

3.1 How fast have farmers raised production in a steady climate? How fast have farmers and the associated commerce adapted to several kinds of changes—except climate?

Clues to the adaptability of agriculture to climate change lie in the speed of adjustment to other changes during the past century of more or less steady climate. Adaptability, the ability to transform new knowledge into new equipment, material, and practice that fit changing physical and cultural endowments, is the single most important quality accounting for differences in agricultural productivity among regions and eras. This is the ability envisioned when the United Nations conferees wrote, "Some nations, sectors, and groups may have the ability to respond or adapt to climate change, turning this to their future advantage" (Glantz et al., 1990).

Productivity as Evidence of Adaptation

The growth in productivity is evidence of the ability to adapt. Productivity is a ratio of output per unit of input. Productivity change is a change in the ratio. Inputs are labor, real estate, machinery, and supplies like fertilizer. Outputs are animals, crops, and so forth. Partial productivities are calculated to describe change in output per unit of a single input. Common partial productivity measures are output per hectare (land productivity) or output per worker (labor productivity).

Only change in total productivity, which measures total output per unit of total input, can properly be regarded as a change in efficiency. For example, changes in a partial productivity, such as output per worker, might be caused by some combination of substitution of capital for labor and a gain in efficiency and thus not be wholly a gain in efficiency. In recent decades the ability to analyze productivity and the data to support the analysis grew.[5]

The history of productivity told in Table 3.1.1 begins with the 2.9% per year improvement in output following the Civil War. During the 19th century the total productivity of agriculture, its output per input, began rising steadily. Between 1870 and 1900 rapid growth in labor productivity (output per worker) was partially offset by a decline in land productivity (output per hectare). Between the turn of the century and the mid-1920s total productivity (output per unit of total input) actually declined. As Americans came to the end of the land frontier, the rate of growth in output fell below the rate of growth of input.

It was not until after the middle of the 1920s that technology began to overcome the land constraint and total productivity began to rise again. Note the lesson that at least a generation was taken to put into place the capacity in science and technology to overcome a major constraint such as the closure of the land frontier. This may suggest how long it will take to overcome environmental constraints.

Returning to Table 3.1.1, we note that after 1925 the input of labor declined steeply with an accompanying rise in its productivity. At the same time the input of land was steady or actually fell during one period, while its productivity, the yield per acre, rose. Before 1925, growth in labor productivity carried the burden of growth in total productivity, but since 1925, the productivity of land and labor have both grown. In fact, they grew so fast that their growth overwhelmed a decline in the output per unit of capital and expenses

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[5] The methodology involves construction of productivity accounts aggregating inputs and outputs into measures of total input and total output. The aggregation is achieved by weighting the quantity of each input and each output by its price (or its share of total input or total output). The rate of productivity change is based on change in output relative to the change in inputs between two periods. This can be illustrated for the period 1979 to 1989 by setting the 1979 level of output and input equal to 100.

	1979	1989	Annual change (%)
Farm output	100	114.9	1.4
Total inputs	100	88.5	−1.2
Total productivity	100	128.6	2.6

Table 3.1.1. Average annual rates of change (percentage per year) in output, inputs, and productivity of U.S. agriculture, 1870 to 1990 (Durost and Barton, 1960; U.S. Department of Agriculture, 1979; U.S. Department of Agriculture, 1991a)

Item	1870–1900	1900–1925	1925–1950	1950–1965	1965–1979	1979–1989
Farm output	2.9	0.9	1.6	1.7	2.4	1.4
Total inputs	1.9	1.1	0.2	−0.4	1.1	−1.2
Total productivity	1.0	−0.2	1.3	2.2	1.3	2.6
Labour inputs[a]	1.6	0.5	−1.7	−3.8	−2.1	−2.6
Labour productivity	1.3	0.4	3.3	5.9	4.5	3.0
Land inputs[b]	3.1	0.8	0.1	−0.9	0.8	−1.1
Land productivity[c]	−0.2	0.0	1.4	2.6	2.1	0.5

[a] Number of workers, 1807–1910; worker-hour basis, 1910–1989.

[b] Cropland use for crops, including crop failures and cultivated summer fallow.

[c] Crop production per hectare.

for such things as fertilizer and pesticides, which are not shown in the table. So, the consequent total productivity that incorporates all these factors rose steadily 1 to 3% per year, manifesting the ability to adapt.

Since recent experience would hold the best clues to any approaching limits to growth or slowing rises in productivity, the trend since 1950 is graphed in Figure 3.1.1. Productivity climbed enough that total output also climbed despite the falling total inputs into agriculture.

This experience of U.S. agriculture is mirrored in that of other rich countries. It shows clearly that new technology has overcome the limits of unfavorable endowments of resources. It has also overcome inelastic supplies of resources, supplies of resources that rise a smaller percentage than the percentage increase in investment needed to expand their supply. Preeminently in the United States, technology has raised the productivity of labor as it allowed first animals and then machines and fuel to replace humans. The limits of inelastic supplies of land area have, as in Japan, been offset by high yielding varieties of crops that responded to fertilizer and other inputs for land. Elsewhere, the decline of land fertility has been offset by lime and fertilizer.

Machinery overcame labor shortages, higher yielding varieties overcame shortages of hectares, and chemicals overcame falling fertility. These alternative paths of technical change were induced by changes in resource endowments reflected in changing relative prices (Hayami and Ruttan, 1985; Ruttan, 1982). Governments foresaw the benefit of ample food and its source in research. Then prices telegraphed the relative endowments of manpower, resources, and other inputs. Prices telegraphed the message to farmers and the engineers and researchers who aid them. In the United States, the long rise in wages relative to the prices of land, machinery, and fuel encouraged, first, the substitution of land and, then, of machinery and fuel for labor. After the closing of the frontier and its abundant land nearly for the taking, land prices climbed relative to prices of inputs from industry, inducing such biological technology as hybrid corn. Almost two generations were required, however, to put in place the institutional capacity like public and private research institutions to generate a stream of new biological technology to raise yields per hectare.

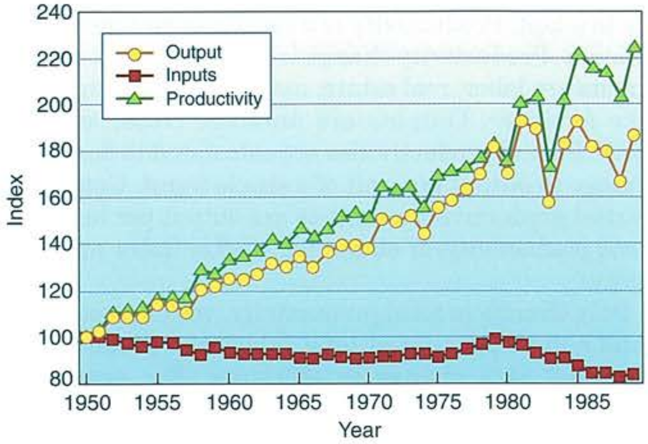

Figure 3.1.1. Index of total farm output, input, and productivity in the United States, 1950 to 1989. The index for 1950 is set at 100 (Durost and Barton, 1960; U.S. Department of Agriculture, 1979, 1991a).

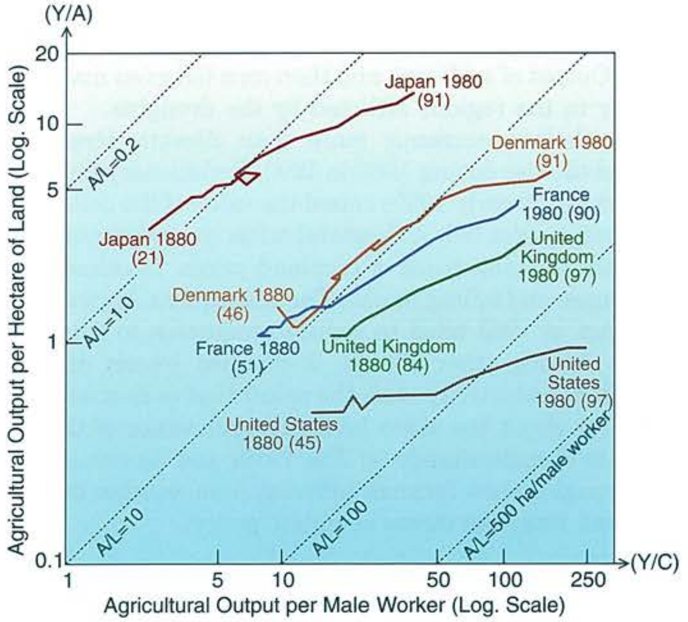

Figure 3.1.2. **Paths of the growth of agricultural productivity in Japan, three European countries, and the United States (Hayami and Ruttan, 1985).**

The Induction of Adaptation

Because our goal is foreseeing how climate change will induce adaptation to exploit any benefits and temper any harm to productivity, we expand a bit on the inducement of technical change. The basic idea is that the direction of technical change, and consequent growth of productivity is induced by a change in relative endowments of resources. In market economies these changes in endowments are interpreted for farmers by changes in prices. Researchers respond by inventing or refining technology to substitute increasingly abundant or cheap inputs for increasingly scarce or expensive ones.

Induction is illustrated by the paths from 1880 to 1980 of productivity in Japan, three European countries, and the United States. These paths are mapped on Figure 3.1.2 on coordinates of labor and land productivity and against a background of current productivities in other nations. In Japan, land was expensive and its labor cheap. Its land productivity was high and its labor productivity low. As the years passed, biological and chemical technology provided substitutes for land and the path of productivity advanced along the land as well as labor coordinates. As fertilizer became less expensive, Japanese scientists developed crop varieties that benefitted from fertilizer.

In the United States, shortage and expense of labor induced engineers to invent and farmers to buy machinery that saved labor and raised its productivity. So, the U.S. path tended strongly along the coordinate of labor productivity. The 1930 levels of labor productivity could not have been reached with 1880 machines, nor the 1980 levels with 1930 machines.

Given intermediate endowments, the three European countries took paths between the extremes of Japan and the United States.

The validity of the hypothesis that need induces technology is confirmed by the similar paths of dissimilar Japan and the United States when their paths are plotted on coordinates of (1) the relative price of fertilizer and land and (2) fertilizer per acre (Figure 3.1.3). When the relative prices of fertilizer and land were the same, the farmers of these dissimilar lands were induced to use the same amount of the technology called fertilizer. Similarly, in the two nations a given relative price of power and labor induced about the same amount of

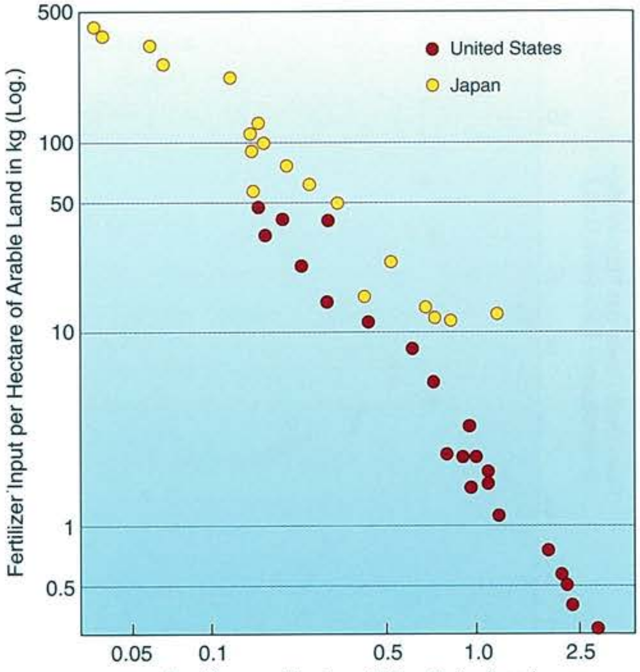

Figure 3.1.3. **The inputs of fertilizer per hectare of arable land the ratio of the prices of fertilizer to arable land in the United States and Japan. The parameters are plotted on logarithmic scales to show the percentage rather than the absolute changes in the input ratios (Hayami and Ruttan, 1985).**

technology in the form of draft power per worker (Figure 3.1.4). East resembled West when induction was the same.

Applying Past Lessons to the Future

In the end, we must think how relevant the experience of the past century can be to foreseeing a future that may include a climate change. A climate change may resemble the closing of the frontier at the end of the 19th century. The resources of regions of the United States may be eroded by warmer, drier weather. There, water will be scarcer. The resources of other regions may be harmed or enhanced by warmer, wetter weather. If prices are allowed to telegraph these new scarcities and abundances from a closing of a frontier of land almost for the taking, they will induce the invention and adoption of more efficient ways to use water, and discovery and use of newly favored regions to farm.

If climate changes in the future, it will be amidst other changes. In 1983 and 1988, regional droughts were sufficiently severe to affect national output (Figure 3.1.1). Output of soybeans and then corn fell even more sharply in the regions afflicted by the droughts.

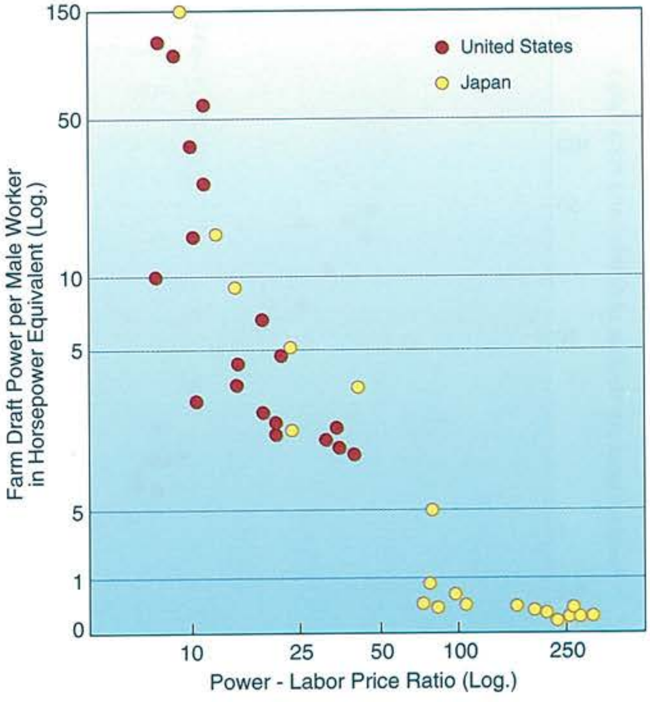

Figure 3.1.4. Relation between farm draft power per male worker and power-labour price ratio (in hectares of work days, that can be purchased by one horsepower of tractor or draft animal), the United States and Japan, quinquennial observations for 1880-1980 (Hayami and Ruttan, 1985).

Nevertheless, economic more than climatic stress damped the rise during 1980 to 1990. Deflationary policies during the early 1980s raised the value of the dollar and foreign sales fell. A financial crisis was precipitated by the ensuing crash of cropland prices, foreclosed mortgages, and failing banks. The subsequent Agricultural Act of 1985 tried to reduce production to raise prices. Among other things, it damped inputs and enhanced productivity with the result that output continued at about the same level. The relevance of the lesson to climate change is: The 1980s and its two severe droughts show farmers suffering from weather but less than from the stress of public policy.

In Brief

The ability to respond or adapt to climate change resembles the ability to raise productivity during the past century. It depends on many factors. These include the capacity to organize and sustain the institutions that generate and transfer scientific and technical knowledge, the ability to embody new knowledge in equipment and materials, the level of husbandry and education among farmers, the efficiency of markets for inputs and products, and the effectiveness of public policy in easing rather than hobbling adaptation or leading it astray.

3.2 What is the history of disruption or impact of extended periods of weather, such as the Great Drought of the 1930s, that were extremely different from the climate farmers had adapted to?

The clues to the adaptability of agriculture to climate change described in the preceding section lie in the speed of adjustment to other changes during the past century of more or less steady climate. Specially pertinent clues can also be found in the disruption and recovery from runs of bad weather in the past.

Drought in the Great Plains

The persistent, dry years of the 1930s, the Dust Bowl years in the farm belt, represent the most serious deviation from normal weather in the last century. For the decade as a whole and in some states, temperatures averaged 1°C warmer than normal and precipitation as much as 15% below normal. Average wheat yields in the Great Plains fell a third, and during the decade nearly 30% of the wheat fields planted had to be abandoned rather than harvested. The drought also affected people cruelly. Farm income fell, and people fled the Dust Bowl (Rosenberg, 1988). Because this drought coincided with the worldwide Great Depression, the suffering dramatized by John Steinbeck's *Grapes of Wrath* was not caused entirely by the drought. Nevertheless, the soil drifting around sod houses was real and caused suffering enough.

Although later droughts did not approach the Dust Bowl years in persistence, severity, and subsequent disruption, several climatic extremes since the 1930s have significantly disrupted U.S. agriculture. The droughts from 1925 to the present are depicted in Figure 3.2.1 with their effect on wheat yields. Drought hit the Great Plains during the 1950s, again in 1974 to 1976, and still again in 1987 to 1989. As Figure 3.2.1 shows, droughts following the 1930s Dust Bowl did not cause abandonment of seeded acreage to nearly the same extent. Absolute loss of yield was about same in the 1930s, 1950s, and 1970s, but because of the rise in average yields over time, the percentage losses were less. An exception to this statement is the severe loss of yield during the 1988–1989 drought. During the later droughts crop yields fell, but few people fled. The evidence showed no collapse like the 1930s of schools, banks, and communities.

During the years of the Dust Bowl, crops were hurt indirectly through pests as well as directly through lack of water. The weed, prickly pear, the insect, grasshopper, the animal, jack rabbit, and the disease, wheat rust, amplified the damage of drought (McCullough, 1981; Schlebecker, 1953; Waggoner, 1983).

The drought of the late 1980s resembled the Dust Bowl drought in severity and geographical expanse. Indeed, Riebsame et al. (1990) described it as "the most expensive natural disaster ever to affect the nation," citing crop losses of 20 to 50% and estimating the national cost of the drought by all affected industries and affairs at $39 billion. The drought was not, of course, as protracted as the Dust Bowl drought. But

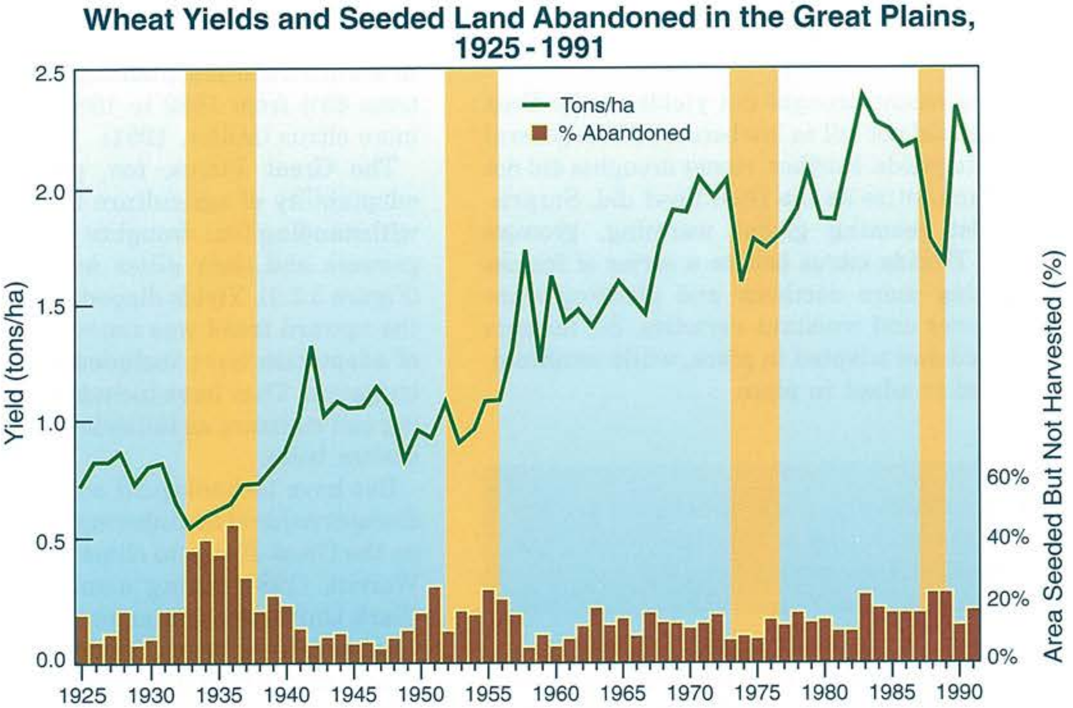

Figure 3.2.1. **The impact of four notable droughts shown by rises in the percent of the area seeded with wheat but not harvested and falls in yield of wheat in the Great Plains, 1925 to 1990. The drought years are identified by gold bars, the abandonment by brown bars, and the yields by the line. Here the states of Colorado, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, and Texas are included in the Great Plains. (U.S. Department of Agriculture, National Agric. Stat. Serv., 1992).**

in spite of the headlines, the 1987-89 drought caused less human and financial disruption than the Dust Bowl, a phenomenon that will be discussed below.

Freezes in Florida

Florida oranges are vulnerable to freezing temperatures as wheat is to drought. Citrus grows well between 13 and 38°C, but freezing temperatures cause problems. Although citrus trees when dormant can withstand temperatures well below freezing, the fruit is easily damaged if temperatures fall only as far as −2°C. While the climate of central Florida is generally excellent for growing oranges, severe freezes also occur there. Recently, severe freezes damaged and killed trees in 1962, 1971, 1977, 1981 to 1983, and 1985 to 1986. Miller (1991) cites the freeze of 1962 and subsequent rise of price as the sparks that set off the development of the Brazilian orange industry and then decline of Florida oranges on the world markets during the 1980s. In the winters of 1983 and 1985 some Florida counties lost almost 90% of their trees, and in eight counties in 1982 to 1986 the loss of trees related to freezes exceeded 85%.

In Brief

Although a recent drought cut yields as the Dust Bowl did, they did not fall as low because of the general rising trend in yields. Further, recent droughts did not collapse communities as the Dust Bowl did. Surprisingly, amidst seeming global warming, growers adapted the Florida citrus belt to a series of freezes by abandoning more northern and planting more southern groves and resistant varieties. So, farmers have both fled and adapted in place, while communities have had to adapt in place.

3.3 Have farmers only endured extended periods of extreme weather or have they sometimes adapted and prospered?

Our goal is finding ways U.S. farming and forestry can prepare within a few decades to sustain more production despite a climate change. So, after examining the disruption of extended periods of extreme weather that are conceivably analogs of a climate change, we must see whether farmers only endured. Or did they sometimes adapt and prosper, giving us clues to preparations that make sense now.

A popular view pictures farmers forever suffering under the blows and trials nature deals out. While their fortunes do indeed vary greatly because of natural phenomena—bad weather and pests especially—farmers also show great ability to adapt their practices and increase their productivity despite severe and frequent stress. We shall find clues to sensible adaptations.

Adaptations

In climates where rainfall is short or unreliable, farmers irrigate. When the weather is dry or stormy, they reduce erosion by minimum tillage and management of residues of crops. To cope with short growing seasons, they plant crops and varieties of crops that mature more quickly. To fight frost, fruit growers heat their groves by burning fuel, release the latent heat of freezing from sprinkled water, and sometimes even employ helicopters to mix warmer air above with colder below.

The five severe freezes of Florida citrus during 1960 to 1990 induced adaptation. Growers perceived an increase in the risk of freezes. In the counties affected by the freezes, growers actively changed toward less susceptible although less valuable varieties. Further, in southern Florida, planting increased the number of trees 63% from 1982 to 1988. And, Brazilians grew more citrus (Miller, 1991).

The Great Plains, too, provide evidence of the adaptability of agriculture to stressful climate. Notwithstanding four droughts and their impacts, wheat growers and their allies more than doubled yields (Figure 3.2.1). Yields dipped during the droughts, but the upward trend was renewed after each. The tools of adaptation have included improved varieties and irrigation. They have included such means of improving soil moisture as fallowing, stubble mulching, and shelter belts.

But have technological advances and institutional changes reduced the inherent sensitivity of agriculture on the Great Plains to climate variability and stress? Warrick (1980), using a methodology developed at Clark University, attempted to test the validity of the "lessening hypothesis," which states that adaptations of societies to climatic events will lessen the impacts of such events in the future. His finding with respect to wheat production is consistent with Figure 3.2.1, i.e., in the 1950s and 1970s a smaller percentage of yield was lost than in the 1930s. When adjusted for the length of the drought, however, sensitivity, he concluded, was unchanged.

Other facts such as migration, health, transfers of farms, and government relief, however, provide evidence of lessening since the 1930s. They provide even more evidence since the drought of the 1890s, which killed as well as drove people to migrate. During the drought of the 1930s the U.S. government first assisted drought-stricken families significantly. On the other hand, farm transfers—about half involuntary—rose greatly in the 1930s. To what extent people's distress during this period was caused by economic factors, by drought or by their interaction is unknown.

In the 1950s and 1970s, few migrated from drought stricken areas, and the amount of land transferred did not rise significantly. Government response was quick and applied significant resources. Despite the difficulty of factoring out differences in drought severity and economic conditions, Warrick still concluded that there has been a " . . . progressive lessening of the impact of drought on local agricultural residents."

The expansion of the geographic extent of a crop may be expansion of its climatic extent, illustrating adaptation to an enduring climate. Perhaps the most impressive example is the near doubling of the area where hard red winter wheat is profitably grown in the United States. Winter wheat has advantages over the competing spring wheats. Planting it in the fall, a farmer avoids planting spring wheat in the normally wet and cold soil of the spring. Winter wheat is harvested in the early summer before it suffers the heat and drought of mid-summer. The adaptations of genetic and other improvements through 60 years allowed winter wheat to expand (Figure 3.3.1). At its northern boundary in 1980, winter wheat grew with 20% less precipitation and 10 days shorter growing season than at its northern boundary in 1920. The temperature at the old boundary is about 4°C warmer than at the new.

Have farmers adapted to pests encouraged by extended periods of weather favorable to their outbreak? Although heroic controls of swarms of locusts or grasshoppers encouraged by the weather might be cited to answer "Yes," adaptation to the pests characteristic of the climate of different places provides a better answer. Most certified seed potatoes are grown in northern states where the environment is less favorable to the spread of viruses by insects. When the seeds of cabbage, turnip, and rutabaga were grown in the Middle West and East, the crop was attacked by bacteria. So, the seed growing was moved to a drier region in the West. Similarly the growing of bean seed was shifted to irrigated Rocky Mountain and Pacific regions to avoid pathogens spread by spattering rain.

During the 1920s the production of pea seed was concentrated in the Northeast, where seed-borne diseases flourished in rainy years. Over a period of several years, its production was shifted to dry, irrigated sites in the West, where reliably disease-free seed was grown. The shift was complete by 1950 (Walker, 1950). Clearly crops are adapted by moving to regions where pests are less severe.

Alternatively, pesticides can adapt crops to a climate that encourages the pest. The proportion of fungicides applied to tomatoes in the Southeast is far higher than the proportion of the U.S. crop from that region, but the fungicides are an adaptation that allows tomatoes to be grown there (National Research Council, 1987).

Although we concentrate on the United States, adaptation in a less technological agriculture tests the robustness of the ability to adapt (Jodha, 1989).

Warnings

What warning must be added to these encouraging examples of successful adaptation? First, as revealed in the example of wheat in the Great Plains, in spite of a trend of rising average yields of major crops, production is still vulnerable to severe weather. The 20 to 50% drop in corn, soybean, and spring wheat production during the drought of 1987 to 1989 shown in Figure 3.2.1 shows that while agriculture as a whole is indeed more robust now than in the 1930s, plants still fail when rains fail.

The second warning is that some adaptations of the past may prove environmentally or economically unsustainable in the future. Already the expanding irrigation that boosted production in the Great Plains is drawing down the Ogallala Aquifer. Extinction of

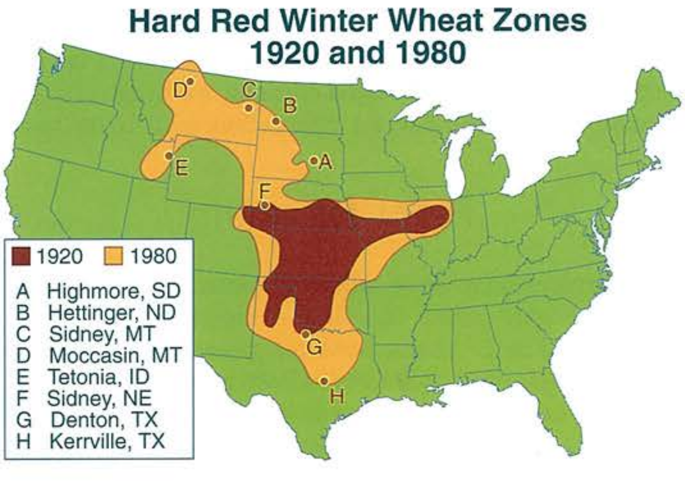

Figure 3.3.1. Extent of the hard red winter wheat in 1920 and 1980 (Rosenberg, 1982).

wild relatives, perhaps by climate change (Wilson, 1989), could slow future advances in crop breeding. Environmental restrictions on pesticides could prevent the adaptation of a crop to a climate that encourages the pest.

The third warning is that more than weather affects farming. What crops farmers will grow, where they will grow them, and how much they will grow will be conditioned not only by climate and adaptation to it but also by international markets and national policy.

In Brief

From the continental climate with its wild swings in temperature in the semi-arid Great Plains to subtropical, humid Florida, farmers have successfully adapted to extended periods, even seemingly permanent, of extreme weather. There are always costs of adaptation and as in the Dust Bowl they may be high. In the end, we note that our examples are for adaptation to unfavorable climate. Should the climate change to more favorable, the adaptations would be easier but nevertheless require thought, preparation, and investment to capture the benefits in the lucky regions.

3.4 What tools enabled farmers to adapt, where did they come from, and what caused farmers to take them up?

The tools that adapted farming in the past suggest the new tools, where farmers will get them, and what will encourage farmers to take them up. Because of the aptness of crop breeding and irrigation for fitting farming to a changed climate, we illustrate the many tools available for adaptation with these two.

Plant Breeding

Farmers have been adapting plants to cultivation and climate since the first domestication of wild species. For 75 years, however, plant breeders have been specialized scientists in both public and private teams, employing genetics as well as agronomy, entomology, pathology, physiology, and molecular biology. They may take two to five decades to breed an entirely new crop from a wild species, spend two decades to breed a markedly new variety, but sometimes manage a precise trait like disease resistance in a single season (Duvick, 1984b). We shall exemplify the capacity of breeders and associated scientists, services, and trade to adapt crops by several case histories.

Drought

If the climate becomes drier, plant breeder's ability to raise yields will matter. Figure 3.4.1 shows they can. Forty-eight hybrids developed from 1930 to 1984 are arranged from left to right in the figure. The upper squares and line show the yields of the hybrids with the plentiful rainfall of 1987. The genetic gain in yield was 74 kg/ha per year of origin of the hybrids. The line indicates that with the abundant moisture of 1987 a hybrid developed in, say, 1980 yielded (1980-1950) times 74 kg/ha per year or 2.2 tons/ha more than a hybrid developed in 1950.

The question is, of course, whether the 30 years of breeding caused genetic gains as great during dry weather. The lower circles and line in Figure 3.4.1 show the outcome of drought during 1985. During that dry season the genetic gain in yield was 85 kg/ha per year of origin of the hybrids, slightly more than the 74 kg/ha per year during the year of abundant moisture. So, plant breeding raised these yields in dry as well as wet seasons.

Pests

Mixtures of varieties and targeted, fast breeding have promptly countered insect invasions. When the European corn borer invaded the Corn Belt in the 1940s, farmers lost yield, especially those growing susceptible varieties. Farmers and seed companies promptly found and dropped all seriously susceptible hybrids, immediately raising tolerance of the crop. Within a decade, both selection of inbreds and the identification of needed genes brought forth markedly more tolerant commercial hybrids, and steady progress continues (Dicke and Guthrie, 1978).

To combat a sudden epidemic, breeders have multiplied resistant seed in the tropics during the Northern Hemisphere winter. The nation-wide epidemic of southern corn leaf blight in 1970 was countered by 1972. In the corn belt in 1971, only the most tolerant lines were planted. A little seed of thoroughly resistant counterparts of the susceptible hybrids and their parents were on hand. During the winter of 1971 this seed was multiplied in warm climates. The control of the blight by 1972 showed the sureness and rapidity of adaptation by U.S. farming when tools were available (Duvick and Noble, 1978; Tatum, 1971).

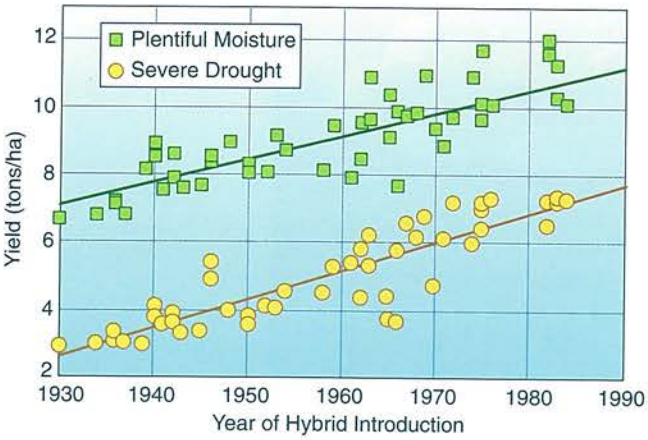

Figure 3.4.1. **In a wet and a dry year, the yield of hybrid corn arranged from the oldest varieties on the left to the newest on the right. The gains of yield from breeding were no less in the dry than in the wet year. Gains averaged 74 kg/ha/yr in a wet year and 85 kg/ha/yr in a dry year (adapted from Duvick, 1990).**

Combining Tools

Farmers have combined several technologies to adapt quickly to changes in water supply. When hybrid sorghum was developed in the 1950s, Texas farmers switched from their open pollinated varieties to hybrids in about five years. At the same time they began to irrigate the hybrids whose higher yield merited the expense. Soon the flow of water from some wells began to slow, and farmers in Texas switched to still more valuable crops, and began growing sorghum again without irrigation. This reversal to dryland cropping, including the introduction of new hybrids more tolerant to heat and drought, took less than five years. These multiple changes, worked by tools of breeding, irrigation, fertilizer, machinery, and pest controls, showed farmers quickly and effectively adapting when they have the supporting infrastructure (Miller and Kebede, 1984).

An Entirely New Crop

Although farmers in the Red River Valley of Minnesota and North Dakota traditionally grew diverse crops, soybeans was not one of them. Then during 1980 to 1985, production of soybeans in the two states shot up from 1 to 8% of the total planted area. Once again, breeding was essential: New, super-early varieties of soybean allowed farmers to experiment and then adapt. (Minnesota Agricultural Statistics Service, 1975–1985; Orf, pers. com., 1991).

An Adaptation That Failed

Another example from the Red River Valley shows that some adaptations fail despite success nearby. Before adopting soybeans and for three to five years around 1975, Valley farmers had tried hybrid sunflowers on a large scale. A native of the United States, the sunflower was surrounded by pests that had evolved with it and as fast as planted area increased, pests attacked. Although successful on less intensive farms of North Dakota outside the Valley, growing sunflowers amidst the intensive farming of the Valley proved unprofitable (Hanzell, pers. com., 1991; North Dakota Agricultural Statistics, 1975–1985; North Dakota State University, 1978). So among the many successful adaptations built on new crops and varieties, failures can be found.

Irrigation

Regardless of crop species or variety, water is still the main natural resource and lever by which climate raises and lowers plant growth and farming. And irrigation is the obvious adaptation for coping with too little water, but irrigation consumes large amounts of water.

U.S. Water Balance and Water Resource Management

The water balance of the 48 conterminous states, shown in Figure 3.4.2, indicates that about two-thirds of the precipitation is returned to the atmosphere by evaporation from soil and transpiration from plants, a combination process called evapotranspiration (ET). When soil water is available, the daily rate of ET from a crop is controlled largely by solar radiation intensity. About one-fifth of the precipitation flows in rivers to the Atlantic ocean and Gulf of Mexico and one-tenth flows to the Pacific Ocean.

Storage of water in surface reservoirs is the technology that is used to cope with the regional as well as annual and seasonal variations. The comprehensive balance of 48 states averaged over years hides vital dissimilarities among the 18 water resource regions. Of the average water outflows from the water resource regions, only about one-half is dependable 95 out of

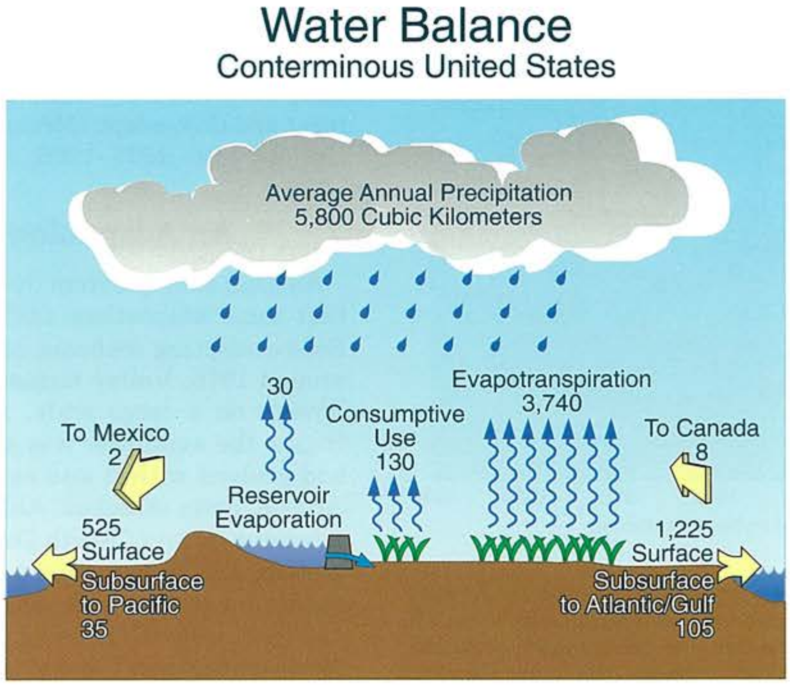

Figure 3.4.2. The water balance of the conterminous 48 states.

100 years, and only about a one-seventh of this low flow is in the eight western resource regions outside the Pacific Northwest region (U.S. Water Resources Council, 1978). The mean annual supply does not, of course, reflect the difficulties associated with multiyear droughts.

Surface reservoirs can store just over one-half the annual renewable supply of water in the West and about one-third in the other states. Surface reservoir capacity developed rapidly from 1930 to 1970, and it then leveled off at about half the potential (Langbein, 1982). Development of major multipurpose water storage reservoirs may require 20 to 30 years from authorization to funding, design, construction, and operation.

Water is also stored in ground water aquifers that are recharged naturally or by spreading flood waters. Although water in ground water aquifers does not evaporate like that in surface reservoirs, pumping water can be expensive. For example, a timely irrigation can increase the yield of sorghum 2 kg per cubic meter of water making the marginal gross return of about 20 cents per unit of water. Lifting the water 150 meters and applying the water with a sprinkler system requires about 1 kWh, which costs a third of the gross return (Jensen, 1984).

Irrigation Trends and Practices

As shown in Figure 1.1.4, the area of irrigated land is decreasing in the West and especially in the Great Plains. The chief cause is the depletion of the Ogallala aquifer in the southern Great Plains, which is recharged only 1 mm/yr in Texas and 150 in parts of Kansas and Nebraska (Weeks, 1986).

The area of irrigated land expanded 4.4% per year from 1949 to 1969 in the southern Great Plains where level land permitted furrow irrigation, cheap energy was available for pumping, and water was easily accessible from the Ogallala aquifer. As the groundwater level declined, well yields decreased, and pumping lifts increased, farmers began to switch from furrow irrigation to sprinklers. Also, technology called surge-flow for furrow irrigation and a low-energy-precision-applicator sprinkler method made the water go further. Farmers also switched back to drought tolerant crops and applied fewer, well-timed irrigations, which gave them large yield increases per unit of water applied (Musick et al., 1984; Musick, 1990). In California, ground-water over-draft is still occurring, which will eventually result in a decrease of irrigated land in that state (U.S. Geologic Survey, 1987).

In the Pacific Northwest where water was more abundant, and cheap electricity was available for pumping from rivers, the irrigated area expanded 1.7% per year from 1944 to 1982.

In the central Great Plains, the irrigated area expanded 5.8% per year from 1964 to 1982. Ground water was easily accessible and commercially available center pivot sprinkler systems that required little labor were two major factors affecting this rapid expansion (Jensen, 1987).

Transfer of Water from Agriculture to Urban Uses

Transfers of water rights to growing cities and industries in the West is also reducing irrigated land. Just east of the Rocky Mountains during the past 25 years, shares in the Colorado-Big Thompson project have been transferred from agriculture to cities for domestic and industrial use (Figure 3.4.3). In another project in Arizona, the transfers of water from irrigated land to urban use was even more dramatic (Figure 3.4.4).

Similar transfers are occurring in other western states, but differ according to state laws and hydrologic region. During 1974 to 1986 there were 3,853 applications to transfer water rights to other uses or locations of use in Utah, 1,133 in New Mexico, 858 in Colorado, and 42 large-volume applications in Wyoming (MacDonnell, 1990). Over 95% of these applications were approved except in Wyoming where about 75% were approved. Law and policy in the states generally support transfers if holders of rights are not injured or are compensated. In Utah the transfers were among various uses, in New Mexico one-third was from agriculture to nonagricultural uses, in Colorado and Wyoming most were from farming to other uses.

The West has a long history of water transfers to provide water to meet changing demands. Water transfers, which have increased in recent years as competition for water has increased, can also affect third parties not directly involved in the transfer. A Committee of the National Research Council in a recent study emphasized that recognition and protection of third party interests are essential if transfers are to achieve their potential to reallocate water to meet new demands (National Research Council, 1992).

In 1991, California responded to a five year drought by establishing a water bank to facilitate market-like reallocations of water (California Department of Natural Resources, 1992). Idaho farmers began renting unused water in the 1930s and the State has had a water bank statute since 1979 (Higginson, 1989; Idaho Natural Resources Board, 1991). Water banking is a market-like mechanism that permits water users who have water rights and who may own storage space in reservoirs to rent water that they do not need during a season to others who need the water. Such seasonal exchanges do not affect the established water rights. It enhances the annual distribution of water to cope with local drought, changes in cropping patterns, and urban needs. The procedure varies between states, but usually the water users involved are under the same water storage-distribution system that facilitates exchanges.

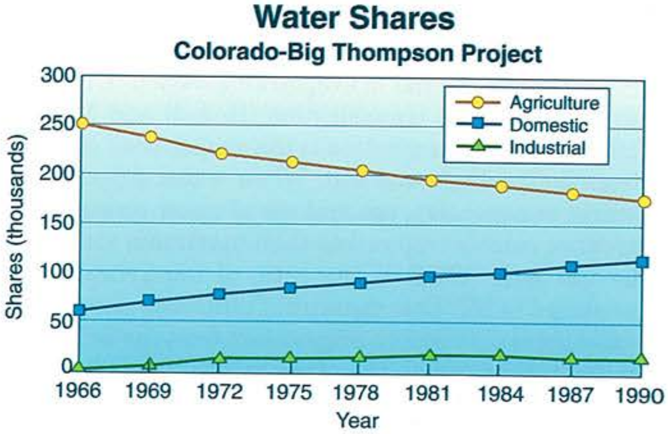

Figure 3.4.3. Shares held in the Colorado-Big Thompson Project in Colorado from 1966 to 1990 (Northern Colorado Water Conservancy District, 1991).

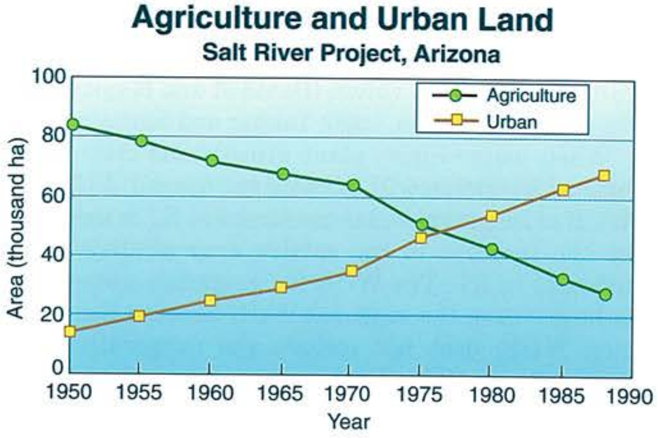

Figure 3.4.4. Land in agriculture and urban uses in the Salt River Project in Arizona from 1950 to 1988 (MacDonnell, 1990).

Water-Use Efficiency

Water use efficiency (WUE) is a measure of the productivity of water use in agriculture. Simply and after adjustment for humidity, the yield of a crop is roughly proportional to evapotranspiration (ET) when soil water limits transpiration (Howell and Musick, 1985). Evapotranspiration is the evaporation of water from both foliage and soil. When water supplies are scarce or expensive, optimal use of water consumed to produce salable crop rather than maximum yield may be the goal. WUE is the ratio of marketable crop produced to ET. This measure of efficiency encourages management to reduce evaporation from the soil to put more water through the plant, which increases plant growth and makes more of it salable.

The highest WUE occurs at the highest yield and usually at the highest ET. Too little precipitation or irrigation may produce no salable crop because the crop must develop through the vegetative stage before any seeds are produced. The WUE for a range of crops and climates was summarized by the U.N. Food and Agriculture Organization (Doorenbos and Kassam, 1979). Agronomic publications reporting the effects of water management and cultural practices on crop yields typically include WUE values (Davidoff and Hanks, 1989; Stewart and Nielson, 1990; Tanner and Sinclair, 1983).

When water limits plant growth and crop yields, limited irrigation will increase the overall WUE. The WUE of irrigation water consumed in ET is measured by the increase in the salable crop relative to the increase in ET. The WUE for irrigation water alone is larger than the seasonal WUE because the irrigation WUEi does not include the evaporation that occurs during the vegetative stage of crop growth. For example, the average nonirrigated yield of grain sorghum in Texas of 2.5 t/ha produced with an average ET of 300 mm would have a WUEi of 0.8 kg per cubic meter of water consumed. An irrigation that would increase the ET to 400 mm would increase the yield to 4.0 t/ha. The yield increase of 1.5 t/ha from an additional 100 mm of ET would produce 1.5 kg per cubic meter of water consumed.

Improving Water-Use Efficiency

Breeding better crop varieties during the past three decades raised the WUE of grain in Texas by raising yields without raising ET (Figure 3.4.5). Changing the species of crop from one that will wholly fail to one that will produce some salable yield with a small supply of water in the soil can avoid a zero WUE.

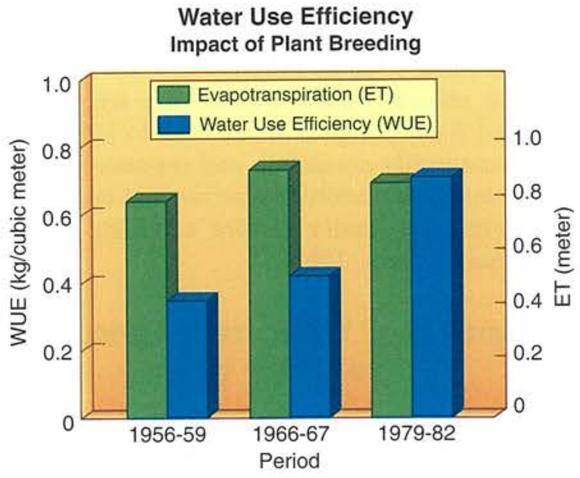

Figure 3.4.5. Evapotranspiration (ET) and water use efficiency (WUE) values for winter wheat at Bushland, Texas from 1956 to 1982 (Jensen, 1987).

Increasing storage of water in the soil and increasing the portion of water that is transpired by the crop rather than by weeds or that is evaporated from the soil improves WUE. Therefore, minimizing runoff by shaping the land, reducing evaporation from soil by maintaining crop residues on the soil surface, optimizing planting dates, and controlling weed growth all contribute to higher WUEs. In a semiarid area like western Texas, limited irrigation of a wheat crop produced more residue, which when maintained on the soil surface doubled the storage of soil water during the following fallow period (Unger, 1978, 1988; Unger and Stewart, 1983). Managing the soil to increase infiltration and catching snow with barriers of grass reduces runoff and stores more winter precipitation (Black and Siddoway, 1971).

New irrigation methods and practices can also reduce evaporation during irrigation. These include installing drip tubing under plastic film, which has become a common practice on high-value vegetable crops, and installing drip tubing below the soil surface. New sprinkler systems now discharge water close to the crop or deliver water to furrows in drop tubes between crop rows, which reduces evaporation compared to spraying water high into the air. Operating sprinkler systems only at night also reduces evaporation (Hoffman et al., 1990).

In Brief

Plant breeding, water resource management, and irrigation exemplify the many tools farmers have used to adapt crops to climate. U.S. farming can promptly adopt new crops and the technology they require, five years being a typical period for the adoption. For adapting to dry climates, irrigation is a going concern but requires a regional source of water as from mountain snow packs. However, setting up a system for storage and distribution of the water may require 10 to 20 years. More productive varieties and irrigation methods that reduce evaporation raise water-use efficiency. Recent history shows more expensive water and effective institutions induced tools that innovative farmers also put to use, raising water-use efficiency. Profitability to the farmer, of course, is the guide to adaptation, and the profitability has been affected by such forces as more costly fuel for pumping water in Texas or more money from soybeans than sunflower in the Red River Valley.

Farmers and their supporting researchers invent and learn quickly. The large foundation of U.S. research, development, education, and trade supports them.

3.5 How have trade, storage, and other economic adaptations helped humanity adapt to climate, particularly to extended extremes like the droughts of the Dust Bowl or Sahel within a climate?

Beyond the physical and biological tools that have adapted farming and forestry to climate, economic tools have also proven useful facilitators of change. Through a long history of innovation and adaptation, U.S. and world agriculture have developed three main economic tools for tempering over both space and time the shocks of shortage or surplus caused by changes in weather.

1. **The world food market** adjusts food supplies among regions in both the short and long run. In the short run, price adjustments reallocate available supplies among consumers and encourage trade between regions. In the long run, the market's price signals encourage the production of new sources of supply, to the extent the resource base allows.
2. **Grain reserves** smooth and, thus, adjust supply over time, from good years to bad.
3. **Crop insurance** is a "rainy day fund" that adjusts farm income across both time and space.

The World Food Market

The world food market is a highly effective mechanism for helping producers and consumers to adjust and adapt when weather varies the supply of food. The "market" is a common name for the central meeting place where farmers and consumers come together to determine the price of food. In fact, the market is a series of loosely confederated commodity markets where traders communicate globally 24 hours a day. These markets serve as the central nervous system of the world's food supply; that is, they send the signals that encourage adaptation to external shocks. For example, when adverse weather cuts production of a crop in a major region of the world, market prices go up, in turn encouraging consumers to cut demand and farmers to increase supply. Conversely, when crop supplies are big, market prices go down, encouraging consumers to buy more and farmers to produce less.

The price signals telegraphed by the world food market guide affected parties to adjust to shocks related to weather. Almost instantly, commodity futures markets, many centered in the United States, translate weather developments into meaningful price signals for producers and consumers. As prices rise and fall, they set in train responses that tend to temper the effects of weather disruptions. Shortfalls push up prices, forcing consumers to reduce consumption or seek substitutes. Simultaneously, the higher prices encourage producers in other regions or countries to increase production if they can. The world market thus serves as the official clearinghouse that balances adjustments in both supply and demand.

The markets also serve as the critical place where international grain trade is conducted. In particular, the markets adjust the world's supply of grains and oilseeds from regions with surplus to regions with deficit. Amounting to roughly 2 billion tons a year, grains and oilseeds are the world's basic foodstuffs: They are grown in abundance in many regions of the world and can be easily transported.

Trade is a small but critical portion of world food consumption. In 1990, trade accounted for about one-eighth of world consumption of grains and oilseeds in 1990. While that is a thin slice of total world use, it is the critical portion that keeps world supply and demand in balance. The balancing is both crucial and difficult when weather varies the supply.

The trade facilitated by world food markets relieves local food shortages from variations in weather. Before world food trade became well-established in the twentieth century, drought often led to famine in localized regions. But with the advent of trade and a market mechanism to implement it, weather-related shortages have largely been replaced by adjustments in prices and trade. The history of drought in India offers a compelling illustration of how trade is a powerful adaptation to variation in weather. A severe drought in India in 1896 led to 5 million deaths due to starvation and disease the following two years. By contrast, a severe drought in 1965 led to comparatively few deaths because the country was able to import vast amounts of food through aid and outright purchases (*Encyclopedia Brittanica*, 1987). The present conflicts in Africa that inhibit distribution of food to the starving people demonstrate anew the role of imports in averting famine.

The world market facilitates trade in food, but infrastructure provides the essential conduit through which trade actually passes. An extensive rail and waterway network brings Kansas wheat, for example, to a buyer halfway around the world. The value of physical infrastructure in facilitating trade has been highlighted recently by the problems facing agriculture in the former Soviet Union due to inadequate roads, equipment, and storage facilities (Barkema, 1991).

Market reactions to the 1988 U.S. drought illustrate the power of price signals to encourage short-run adaptation. The drought cut the 1988 U.S. corn crop in half. As the extent of the drought became evident in June 1988, corn prices rose about 50% above early May levels. The spike in prices encouraged livestock feeders and other users to cut total corn consumption 7% by switching to other feed grains. (As discussed below, a large reserve of corn was a key factor in limiting the decline in use.) At the same time, the higher U.S. prices encouraged corn growers in the Southern Hemisphere to plant more corn during their October planting season. The combination of declining demand and prospects for more corn in the world market by the spring of 1989 caused U.S. corn prices to fall, not rise, throughout the remainder of 1988. In retrospect, the worst drought in 50 years had relatively modest effect on U.S. corn consumption.

In the longer term, the world food market encourages shifts in food production essential to offsetting the effects of a climate change. With short-run weather disruptions, like a one-year drought, price adjustments and trade can mitigate most of the negative effects. But when the change in climate is more systemic, market adjustments are more difficult. When the change in average climate reduces the supply of food, prices remain high and signal producers to search out new production techniques. Ultimately, how much production is restored depends on the ability of agricultural resources to adjust. National agricultural policies often impede resource adjustment. For example, U.S. federal commodity programs encourage producers to maintain the area of one particular crop instead of seeking out alternative crops better suited to the new economic environment or the new climate. Such rigidities make long-run market adjustments more difficult.

Grain Reserves

From the time of Joseph, grain stocks have been humanity's best defense against the ravages of drought and other shortfalls caused by weather. Like the reservoirs of water for the irrigator, reserves of grain smooth variations in supply over time, from good years to bad. Thus, grain reserves are adaptations to variability if not to a change in the average.

The social value of stocks is well-established in economic theory and practice (Newbery and Stiglitz, 1981). The United States has subsidized public grain stocks for more than 50 years. Today, those stocks are quite large and comprise one-third to one-half of global stocks (Figure 3.5.1). Other countries have much smaller stocks, in part because the stocks paid for by the U.S. taxpayer are so large.

Harvesting of corn and a ship being loaded with grain. Credits: Charlton Photos, Inc., Mequon, Wisconsin.

Large U.S. grain stocks helped the nation withstand the severe 1988 drought with limited consequences. When 1988 began, the United States had a big reserve of corn, fully 109 million tons—more than half the use in all of 1987. When the drought hit in 1988, users of corn cushioned the shortfall by first drawing down corn in storage. The cushion was a main reason corn prices increased only 30% despite a 50% fall in output. Reduced demand and increased foreign production, as discussed above, also tempered the rise in prices.

Conversely, world reserves in 1973 were too small to keep prices from soaring when world crops were less than expected. U.S. crop prices more than doubled that year.

The large reserve in 1988 was largely serendipitous. That is, it was the unintended consequence of a farm policy in previous years aimed at keeping farm income high, a policy that just happened to cause a large grain reserve. Had stocks been at the more normal level of 50 to 60 million tons of corn, the effects of the 1988 drought would have been much more severe (Food and Agricultural Policy Research Institute, 1990).

Today's world grain reserves are relatively small, especially when compared with rising production and trade (Figure 3.5.1). World stocks of grains and oilseeds were 327 million tons in 1990, about 17% of total annual use. The United States held about one-fifth of the world reserves, half the share it held three years before.

The question remains whether world and U.S. stocks are sufficient if weather becomes more variable. Following the 1973 run-up in commodity prices, the World Food Conference in Rome urged global cooperation in maintaining adequate reserves. An FAO study in 1977 concluded that reserves at a level of 17% of annual grain consumption were a "minimum safe level of world food security" (Food and Agriculture Organization of the United Nations, 1977). The infrastructure supporting world grain trade has become more efficient since then, suggesting that smaller reserves might be needed. Nevertheless, the 1990 reserve of 17% seems near the minimum for security.

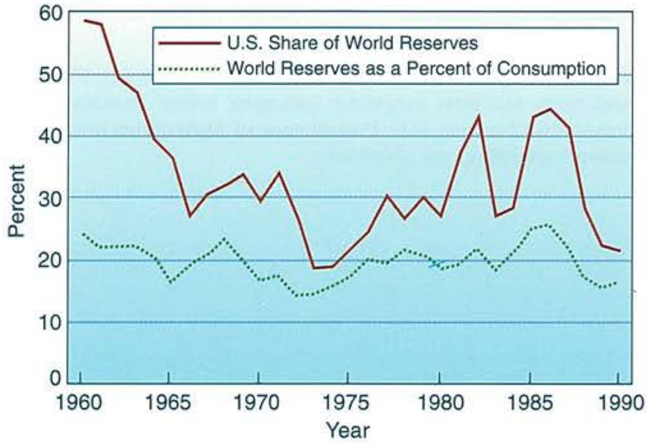

Figure 3.5.1. **Comparisons of world grain and oilseed reserves (U.S. Department of Agriculture Production, Supply, and Distribution Database, 1990).**

U.S. grain reserves are directly influenced by U.S. farm commodity programs. When those programs were aimed at keeping farm incomes high during the mid-1980s when world markets were weak, for instance, the government acquired huge storehouses of grain. Although farm programs do contain provisions for maintaining minimum grain reserves of major crops, commodity programs are generally managed by the government in response to changing farm economic indicators, not the size of the reserve.

Just as the likelihood of changing climate raises the need for more reserve, coordinating the grain reserve policies of different countries becomes more important. But deciding how to apportion the costs of holding reserves is a serious impediment to improving global reserves (McCalla and Josling, 1985). Developing countries stand to benefit most from a global stocks policy, but are least able to pay for such stocks.

Responding to the funding problem, the International Monetary Fund (IMF) created a special insurance fund, of sorts. The Cereals Compensatory Financing Facility is intended to ease the costs of grain supply disruptions to developing countries (Adams, 1983). Because storing money is cheaper than storing grain, the fund is sound in theory (Huddleston et al., 1984). Unfortunately, the facility has not been used much because the countries that need it most have limited capacity to borrow from the IMF and are unwilling to accept the economic reforms required to increase that capacity (Kennedy and Nightingale, 1989).

Crop Insurance

Farmers suffer the first and often most severe impact from bad weather. Crop insurance has evolved as an efficient market tool that allows producers to manage the risk of crop loss from variable weather. The United States has had a federally subsidized all-risk crop insurance program since 1938, the same year that subsidized grain stocks were created.

Economically, crop insurance is a sound way for farmers to manage the risks of weather. Actuarially, it can be sound because the United States is large, making bad weather everywhere unlikely. In brief, unaffected regions provide the reserve to operate the insurance fund. Its actuarial soundness is threatened, however, because only about a quarter of U.S. cropland is enrolled in the program. U.S. farmers have opted out of the insurance program because the federal government has often given disaster assistance in the wake of natural disasters. Thus, it is less costly for farmers to receive disaster assistance than to pay for crop insurance, even though the premiums are subsidized by U.S. taxpayers.

Again the question remains, "Who should pay?" Crop insurance is a sound tool for managing the risks of climate change, but should farmers or consumers pay for it? Currently, taxpayers pay a large portion of the cost. And so long as disaster assistance is readily offered, producers will avoid a program where premiums reflect the actual cost of the insurance.

In Brief

Overall, the world food market, grain reserves, and crop insurance form a strong arsenal of tools that can allow agriculture to adjust to the effects of weather. They are especially effective in prompting short-run adjustments to variations in weather. Changes in price, increased trade, and crop insurance payments all mitigate the effects of adverse weather.

In the long run, these economic tools are vital in promoting adjustment to climate change. The amount of adjustment can be limited, however, by farm policies that distort prices and trade and by farm resources with limited capacity to adapt. If the climate changes, the new price signals in the world food market would encourage new avenues of trade and new sources of supply. Critical to these adjustments, however, is a world market that sends the right price signals while facilitating the right amount of trade. Unfortunately, current farm policies around the world distort the price signals and impede trade. Thus, long-run adjustments to climate change will be more difficult in a world market beset by distorting farm policies. Even if price signals are true, the long-run response to climate change may be limited by how well resources adjust to the new climate. If farm resources cannot adjust to offset a drop in production, the problem must be answered by new technology, that is, making old resources more productive in the new climate. There is good reason to believe the new technology may be induced by the higher prices caused by the change in weather.

During the Dust Bowl era, wind erosion buried equipment. Modern lateral-move sprinkler irrigating Nebraska crops. Credits: Soil Conservation Service, U.S. Department of Agriculture (top) and Valmont Industries, Inc. (bottom).

4 Exchange of Greenhouse Gases

4.1 What is the order of magnitude of the emissions of greenhouse gases from U.S. farming, and how do the farm emissions rank among other factors in terms of forcing greenhouse warming?

Greenhouse gases range from natural water vapor to synthetic chlorofluorohydrocarbons (CFCs). Human activity emits several of them, adding to the atmospheric concentration of natural ones and supplying the synthetic. Because attention concentrates on climate changed by humanity, people concentrate on emissions caused by human activity, especially those of CO_2, which are preeminent. Farming emits three greenhouse gases—CO_2, methane, and nitrous oxide—in consequential amounts. The three columns of Table 4.1.1 concern these.

Because the characteristics of the gases affect the climate change that a given emission can cause, they must be considered in Table 4.1.1 along with the amount emitted. The first characteristic is radiative forcing, the effect on the radiation balance of the earth expected from an addition to each gas in the atmosphere. Both the ability of a gas to absorb a unit

Table 4.1.1. Emission and global warming potential of three gases from global, United States, and U.S. farming activities

	CO_2	Methane	Nitrous oxide
Radiative forcing, per unit mass relative to CO_2[a]	1	58	206
Mean lifetime, years[a]	120	10	150
GWP, 100 years relative to CO_2[a]	1	21	290
Emissions, Gt/yr			
Global	21.9[b]	0.5[c]	0.021[e]
United States	4.9[b]	0.05[f]	0.004[h]
U.S. agriculture	0.09[d]	0.007[g]	0.0003[i]
Emissions, GWP of emissions			
Global	21.9	10.5	6.1
United States	4.9	1.1	1.1
U.S. agriculture	0.09	0.15	0.09

[a] Shine et al., 1990.

[b] Marland, 1992.

[c] Net of emission less absorption (Crutzen, 1991).

[d] The emissions from farming are from fossil fuel burned on farms or to generate electricity for farming (Marland and Pippin, 1991). The annual uptake of CO_2 by crops and emission from consumption of food and feed and decay of crop residues is omitted. Uncertain additions could be 0.04 from manufacture of fertilizer and 0.01 from oxidation of soil organic carbon.

[e] Net of emission less absorption (Elkins, 1989).

[f] Lashoff and Tirpak (1989) on page V-70 show the United States' share of methane emissions is 10% and on page V-65 show the global emission is 0.5 Gt.

[g] Emission from U.S. rice paddies is negligible and Lerner, Matthews, and Fung (1988) calculated annual emission by animals in the United States is 0.007 Gt.

[h] Calculated from Elkin's (1989) estimate of about 0.018 Gt emissions from all land and an assumption that the United States emits the same 22% of nitrous oxide from land that it emits of global CO_2.

[i] The estimated emission is the product of 2.2 Gt global emissions of nitrous oxide from fertilized soils calculated by Elkins (1989) multiplied by the 0.137 of the global use of nitrogen fertilizer that the United States uses according to Lashoff and Tirpak (1989).

of long-wave radiation cooling the globe and the scarcity of other gases absorbing radiation of the same wave lengths increase radiative forcing. The radiative forcing of the gases on the first line of the table is related to that of CO_2. It shows that in the atmosphere a unit of methane is 58 times and of nitrous oxide is fully 206 times as effective in warming as is a unit of CO_2.

The second characteristic is the lifetime in the air, how long the forcing by a unit of gas will go on. Among the lifetimes shown on the second line of Table 4.1.1, the 10-year life of methane stands out. A unit of methane may have greater radiative forcing than one of CO_2, for example, but that forcing lasts less than one-tenth as long as the forcing by the unit of CO_2.

Although we do not incorporate it in our table, a third characteristic of a gas is its reaction with other greenhouse gases, causing changes in their concentrations. Scientists suspect methane causes such reactions, but knowledge is insufficient today to put a calculation in the table.

The characteristics of radiative forcing and lifetime are combined into one parameter that shows the potential of a unit of each gas for warming the globe. The GWP or global warming potential is the radiative forcing of a unit of the gas multiplied by its concentration in the air integrated for 100 years. In the integration, the concentration decays according to the lifetime of the gas. The GWP on the third line of the table is relative to the GWP of CO_2.[6]

Next in Table 4.1.1 are the emissions themselves. For the vast globe, the emissions are given in large units, billions of tons or gigatons (Gt) per year. The largest by far is the emission of CO_2, nearly 22 billion tons per year. The emissions of the other two gases would be inconsequential if it were not for their large GWP. Since our report concerns the United States, the global emissions are followed in the table by those from the United States.

The next line in Table 4.1.1 shows the emissions from U.S. agriculture alone. Estimating the emission of CO_2 from farming presents a problem. Annually a vast amount of CO_2 is taken into crops via their photosynthesis, some of it stored, and much of it returned to the atmosphere as people and animals consume the crops or residues decay in the field. We omitted from our table this large, uncertain annual exchange that would have obscured other emissions. We also omitted emissions from clearing forests. Although we shall see in Section 4.3 that clearing forests may emit 5.5 plus or minus 3.7 Gt/yr globally, the fairly constant area of U.S. forests and cropland (Figure 1.1.3) and the uncertainty of the global estimates caused us to omit them from the table. Instead, the 0.09 Gt/yr in the table is from the fossil fuel burned on farms or used to generate electricity for farming.

Other emissions might have been added, but we omitted them because of their small size, their uncertainty, and the lack of comparable, global estimates. They are some 0.04 Gt/yr from fossil fuel used in making fertilizer and some 0.01 Gt/yr lost from soil organic carbon. Had these been added, the stated emission from farming would still be about 0.1 Gt/yr as it is for energy used on the farm. Estimating the emissions of methane and nitrous oxide was more straightforward: They are the net of emission and any absorption of the two gases in farming. A preliminary estimate of 0.004 Gt/yr of methane from manure in the United States is too uncertain to incorporate in the table (Safley et al., 1992).

From the GWP and the emissions we can now turn to "How does the emission of greenhouse gases from U.S. farming rank among other factors in terms of forcing greenhouse warming?" The final three rows of Table 4.1.1 are the emissions multiplied by the GWP to show their rank in terms of forcing warming. First, readers see the preeminence of CO_2 as a forcer of greenhouse warming, but they then notice that methane and nitrous oxide are consequential for this century-long integration. All the activity in the United States taken together emits 22% of the global CO_2 but smaller percentages of the other two gases. Adding the three gases together, one sees the United States emits 18% of the warming potential of global emissions of the three gases.

For our report, of course, farming is the interest. As the short, red caps on the bars of Figure 4.1.1 depict,

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[6] We followed the Intergovernmental Panel on Climate Change (IPCC) in calculating GWP, the time integrated commitment to climate forcing from the instantaneous release of 1 kg of gas relative to that from 1 kg of CO_2:

$$GWP = \int_0^n a_i c_i \, dt \Big/ \int_0^n a_{CO2} \, c_{CO2} \, dt$$

where a_i is the instantaneous radiative forcing due to a unit increase in the concentrations of gas i, c_i is the concentration of gas i at time t after its release and n is the number of years over which the integration is performed. We integrated over the period $n = 100$ years. The period is important because the radiative forcing and lifetime of the gases differ. For example, the short life time of methane lowers its GWP from 63 at 20 years to 21 at 100 years to only 9 at 500 years. Because nitrous oxide has a lifetime near that of CO_2, on the other hand, the GWP of nitrous oxide changes only from 270 to 290 and then 190 as the period is changed from 20 to 100 and 500 years. The IPCC acknowledged that the figures, "must be considered preliminary only" because of the uncertainties about (1) the lifetime of methane, (2) a single lifetime specified for CO_2 despite greatly different rates of its transfer amongst different reservoirs, and (3) the assumption that lifetimes of trace gases remain constant during the integration period.

Carbon Dioxide

One of the largest discharges of CO_2 in agriculture is from fossil fuel use. However, present CO_2 emissions of 0.09 Gt/yr (Table 4.1.1) are much smaller than they were earlier. In 1990, U.S. on-farm fuel use was 10.2 billion liters of diesel fuel, 5.8 billion liters of gasoline, and 2.3 billion liters of LP gas (U.S. Department of Agriculture, 1991b). This is, however, a notable decrease from the 12.1, 12.9, and 4.2 billion liters of diesel fuel, gasoline, and LP gas, respectively, used in 1979 (Stout et al., 1984). Of the total 2,173 petajoules (PJ) of energy used in agriculture in 1981, 1,292 PJ were burned on farms and another 881 PJ were embodied in fertilizers and pesticides. Marland and Pippin (1991) estimate that on-farm energy use emitted 25.9 Mt of C as CO_2 and the emissions embodied in agricultural chemicals are about half that much. The major categories of energy use in production agriculture are, in declining order, fertilizer and pesticides, field machinery, transportation, irrigation, livestock production, and crop drying (Stout et al., 1984). In recent years, energy-saving technology, shifts from gasoline to diesel, and generally reduced planted area (U.S. Department of Agriculture, 1990) cut fuel consumption on farms about 40%. The shift to diesel equipment is now largely complete. The fuel efficiency of diesel tractors reached a maximum as early as the 1960s and continuing declines in fuel use have been primarily because of reduced tillage (U.S. Department of Agriculture, 1989).

Referring now to Figure 4.3.1, we set aside the annual exchange of some 110 Gt of C in CO_2 with the great inventory of some 550 Gt in forests and other vegetation on the land. Here we examine the gain and loss of C from the even greater inventory of 1,400 Gt in soil and detritus on the soil. Thus, the inventory of C in living and dead things on the land plus the soil is about 2,000 Gt. As calculated from data by Buol et al. (1980), a representative hectare of soil in a humid temperate region can have a 6.0 t inventory of C in living organisms and 60 t in dead organic matter to a depth of 15 cm.

The inventories of C and of N were accumulated and distributed through the profile of soil as it formed, taking one to 750 years to form a cm of depth (Buol et al., 1980). As the earth's crust weathered, plants and other organisms grew and died, distributing the C and N of their remains through the profile and eventually approaching a steady state between accumulation and loss.

Carbon and N migrate, often with calcium and magnesium, and C may accumulate in carbonates or in humus. The accumulation of calcium carbonate is greatest where about 400 mm of precipitation falls, as in Sacramento or Colorado Springs. More than 400 mm of precipitation leaches out too much calcium and less than 400 mm of precipitation does not leach out enough for the maximum carbonate accumulation. Irrigation with calcium-rich water can precipitate carbonate, whereas irrigation with saline water may release CO_2 by dissolving carbonate already there

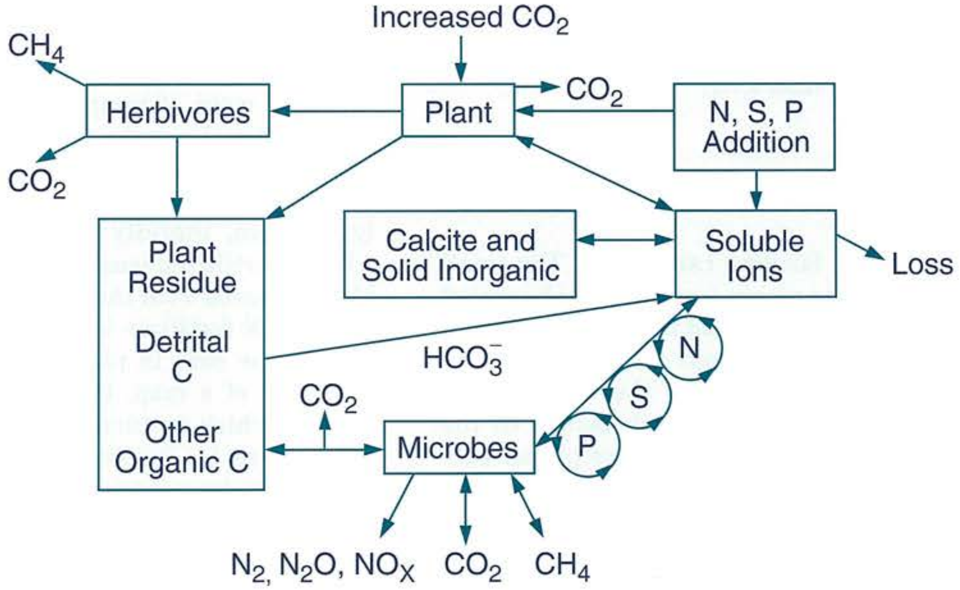

Figure 4.2.1. The cycle of agriculture with production of plants and animals for food and timber, with the cycling of nutrients in the soil and its microbes, and with the leakage of some greenhouse gases (Follett, 1991).

(Bohn, 1990; Stevenson, 1986).

As soil forms, organic matter accumulates and decays, reaching an equilibrium level that is higher in cool and lower in warm places. The equilibrium level of organic matter, and the accompanying N, declines exponentially with rising temperature. Along the East Coast, the organic matter content declines about 10% for each warming of 1°C from 8 to 20°C, and in the Great Plains warmer soils also have less organic matter. Precipitation, too, affects soil organic matter: more precipitation, more organic matter (Cole et al., 1989; Jenny 1930, 1941).

After summarizing the effect of climate on the equilibrium organic matter and N content of soils, we examine how the content is changed when the soils are cultivated. During many years, scientists have measured the changes. Early in this century, Russel (1929) reported that 30 years of cropping reduced the organic matter in Nebraska soils by 25 to 30%. In Missouri, 50 years of observations showed that continuous corn with no manure addition depleted soil organic matter most rapidly, followed in order by wheat, oats, and timothy grass (Smith, 1942). Treatments that maintained soil organic matter were all manured, with timothy the best, followed by oats, wheat, and corn. Still other observations spanning 36 years at 14 locations in the Great Plains showed that cropping decreased organic matter and N both about 40% (Haas and Evans, 1957).

Observations spanning a century in Oregon confirm the older, shorter-duration findings (Figure 4.2.2). In general, organic matter and N in the soil continue to decrease long after the cultivation of land begins, except where sufficient organic matter (such as manure) is applied. Maintaining soil organic matter is much harder where the soil is fallowed. Less soil organic matter in soils and higher yield goals require more N. Nitrogen fertilization slows the loss of organic N in the soil and increases the production of crop residue and, hence, organic matter in the soil. Although the crop recovers about the same fraction of the applied N whether the fertilizer is inorganic or organic, the recovered fraction decreases with higher application rates.

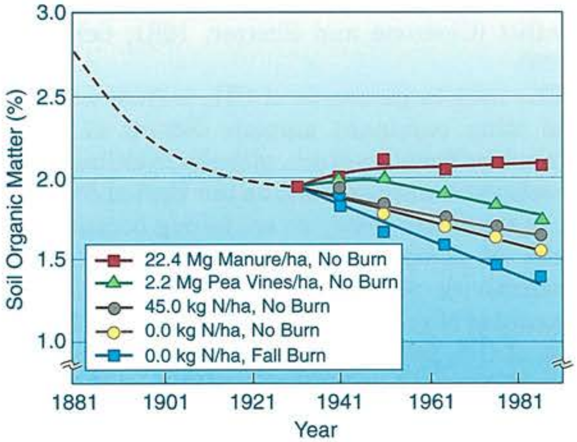

Figure 4.2.2. **Change in soil organic matter in the top 30 cm of soil from 1881 to 1986 during rotation of wheat and fallow with five recent regimes of annual manuring, fertilizing, and burning (Rasmussen et al., 1989).**

Recently, the effects of climate and cropping have been combined in a simulation model that earlier incorporated factors controlling soil organic matter in grasslands of the Great Plains, and was applied to study land-use effects on soil organic C. The model was validated by comparison to 40 years of historical C and N contents in the top 15 cm of soil at 11 stations. It was also used to simulate soil-C levels in virgin sod and croplands at 55 sites along seven transects from east to west across the Great Plains (Figure 4.2.3). The computations for grasslands and for croplands after 40 years of wheat-fallow rotation confirm that soil organic C is lost at the rate of about 40% (during 40 years) from cultivation, 6 to 8% per °C of mean annual temperature from warming, and about 0.09% per mm of decrease in mean annual precipitation (Cole et al., 1988; Parton et al., 1987, 1988).

Earlier we noted that, as the earth's crust weathers, plants and other organisms grow and die, distributing the C and N of their remains primarily near the soil surface but also deeper within the soil profile. Then it is distributed more by the activity of soil animals, by precipitation, and by other processes. So, loss of C from the entire inventory in the profile is proportionally less than loss from samples of upper soil that we have discussed until now. For example, in a Canadian grassland soil, 55% of the organic C in the surface soil (0 to 15 cm depth), but only 46% of the organic C in the entire profile (0 to 80 cm depth) was lost during 70 years by cultivation of a virgin site (Schlesinger, 1986; Tiessen et al., 1982; Voroney et al., 1981).

A recent investigation of tillage for mitigating emissions of CO_2 from agriculture (U.S. Environmental Protection Agency, 1991b) indicates that up to 0.078 Gt of soil C may be lost from U.S. agricultural land between now and the year 2020 under current management. Our review of organic matter in soil shows how a warmer and drier climate might cause some loss of organic C and suggests that some practices of husbandry can raise the equilibrium level stored in soil.

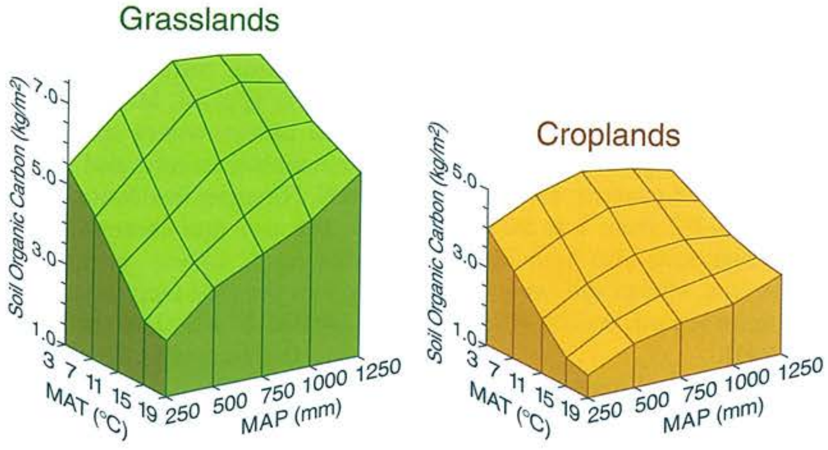

Figure 4.2.3. Simulated levels of soil organic C in fine textured soils as a function of mean annual temperature (MAT) and precipitation (MAP) in the Great Plains. (A) Native grasslands and (B) croplands after 40 years of cultivation in wheat-fallow (Cole et al., 1988).

Methane

Of the estimated 0.5 Gt of CH_4 emitted into the global atmosphere annually (Table 4.1.1), two-thirds is produced biologically. In percentages of the total CH_4 emission, the biological sources are estimated to emit: rice paddies, 28%; ruminants, 20%; swamps and marshes, 11%; and others, 6% (Seiler, 1990).

Methanogenic bacteria are the exclusive biological producers of CH_4. They live only in strict absence of oxygen, which is in waterlogged swamps, bogs, rice paddies; in the rumens and guts of livestock and other animals; or in the guts of termites. On the other hand, methanotrophic bacteria oxidize CH_4 where oxygen is available. When CH_4 is produced abundantly and escape is easy, considerable CH_4 can reach the atmosphere. In productive submerged sediments, so much CH_4 may be produced that it bubbles through the overlying sediments that may be rich in oxygen but cannot oxidize it quickly. Thus it escapes to the atmosphere. On the other hand, if CH_4 is produced slowly and must travel a long path through the sediments, much may be oxidized on way to the atmosphere (Conrad, 1989). Methane may also be transported from the sediments to the atmosphere through the stems of plants.

Several observations indicate aerobic soils serve as a sink for atmospheric CH_4. Confirmation of the phenomenon is widespread (Born et al., 1990; Bouwman, 1990; Keller et al., 1990; Mosier et al., 1991; Schutz et al., 1990; Steudler et al., 1989; Whalen and Reeburgh, 1990). Several factors influence how much CH_4 the soil takes in, including—soil water content, soil temperature, N-dynamics, and microbial population; but the role of these factors on the dynamics of CH_4 uptake is still unclear as is the effect of cultivated and fertilized soils versus natural soils. Recent studies by Melillo et al. (1989) and Mosier et al. (1991) indicate that land use change and N additions may contribute to a decreased soil CH_4 sink.

Emissions from the strongest source, rice paddies, vary seasonally and daily, with climate and with management. Measurements from China and Italy showed that CH_4 emission doubled when temperature warmed 5°C. Although adding and incorporating organic fertilizers seems to increase CH_4 emissions while incorporating urea or ammonium sulfate deep in a paddy seems to decrease them, observations conflict (Cicerone and Shetter, 1981; Schutz et al., 1990).

The next large source of CH_4 is from cattle, sheep and other ruminant animals (Schutz et al., 1990). Emissions from livestock, globally, continue rising. In developed countries, such as the United States, emissions are either steady or are falling because management of domestic livestock continues to improve productivity per animal. Increases in the genetic capacities of ruminant livestock decrease the production of CH_4 per unit of livestock product by decreasing numbers of animals required to satisfy demand. Methane production associated with the digestion of feed required to satisfy maintenance requirements of livestock populations decreases in direct proportion to the decrease in animal numbers. Improved feeding and management practices contribute significantly to the continuing decrease in numbers of domestic ruminants in the United States.

Predicting the impact of climate change on CH_4 emissions from livestock and from other herbivores in particular is difficult without knowledge of future feed efficiency. Consider the scenario: Less corn and soybeans are grown and range and permanent pasture expand, fewer calves are diverted to feedlots at weaning and more grow up on range and pasture. Compared to grain, forages yield more CH_4 per unit of available energy and cattle grow more slowly on forage. So, more CH_4 is emitted per kg of edible beef. On the other hand, if sorghum replaces corn, husbandry would change little, and producing a kg of beef would emit less CH_4 because cattle emit less CH_4 from a sorghum than from a corn diet.

Nitrous Oxide

Emission of N_2O from cultivated land and perhaps from fossil fuel use are the two primary contributions by agriculture to global N_2O emissions. Cultivated land is estimated to contribute less than one-fourth of the N_2O emitted from fertilized and natural soils (Seiler and Conrad, 1987); soils may contribute 0.008 Gt to net annual global N_2O emissions of 0.021 Gt (Table 4.1.1).

As organic matter in soil decomposes, first ammonium, then nitrite, and finally nitrate ions form. This chain of oxidative processes, called nitrification, causes the emission of a small amount of N_2O (Blackmer et al., 1980; Tortoso and Hutchinson, 1990). Reversal of the chain by reductive processes is the route for most losses of gaseous N compounds to the atmosphere. Called denitrification, it makes N_2O and proceeds in soils poor in oxygen. Nitrate, which is a desirable nutrient for plants, is reduced first to nitrite, then to nitric oxide, next to N_2O, and finally to N_2. In addition to limited oxygen, denitrification generally requires effective microbes, suitable reducing agents like organic C, and oxides of N (Broadbent and Clark, 1965; Firestone and Davidson, 1989; Klemedtsson et al., 1988).

Although any loss of N is a loss to the farmer, the significant factor for climate change is loss as N_2O rather than N_2, which comprises over three-fourths of the atmosphere. The ratio of N_2O to N_2 lost from soil depends on conditions listed in Table 4.2.1. For example, per unit of elemental N emitted more N_2O escapes to the air from a cool, well-aerated (well-drained) soil low in organic matter than from a warm, poorly-aerated (wet) soil rich in organic matter (Betlach and Tiedje, 1981).

The greenhouse gas N_2O is apparently only destroyed by reaction with atomic oxygen in the stratosphere to form nitric oxide (NO). The NO then reacts with ozone (O_3), leading to an overall decrease in this important stratospheric component (Bouwman, 1990).

Table 4.2.1. Factors raising the relative proportion of the greenhouse gas nitrous oxide (N_2O) to dinitrogen (N_2) when they are produced by denitrification (adapted from Betlach and Tiedje, 1981)

Soil factor	Change	Example
Oxidant level	Higher	$[NO_3^-]$ or $[NO_2^-]$
Oxygen content	Higher	Degree of soil aeration
Carbon content	Lower	Amount of available C
pH	Lower	More acidic soil
Sulfide content	Higher	H_2S level in soil
Temperature	Lower	Cool soil temperatures
Enzyme status	Lower	Less N_2O reductase

A recent investigation of policies for mitigating emissions of greenhouse gases (Committee on Science, Engineering and Public Policy, 1991b) listed options ranging from controlling erosion of the soil and tailoring N fertilization to the crop on to adding microbial inhibitors to fertilizers. The effective options are those that raise the fraction of the N in the soil that is taken up by the plant, decrease the nitrification of ammonium to nitrate, decrease the reduction of nitrate to N_2O and N_2, and also decrease the fraction of the two that escapes as N_2O.

In Brief

In understanding the cycle of agriculture that produces food from soil nutrients and atmospheric CO_2, we may find ways of storing greenhouse gases or tempering their emission. The cycle is underlain by soil with its fertilizing nutrients, organic residues, and microbes. All are connected as nutrients move into plants, which are harvested and eaten or decompose, and wastes are returned to the nutrient and carbon pools in the soil. In this cycle the greenhouse gas CO_2 is taken into crops by photosynthesis and returned to the atmosphere by respiration and decomposition.

The greenhouse gas CH_4 also cycles but through a different route. The greenhouse gas N_2O is emitted from soil and perhaps by fossil fuel burning, but the only apparent sink is through stratospheric loss.

Emission of CO_2 from the soil can be tempered or even reversed to an intake by less tillage, the return of manure and wastes, and fertilizing with N and P. Methane is produced when oxygen is lacking and carbon is abundant as in rice paddies or the rumen of livestock, but it can be taken into aerobic soils. In livestock the emission of methane per unit of milk or meat can be decreased by improved breeding, feeding and management, and by biotechnology. The reduction or denitrification of nitrate to gaseous N compounds release the greenhouse gas N_2O. Curbing the accumulation of nitrate and lowering the ratio of N_2O to N_2 in the soil both decrease the emission of N_2O.

4.3 What rates of net sequestration of CO_2 could be attained and sustained by plants and soil, how would the carbon be kept sequestered, and what would be the cost of a sustained system in carbon emission?

To think practically about sequestering CO_2 from the global atmosphere, we must begin with some perspective. Figure 4.3.1 shows that the atmosphere held an inventory of about 740 Gt in 1986, now about 755 Gt of carbon, and each year the inventory rises about 3 Gt. Annually some 110 Gt pass into plants on the land via photosynthesis. Respiration and decay of living things and soil emit about the same amount back to the atmosphere. Scientists are not yet able to understand accurately the balance of carbon flows. Nevertheless, amidst the flux of about 6 Gt carbon from burning fossil fuel, they estimate a net 0.4 to 2.5 Gt stream to the atmosphere from deforestation, that there may be a net uptake by other plants because of the faster photosynthesis caused by the enrichment of the air with CO_2, and that there is possibly some sequestering of carbon as forests and soils recover from earlier degradation (Post et al., 1990).

Since the inventory of carbon in living and dead things on the land plus the soil is about 2,000 Gt, it would only have to be increased by 3/2,000 per year to arrest the annual 3 Gt rise in the atmospheric inventory. Or, the 110 minus 50 Gt net flux of carbon from the atmosphere to living things would only have to be increased 3/60 to arrest it. Although adjustments in the entire carbon cycle would follow such an increase in the flow and storage of carbon in living things on the land, these simple reckonings show moderate changes in total photosynthesis less respiration and decay on land could slow, or accelerate, the CO_2 enrichment of the atmosphere dramatically.

Because nine-tenths of the living carbon above ground is in trees and more than one-third of the carbon in soil is under forests, forests are the obvious place to look for increasing carbon storage. Another quarter of soil carbon is under tundra and in wetlands. Cultivated soils contain one-eighth of the carbon in world soils, and its conservation would help (see Question 4.2) (Post et al., 1982, 1990). Here we concentrate on forests, examining first how they would adjust to a climate change. Then we examine how much emission of CO_2 could be mitigated by slowing deforestation, how much CO_2 could be withdrawn from the atmosphere and stored in forests, and how the emissions from fossil fuels could be abated by sustained production of fuel wood.

Adjusting to Climate Change

We have noted above that forests have the sensitivity to CO_2 and weather, especially moisture, that crops have but are distinguished from typical crops by their longevity, by the diversity of the species within a single forest, and by less management. Orchards, of course, share some of the traits of a forest.

When a forest is not managed at all and contains diverse plants, plants that are not suited to the new climate will decline, for many years if they are trees, and be replaced by ones that were present and are favored by the new climate. The disturbance of a fire or storm can, of course, hasten the passage of the unsuited and succession of the suited. If plants suited to the new climate are not present, adjustment of the forest must await the arrival, likely a chancy process, of plants that are suited (Shugart et al., 1986).

Forests are not static, and adjustment is normal as the death and replacement of the chestnut in the eastern forest recently demonstrated. The worry is how abnormal or disruptive the adjustment accompanying a rapid climate change would be. Both the changes in forest that followed the Ice Age, Figure 4.3.2, and those computed by models suggest the changes would be large (Botkin, 1991).

Practically, many forests are more or less managed. Artificial regeneration of forests could be costly and difficult and needs adapted species or varieties. The adaptation of valuable forests might be achieved through more intense management if the methods are robust enough to work in many climates and flexible enough to change quickly and cheaply. Attention would have to be paid to the preservation of the species diversity (Committee on Science, Engineering and Public Policy, 1991a). That is, wide replacement of natural stands by uniform ones of a few species could decrease the diversity needed for later adaptation to changes in climate and other factors.

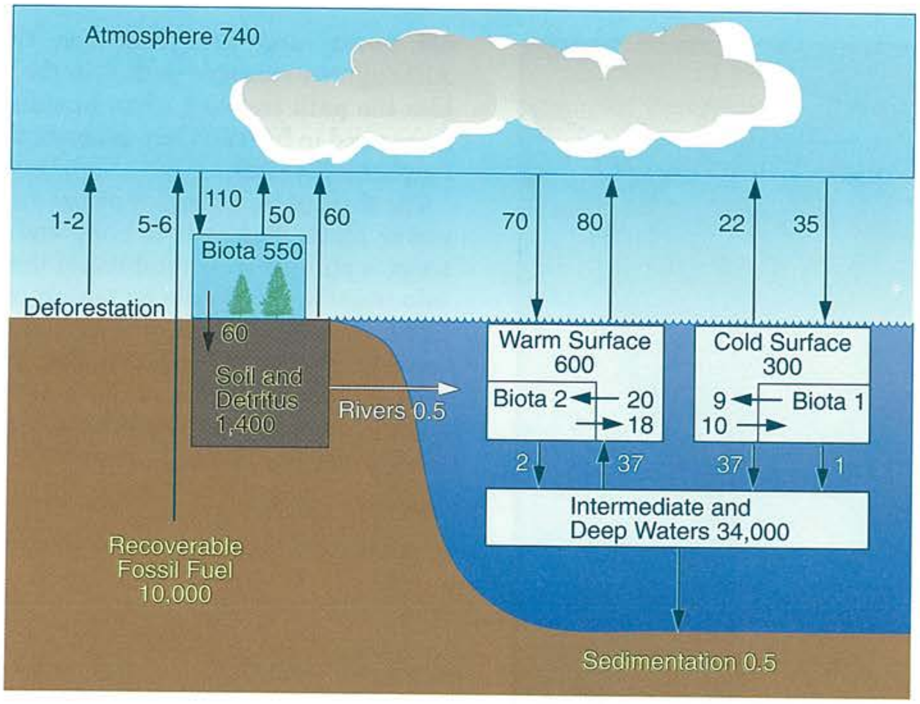

Figure 4.3.1. The global inventories in 1986 and flows of carbon in gigatons (Gt) and Gt/year (adapted from Moore and Bolin, 1986).

Slowing Deforestation to Mitigate Emission of CO_2

Worldwide changes in the use of land, particularly deforestation, caused the emission of 1.5 plus or minus 1.0 Gt of carbon per year during the early 1980s and may be causing more now. In the United States the area of forest land has changed only slightly during the last several decades, and the inventory of living carbon has probably increased somewhat (Haynes, 1988; Houghton, 1991). At present, deforestation is a problem for the emission of carbon principally in poor, tropical countries and, as such, is a situation the United States might hope to influence but cannot directly control.

Stashing CO_2 in Forests

The transitive verb *stash* of unknown origin means to hide or store away in a secret place. The hoped-for capturing of CO_2 from the atmosphere and keeping it as a store or cache of valuables is implicit in 'to stash.' The paths mapped on Figure 4.3.3 show that stashing is one of three beneficial ones that forests might carry affairs along.

The paths are those travelled by the net of the cumulative emissions from burning fossil fuel in a power plant less the carbon stashed away in an accompanying forest. Although the paths do not incorporate the quantities or details that set the efficiency of the power plant or the effectiveness of the forest, they do illustrate the nature of how the power plant and forest would function together.

The cumulative emission of the power plant without the forest follows straight path A, rising steadily with time as fossil fuels are removed from the earth, are burned to generate electricity, and added to the CO_2 in the atmosphere.

Path B is the net of the power plant and a forest planted to take in photosynthesis promptly and exactly all the CO_2 emitted by the power plant—and stash it away. At first, path B of the pair, power plant and forest, would travel along zero emissions. Eventually, however, the new or managed forest would begin to mature. Its net photosynthesis and growth would slow until it was nil. Then path B would climb parallel to path A but below it at the distance a – b, representing the carbon stored in the trees. The path might be kept from turning up by the planting of more forest as the first forest matures or by people really stashing the trees away in building frames or under the ground or sea. Or, path B might be only considered a way to buy time.

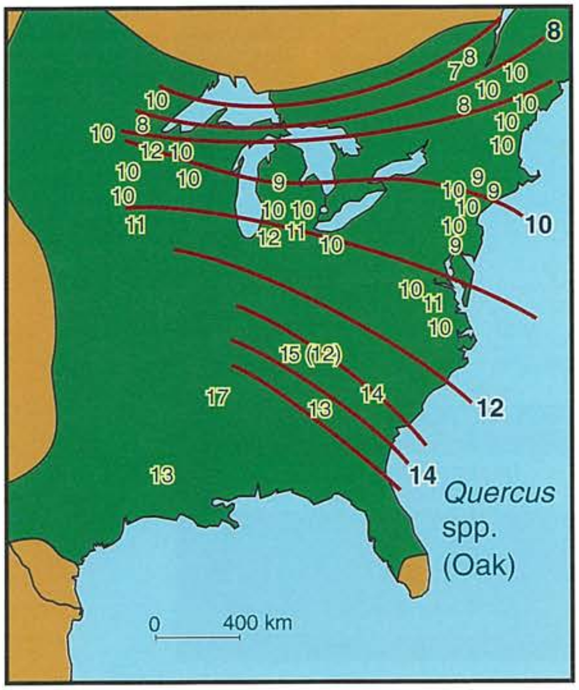

Figure 4.3.2. **The migration of oak (*Quercus* spp.) as the climate warmed 10 to 16 thousand years ago, continental ice melted, and vegetation changed rapidly. The numbers and isolines show the first appearance in thousands of years before present when oaks first appeared at each location as the ice withdrew. Green shows the present range of oaks (Davis, 1981).**

Abating Emissions by Sustained Growth of Fuel Wood

The cumulative emissions would travel path C if the power plant gave up fossil fuel and instead burned first the wood of an established forest and then the wood of a plantation that replaced the old forest. At first, the path would climb as carbon stored earlier in the old forest was released. Later, the wood from the plantation that replaced the old forest would fuel the power plant, and path C would level off because the growth of the new plantation balanced the emissions of the power plant. Actually the plantation would have to take in the emissions of the power plant plus those given off in its own maintenance. The distance between plantation and power plant would set how much more CO_2 would have to be taken in to balance that burned in carrying the fuel wood. On the figure, a – c represents the mitigation of emissions, and it would grow with time, while c – 0 represents the difference in standing crop of carbon between the original, old forest, and the plantation that replaced it. Although we conceive path C in the future, it resembles the path traveled when humanity burned little more wood in fires and hay in horses than was replaced by photosynthesis.

The final path, D, begins before emissions from the power plant. Before it is built and without cutting trees, a plantation is established that carries path D into negative emissions by taking in CO_2. When the power plant begins generating electricity from the fuel wood harvested in the plantation, its photosynthesis exactly balances the emissions of the power plant. Again, the plantation would have to balance the emissions from its maintenance and the transport of the

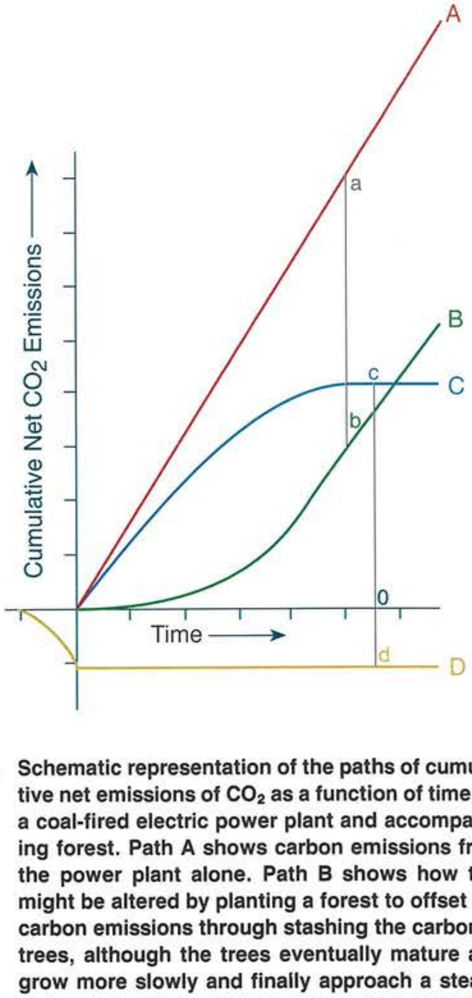

Figure 4.3.3. **Schematic representation of the paths of cumulative net emissions of CO_2 as a function of time for a coal-fired electric power plant and accompanying forest. Path A shows carbon emissions from the power plant alone. Path B shows how this might be altered by planting a forest to offset the carbon emissions through stashing the carbon in trees, although the trees eventually mature and grow more slowly and finally approach a steady state. Paths C and D are those that might be followed using sustainable forest plantations to supply wood to replace coal as fuel for the power plant. Path C would be followed if the plantations were established after harvesting an existing forest and path D if the plantation were established where none existed.**

fuel wood as well as those from the power plant. The standing crop of carbon in the plantation is 0 – d.

Choosing a Path

The distance c – d is the advantage of setting the plantation on bare ground. It equals a – b and is the standing crop in the mature forest that was replaced to start on path B. Although comparison of the paths shows the advantage of a sustained energy crop for mitigating CO_2 emission, seeming details can overwhelm the outcome. We know that both the standing crop of mature forests and the growth of new plantations vary with site, species, and management. We know establishing and protecting take energy, and we know that harvesting and transporting fuel wood take energy. The paths of the figure suggest that an energy plantation on new ground mitigates most. However, where the site sustains only slow growth or much standing forest or is hard to harvest, net CO_2 emissions may be reduced most by planting trees to sequester carbon or simply protecting the trees already there.

Although paths C and D might be called forest strategies, one must realize that the envisioned plantations won't look like the primeval forest. Plantations harvested every 4 to 10 years for fuel will protect the soil and shelter wildlife. They may, however, be managed and look more like crops. In fact, the goal of replacing fossil fuel requires growing the fastest crop, which may not be trees, and growing them in the fastest way, which may be a challenge for farmers.

If stashing carbon away along path B is the goal, trees with massive boles and roots to stay in the forest or massive boles to be harvested and used or stored would seem the best crop. On the other hand, if path C or D are to be followed, the crop is for fuel, and the best crop is one that puts the most carbon in harvestable parts; any other parts like roots that do not decay only increase distance 0 - d in the figure.

Area, Yield, and Energy

The question then is, for the United States: How much land might be available for sequestering carbon in trees or growing biomass fuels. How much opportunity have farmers or other land owners to produce carbon stashes or energy crops? Questions concern more than availability of land. They concern expected yields, efficiency of harvesting, and using the fuel. They concern the diminution of genetic diversity by the stashes or crops, their demands on water supply, and their darkening the landscape and so reflecting somewhat less solar radiation. Moulton and Richards (1990) suggested that the United States could offset half its current emissions of CO_2 related to fossil fuel by planting 140 million hectares with trees. They visualized planting only environmentally sensitive and economically marginal pasture and crop land and under-utilized forest land. A more modest projection (U.S. Congress, Office of Technology Assessment, 1991) envisioned that trees might be profitably planted on 30 million hectares. See Figure 1.1.3 for the land areas in different uses in the United States.

The latter projection also envisioned that energy crops might eventually supply 6 to 8% of current U.S. energy. The 6 to 8% is 2 to 3 times the energy consumed by U.S. agriculture in 1981. Even more could be produced if energy crops became profitable through achievement of high yields and their efficient use. The virtue of energy crops is not always a foregone conclusion. For example, critics frequently claim that the production of ethanol from corn for energy consumes more energy than it makes. Marland and Turhollow (1991), however, recently calculated that making ethanol from corn does produce a net of energy while cutting reliance on imported petroleum. Although there is no question that a boiler built to burn wood will return more energy than is needed to supply the wood, the largest net of energy, profit, and reduction of emissions of greenhouse gases will occur if we ensure high crop yields and efficient fuel use.

Despite the disparity among these visions as well as among others, land owners have a great potential for supplying energy crops or sequestering carbon. The opportunity includes achieving other goals like conserving soil, protecting watersheds, and providing habitat for wildlife. Figure 4.3.4 encapsulates the potential for production of energy crops. The figure shows the relationship among the quads of energy that could be produced, the production per hectare per year, and given allotments of land. These are related to the cropland and idle cropland in 1989 and to the projected surplus of cropland in 2030. Since the total production of energy in the United States in 1988 was 69.6 exajoules (EJ) and use was 84.4 EJ, the highest curve or 27.4 EJ for energy crops is substantial. The lowest of 4.2 EJ exceeds the 2.7 EJ of wood energy consumed in the United States in 1984.

Concluding our discussion of abating emissions by growing plants for energy, we reiterate that herbaceous crops like sugar cane or switch grass may serve as well as trees. Because fuel wood is familiar, we frequently wrote of trees and fuel wood in the preceding paragraphs. The goal, however, is economically and cleanly fixing carbon from the air and burning it for useful energy. A crop and husbandry resembling farming may serve as well as a forest, and circumstances of a region will determine whether a forest, a crop, or a mixture or alternation is best.

In Brief

A small percentage increase in annual net photosynthesis or the inventory of carbon in living things could abate for a while the annual rise of 3 Gt in the atmospheric inventory. Several strategies might be pursued. They range from protecting existing forest that might otherwise be destroyed, to planting trees where trees do not now grow, to recycling carbon by burning energy crops in place of fossil fuels. The options of planting trees and growing energy crops open new opportunities for farmers and land owners. The hard questions are about land, actual sustainable yields, time, the efficiency of using energy crops, environmental issues, nutrients, aesthetics, and the practical management of the enterprise.

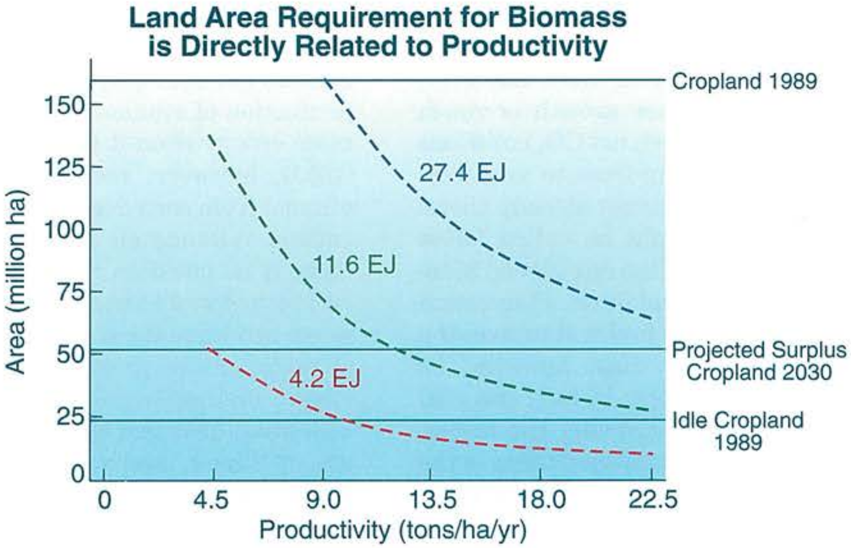

Figure 4.3.4. **The production of energy in exajoules (EJ) from combinations of productivity in tons/ha/yr of dry crop and millions of hectares of land. For reference the U.S. area of cropland in 1989 and the idle cropland in the same year are shown. The surplus of cropland projected for 2030 is also shown. For further reference 26.3 million hectares produced an average yield of 9 tons of corn grain in 1989, and 84.4 EJ of energy were used in the United States in 1988 (Wright, pers. com., 1991).**

5 Autonomous Adaptations

After sketching the background of warmer climate, more people, more trade, and more CO_2, after reviewing the lessons history teaches about the impact and adaptation to weather, and after learning how much greenhouse gas agriculture emits and can store, we are ready to guess how farmers and foresters will adapt—first, autonomously within the present rules and incentives. Our goal is preparing for the new world with an arsenal of encouragements for successful adaptation. Before preparing those encouragements, however, good sense commands us to visualize the spontaneous adaptations that will generate themselves without new encouragement. We call the spontaneous adaptations generated from internal causes autonomous ones, and we examine them before suggesting encouragements for still more adaptations.

5.1 Given the other changes specified in The Big Question—but unchanging farmers, how would trade respond to the new distribution of food production?

As shown earlier, the world food market can adjust rapidly to changes or even expectations of changes in supply caused by weather. Trade, therefore, is a good starting point to examine autonomous adaptation to a more enduring change in supply caused by climate. Amid a wide range of uncertainties, predicting a new pattern of trade called forth by a change in climate is nearly impossible, and trying would lend a false sense of accuracy. What is more valuable is identifying the key factors that will shape the new flows of trade and making some educated guesses about the new directions in which trade might flow.

Although the United States has become accustomed to viewing itself as a major exporter of food, some conceivable changes in climate could cut U.S. agricultural production enough to make us a net importer. Though unlikely, such an outcome would have far-reaching consequences, from a higher cost of food to a fall in the nation's balance of trade. Under such circumstances, the world market would be just as valuable to the United States, but more as a means of locating additional sources of supply, not additional foreign customers for U.S. farm products.

How Easily Can Trade Flows Adjust?

The trade environment, which is a byproduct of economic growth and trade policy, will determine the ease with which the world food market can redirect food from surplus regions to regions hurt by any climatic shift.

World food trade has been volatile in recent decades. As shown earlier, grains and oilseeds dominate world food trade; grain and oilseed trade is shown in Figure 5.1.1. In the 1960s, trade grew slowly. In the 1970s, the world's grain trade more than doubled, markedly improving nutrition in the developing world while profiting farmers in the United States and elsewhere. In the 1980s, world trade did not grow at all as the developing world struggled with economic problems, including repayment of debt. Stagnant trade in the 1980s created financial hardship for U.S. farmers and agribusiness and, as a result, a significant share of U.S. and world capacity to export grain was idled.

The world's margin between the supply of and demand for world grain is slim, as shown in Figure 5.1.2. Swings in supply influence trade to a considerable extent, but trade (shown in Figure 5.1.1) is governed primarily by two other factors: economic growth and farm trade policy. During the 1970s, grain was in short supply, partly due to weather. More important, demand for grain was strong, making it relatively scarce. World GNP grew a robust 4.1% annually as developing and centrally planned economies, where the demand for food was high, could obtain credit easily. During the 1980s, grain was in surplus because economic growth was only 2.9% annually, which slowed the growth in food demand. At the same time, farm and related trade policies encouraged surplus production in developed countries and generally discouraged world trade.

In the 1990s and beyond, the rate of economic growth and the trade policy that governs world trade flows will

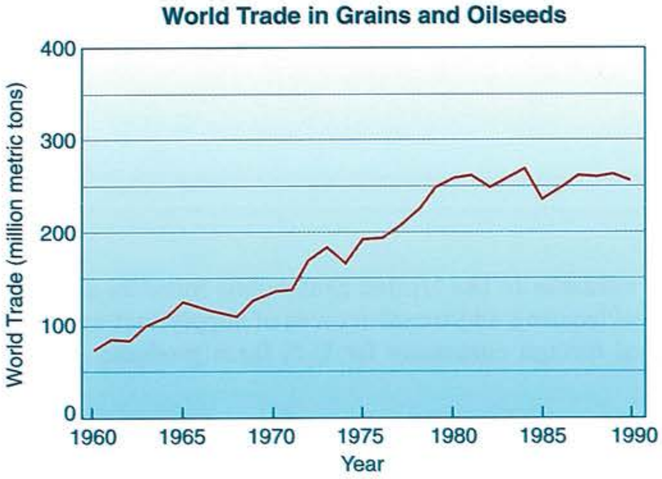

Figure 5.1.1. World trade in grains and oilseeds (U.S. Department of Agriculture Production, Supply, and Distribution Database, 1990).

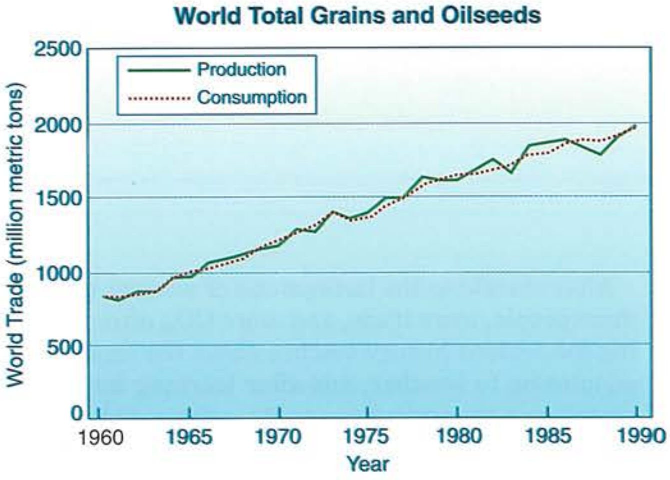

Figure 5.1.2. Production and consumption of world total grains and oilseeds (U.S. Department of Agriculture Production, Supply, and Distribution Database, 1990).

critically influence the ability of new trade flows to offset changes in crop production that might accompany climate change. During the 1990s, the world economy will probably grow at its long-run potential rate, the so-called trend rate, of 3.0% or a little better. Only slightly faster than in the 1980s, the growth may be redistributed in ways that benefit world food trade. Namely, economic growth in the 1990s may be slower in the United States than in the 1980s, while growth may be somewhat faster than the 1980s in Latin America, the Pacific Rim, and Europe. Smaller federal deficits in the United States will leave more investment capital for the rest of the world, especially the developing world. Economic growth in developing countries will depend on continued success in working through debt problems left from the 1980s, but early signs are encouraging that success will continue. The republics of the former Soviet Union face enormous challenges reforming their economies and will have difficulty financing food imports for the foreseeable future. Trade with the republics will also be critically affected by the overall political stability in the region. Overall, moderate growth in the world economy will support moderate growth in world food trade in the 1990s, an improvement over the much more sluggish 1980s.

Farm trade policy may influence the capacity of world trade to respond to shifts in climate more than economic growth. Today, policy governing world agricultural trade stands at a crossroads, where its fate will be set for the decades that may coincide with climate change. Freeing agricultural trade is the central topic of the current Uruguay Round of trade negotiations sponsored by the General Agreement on Tariffs and Trade (GATT). Freeing farm trade requires two fundamental changes in policy: (1) cutting or eliminating domestic price supports that lead to surplus production, and (2) eliminating tariff and nontariff trade barriers around the world. Most analysts expect freer trade in agriculture would lead to a significant boost in world food trade. Countries whose agriculture is highly subsidized now, like Japan and members of the European Community, would probably produce less and import more farm products. Conversely, countries whose agriculture is subsidized comparatively less now, like Australia and the United States, would produce and export more farm products.

If climate changes, freer trade in agriculture will be vital to maintaining stable food consumption around the world. Current trade barriers discourage trade between some nations. Bottlenecks in world trade caused by distortional farm policies force the world market to make a bigger adjustment in prices than would otherwise be the case. Consider the case of a country that restricts imports of corn. Suppose that same country experiences a drought that cuts its own corn production. Due to the fall in supply, corn prices would rise in that country. If corn imports were allowed into the country to offset the drop in domestic corn production, the rise in prices would be reversed. But because corn imports were limited, prices would rise more than they would under free trade. Trade barriers, therefore, result in market prices that are more unstable than under free trade. In turn, the greater instability in prices makes adjustments to climate change more costly, especially to developing nations. In short, trade needs to flow freely in a world where climate may make crop production more variable.

The same farm policies that restrict trade also encourage a misallocation of resources and discourage farmers from more flexibility and innovation. In the United States, for example, government payments are tied to maintaining the land planted in a given crop. Farm policy, therefore, has the unintended consequence of actually discouraging farmers from trying new crops better adapted to a new climate.

Finally, freer trade in agriculture will be essential in allowing developing countries to earn the foreign exchange necessary to offset the effects of a change in climate. Developing world farmers may be one of the biggest beneficiaries of farm trade liberalization (Barkema et al., 1989). The hard currency these countries earn from increased agricultural exports could pay for adaptations to harmful climate change or adaptations that exploit beneficial climate change.

The outcome of the Uruguay Round is still unclear, but some freeing of trade may occur. The world currently spends about $300 billion a year on farm subsidies, an amount that appears unsustainable (Organization for Economic Cooperation and Development, 1991). Moreover, agriculture is clearly the linchpin to progress in 14 other areas of negotiation in the Uruguay Round, including services and intellectual property. But the move to freer trade will almost certainly be slow; it is difficult to wean farmers in the developed nations from their accustomed subsidies and protective trade barriers. There is a risk that the world might give up on multi-lateral trade reform and retreat into a series of trade blocs: Europe, North America, and the Pacific. Such blocs would almost certainly retain trade restrictions that would make trade less adaptable to climate change.

Overall, the world food market will engender critical trade adaptations to climate change. But lingering trade restrictions, most tied to domestic farm policies, will temper both the amount and speed of adaptation.

Where Are Crops and Exports Concentrated?

Where crops are concentrated is the second key factor that will determine the extent to which trade can adapt to climate. Crops have very different production and trade profiles in the world grain market. Production and trade characteristics for three major world crops are shown in Figure 5.1.3.

Corn, represented by the first profile, grows mostly in the Northern Hemisphere, where the United States dominates its production. More importantly, the United States exports a large share of its corn crop, thus accounting for fully three-fourths of world trade in corn. Developing nations, meanwhile, purchase less than a quarter of the corn traded in world markets.

The dominant role of the United States makes world trade in corn highly sensitive to the effect of climate change on the U.S. crop. Setting aside any effect of global warming on production elsewhere in the world, a 20% drop in U.S. corn output would quickly translate into a smaller world supply, less trade, and higher prices. Most of the effect would fall on developed nations because developing nations buy only 23% of the world corn trade. There is a relatively small amount of corn produced in the Southern Hemisphere and an unknown potential for growing corn in newly warmed but far north latitudes of America and Asia, suggesting only a limited world buffer against persistent shortages of U.S. corn caused by a global warming.

Wheat, meanwhile, presents a different profile. Production is concentrated in the Northern Hemisphere, but the United States produces little more than one-tenth of the world's wheat supply. The

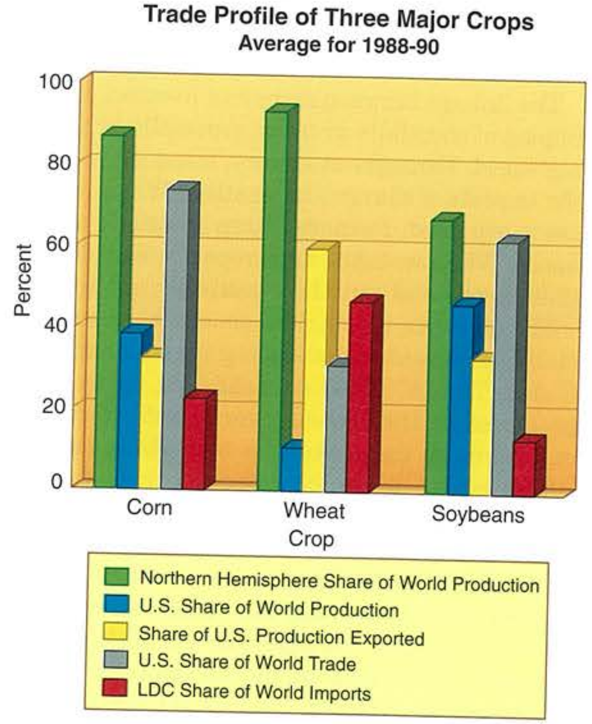

Figure 5.1.3. **Trade profile of averages for 1988 to 1990 for three major crops (U.S. Department of Agriculture Production, Supply, and Distribution Database, 1990).**

United States exports more than half its wheat, but controls only about one-third of world wheat trade. So, a climate that cut U.S. wheat production 20% would affect world wheat prices and trade only modestly. Since developing countries import about half of the wheat traded in world markets, they would feel keenly any changes in price. But wheat is grown very widely around the world, suggesting substantial capacity elsewhere to offset any U.S. shortfall.

Soybeans offer yet a different profile. The Northern Hemisphere produces only about half this crop. The United States dominates the world soybean market, with nearly half of world production. Exporting one-third of its vast crop, the United States controls 62% of world trade. A 10% drop in U.S. production would push world prices higher while trimming world trade. The large and increasing soybean crop in the Southern Hemisphere can be expanded considerably, providing a substantial reserve to offset some of a shortfall of soybeans from the United States. In addition, expanded production of other oilseeds in other parts of the world may offset part of any decline in U.S. soybean production. Changes in the soybean market would affect developing nations less because they import only 14% of the world soy trade.

How Will Livestock Production Respond to Weather Change?

The linkage between crops and livestock modifies the impact of shortfalls in crops, especially in the developing world. Throughout history, livestock have buffered the impacts of changes in weather. When weather and crops are good, farmers fatten livestock and expand herds. When weather and crops are bad, farmers cull their herds and put the remainder out to graze.

The livestock adjustment to weather has been especially important to developing nations and the Soviet Union. The 1972 Soviet wheat deal, for example, was prompted by the Soviet government's decision *not* to cull herds in the wake of a bad wheat harvest.

The extent to which livestock help to adjust to climate change will be guided by two opposing forces. First, global warming may cut feed grain output in key regions like the United States and raise feed costs. Second, global warming may cause some cropland to revert to grazing purposes. In the United States, for example, grain yields might fall below profitable levels in parts of the southern Plains and Corn Belt. The land that reverts to grazing will have little alternative use and therefore may be used to support larger cattle herds. As a result of the change in climate, U.S. cattle feeders may pay more for corn but less for feeder cattle. How these different effects play out is uncertain for the United States, and even more uncertain for the world.

The Great Plains of the United States offer an interesting example of how one important agricultural region may respond to global warming. The ten states that stretch from Texas to Canada encompass 80 million hectares of cropland, or 43% of the national total.[7] They include 177 million hectares of rangeland, or 54% of the national total. Much of the cropland has low productivity unless irrigated. As climate warms, increasing evaporative demands and irrigation water requirements may not be met because of limited renewable ground water supplies. The net effect will be a more rapid decline in irrigated land area than is now occurring in the Great Plains except in Nebraska. Land not irrigated will revert to dryland farming or to grazing.[8]

But as more land is devoted to grazing, an increase in cattle production would offset the drop in crop production. Already, the region earns more than half its farm receipts from cattle and calves (Drabenstott and Barkema, 1991). The region thus has a strong livestock infrastructure on which to build. The fact that scientists have bred heat-tolerant cattle only enhances the ability of the region to expand its cattle industry if climate changes.

In Brief

The world food market has the capacity to encourage significant adaptation to climate change. For the market to temper the impact, global economic growth must continue to provide the currency to finance increased trade. Prospects for growth in the 1990s are reasonably good. The rules governing agricultural trade will need to be changed to allow freer trade. Prospects here are mixed at best. The world's livestock producers offer an additional means to adapt to climate change. If the United States becomes warmer and drier, it would likely grow more cattle, certainly more range-fed cattle. Speculation about the world's herd is more uncertain.

Overall, trade probably will offset only part of the effects of climate change on agricultural production. Farm policies will continue to distort market prices

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[7] The ten states included in the Great Plains are Colorado, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming.

[8] For a further discussion of the effect of climate change on the cattle industry see Section 2.1.

and trade flows, preventing producers and consumers from making the best adaptations to change. If climate change leads to an overall drop in crop production, trade will increase but probably not enough to keep prices from rising.

5.2 Now, if farmers receive new technology much as in the past and take it up much as in the past, how will they change production?

We examined how changing trade might adapt the world to changed climates by directing food from places where future farmers grow abundant crops by present techniques to places with new demands. Now, we turn to changing farmers. Rising output, falling input, and improving productivity of U.S. farms for more than a generation (Figure 3.1.1), suggest U.S. farmers will keep on changing. Rising production of grains and oilseeds by all farmers of the world (Figure 5.1.2) suggests all farmers will keep on changing, perhaps impelled by climate change. What might these autonomous changes by farmers be?

In assessing changes in trade, we wrote that amidst the uncertainties of climate change only new directions, not specific quantities, could be stated without lending a false sense of accuracy. So it also is with changes in farm management. We can, however, clearly see the directions farmers would change given certain climate changes, and exemplify them by the crucial Corn Belt. We shall first visualize the changes in the place where the Corn Belt is today, and then visualize a new Corn Belt in another place.

Climate Change in Place

A change in the midwestern United States to moderately warmer and more arid, say 3°C warmer with 10% less precipitation, would reduce yields of corn and soybeans in the Corn Belt states. In time farmers would grow less of these crops and instead a mix of drought tolerant crops like those grown today in Kansas or Oklahoma without irrigation. Irrigation needs would increase about 100 mm per year. Because the Corn Belt states do not have the equivalent of the Ogalalla Aquifer, the practical potential for irrigation is in the relatively small areas of river valleys. Peterson and Keller (1990) calculated that for this climate scenario, irrigation in Iowa, for example, would increase from less than 1% only to 1 to 4% of the harvested cropland.

Some corn, therefore, would be replaced by dryland sorghum, and the remaining corn would be planted less densely, which would reduce the potential yield. Sorghum is more drought tolerant than corn, but because the sorghum would be planted on the drier sites, its yields would be, at most, similar or even less than corn. The reduction in area of soybeans would depend on whether breeding could add more drought tolerance than present beans have. Winter wheat would be widely grown to make a crop of grain before summer heat and drought set in.

The farming methods as well as many varieties now used in Kansas and Oklahoma would be promptly adopted in the present Corn Belt. Also, new methods and varieties would be steadily developed during the years of climate change. For example, for the new Minnesota, breeders would develop new varieties adapted to old Kansas weather but also to the longer days of southern Minnesota. These new varieties would produce more than old varieties adapted to both the shorter days and old weather in Kansas.

If, instead, the Corn Belt became warmer but more humid, how would farmers change? They would likely keep the present mix of crops but use new varieties. They would choose varieties with more tolerance to the diseases and insects favored by a warmer, wetter climate like the southeastern United States today. For example, they would likely need varieties with tolerance of corn virus diseases, fungi like the anthracnose and southern corn rust pathogens, and insects like the fall army worm. Faster respiration during warmer nights might subtract some sugar made by photosynthesis during the day. Farmers would, however, be partially compensated for solving these problems by the higher yields possible from the longer-season hybrids they could grow in the warmer climate.

A New Corn Belt in Another Place

Now, how would farmers change if a changing climate put the present rainfall and temperature climate of the present Corn Belt further north? The present Corn Belt, in addition to having some of the most fertile soils in the world, has a seasonal distribution of precipitation and temperature that is ideal for producing corn and soybeans. So, the new Corn Belt should have the seasonal distribution as well as annual average of precipitation and temperature of the present Corn Belt. If that combination of seasonality and average were to shift to another part of the continent, corn and soybeans might shift with the combination.

If the present Corn Belt climate were to shift northeast to form a new Corn Belt centered in northern

Wisconsin and Michigan, we can visualize the outcome. Even the perfect Corn Belt climate over the Great Lakes themselves would not, of course, allow corn to grow in them. On the land, corn and soybeans would generally yield less because the typical soils of the new Corn Belt are recent glacial deposits, including sand and gravel without the deep layers of fertile topsoil characterizing the present Corn Belt. In the new Corn Belt natural drainage systems are not well developed, and the land alternates between dry hills and lakes or marshes, creating problems of water and fertility.

Varieties would be bred to tolerate drought or poor drainage, drains would be laid, and fertilizer would be carefully applied. Still, the present Corn Belt yields would be hard to equal. Likely, other crops would be grown in the new Corn Belt. They would be chosen to suit either the well drained or the poorly drained soils. For example, vineyards might be established on the droughty hilltops and plantations of special poplar for pulpwood in the poorly drained low places. Thus, the new region would not be covered by miles and miles of corn and soybeans. Its diversity in soil types would promote diversity in crops, as well.

Another possible shift of the Corn Belt, this one corresponding to a change to a wetter warmer climate, might be northwest to the Dakotas. To the extent that moistening is less likely to accompany the warming than is drying, a shift to the Dakotas is less likely. Because soils there resemble those in the present Corn Belt, yields and the mixture of crops might stay much the same. In fact, yields might be higher in the new than the present Corn Belt if the long days in the north were combined with the ideal temperature and precipitation. More hours of photosynthesis might combine with optimal temperature and moisture to raise the yield of varieties bred for the new combination.

A shift of the Corn Belt would entail large social and environmental costs. Rural communities and physical infrastructure would become obsolete or need relocation. Natural communities of plants—the forests and lakes of northern Wisconsin, for example—would give way to cultivated fields of corn, soybean, and other crops. In some cases and places, the costs of moving the Corn Belt could be prohibitive.

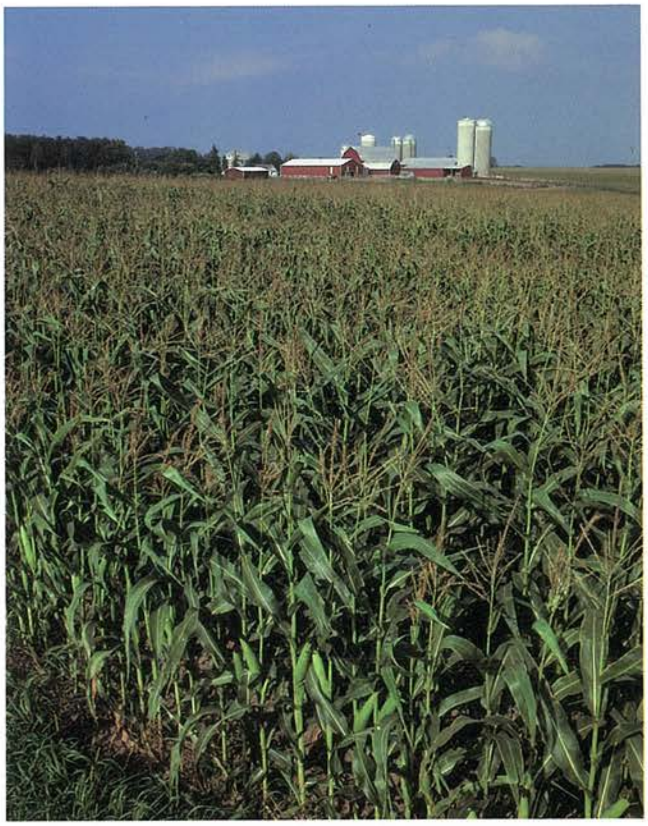
The Foundation for Continued Autonomous Adaptation

Despite the uncertainty of the climate scenarios, we have made one prediction with confidence: U.S. farmers will adapt and so temper the harm and exploit the help of climate changes. We would mislead the reader however, if we did not emphasize the prerequisites for the prediction. U.S. farmers have and we assume they will continue to have a strong foundation or supporting infrastructure. Its constituents include skill, credit, seed, equipment, chemicals, and transportation. It includes signals from the market that induce productivity and research to raise productivity still more. Supported by this infrastructure, U.S. farmers have proven for decades that they can adapt efficiently and rapidly to new regions with new environments and to new markets. Given the infrastructure, we know no reason why they will not adapt in the future.

Breeding and the basic sciences that support it are an indispensable part of the infrastructure. Plant breeding, especially, has a long experience in adapting varieties to specific environmental constraints. During the past 75 years, breeding, by developing a steady steam of improved varieties, has raised U.S. crop yields an average of 1 to 2% per year. Management changes in culture, machinery, and chemicals have added an equal amount of gain so that farm yields of major crops have risen a total of 2 to 3% per year. Breeding and management have interacted and complemented each other over the years, and neither claims sole credit for the gains. Breeding and management, working together, have also improved the dependability of getting high yields, which is essential for withstanding the vicissitudes of harsher climates or moving to new locales (Fehr, 1984).

Genetic diversity is essential for successful breeding. Plant breeders require a highly diverse set of parental material to improve varieties as well as turn out diverse arrays of new varieties. The essential base of genetic diversity is provided by a series of collections of present and extinct varieties farmers have used. These collections maintained in special storages or germ plasm banks number in the tens of thousands for each major crop. When needed, they can be combed through for sources of resistance to new disease or insect pests, tolerance of new kinds of environmental stress, or employment of new opportunities (Duvick, 1984a).

Plants growing in gardens and in their native sites, of course, complement the banks. During climate change natural selection would proceed among diverse populations in native sites and help breeders looking for new combinations to fit new climates. Because the diversity of the dozen or so crops that feed most people is concentrated in so-called centers of genetic diversity, a wise strategy for preservation would concentrate on these centers. The banks and the centers of diversity are the ultimate back-up for all plant breeding.



The adaptation called hybrid corn was propelled forward about 1920 by Donald F. Jones' invention of the double-cross hybrid. Henry A. Wallace began inbreeding corn as a youngster, condemned "pretty ear" corn shows, and in 1926 organized with friends the first company ever to be formed exclusively for the purpose of developing strains of hybrid corn and for the production and distribution of the seed. About 1950 Jones and his colleague, Paul C. Mangelsdorf, devised a genetic way of producing hybrid seed without removing the tassels from the male parents. The 1955 photo shows Jones, Wallace, and Mangelsdorf on the Connecticut Station where double-cross hybrids were first grown. One modern photo shows hybrid seed being grown today. The modern photo of plants being cloned exemplifies the application of biotechnology in agriculture. Meristem tissue culture of (left to right) Cape sundew (*Dorsera capensis*), Venus flytrap (*Dionaea mascipula*), Boston fern (*Nephrolepis exltata* var. *bostoniensis*), African violet (*Saintpaulia* sp.), and Kalanchoe (*Kalanchoe* sp.). Credits: The Connecticut Agricultural Experiment Station (top left), Pioneer Hi-Bred International, Inc. (top right), and Runk/Schoenberger from Grant Heilman (bottom right).

In Brief

By autonomous adaptation, U.S. farmers seem capable of mitigating the deleterious effects of considerable climate change by changing their crops, varieties, and farming systems. For example, in tandem with farmers, breeders have in the past regularly brought out new varieties of existing crops or even wholly new crops adapted to new environments. Continuation of this autonomous adaptation does depend, fundamentally, on vital and unfailing research and development, fulfilling new needs. In the illustration of breeding, research and development annually must produce recommendations of existing varieties and supply new varieties soundly tested for performance in new locations and climates. And it must do so without faltering.

5.3 Do the scenarios specify circumstances beyond the adaptive capabilities of the past?

After seeing the demonstrated adaptive capacities of trade in food and of technology in farming, we still must ask whether the likely change in climate ahead will exceed the capacities. Does the apocalypse or prediction by GCMs render meaningless past adaptations that helped farming recover during the Dust Bowl and that multiplied yields during 1940 to 1990?

Scenarios We Use

The predicted climates underlying the simulated yields near Des Moines do not seem greatly different from present climate (Figure 2.1.1). Although the climates plus enrichment of CO_2 predicted for the future uniformly harmed corn without adaptation, the climates predicted by some GCMs helped and by others harmed simulated soybeans and wheat.

Using the Dust Bowl climate of the 1930s as analog of a future, warmer climate, we saw computed yields of corn and soybeans with present technology would have fallen in the four MINK states (Figure 2.1.2). Wheat, on the other hand, would not have been affected much. Were the climate change to occur today accompanied by a 100 ppm increase in CO_2, adaptation such as adjusting planting time, conserving moisture with furrow dikes and using new varieties with longer growing seasons, would temper the harm of the drier and warmer Dust Bowl climate. Were the climate change to occur 40 years from now, other adaptations encouraged by the fear or reality of climate change, such as drought resistance bred into crops plus those adaptations already considered, could counteract much of the loss of yield from a return to the climate of the 1930s. The adaptations are exemplified in Figure 5.3.1 by dryland corn. Technological advances unrelated to climate change raise yields from the present baseline of 8 t/ha to 13 by 2030. A change to the climate of the Dust Bowl would limit that rise to about 10 t/ha. The rise in CO_2 would add 1 t/ha. Finally, adaptations would raise the yield in 2030 and the Dust Bowl climate to about 12 t/ha (Easterling et al., 1990).

More Extreme Scenarios

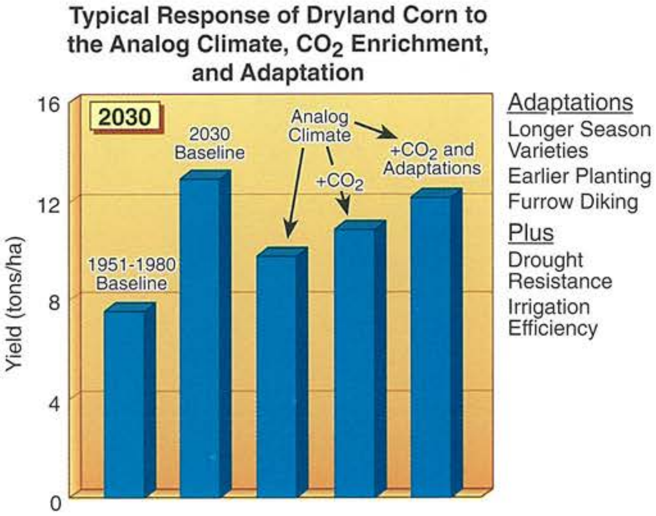


Figure 5.3.1. Computed response of dryland corn in the MINK region in A.D. 2030. First, during 40 years improved farming and technology raise the present yields. Then changing climate to that of the Dust Bowl lowers yields, enrichment of the CO_2 in the air raises them, and finally adaptations raise them further (Rosenberg and Crosson, 1991a).

Some GCMs do compute climate change far beyond those employed for Figure 2.1.1 or the Dust Bowl. The prediction of an international panel is for a "global mean temperature of about 1° above the present value by 2025 and 3°C before the end of the next century" (Houghton et al., 1990). One computation (Manabe and Wetherald, 1986) predicted summers 8°C warmer and precipitation 1 mm/day less in the Great Plains when its climate had come into equilibrium with doubled greenhouse gases. An assessment of all computations put the change at 1 to 5°C (Committee on Science, Engineering and Public Policy, 1991c). So, climate changes beyond those encountered for many centuries have been computed by some GCMs, and these computed climates would render anything like present farming without irrigation impractical in parts of the present Farm Belt.

In these extreme, envisioned climates, irrigation might prove impractical. A case in point is in the Great Plains, where the Ogallala aquifer is being depleted without a climate change. The analog of the Dust Bowl climate was not so hot as the 2°C warming that we envision adapting to. Nevertheless, even in the Dust Bowl climate, water resources in the MINK region would decline more rapidly as crop demands increased (Frederick, 1991). So, irrigation might not be expanded, and more likely, large portions of the Great Plains would revert back to dryland farming or to grassland. Farmers would adapt the land by grazing and the grain production by moving it to newly warmed northern regions or to regions where more precipitation offset the warming, and irrigation would likely shift from western Nebraska and Kansas to the eastern portion of those states and to Iowa and Missouri.

Uncertainties Make Adaptation Harder

We must also mention one other proviso about adaptation to climate change. Earlier, we described the manifold uncertainties about any change. More important than uncertainties about the global average temperature, are those uncertainties about precipitation and water supply, the rate of change, variability and frequency of extremes, and the timing of seasonal events. For the future, should a farmer build drains or ponds? Thus while in the past farmers have known the conditions they were adapting to, adapting to future climates includes the peril of not knowing what they will be.

In Brief

Adaptation to some projected future climates or to one analogous to the Dust Bowl is clearly within the range of ones adapted to in the past. Some computations, however, produce scenarios beyond experience. Even adapting to climate change encountered in the past may require more water than now seems available, and it will be harder because the target, the future climate, is uncertain.

5.4 Will these autonomous adaptations change emissions and sequestrations of greenhouse gases greatly?

In the beginning the first farmers must have simply, and single-mindedly sought more food for the family. Now, however, incentives and rules add the goal of more income from food sold and payment collected. For soil management, the goals are less erosion, enhanced soil quality, and more fertility. For water management, the goals are evaporation control (especially for dryer climates), more infiltration, less runoff, and high quality water (Follett and Bauer, 1986; Follett and Walker, 1989). If climate changes, these goals will continue as farmers and foresters are guided to autonomous adaptations by signals of weather and price. Will the adapted farms and forests emit more or less greenhouse gas? Will they store some?

Carbon Dioxide

With fossil fuel use as a major source of greenhouse gas emissions, we are driven to speculate how fossil fuel use in agriculture might be affected by climate change. Section 4.2 notes that use of fossil fuels has declined markedly over recent decades as a consequence of rising fuel prices and it is likely that the search for energy efficiencies will continue, although progress will probably be at slower rates. On the other hand, many climate change scenarios suggest a drier climate in major agricultural areas. If water is available, irrigation and energy for pumping might increase. Migration of agricultural production to less fertile soils could similarly increase energy inputs by calling for more fertilizers, and warmer climates could change the need for pesticides. Significant changes in agricultural production patterns might also increase fuel required for transport of farm products to markets and to population centers.

A warming or drying of climate would itself deplete the great store of C in the soil, several percent per degree Celsius or one-tenth percent per mm precipitation (Figure 4.2.3). Will autonomous adaptations in the cycle of agriculture pictured in Figure 4.2.1 offset or speed the depletion caused by climate itself? The answer depends first on the area cultivated and then on how it is cultivated.

From 1930 to 1987, the U.S. cropland area used for crops shrank by one-seventh while population nearly doubled (U.S. Department of Agriculture, Agric. Stat., 1972, 1990). The USDA appraisal of resources (U.S. Department of Agriculture, 1990) states that in 1982 the land with high-to-medium potential for conversion to cropland was about one-third as great as the existing area of cropland. The appraisal goes on to project requirements for cropland in 2030 in a steady climate but with three levels or scenarios of demand (Figure 5.4.1). If current trends in demand continue, creating the so-called intermediate demand, the cropland area to meet domestic demand will decline and the area for increased exports will be offset by increased yield from technology. Thus the intermediate demand scenario would require an area, for all cropland, of about 88 million ha in the year 2030, versus 134 million ha in 1987. If export demand accelerates and yields rise slowly, however, cropland area will stay about the same. A change in climate causing a national, total decline in yield of about a quarter seems necessary to halt the decline in land area cultivated for crops.

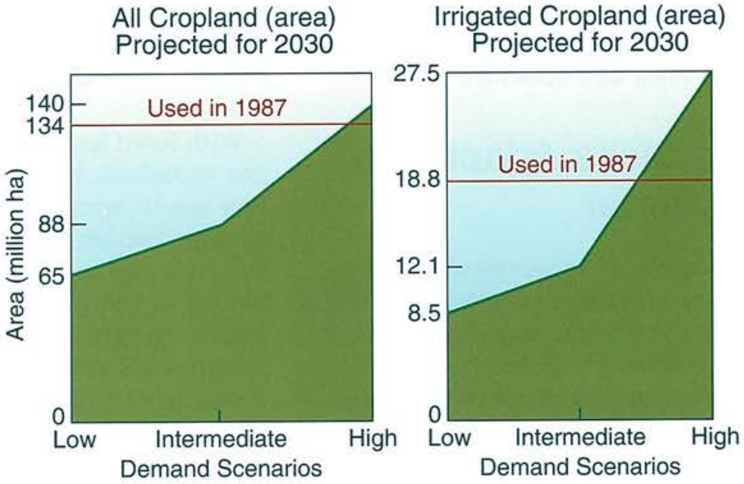


Figure 5.4.1. **Requirements for alternative demand scenarios projected for 2030 for all cropland in crops and for irrigated cropland in crops (without restrictions on water supply) (adapted from U.S. Department of Agriculture, 1990).**

The emissions of CO_2 from the adaptive strategies of moving crops or expanding or shrinking their area can be gauged by examining emissions that have occurred so far. Based on the simulations of Figure 4.2.3, maps of C loss can be constructed as shown in Figure 5.4.2. Maps in the left column indicate historical losses of 1 to 2 kg/m^2 of C during the 40 years after breaking the sod of the Great Plains. Such losses may approach a maximum rate of loss resulting from cultivation. These loss rates may be different from the rates in other ecosystems more humid than the Great Plains where the farming practice of bare fallow for moisture conservation was practiced.

Let us compare these historical losses to the annual 21.9 Gt global CO_2 emissions, Table 4.1.1. The arable cropland area (cropland used for crops, idle cropland, plus cropland used for pasture) in the United States is about 190 million ha; of that about 70% was in cropland used for crops in 1987. Arable cropland in the United States is about 13% of the world's arable cropland area. Assuming that, of the world's arable cropland, 70% is also in cropland used for crops, then an emission rate of 1 kg/m^2 for all world cropland used for crops and spread over 40 years is equivalent to about one Gt CO_2 per year, one-twentieth of annual global CO_2 emissions (Table 4.1.1). Emission from U.S. cropland represented only one-eighth Gt CO_2 per year.

It is important to compare the above estimates with other studies where possible, especially for the United States. A recent study (U.S. Environmental Protection Agency, 1991b) indicates that historic soil organic C losses since cultivation began for major field crops in the United States has resulted in a loss of 1.3 Gt C. Interestingly, the 1 kg/m^2 of C loss rate shown in Figure 5.4.2. is also equivalent to about 1.3 Gt C during 40 yr for U.S. cropland used for crops in 1987, thus giving confidence to both methods of estimation used. Estimates in the U.S. EPA (1991b) study for the current mix of tillage practices (conservation tillage usage on 27% of total crop land) used in 1990 indicate a C emission rate for U.S. agriculture of 0.008 Gt CO_2 each year from soil organic C. Scenarios where increasing percentages of cropland in conservation tillage are projected (up to 76% in 2030) would sequester about 0.044 Gt CO_2 per year as soil organic C in U.S. cropland and thus serves to offset the effects of fuel and chemical use by U.S. agriculture that are shown in Table 4.1.1.

Finally, how might adaptations change emissions on a given area? Adapting autonomously, a farmer might grow high yielding varieties, apply N and P fertilizers, remove no straw, and use minimum tillage practices. Using the method already employed for computing changes in soil C in Figure 4.2.3 and the left maps of Figure 5.4.2, Cole et al. (1988) calculated the rebuilding of soil C by such adaptations. The changes or storage during 40 years are 0.1 to 0.3 kg of C per square meter. Like the loss on cultivation, this rebuilding by husbandry is dwarfed by the annual 21 Gt global emission (Table 4.1.1). Nevertheless, it suggests that autonomous adaptations under current climate will not amplify emission of CO_2. With climate change

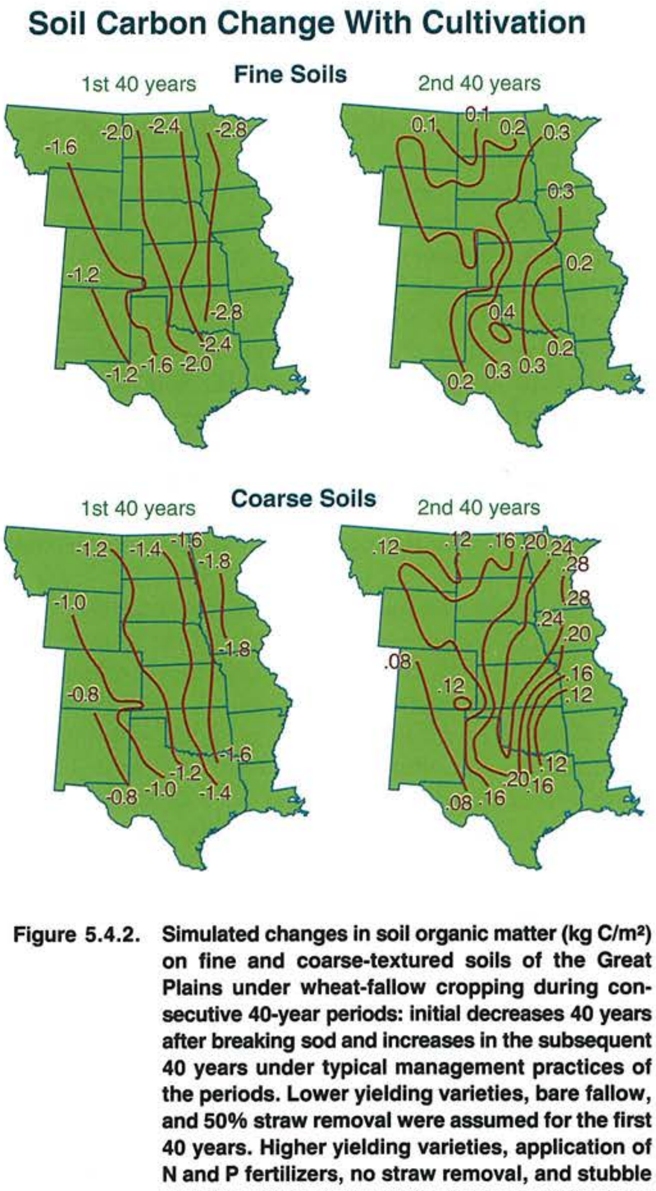


Figure 5.4.2. **Simulated changes in soil organic matter (kg C/m²) on fine and coarse-textured soils of the Great Plains under wheat-fallow cropping during consecutive 40-year periods: initial decreases 40 years after breaking sod and increases in the subsequent 40 years under typical management practices of the periods. Lower yielding varieties, bare fallow, and 50% straw removal were assumed for the first 40 years. Higher yielding varieties, application of N and P fertilizers, no straw removal, and stubble mulching were assumed for the second 40 years (Cole et al., 1988).**

to increased temperature and/or decreased precipitation, even these small changes in storage may be prevented, although losses of stored soil C with improved technology should be small relative to those that have already occurred.

Methane

Ninety percent of the land area in paddy rice is in Asia; in 1987 only 944 thousand hectares or about 0.7% of the total rice production area of the world was in the United States. Because of the small percentage of area in paddy rice in the United States, relative to that of the world, autonomous adaptations in rice production practices within the United States can scarcely affect global emissions. Rice grown in the United States is almost entirely under standing water. Substituting upland rice for the paddy rice would lessen even the small U.S. emissions, but the substitute rice would be grown in semi-arid places—not where the paddy rice is grown today. A search, by a recent panel, among taxes, quotas, and buyouts as mitigation policies (Committee on Science, Engineering and Public Policy, 1991b) showed none that would cut emissions more than 0.003 Gt/yr compared to total United States and global CH_4 emissions of 0.05 Gt and 0.50 Gt, respectively (Table 4.1.1).

Next, how might adaptations change emissions on a given area? Adapting autonomously, a farmer who grows paddy rice might grow high yielding varieties and apply N and P fertilizers. There appears to be an interaction between placement depth of fertilizer and CH_4 production and deep placement may decrease CH_4 production. Incorporation of organic materials as N sources generally enhances CH_4 emissions. Therefore, if organic material and residues are used, an autonomous adaptation might be to leave them unincorporated and to use deep placement of applied fertilizer N. Although CH_4 emissions from paddy rice production in the United States are small compared to global emissions and emissions from other sources, the above discussion suggests that autonomous adaptations to decrease CH_4 emissions may be of some very small benefit and certainly will not amplify emission of CH_4.

Factors that can mitigate CH_4 emission from ruminants are genetic improvement, use of biotechnology products, and improved feed formulations, and pharmaceuticals that alter fermentation in the rumen and improve efficiencies of protein production. Unfortunately, these measures can only be applied to intensively managed animals, e.g., lactating dairy cattle and beef cattle in feedlots. Lactating dairy cattle and their replacements produce 1.2 to 2.3 Mt/yr of CH_4. Using a current milk production per cow of 7,500 kg/yr, which is commonly achieved in well managed herds, as a base, an increase in genetic potential to 10,000 kg/yr per cow is clearly achievable because a number of herds already produce at this level. This improvement would reduce CH_4 emissions by 10%. Adoption of recombinant bovine somatotropin (+BST) would yield a comparable reduction. Genetic improvement plus +BST would reduce CH_4 emissions by up to 20% to 1.0 Mt/yr. Lesser gains would result from improvements in feed formulations including fat feeding (3 to 4%). Feedlot cattle produce 1.15 Mt/yr of CH_4. Pharmaceuticals that reduce CH_4 are already in common use in feedlots. Agents that promote protein gains at the expense of fat, currently in development, could reduce emissions by 20% to 0.9 Mt/yr of CH_4 if consumers accept the leaner product. Extensively managed beef cows and their replacements produce 2.5 to 2.7 Mt/yr CH_4, or about one-half of all emissions by ruminant livestock. Mitigation strategies are feasible, but are not likely to be successful because of the major increases in costs for labor and facilities (Baldwin, 1992, unpublished).

Nitrous Oxide

Encouraged by the conditions listed in Table 4.2.1, N in the soil can become the greenhouse gas, N_2O. Although farmers have raised yields using manure and legumes as N sources for aeons, since 1950 abundant synthetic-N fertilizer has been manufactured, allowing its liberal use. How might autonomous adaptations to climate alter, first, the quantity of N farmers add to the soil in synthetic fertilizer and manures and then, the quantity of it that eludes the crop to escape as N_2O?

Production and evolution of natural and fertilizer-derived N_2O from the soil surface are dependent upon management practices, biogenic processes, soil properties, and climate. By providing an additional N source, inorganic fertilizers increase N_2O emissions. About 79.6 Mt N-equivalent fertilizer were consumed worldwide in 1988 of which 9.6 Mt or 12% was consumed in the United States. The total loss of N fertilizer as gaseous N and the relative proportion of N_2O to N_2 are highly variable. Most experimental data are from short term studies. Therefore, estimating annual emissions of N_2O from a given amount of fertilizer requires assumptions about the level of fertilizer derived emissions beyond the experimental data.

Keller et al. (1988) summarized data on relative emissions per unit of applied N which ranged from 0.001 to 0.5%, 0.011 to 1.8%, and 0.12 to 2.08% from nitrate, anhydrous, and urea fertilizers, respectively. Bremner et al. (1981) measured the loss of N as N_2O of about 2.0% for anhydrous ammonia. Conrad et al. (1983) estimated total emission from the direct application of fertilizer N as 0.016 to 1.7 Mt N_2O in 1980. Eichner (1990) estimated global N_2O emissions were 0.31 to 3.3 Mt N_2O in 1984. Finally, Elkins (1989) estimated global emissions as 0.024 to 2.2 Mt N_2O in 1986. These various estimates of the N_2O emitted from applied fertilizer-N and information about fertilizer-N use (Food and Agriculture Organization of the United Nations 1982, 1987, 1989) lead us to a range of 0.17 to 3.52 (average of 1.84) kg of N_2O emission per 100 kg of N in the applied fertilizer. So the global and U.S. use of synthetic N fertilizer contributes on the order of 7% and 1% to the global emission of 0.021 Gt N_2O shown in Table 4.1.1. and on the order of 5% to the U.S. emission.

Cultivated legumes are a common green manure and source of N for crops. Currently the picture for legumes is unclear. Eichner (1990) estimated that 0.17 to 2.4% of total global emissions of N_2O comes from cultivated legumes. This did not include emissions from legumes not harvested, or from seedlings, nor from fertilizer applied to legume fields before planting. If the area of cropland devoted to legumes increases significantly or if leguminous fields emit more N_2O than fertilized fields, dual cropping with legumes, or rotating hectares under cultivation with legumes as an alternative to N fertilizer use could increase the atmospheric burden of N_2O.

Fortunately, the cost of fertilizer and reward of yield can help guide farmers to apply fertilizer in amounts, by methods, and at times, to minimize the loss of N to the environment (Smith et al., 1990). Again fortunately, fertilization for a goal approaching maximum economic yield, but avoiding excess amounts is generally consistent with minimizing N_2O emissions. Autonomous adaptations to climate change would not seem to endanger the guides of yield and profit leading farmers to minimize the total loss of N_2O from fertilizer.

But will the adaptations change the total amount of N applied or the portion of the total lost N that is N_2O? The practice called no-till leaves organic matter, which should increase soil organic C levels. It may also, however, increase the portion of N that escapes as N_2O (Dorland and Beauchamp, 1991; Groffman, 1985; Rice and Smith, 1982). Also, applying manure or sewage sludge increases N_2O (Mosier et al., 1982). Substitution of legumes that biologically fix atmospheric N_2 for fertilizer N may increase the atmospheric burden of N_2O, but evidence is still unclear. On the other hand, deep-placement of fertilizer in the soil decreases the portion of N that escapes as N_2O. Should any of these practices be evoked by climate change, adaptation would change the emission of N_2O.

The adaptation of irrigation would clearly be evoked by a warmer, drier climate. When a deep, well drained, and fertilized soil was irrigated, the two N gases soon escaped (Figure 5.4.3). The N_2O emission was 0.37 to 0.19 as much as the N_2 emission. The infrequent application of larger amounts of water leached N down into the soil profile, causing the escaping gases a longer trip to the surface and allowing further reduction of N_2O to N_2 but potentially resulting in leaching of nitrate below the crop rootzone and into ground-

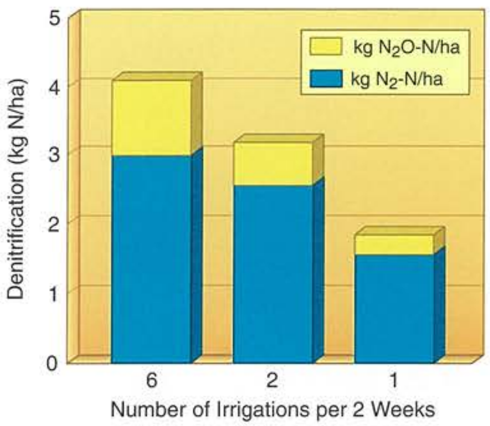


Figure 5.4.3. **Cumulative N_2O and N_2 flux at the soil surface for two months as a function of irrigation frequency (Rolston et al., 1982).**

water supplies. Conversely, an autonomous adaptation of more frequent, lighter irrigations could raise the portion of escaping N gas that is the greenhouse gas N_2O.

In Brief

The harvested U.S. cropland is expected to decline if trends in demand and technology development continue. A climate change that decreases total national yield by about one-fourth seems necessary to halt this trend.

Agriculture in the United States has accomplished a significant decline in emission of CO_2 from fossil fuels in recent years as a result of dramatic decreases in combined gasoline and diesel fuel use, shifts from gasoline to more fuel efficient diesel-powered units, and technology. Further, a decline in CO_2 emissions is expected if there is less U.S. land in crops and there is increased use of conservation tillage. Sequestration of C into soil organic matter can be accomplished autonomously by high yielding varieties, N and P fertilizer, and improved crop-residue management—all now considered good farming practices. However annual global emission of CO_2, most not from agriculture, dwarfs this sequestering of C into soil.

As with CO_2, adaptations in livestock production to decrease CH_4 emissions are significant and include improved genetic capacity, feeding and management, and biotechnology. These approaches increase efficiency and decrease CH_4 emission per unit of livestock product. The result is that fewer animals are required to satisfy demand. The U.S. rice production area is only 0.7% of that in the world, and thus the United States is a small contributor. To decrease CH_4 emission from paddy rice, organic residues may be left unincorporated, deep placement of N fertilizer may be practiced, or upland rice may be substituted for paddy rice.

Global release of fertilizer derived N_2O may contribute about 7% to global emissions with perhaps 1% from U.S. agriculture. Biologically fixed N (from legumes) and manures would contribute additional amounts of N_2O. Autonomous adaptations should include improving efficiency of use of N, possibly by deep placement, timing, and proper amounts.

5.5 Will the autonomous adaptations deplete the natural resources that underlie farming severely?

In the preceding question our special interest in climate change caused us to concentrate on autonomous adaptation and emission of greenhouse gases. Now we must examine the broader question of whether the adaptations will seriously deplete the natural resources that underlie farming. In the examination we must remember that the Big Question we have set out to answer pertains to a planet with more people, more income, and more trade as well as a warmer one with more CO_2 in the atmosphere.

The Global Supply and Capability of Cropland

The answer to whether autonomous adaptations will deplete the natural resources that underlie farming severely is a resounding "Yes!"—unless world and U.S. agricultural research generates a steady stream of new technologies and unless rules and incentives encourage farmers to use them. Using present technology on the global supply of land and water, farmers could not produce at acceptable social costs the grains and soybeans for the future demands described in answering questions. In the literature on agricultural development one finds a consensus that most of the world's best land for crops is already growing crops. This consensus surely implies that in the absence of technical advance, the land resource will hold back the needed increase in crop production.

The capability of a natural resource to meet a demand, however, is in good measure set by the available technologies. Present estimates of the capability of global and U.S. land for crop production implicitly reflect present technology. Over a period of several

The leveling of land to speed the advance of irrigation water across a field and so increase the water use efficiency. The leveling is guided by a laser seen in the foreground of the lower photo. The laser beams can be seen in the upper photo. Credits: Robert C. Bjork, ARS, U.S. Department of Agriculture (top) and A. R. Dedrick, U.S. Water Conservation Laboratory, Phoenix, Arizona (bottom).

decades, however, technology, and rules and incentives, too, can change, increasing the productivity of the land. Autonomous adaptations can produce more yield on the present cropland as described in answer 5.2. Also, technology can expand the area of cropland. For example, technologies already tested could make it possible to intensively farm the acidic, infertile soils prevalent in tropical America and parts of Africa (Sanchez, 1992).

Depletion of the Supply of Soil by Erosion

The quality of land, of course, does affect yield, which provokes worries that erosion, salinization, and encroachment by deserts will threaten the enduring productivity of soil. Erosion is generally considered the major threat to soil (Brown, 1990). The fact is, however, that we have no comprehensive estimate warranted by science of how much soil is eroding in the world, let alone how it is affecting soil productivity (Dregne, 1989; Stocking, 1984). The evidence of erosion is anecdotal and based primarily on observations of massive erosion in, e.g., Nepal, parts of Latin America, and east Africa. While clearly important in these places, the significance of soil erosion for the long-term productivity of global agriculture is today unknown. [Since the above was written, new estimates of the global extent of human-induced soil degradation (mostly from wind and water erosion) have been published (World Resources Institute, 1992). The estimates show that 17% of the world's 12 billion hectares covered with vegetation have experienced some degree of such degradation since 1945. Fourteen percent of the land is lightly-to-moderately degraded and 3% is severely-to-extremely degraded.]

The Supply and Capability of Water

In the generation from 1950 until the early 1980s, the area irrigated in the world rose from 94 to 250 million hectares (Postel, 1989). More than doubling, the spreading area irrigated accounted for 40 to 50% of the increase in agricultural output (World Bank, 1982). Today a third of global crop production is from the sixth of the cropland that is irrigated, and more than half the food is grown in irrigated fields in some of the largest countries—China, India, Indonesia, and Japan among them (Postel, 1989).

During the 1980s, however, the expansion of irrigation slowed drastically. One primary cause was rising cost of energy for pumping water from aquifers. Another was using up the cheapest sites for irrigation (Postel, 1989). Although energy prices may restrict irrigation less for several decades than during the past one, the lack of new, economical sites is permanent.

Again, the capability of a natural resource to meet a demand is in good measure set by the way it is used. In the United States and elsewhere water is used inefficiently. A low price, if there is any price at all, largely causes the inefficiency. Prices are generally far below the social value of the water because rigid institutions and rules hinder transfers from less to more valuable uses. Prices and reforms of rules and institutions would encourage farmers and others to raise efficiency. Thus the capability of the natural resource would be raised, loosening the constraint on new irrigation (Postel, 1989). Such reforms are beginning in the American West as can be read in Section 3.4, and their spread is plausible as rising social costs of existing irrigation schemes become evident. Nonetheless, irrigation almost surely will contribute less—probably substantially less—to the growth of global grain and oilseed production during coming generations than it did during the past generation.

Knowledge as a Resource

The supply of knowledge embedded in people, technology, and institutions can be expanded by investments in research, extension, and education. During the last 40 years, increases in the supplies of knowledge relative to the supplies of land, water, and unskilled labor caused most of the increases in global agricultural production. Although increasing knowledge requires some use of material resources, it mainly depends on the capacity of the human brain to acquire knowledge. Unlike the earth's endowments of land and water, which are fixed and growing relatively smaller compared to the demands on them, the capacity for acquiring knowledge has no known limit. So, among the resources used in agriculture, knowledge is the one that sustained hard work can expand, which makes it the likely tool for increasing production in the future.

In Brief

Autonomously adapting to a warmer, more populous world by simply expanding production will be impossible at acceptable social costs without a steady stream of new knowledge embedded in people, technology, and institutions. The knowledge must increase the productivity of the world's water and land. The significance of soil erosion for the long-term productivity of global agriculture is today unknown. The fast expansion of irrigated area has slowed, and new expansion of irrigated production depends upon raising the productivity of existing irrigated land.

5.6 Will the autonomous adaptations by farmers produce external results that will harm others and perhaps cause the restriction of the adaptations?

Farming currently has numerous effects off the farm, and this is not going to change in the future, with or without climate change. Most of these effects fall within one or more of the following categories:

1. Effects of pesticides on human health and wildlife.
2. Health effects of nitrates in ground water, and effects of nitrogen and phosphorus fertilizers in stimulating eutrophication of lakes and reservoirs.
3. Effects of sediment from farmer's fields on the quality of water in streams, lakes, and reservoirs.
4. Downstream effects of increasing salinity of return flows of irrigation water; effects of irrigation on instream flows needed to protect aquatic habitat.
5. Loss of wildlife habitat from drainage of wetlands for crop production.
6. Effects of animal wastes on the quality of ground and surface water, especially where confined animal feeding is concentrated.

Pesticides

Since the 1970s farmers have used less and less insecticide, both because the compounds are more effective and because farmers integrated them with other controls (Figure 5.6.1). So-called integrated pest management decreased use especially in cotton fields in Texas and in orchards and vegetable fields in California where much was formerly used. Moreover, the compounds increasingly used persist a shorter time and are less hazardous to workers.

Designed to control the plants out of place, i.e., weeds, herbicides are naturally less toxic to animals than insecticides. Nevertheless, during the 1980s herbicide use began to decline. Fungicide use, which was never great, has declined slightly.

Federal and state regulators control pesticides relatively vigorously and are not likely to weaken. In addition, federal policies are gradually moving toward encouragement of so-called alternative agriculture, which uses less pesticide than the current agriculture. Thus for several reasons, the effects of pesticides off the farm seem likely to diminish rather than stay the same or rise. The changes in the nature rather than quantity of pests envisioned to accompany climate change seem unlikely to reverse the decline.

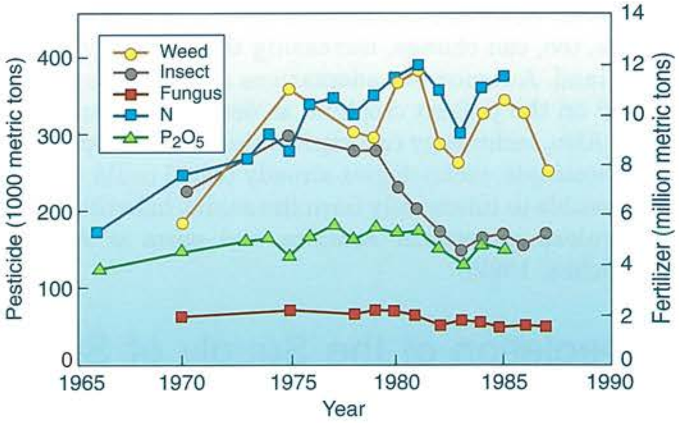


Figure 5.6.1. **The course of pesticide and fertilizer use in the United States. Note that the pesticide amounts are thousand tons while the fertilizer amounts are million tons of nitrogen or phosphate P_2O_5 (Statistical Abstract of the U.S., 1990; U.S. Department of Agriculture, 1991a).**

Fertilizer and Erosion

From the first half of the 1970s to the second half of the 1970s, fertilizer, especially nitrogen, use grew rapidly. The use of phosphate did not rise so much. The rise in quantity of total fertilizer for the entire United States (Figure 5.6.1) almost tripled the amount of fertilizer applied per hectare from 1960 to 1980 (U.S. Department of Agriculture, 1991a). Recently, however, farmers have not increased fertilizer use. It is noteworthy that average annual crops output per hectare increased 15% from 1975/79 to 1985/89 even though fertilizer applied per hectare declined 4%.

The leveling off of fertilizer use primarily reflected higher prices for fertilizer relative to prices for crops. Future trends in fertilizer use will also be guided by the ratio of crop to fertilizer prices and how much fertilizers raise yields. In the dimly perceived future, the trend seems more likely to resemble the level trend of the 1980s than the rising trend of 1960s and 1970s. The USDA Resource Conservation Assessment of 1985 projects total cropland will shrink from now to 2030 (U.S. Department of Agriculture, 1990). The scenario of demand for grain and soybeans in Answer 1.1 means a steady area of those crops. If the projection of the USDA and the scenario of Answer 1.1 are right, total fertilizer use is unlikely to rise and may decline, easing the externality of escaping fertilizer.

A second consequence of steady or shrinking harvested cropland is less erosion. Shrinking cropland combined with the trend toward more conservation tillage means less sediment in water. Because phosphorus generally limits the growth of the weeds and algae whose decay causes eutophication of water, and because phosphorus is usually attached to sediment, less sediment means less eutrophication.

The effects of climate change on fertilizer and erosion externalities depends heavily on whether the change encourages expansion of harvested cropland. The study of the MINK region suggests it will affect the area little after the adjustments farmers would make to the climate change (Crosson and Katz, 1991).

Manure

The Environmental Protection Agency (EPA) now regulates the management of wastes from confined animals, and their regulations are unlikely to weaken. More important, per capita consumption of beef is declining in the United States, from 58 kg in 1976 to only 46 kg in 1980. This has caused the number of cattle on feed to fall from about 13 million in the 1970s to only 9 in 1989 (U.S. Department of Agriculture, Agricultural Statistics, 1989). Study of the MINK region revealed no strong direct effect of climate change on cattle and hogs (Crosson and Katz, 1991). Combined with continued regulation of waste management, the falling numbers may actually lessen the externality of escaping wastes.

Habitat for Wildlife

The anticipated steady or shrinking area of harvested cropland in general is, of course, no increased threat to wildlife. Nevertheless, the clearing and draining of wetlands, particularly in the hardwood forests of the Mississippi Delta and the pothole region of the Dakota prairies, are worries. If the area of cropland shrinks, the incentive to clear and drain will fade. Further, the present federal administration has adopted a policy of wetland protection. The outcome of the policy is ambiguous, however, because the policy adopted a definition of wetlands that greatly reduced their area. Thus, much land formerly defined as wetland could be converted to cropland and still be consistent with the policy. The outcome of this policy for wildlife habitat is unclear.

Irrigation

For water, urban and industrial growth in the semiarid and arid West now compete and will likely continue competing strongly with irrigation. Also the demand for water to protect in-stream plant and fish habitat is rising, reflecting the general rise in demand for environmental services or preservation. The outcome of the competition between irrigation and other water uses is complicated by rigidities in the institutions that control uses of water. The outcome of these tangles is unclear but seems sure to inhibit any expansion of irrigation and more likely will diminish it and thus its externalities.

The external effects of a fixed area of irrigation could, of course, change. Providing proper drainage and thus avoiding salinization in the drainage from irrigation is growing harder, particularly in the western San Joaquin valley of California. Although employing known techniques could overcome the problems, institutional rigidities impede their employment. Until the impediment is overcome, salinity will likely increase, decreasing the irrigated area.

In Brief

Surprisingly, perhaps, some trends in farming technology and management seem likely to lessen external effects of farming, and adaptation to climate change seems unlikely to reverse this happy outcome. The exception to this optimistic outlook regards water and irrigation. Competition for water is already strong in the West, exacerbating problems of salinity and maintenance of in-stream habitat. A change to a warmer, drier climate seems certain to heighten these problems and extend them to other places.

5.7 Can autonomous adaptation by, say A.D. 2030, conceivably meet the challenge and demands implied in The Big Question?

Answering Question 2 above, we concluded the outlook for the impact of A.D. 2030 weather on A.D. 1990 crops is not bright. Further, we wrote that the outlook for the present forests is affected by uncertainty about both future climate and the presence of species favored by it. In the intervening pages we examined autonomous adaptations by a multiplying population on a warming globe. Now, taken together, do the adaptations brighten the outlook for A.D. 2030 farming and forests in A.D. 2030 climate? Taking the tools of adaptation together, weighing their interactions and combined outcomes on a future farmer's scale, is harder than listing or even examining them, one by one.

Trade

When we think of the whole of agriculture, the world market in food is its nervous system, signaling needs and surpluses, and its circulatory system, carrying subsistence and bargains. If the signals are not distorted and the circulation is not inhibited, they seem bound to adapt the world to its supply of food, season by season, by guiding it to the places of greatest demand. The demand will, of course, be compounded from local supply, population, and wealth. In the longer run, the signals will induce researchers to invent technology and farmers to use it within the bounds of rules, adapting production to population and resources, including climate. The signals can encourage consumers to change their diet as between meat and vegetable. We repeat that grain stocks were luckily above average before the 1988 drought but are now lower, while population grew about 1.7% per year. Although prospects are never as bright as one wants, those for freer trade, growing wealth, and adaptable diets seem reasonably good for the world during the coming half century and so reasonably good for trade to play its role in adaptation.

New Technology

About 1940 farmers in the United States and other rich countries, applying new technology, began increasing yields in a trend that has risen steadily for a half century. By 1970, a green revolution of technology began raising food production in other nations faster even than population was rising. So wherever farmers have received clear signals to raise food and domestic tranquility has reigned they have autonomously adapted with new technology. They continue raising yields with new technology—today.

Tomorrow, of course, is our precinct. Climate change beyond a limit of adaptation, restrictions on emissions of gases, or even exhaustion of natural resources could prevent adaptations feeding a more populous world. In this section on new technology, however, the most important proviso about future adaptation concerns research and development of the technology itself. We expect that new technology will continue raising yields to match population despite considerable warming. But underlying that expectation is another expectation: Vital research and development will move forward—without flagging. Impediments to moving forward are exemplified by fear of new things and opposition to management of water. If research and development move forward without flagging, farmers in a warmer world have a good chance to answer signals autonomously with more food for trade to distribute.

Limits to Autonomous Adaptation

At this point the conservative reader, certainly the pessimistic one, will ask what might frustrate autonomous adaptation. Even with trade sending clear signals and freely carrying food, even with effective research developing new technology, where are the bounds around autonomous adaptation?

Although population still explodes in some places, its growth is slowing in other places, making plausible the hope for stabilization after doubling or tripling. Doubling or tripling food supply seems possible for farming.

The snowy deserts at the Poles and sandy ones in Arabia prove climate can exceed practical adaptation. Climate scenarios that duplicate those extremes surely frustrate hopes for adaptation of practical farming. Another cause of worry is the elasticity or relatively greater change in frequency of extreme weather than change in climatic averages. In Des Moines, Iowa, for example, a warming of about 2°C would triple the probability of heat waves over 35°C for five days. And for drought less than some threshold of rainfall, the probability rises relatively more than the average rainfall declines (Mearns et al., 1984; Waggoner, 1989).

A hindrance to adaptation in the future compared to the past is uncertainty about what adaptation should be for. In addition to uncertainty about general warming there is uncertainty about local variations. During the 1980s the global average was warmer than any previous decade and even taken as a hint of climate change (Jones et al., 1986a). But meanwhile in Florida counties long ago named Citrus and Orange, 80 to 90% of the citrus trees froze. Growers adapted by moving the Florida Citrus Belt about 150 km south (Anonymous, 1991). In the process, many millions were lost in land value and tax revenue fell. Starting new groves and installing irrigation was costly, and Florida's water supply was further strained where demand was already highest.

Nevertheless, when the fertilization by more CO_2 in the air that is certain is combined with adaptations that are readily foreseen, a change as to the climate of the Dust Bowl does not frustrate hopes for practical adaptation of farming to a different climate. Local variations in weather in that analog of climate change temper changes in regional averages. Further, the scenarios computed by GCMs for a national examination of climate change and agriculture do not frustrate hopes for adaptation (Adams et al., 1990; Easterling et al., 1990; Rosenberg and Crosson, 1991).

In general, the emission of gases from farming seems likely to decrease. In the United States, the decline of harvested cropland area and greater efficiency of powered equipment should decrease CO_2 emissions. The practices now considered good farming may even sequester some carbon in the soil, while economical fertilization should decrease nitrous oxide emissions. More livestock product per animal and fewer animals should diminish methane emissions.

Despite rising population, logical projections for a steady climate show food would be produced in coming decades on less, not more, cropland. So the physical limit of acreage does not seem a specter, even if climate does change yields or move farm belts to new places and soils. Further the ongoing lessening of the external effects by pesticides, erosion, fertilizer and manure from farms seems unlikely to be reversed by climate change.

So, with an exception about to be examined, physical boundaries seem unlikely to confine practical, autonomous adaptation.

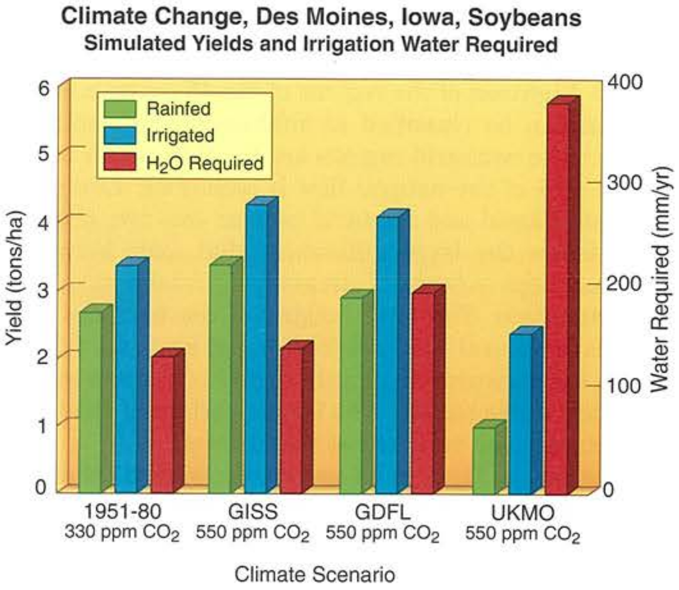


Figure 5.7.1. **The adaptation of soybeans by irrigation in three climate scenarios. The yields computed for the climate of 1951 to 1980 in Des Moines, Iowa are compared with those for climate scenarios simulated by three global circulation models (GCMs), with and without irrigation. The amounts of irrigation ranged from 137 to 388 mm. The scenarios ranged from 2 to 4°C warmer than the 1950 to 1980 climate. Although the scenarios included some increases in precipitation, all had a month during the growing season with below average precipitation (Rosenzweig et al., 1992).**

Water for Irrigation

Irrigation is a key tool for adaption to climate, as we emphasized in answering Question 3.4 about the tools of adaption. Figure 2.1.1 showed how three climate scenarios would change yields near Des Moines. Now Figure 5.7.1 shows how irrigation would adapt soybeans to those same changes. Whereas irrigation would raise the simulated yields only 0.7 t/ha in the climate of 1951 to 1980, it would raise them 0.9 to 1.4 in the three scenarios of climate change. The greater increase in the scenarios suggests irrigation would be more attractive in the changed than present climate, and simulations of soybeans at nine other places come out more or less the same.

If water is available, a farmer will need to consider the cost as well as the benefit of irrigation. The increased yield per cubic meter of irrigation water consumed, or WUEi in Section 3.4, is one way of comparing benefit and irrigation cost. Although the simulated WUEi values varied among locales, they were generally unaltered by the simulated climate changes. Regardless of efficiency, however, irrigation will consume some water. The current trend in transfers of water from irrigation to other uses in the West, which are confirmed by Figures 3.4.3 and 3.4.4, remind the reader of changes that will surely occur at the same time as the envisioned climate change. This transfer of water to other uses will restrict autonomous adaptation of farming by irrigation. In areas that currently do not irrigate, the availability of water supplies may restrict adaption.

After this examination, one is not surprised that in a national examination of adjustments Adams et al. (1990) computed the probable increased irrigated area for both wetter and drier summer scenarios. The drier scenario that cut production naturally raised prices and encouraged an increase in irrigation. They concluded their analysis with the qualification, "The sustainability of any increase in irrigated acreages was not included. . ."

Our answer to Question 5.4 about the depletion of natural resources or sustainability agrees. In a generally hopeful view we saw the troublesome spot of water: The fast expansion of irrigated area has slowed, and new expansion will depend upon developing new supplies and enhancing the efficiencies in the use of the existing water resources.

The supply of water for expanded irrigation in two groups of water resource regions is implied by Figure 5.7.2. Eighteen of the regions of the 48 conterminous states can be classified as subhumid and semiarid ones.[9] The semiarid regions are the 8 in which more than 10% of the natural flow is consumed. Lumping the subhumid and semiarid regions into two classes illustrates the large differences that exist between these groups in terms of streamflow, withdrawals, and consumption. The total heights of the bars are the average natural outflows. With 1,480 km³/year (1,072 bgd), the subhumid regions have 83% of the renewable surface water supply. The lowest portion of the bars represents the volume not withdrawn.

The bars in Figure 5.7.2 are average annual amounts. The volume of runoff varies greatly from year to year and the flow rate varies during the year. In the semiarid regions, much of the flow is from snow melt during the spring of the year. The natural flow rate without storage reservoirs is low during the summer when the demand for irrigation is the highest. In the Pacific Northwest, there is additional land that can be developed for irrigation, but usually high pumping lifts are required. Much of the outflow currently is used to generate hydroelectric power through multiple power plants and for supporting the anadromous fish industry. Expanding irrigated land would reduce the flow for generating power and at the same time increase the demand for energy to pump water. The large amount of outflow in the eastern regions indicates a large potential for developing water supplies for irrigation if suitable surface or ground water reservoirs can be developed. Therefore, there are opportunities for expanded irrigation should climate change make it profitable and should social and environmental restrictions allow developing storage facilities. The reader should remember that in discussing use and transfer of water for irrigation in Section 3.4 we wrote that although development of reservoir capacity rose rapidly from 1930 to 1970, it has leveled off.

The picture in the semiarid regions is different. Currently, the rate of water withdrawn from some ground water aquifers is greater than the average recharge rate, or ground water is being mined for irrigation. In addition, water is being transferred from agriculture to meet expanding municipal, industrial, and various instream and offstream environmental uses. Therefore, opportunity is slight for expanding irrigation.

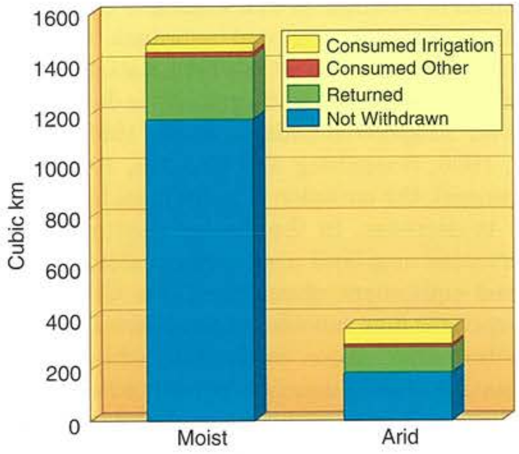


Figure 5.7.2. **The average annual outflow of water in 10 moist and 8 less moist water resource regions of the United States shown by the height of two bars. The top three segments indicate the volume withdrawn. These three segments show consumption by irrigation, consumption by other uses, and the return of used or withdrawn water. The lowest segment of each bar shows the volume not withdrawn.**

So, remembering all the proviso about dry seasons, dry years, and storage, we end by paraphrasing the summary of computations about a climate 3°C warmer with 10% less precipitation (Peterson and Keller, 1990): The greatest impact would be in the West, more in the Great Plains, and less in the Northwest, with the warm dry scenario increasing depletion of streams and reducing the irrigated area by 20 to 25%. New supplies of water would be more costly than current supplies. Pumping more ground water than the annual recharge would hasten its depletion. Eastern farmers, on the other hand, could raise production by expanding irrigation, especially in the Southeast. The depletion of eastern rivers would not be as great as in the West because the normal flows in the rivers generally are larger. Storage reservoirs may be required to deliver water to meet crop needs.

In Brief

If the supports of trade and research move forward, the autonomous adaptations of farmers can go a long way toward sustaining more production under the challenge of climate changes as calculated by most GCMs. As in other times of change, however, these adaptations will be costly, and these costs will be

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[9] The U.S. Water Resources Council designated 21 hydrological regions of wich 18 water resource regions are within the conterminous United States. (U.S. Geologic Survey, 1988 U.S. Water Resources Council, 1978. The 8 regions classified as semiarid are: Missouri, Arkansas-White-Red, Texas-Gulf, Rio Grande, Upper and Lower Colorado, Great Basin, and California. The natural outflows are taken from pp. 54-55 of the USWRC report, and the withdrawals and consumptions are from p. 23 and p. 57 of the USGS Circular.

uneven across the nation. The adaptations should generally not pollute and can reduce emissions of greenhouse gases. The costs would become unacceptably high well before physical boundaries of natural resources are reached. The exception is water for irrgation because its expansion, especially in the West, depends upon increasing the effectiveness in the use of existing water resources by increasing surface and ground water storage and reducing unproductive consumption of water.

6 How Can Farming and Forestry Be Changed at Acceptable Cost to Emit Less or Stash Away More Greenhouse Gases?

Although the main concern of U.S. agriculture, faced with the threat of changing climate, is with how to adapt to change, agriculture is also a source and potential sink for greenhouse gases and may be expected to play a role in trying to limit the magnitude or rate of climate change. If limiting net emissions of greenhouse gases were to be added to the list of objectives of farmers, how much of a role might they play and at what cost to their other goals? We can also speculate how the multiple objectives of forest management might be altered if uptake and storage of CO_2 were recognized as an important objective. We recognize that both farmers and foresters have, in recent years, increasingly adopted objectives related to minimizing their impact on the environment.

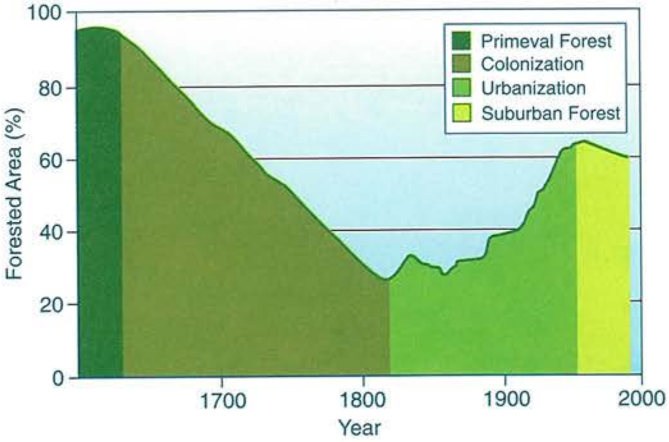
Carbon Dioxide (Emitting Less and Sequestering More)

The level of atmospheric CO_2 can be controlled by lowering emissions; for example, by encouraging additional measures to reduce energy consumption in agriculture or by reducing rates of soil oxidation. Conversely, CO_2 can be taken from the atmosphere during photosynthesis and thus additional C storage in soils or standing plants might be encouraged.

More energy efficient farm equipment, less mechanical crop drying, less use of agricultural chemicals, less irrigation, and minimum tillage would all save CO_2 emissions but at some cost to productivity after optimal levels are passed. On the other hand, high productivity can yield returns in C storage because it implies minimum land area in cultivation and potentially more land available for protection or establishment of forest. Commitment of some agricultural land to energy crops creates the potential to circumvent burning fossil fuels but might raise land rents and food costs to consumers. Many of the strategies named in this section would help minimize net C emissions to the atmosphere and are also consistent with good farming practice. Other strategies might conflict with the maximum productivity or profitability of farms and for still others the optimal level of implementation simply is not yet clear.

Protection of old growth forests would certainly aid long-term C storage and environmental aesthetics but is widely debated for a variety of economic issues. As mentioned in Section 4.3, maintaining maximum C storage in forests means protecting old growth (especially in areas where the ratio between standing mass and productivity is low), prompt replanting after harvest, and efficient utilization of forest products. We do not yet know at what level of forest productivity and forest management the goal of C sequestering is best served by stashing C in trees as opposed to using efficient harvest to cycle C through energy systems and industrial products.

Strategies for use of trees to sequester C in the United States range from protecting existing forests, to planting trees where trees do not currently grow, to recycling C by burning energy crops instead of fossil fuels. If renewable crops could supply 8% of current U.S. energy demand (about 6 EJ, as suggested in Section 4.3) to displace an equivalent amount of fossil fuel burned for electric power generation, we would offset over 0.5 Gt of CO_2 emissions, over 10% of the



The de- and then re-forestation of Connecticut with accompanying storage of carbon in trees and litter exemplifies the change in the landscape of the Northeast. Drawn by J. S. Ward, The Connecticut Agricultural Experiment Station, New Haven from Harper, 1918; Dickson and Bowers, 1976; and Dickson and McAfee, 1988.

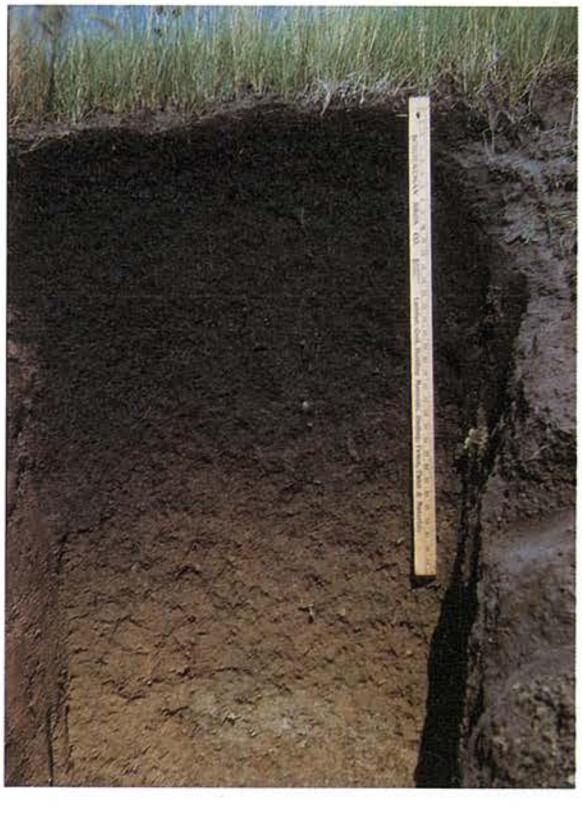
By 1966, the open field pictured in 1920 on the left grew without management into the second-growth woods shown on the right. Credit: The Connecticut Agricultural Experiment Station, New Haven.

U.S. total (Table 4.1.1). This is nearly 4 times the total CO_2 emissions from U.S. agriculture. Biomass fuels are now economically competitive under some circumstances (Committee on Science, Engineering and Public Policy, 1991b; Solar Energy Research Institute, 1990), but gaining higher levels of fossil fuel displacement will require more incentives than current markets provide. For example, if trees were planted on an area equivalent to that of currently idle cropland in the United States (about 27.5 million ha in 1987) to take up and store C and achieved an average net storage of 5.3 t/ha of C each year as suggested by Moulton and Richards (1990), the total C offset would similarly amount to over 0.5 Gt/yr of CO_2.

Soils are important in the C cycle because they support plants and store much C below ground. Fixation of C by photosynthesis is the ultimate source of soil C and provides the energy that drives soil biological processes. Organic C in soils can be in either living organisms or their residues. An important character of soil C is its retention or turnover time. Soil retains C from a few to thousands of years. Longer times are related to cold, wet climates and greater depth. Organic C, deep within the soil profile, tends to be protected and less susceptible to decomposition than C on or near the surface.

In a recent workshop (U.S. Environmental Protection Agency, 1991a), strategies were identified to maintain and enlarge pools of C in the soil and to restore C to depleted soils. Generally practices summarized in Table 6.1 enhance cool (mulches, shade) or wet (mulches, irrigation) conditions, increase fertility (fertilizer), and reduce aeration (minimum tillage) of the soil. Raising the pH of acid subsoils is also identified to increase C sequestration.

Managing soils to sequester more and emit less C requires more C entering the soil or less leaving, either through decomposition or erosion. Decomposition is a microbially mediated process that breaks down plant residues and produces CO_2 as a waste product. Plant



Much carbon is stashed in the dark upper horizons of soils such as this extensive, highly productive Nicollet prairie soil in Iowa that is derived from glacial till. Nicollet soils are classified as fine-loamy, mixed, mesic Aquic Hapludolls. The surface horizon texture is typically loam. Credit: T. E. Fenton, Department of Agronomy, Iowa State University, Ames.

Table 6.1. Management strategies to enhance soil carbon sequestration (U.S. Environmental Protection Agency, 1991a)

	Priority[a] of management practices to:		
Practice	Maintain C-pools	Restore C-pools	Enlarge C-pools
Maintain/improve soil fertility	H	H	H
Preserve natural wetlands	H		
Reforestation		H	
Minimize dryland fallowing			H
Use municipal/animal/other waste		H	M
Conservation/minimum tillage	M		H
Retain forest slash on site	M		M
Minimize site disturbance	M		
Leave crop residues	M		M
Control soil erosion	M	M	L
Mulching	M		M
Remove marginal land from intensive production		M	M
Prescribed burns, if needed	M		M
Urban forestry		L	

[a] Relative priority: H = high, M = medium, L = low.

residues are the major substrate, or energy source, for decomposition. Poor substrate quality, high C/N ratio, or phenolic compounds slows residue decomposition. In addition, soil temperature and moisture affect decomposition. Decomposition is slow in cool wet soils and rapid in warm, moist, aerobic soils. In warm and arid climates, microbial decomposition is limited by drought. All practices shown in Table 6.1 and defined below are generally suitable for either autonomous or encouraged adaptation.

Maintain/Improve Soil Fertility

Because soil fertility is essential for plants to grow and sequester C in soils, fertility problems need to be corrected. Farming soils that have lost C or are naturally low in fertility could decrease sequestration of CO_2. Fertilization with such nutrients as N, phosphorus, and potassium, and liming acid soils are important to maintaining or improving soil fertility.

Preserve Natural Wetlands

If undrained, the inundated soils in wetlands contain much C with a very long retention time. Draining them causes rapid oxidation and loss of C to the atmosphere.

Reforestation

Reforestation has the potential to sequester much new C both above and below ground, particularly on C-depleted soils as was discussed in Section 4.3.

Minimize Dryland Fallowing

Fallowing leaves semi-arid farm lands bare in alternate years to accumulate additional soil water for growing a crop in the other year. Fallowing depletes organic C because the soil is usually kept bare by tillage. The stirring and mixing of the soil for ‘bare’ fallow, combined with warmer soil temperatures and lack of cover, increases oxidation of organic C. Improved technology is showing that fallowing can be decreased without great cost to farmers.

Use Municipal/Animal/Other Wastes

Restoring or enlarging pools of C in soil may be limited by lack of nutrients for plant growth or the cost of fertilizer to replenish them. When they do not contain heavy metals or other toxic substances; municipal, animal, industrial, or food wastes can be excellent sources of nutrients and C. Using them in forests or in agriculture, particularly marginal lands, adds nutrients and water (sewage water or water used to carry waste materials through application machines), thereby promoting more growth and sequestration of C above and below ground.

Conservation Tillage

Conservation tillage is an agricultural practice that includes either minimum tillage or no-tillage and farming along the contour of the land. It retains crop

Controlling erosion by terraces maintains the store and no-till husbandry increases it. Credits: Soil Conservation Service, U.S. Department of Agriculture (left) and Larry Lefever from Grant Heilman (right).

residues on-site while decreasing the number and severity of soil physical disturbances used to prepare seedbeds, control weeds, and apply fertilizer. Loss of soil C is diminished as compared to conventional tillage practices. If, as discussed in Section 5.4, increased use of conservation tillage in the United States resulted in a change from the net loss of C from soil organic matter of about 0.01 Gt/yr of CO_2 to a net sequestration of about 0.04 Gt/yr of CO_2 (U.S. Environmental Protection Agency, 1991b), current emission levels from all U.S. agriculture would decrease by one-third (Table 4.1.1).

Retain Forest Slash on Site

Retaining forest slash on site following forest harvesting helps retain nutrients and water to promote reestablishment of new forest vegetation as quickly as possible. If the cycle of burning or removing residues is interrupted, soil C stocks will not only be maintained but will potentially be enlarged.

Minimize Site Disturbances

Forest harvesting may result in extensive compaction or disruption of large portions of the soil in the harvested area. Likewise, yarding or skidding logs to landings can compact and expose the mineral soil. Productivity of the site can be decreased while loss of soil C is promoted by oxidation and soil erosion.

Leave Crop Residues

Crop residues are an important source of C and nutrients in agricultural systems when returned to the soil. Left on the soil surface, crop residues also serve as a mulch to decrease soil temperatures and maintain higher soil moisture.

Control Soil Erosion

The surface layer of soil, or topsoil, is generally more fertile and has better water holding characteristics than deeper soil horizons. Physical loss or degradation of the soil resource diminishes primary production and consequently, sequestration of C below ground. Because of its proximity to wind and rain, topsoil is the most vulnerable part of the soil to physical erosion.

Mulching

The rate of soil organic matter decomposition is positively related to soil temperature. Mulching or using plant residues to cover the soil surface decreases extreme soil temperatures, thereby slowing decomposition, and resulting in retention of more C in the soil. Mulching also decreases evaporation and keeps the topsoil wetter.

Remove Marginal Lands from Intensive Agriculture Production

Marginal lands are usually steep and prone to soil erosion. They also tend to be less fertile and not well suited for agricultural production. The availability of low-cost fuel and fertilizer has allowed these lands to be brought into agricultural production. Their cultivation has resulted in depletion of soil-C stocks. Removing these lands from intensive agricultural production and their reforestation or revegetation will sequester C in above- and below-ground biomass.

Prescribed Burns, if Needed

Burning has been used for centuries as an effective method for removing slash following a forest harvest or in shifting agriculture. Hot slash burns (i.e., hot-dry windy weather with dry slash) may severely damage topsoil and affect its productivity. If burning is required, lighter burns (i.e., in cool-wet weather) will damage the entire system less and ease the growth of a new forest.

Urban Forestry

The use of small forests and individual trees in urban areas helps capture and store C in above- and below-ground biomass and as soil C. Soil C that has been lost because of urban land use can be restored. Additional societal benefits include: recreation, lower urban temperatures, aesthetics, and air purification. Lower urban temperatures during the summer months will conserve the C that would otherwise be used for energy generation for running urban air conditioners.

Methane (Emitting Less and Sequestering More)

Following CO_2, CH_4 is the most abundant atmospheric C species. Soils represent an important global sink for methane, mostly not on agricultural lands (World Resources Institute, 1987). Arable- and crop-land area of the world is only about 13% of the terrestrial land area. If soil CH_4 oxidation is dependent on concentration of CH_4, then CH_4 uptake by soils may be increasing with the rise in CH_4 concentration in and near the soil surface due to the more than doubling of atmospheric CH_4 since 1850 (Ojima et al., 1992). However, the effect of land use change and N additions on CH_4 uptake may be a factor contributing to a decreased CH_4 sink (Melillo et al., 1989; Mosier et al., 1991). Exact mechanisms by which CH_4 oxidation is decreased following conversion to cropland or change in N dynamics is not clear; however factors such as water availability, fertilizer application, atmospheric N deposition, soil structural changes, and cropping management all seem to have an effect (Ojima et al., 1992). Thus, changes resulting from human activities on any of the major terrestrial ecosystems of the world may alter their capacity to serve as sinks for atmospheric CH_4.

Soils also represent the most important CH_4 source, which is produced predominantly by microbial degradation of organic C in rice paddies, natural wetlands, and landfills. However, our discussion is limited to agricultural emissions and will deal only with rice paddy soils. Following rice paddies, ruminant animals provide the next most important global CH_4 source from agriculture.

Rice

Rice cultivation occurs on approximately 10% of the world's arable and permanent cropland area (U.S. Department of Agriculture, Agricultural Statistics, 1990; Food and Agriculture Organization of the United Nations, 1989), an area somewhat greater than all U.S. cropland in crops in 1987. However, U.S. land area used to grow rice occupied only about 0.7% of the world's rice production area and about 0.9% of U.S. cropland area in crops (U.S. Department of Agriculture, Agric. Stat., 1990). Therefore, adaptation and/or mitigation of CH_4 emissions for rice production in the United States will have minimal impact, except for technology that is developed and transferred to other countries. Adaptations might include improved crop residue, organic waste and fertilizer management, and improved biological efficiency. Mitigation might range from increased to total substitution of other cereals (including upland rice) for paddy rice.

Crop Residue and Organic Waste Management

Incorporating organic materials (crop residues and other wastes) as an N source or for other purposes generally increases CH_4 emissions. If crop residues are instead burned, the benefits of return and sequestration of some of the C contained in these materials into soil-C pools are lost. Adapted cultural practices allowing the return of most of these residues without incorporation would diminish CH_4 emission, including rotation of the land used for paddy rice into other crops.

Fertilizer Management

Although experimental results differ, deep placement of mineral-N fertilizers likely decreases CH_4 emissions. Fertilizer N is extremely important for obtaining high yields. It also decreases the ratio of CH_4 produced per kg of rice produced. However, much more needs to be known to define and improve fertilizer and other cultural management practices that minimize this ratio while still providing required amounts of rice to feed the world's populations.

More milk and beef per unit of feed increases the usable product per methane emitted. Credits: Charlton Photos, Inc., Mequon, Wisconsin (left) and Grant Heilman, Grant Heilman Photography (right).

Improved Biological Efficiency

As the genetic potential for increased rice yield per ha of cropland area increases, the ratio of CH_4 produced per kg of rice should also decrease. Such improvement might also include a lower straw/grain ratio to decrease the relative amount of straw to be returned to paddy fields or burned. Increased grain yield might also help lower the land area of paddy rice required to satisfy demand, thus further decreasing CH_4 emissions.

Substitution for Paddy Rice

Enhancing supplies of substitutes for paddy rice include improvement of non-paddy (upland) rice production as well as improvements in production of other cereal grains. Technological improvements for paddy rice have been achieved much more rapidly than for upland rice. In addition, for a staple commodity such as rice, it is doubtful that consumption will decrease without government intervention, which may be untenable in many countries.

Ruminant Livestock

Of the total number of cattle and buffalo reported for countries of the world (U.S. Department of Agriculture, Agric. Stat., 1990), about 100 million, nearly 10%, are in the United States. Autonomous adaptations by farmers to the changing pressures of agriculture could include improved biological efficiency, improved feed quality or composition, and improved use of biotechnology. An additional strategy to specifically address the risk of climate change might include decreased consumption of animal products.

Improved Efficiencies

Agricultural scientists and farmers have achieved improvements in animal efficiency. The result has been improved animals that convert grains and roughage into meat, milk, and other products more efficiently and the potential for further improvement is considerable. Increases in the biological efficiency of ruminant animals decreases the production of CH_4 per unit of livestock product by decreasing the numbers of animals required to satisfy demand.

Improved feed formulations and pharmaceuticals can alter fermentation in the rumen and improve efficiencies of protein production. These measures can be applied to intensively managed animals such as dairy cattle and beef cattle in feedlots to provide some benefits. However, animals that are not intensively managed, such as cattle on forages, pasture, or range, will continue to yield more CH_4 per unit of available feed energy and grow more slowly than those on grain or other improved feed formulation. Rates of improvement in the efficiency of livestock production have averaged 1% per yr over the past 40 years. These advances are attributable to genetic selection and improvements in feeding and management strategies. These rates of improvement may decline somewhat in the future in some sectors. A conservative estimate of an increase of 10% in efficiency can clearly be defended based upon current knowledge and the management practices of our best producers (Section 5.4). Such improvements would lead to a 10% decline in CH_4 emissions from livestock agriculture.

Improved Biotechnology

Advances in biotechnology provide products such as somatotropin to increase feed efficiency and animal gains. Pharmaceutical or other products and technologies alter fermentation in the rumen and increase efficiency of protein production. All of these technologies serve to decrease CH_4 produced per unit of animal product and have the potential to alleviate CH_4 emissions from livestock in the order of 10%.

Decreased Consumption of Ruminant Livestock Products

Consumption of ruminant products, especially meat, in the United States has been decreasing steadily and could be decreased further either by enhancing the supply of substitute products or by making ruminant products more costly to consumers. Methods might include development of cereal substitutes for meats; through taxes and other price-increasing practices, the price of ruminant commodities could be made to rise relative to prices of substitute commodities. On the other hand, we must realize that 30% of the energy and 55% of the protein consumed by the U.S. population are from animal products. The argument that ruminant animals are not efficient does not apply in this regard since returns on human edible inputs of energy and protein into animal agriculture run from 85 to 100 and 110 to 150%, respectively. In other sections, it has been implied that reductions in consumer demand for livestock products in the United States would further reduce methane emissions. For example, from a peak sale of retail cuts of red meat of 42.8 kg per capita in 1976, sales decreased to 31.2 kg in 1989. However, sales have been stable at 30.4 to 30.8 kg per capita for the past three years. Thus it is difficult to project a reduction in CH_4 emissions attributable to reduced demands for red meat at this time.

Nitrous Oxide (Emitting Less)

Adaptations to emit less N_2O from agriculture could include strategies of fertilizer management, nitrification inhibitors, irrigation water management, and efficient fossil fuel use. Mitigation might include additional fertilizer management requirements. In general, agricultural N_2O emissions can be decreased through N-management practices that (1) optimize the crop's natural ability to compete with processes whereby plant available N is lost from the soil-plant system (i.e., denitrification and leaching), and (2) direct lowering of rate and duration of these loss processes; however, these simple principles may not be easily accomplished by adaptations alone.

Fertilizer Management

Use of fertilizer N is extremely important for obtaining high yields. However, much more effort and information is required to define and improve N fertilizer and other cultural management practices to minimize atmospheric losses of N_2O, such as: (1) use of soil testing; (2) dispense with the "maintenance" concept, which fails to recognize the amount of residual N in the soil and the soil's nitrification potential; (3) adjust the rate of N to a reasonable yield goal for the specific crop and field or soil; (4) place N deep enough in the soil to lower the N_2O/N_2 ratio when denitrification does occur; (5) take into account soil N mineralization and the N from legumes, manures, organic wastes, irrigation water and other potential sources; and (6) time N application to when it is needed by the crop. Timing and amount of fertilizer N application should have a goal of leaving as little residual N in the soil during the noncropped periods of the year as possible. In large measure, these are all strategies that both reduce N_2O emission and improve the efficiency of N fertilizer use.

Change in agriculture, in addition to being a technological process, is also sociological even when economic benefits result. This makes accomplishing improved N-fertilizer use efficiency a long-term endeavor as illustrated by Iowa's large-scale agricultural demonstration and education programs (Iowa Department of Natural Resources, 1991), which are showing significant results. Statewide N-fertilizer use data indicate that even with declining fertilizer prices, Iowa producers have decreased N use on corn since 1985 and diverged from regional trends for the midwestern United States. From 1985 to 1990, N-fertilization rates in the Midwest region increased slightly, possibly in response to declining fertilizer prices. However, during this same period, Iowa departed from parallel regional trends of the prior 20 yr; N-fertilization rates declined approximately 12%, yet no relative reductions in crop yields have occurred.

Nitrification Inhibitors

The NH_4^+ ion is sorbed to the exchange capacity of the soil; whereas, NO_3^- ion is not and can be readily denitrified or leached. Both forms can be readily utilized by crops. Nitrification inhibitors include chemicals added to soils to stabilize fertilizer applied as NH_3 or in the NH_4^+ form by inhibiting activity of the *Nitrosomonas* bacteria in the first step of the nitrification process. Nitrogen losses can be minimized if applied N remains in the NH_4^+ form for several weeks after application, especially when fall applied or when there may be heavy rainfall periods during the spring. An inhibitor, such as nitrapyrin, can be effective in many field crop situations. Denitrification (and NH_3 volatilization) especially leads to low fertilizer use efficiency in rice, (Buresh and DeDatta, 1990; Fillery et al., 1986). An apparent highly-effective nitrification inhibitor for rice paddy conditions is encapsulated calcium carbide (ECC) (Banerjee and Mosier, 1989; Bronson and Mosier, 1991).

Irrigation Water Management

Generally fluxes of denitrification gases occur immediately following each irrigation. Because N_2O may be further changed to N_2 during transport to the soil surface, especially when O_2 is more limiting, there is greater opportunity to decrease the N_2O/N_2 ratio of the resulting gases when the mineral N that is being denitrified is deeper in the soil. An effect of infrequent, compared to more frequent irrigation, is to not only decrease the number of resulting denitrification cycles, but to also help move soluble N deeper into the soil profile where supplies of O_2 are more limited and therefore there is increased opportunity to reduce any N_2O that may form to N_2 (Figure 5.4.3). However, with the same total amount of applied irrigation water, very frequent irrigations tend to result in the largest amount of denitrification, whereas infrequent irrigation may increase leaching losses. Therefore, a balance would need to be drawn between the two types of N-losses.

Efficient Fossil Fuel Use

This option is likely an autonomous adaptation for two reasons. First, combined gasoline and diesel fuel use has fallen dramatically in recent years as a result of energy-saving farm production technologies and shifts from gasoline to more fuel-efficient diesel-powered units (Section 4.2). Secondly, decreasing requirements for land are projected to meet domestic and export demand scenarios to the year 2030 (Figure 5.4.1) along with increasing agricultural technology development. These combined should serve to decrease on-farm and likely off-farm energy requirements for agriculture.

Additional Fertilizer Management Considerations

Nitrous oxide emissions from microbially mediated nitrification and denitrification may need to be decreased beyond what can be accomplished through autonomous adaptations. For example, urea fertilizer is reported to emit more N_2O per unit of applied N than do nitrate or anhydrous fertilizers (Keller et al., 1988). However, energy required to manufacture urea is much less than that required to manufacture, for example, ammonium nitrate. Thus, there is a trade-off between N_2O emissions for the on-farm use of urea versus a higher fossil fuel use to manufacture ammonium nitrate. Deeper placement of some N-fertilizer materials would require more energy and would be less easily adopted with present farming practices.

In Brief

The goals of less expense and more yield per unit of land area used for production have often induced less emission of the three greenhouse gases per unit of food or fiber produced. That is, during the past decade at least, less fuel has been burned and so less CO_2 emitted per unit of production. Higher yields per unit area of land and conservation tillage have lessened emission of CO_2 from soil organic matter. Depending upon their use in the United States, tree crops not only sequester C, but also serve to recycle C as an energy crop. Improvements in animal husbandry and decreased consumption of ruminant animal products have lessened the emission of CH_4. Emission from rice production has always been inconsequential because less than 1% of U.S. cropland grows rice. Careful application of nitrogenous fertilizer has lessened emission of N_2O. Additional decreases in emissions of all three greenhouse gases are possible through autonomous adaptations.

So long as the rules for controlling emission of greenhouse gases from farming and stashing C in soil organic matter and forests reinforce the goals of higher yields per unit of land and lower costs, as the past proves is often sensible, the controls should not hobble and may help U.S. farming. Likely, increased amounts of C will be stashed by farmers and foresters in the future, but incentives beyond those found in current markets will be required. Strong evidence exists that mitigation of about one-third of current U.S. agriculture emissions of C is possible by increased stashing in soil organic matter through increased use of conservation tillage. Possible future sequestration of even larger amounts of C is possible using trees if large areas of land were planted and managed and if the wood products were effectively used. When wood is burned as fuel, it displaces fossil fuel. Displacing enough fossil fuel to reduce U.S. emissions of CO_2 from all sources by 10% and thus making U.S. agriculture effectively a net storer of carbon is a plausible future.

7 How Can the Nation Encourage Successful Adaptation?

In the face of manifold uncertainties—future climate and its consequences, growth in population and trade, efforts to mitigate climate change, and the extent of autonomous adaptations—how can the nation encourage successful adaptation? Global warming may bring many challenges to U.S. agriculture in the decades to come, but the biggest challenge now is uncertainty. The future climate is uncertain, despite the best scientific efforts to predict change. Changes in temperature, precipitation, and cloud cover all seem likely, but how much and how quickly are impossible to predict now. Even more difficult is predicting variations in climate change from one region to the next. These local variations will be more important to agricultural production than general warming. And regardless of the magnitude of climate change, we know that rising levels of carbon dioxide will affect the growth of plants.

So, we come to the crucial, final question. The nation is uncertain about the future climate, but it remembers the autonomous adaptations farmers and foresters will make under the present umbrella of government policies. What policies, or regulations and incentives, should a prudent nation change?

The Justification for Public Policy Action

Climate change may impose several human, economic, and environmental costs on the nation. The nation's agricultural production could fall, and the production from a region could change even more. Regional shifts in production will cause hardship for those places where production declines. Environmental resources like water and soil could change. As agriculture changes, wealth could be redistributed, from one group to another or from one region to another. The nation could export more food if it were favored by climate change or even become a net importer of food if it were harmed more than other nations. The human, economic, and environmental costs of these changes cannot be calculated today. Nevertheless, this vast array of potential costs, which we shall call social costs, argues for improving agriculture's ability to adapt in the future.

The social costs just mentioned will be reduced, at least partially, as U.S. agriculture adapts autonomously to a new climate. As shown in preceding chapters, U.S. agriculture is resilient and can adapt to climate change in many ways. But autonomous adaptation will not mitigate all social costs. To reduce the remaining costs as much as possible, further adaptation will need to be encouraged through a series of policy steps.

Therein lies the goal for agricultural policymakers: pursuing policies that encourage adaptation to a range of possible climate outcomes with minimum social cost. 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, 1970). 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 maximum 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, 1959). 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 enables U.S. agriculture to measure its current preparedness to adapt to a changing climate. Two weak spots appear immediately. First, many agricultural resources are not currently viewed as "climate change assets." We define climate change assets as those agricultural 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 Assets to Prepare for Climate Change

U.S. agriculture has ten assets for adapting to climate change (Table 7.1). Other assets might be added to the portfolio, but these ten form what we believe 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, 1991). 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 minimum social cost.

Clearly, 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. Through its assistance programs, the United States can also contribute to the development of a global portfolio of assets. Notwithstanding the overall strength of the U.S. portfolio, however, the nation will have to make new efforts to both strengthen some assets and allow greater flexibility in using them. Below, we discuss each asset and the policy actions needed now to use the asset effectively in the future.

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. The nation has another 239 million hectares of pasture and range and 262 million hectares of forest land. The wide expanse of U.S. agricultural land ranges across a diversity of climates, offering some built-in insurance against whatever changes in climate that 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. The nation has an extensive land asset, but 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 area in most regions. That growing competition would be heightened by any change to a drier climate.

Several water options are available for responding to

Table 7.1. Portfolio of assets to prepare for climate change

Asset	Value for adapting to climate change	Policy steps to increase flexibility
Land	Extensive cropland across diverse climates provides diversity for adaptation.	Reform agricultural policy to encourage flexible land use.
Water	Water, which already limits farming in some regions, is crucial for adaptation if climate becomes more dry.	Change institutions to encourage more prudent use of water. Raise the value of crop produced per volume of water consumed.
Energy	Reliable energy supply 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.
Physical infrastructure	Facilitates trade and input flows when market signals change.	Maintain and improve input supply and export delivery infrastructure.
Genetic diversity	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.
Research capacity	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.
Information 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.
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.
Political institutions	Determine the policies and rules that facilitate or hinder adaptation to new climates.	Harmonize agricultural institutions and policies.
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.

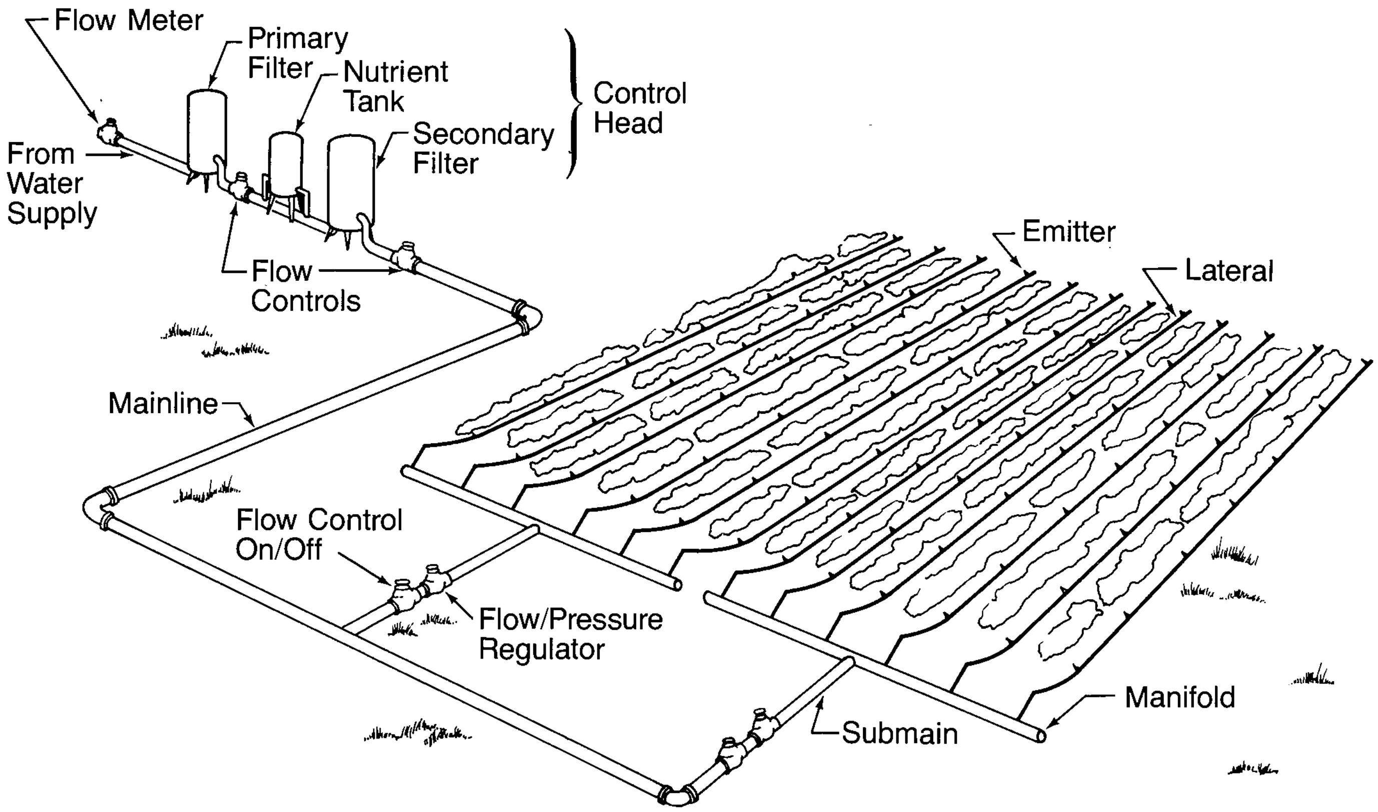
climate change. Farmers can more fully adopt proven technologies that improve water use efficiency, or the quality of farm output per unit of water input. Scientists can search for crops, production methods, and irrigation systems that increase water use efficiency. Water markets could be improved and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

Change institutions 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. 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 produced per volume of water consumed. 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% of the nation's total energy demand, a reliable supply of energy will help adapt agriculture to climate change.



Trickle irrigation which is diagramed here, conserves water by getting most of it to the roots and keeping the surface relatively dry. It is suited for valuable, widely spaced crops like trees or vines.

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 biological fuels 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.

Physical Infrastructure

One climate change asset that should not be overlooked is the nation's physical infrastructure that 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. 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. Though 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. Just how extensive is our genetic resource? A major constraint in developing a cost-effective strategy for collecting, preserving, and using genetic resources is an adequate characterization of the materials in both *in situ* and *ex situ* collections. A thorough description and cataloguing 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 emerge soon 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 valuable, 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.

More than 15 years ago, Goeller and Weinberg (1976) 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. 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 and coping with the changes in trade, population, and climate embodied in the Big Question. Although the contribution of farming to greenhouse gases and the stashing of carbon in biomass are small compared with emissions from consuming fossil fuels, research must consider these—although with a lower priority than production during change. From this new mission flow four recommended actions.

Broaden research agenda to encompass adaptation to 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. Research capacity has always been a critical tool in adapting to climate change, and the nation's research system must be able to respond to uncertain changes in climate that may lead to the displacement of crop and animal production systems.

With the extent and speed of future climate change largely unknown at the present time, 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, it is necessary to consider ways to shorten the time between the discovery of agricultural technology and its applications. Steps that encourage collaboration between elements of the nation's federal-state research system and the private sector may be critical in shortening the amount of time to develop technology that responds to climate change.

Multidisciplinary teams will be critical to the development of new technologies that will enable the nation's farmers and foresters to adapt to climate change. In some respects, agricultural sciences have become more alike as the understanding of genes has increased. Sharing such knowledge will be important as scientists explore all available technological responses to climate change. Some universities are already assembling multidisciplinary teams in biotechnology research. The University of Minnesota, for example, has created a biotechnology of maize program that cuts across several different departments of the university. The aim of this and similar efforts elsewhere is to maximize research synergies while minimizing administrative costs. More team approaches will be needed if the nation's researchers are to respond effectively to climate change.

To broaden the nation's research agenda, more funding will be needed. The United States has a federal-state system of publicly funded agricultural research that involves a unique combination of centralized and decentralized funding and decision making. This structure should enable it to respond effectively to the uncertain regional effects of climate change. But in recent years, the level of public funding has dropped, especially at the federal level.

Part of that drop can be offset by improved efficiency and a greater amount of research in the private sector. Federal and state administrators are squeezing more efficiency from the research system by collaborating more closely and fine-tuning their planning efforts. Some areas of technology development conducted within the public sector can, as a result of more secure property rights, be transferred to the private sector. To induce even more cooperation between the public and private sectors, the nation could encourage more competitive grants that would match private sector support for university research federal and/or state support.

Much of agriculture's research agenda that relates to global warming, however, will be conducted only by publicly-funded researchers. Environmental quality, sustainable agriculture, and conservation practices are among the many examples. These research areas are not attractive candidates for private sector research since the results can rarely be packaged as proprietary products. Nevertheless, all three areas loom large if U.S. agriculture is to adapt successfully to climate change. The National Research Initiative (NRI), of course, helps generally as in raising yields, which for example raises WUE as shown in Figure 3.4.5. It may provide more money for research self-consciously directed to adaptation to climate change. But with many other areas of research competing for its funds, the NRI will not supply all of the funds needed to broaden the research agenda for climate change.

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. Producers may press for regulation to protect themselves from domestic or international competition. Consistent regulatory regimes across nations is an increasingly important factor in international trade negotiations. It will be necessary, therefore, to devote substantial research effort to identifying and quantifying the scientific, technical, economic, and psychological information needed to rationalize regulatory regimes in the future. 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" or "fourth" generation chemical and biological pest management technologies. Another is the design of land use technologies that will help reduce erosion, salinization, and ground water pollution. Finally, researchers may discover 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 will involve radical changes in food sources. Rogoff and Rawlins (1987), for instance, have suggested one such system based on lignocellulose—both for animal production and human consumption.

Information Systems

Agriculture, like nearly all other industries, has been swept along as technology carries the economy into an "information age." Information 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 is 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.

Physics plays a role in agricultural research. On the top left a weather station senses the weather in Nebraska. On the bottom left, Steve Carl, CCT Corporation, uses the Scheduler® Plant Stress Monitor to measure and assess plant water stress. On the right, the flight of spores and the turbulent air that carries them are being studied by Don Aylor to slow the spread of plant disease. Credits: K. G. Hubbard, High Plains Regional Climate Center, University of Nebraska, Lincoln; CCT Corporation; and The Connecticut Agricultural Experiment Station, New Haven.

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 designing that training.

Make flexible skills the hallmark of agriculture's human resources. As shown earlier, we believe that farmers and researchers do 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 19th century must obviously change if it is to cope with the potential climate of the 21st 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. Increased disaster relief can discourage insurance schemes that pay for themselves and could encourage continued production of crops in a climate that was turning unfavorable for them.

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 will likely 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.

Building the Portfolio

Farmers and foresters will autonomously 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. The nation already has a rich allocation of agricultural resources, but these resources must be improved if they

***Dust storm, Cimarron County, Oklahoma, 1936*, Arthur Rothstein. Credit: Library of Congress[10].**

Rainbow over central Iowa corn. Credit: Carl Kurtz, St. Anthony, Iowa.

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 economic and 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 now while substantially enhancing adaptation in the future. 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 also preparing itself for an uncertain climate ahead.

In Brief

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 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 agricultural climate change 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.

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[10] This photograph of a family fleeing a dust storm in the quintessential Dust Bowl county, Cimarron in the panhandle of Oklahoma, dramatized the Depression and the change to a dry climate that persisted for several years. In the half century before Arthur Rothstein of the Farm Security Administration (FSA) took the picture in 1936, much changed in Oklahoma. Cattle barons faded, the Indian Territory became a state, settlers rushed in, oil was discovered, and population boomed from about a quarter to one and a half million. Then, by the time Rothstein photographed farmer Coble, his elder son and his younger son straggling behind, they were a family who had hung on when about one in five Oklahomans migrated away.

Rothstein also photographed the Farmer Raising a Fence, which is on the back cover of our report.

In 1978, the small straggling boy was a father whom Rothstein again photographed, but this time with his own sons walking through fields of waist-high wheat on the family farm. Nevertheless, the hybrid corn pictured in an Iowa field in the Corn Belt climate was even taller.

Arthur Rothstein recalls his work as an FSA photographer in *Documentary Photography*. 1986. Focal Press, Boston.

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Appendix 1 Acronyms and Symbols

Acronyms

AIDS	Acquired immune deficiency syndrome
CAST	Council for Agricultural Science and Technology
CFC	Chloroflurohydrocarbon
ECC	Encapsulated calcium carbide
EPA	Environmental Protection Agency
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GATT	General Agreement on Tariffs and Trade
GCM	Global circulation model
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute of Space Science
GNP	Gross national product
GWP	Global warming potential
LDC	Less developed country
MINK	Missouri-Iowa-Kansas-Nebraska
NRI	National Research Initiative
OSU	Oregon State University
OTCA	Omnibus Trade and Competitiveness Act of 1988
RCA	Resource Conservation Act
SERI	Solar Energy Research Institute
SI	*Le Systѐme International d'Unitѐs*
UKMO	United Kingdom Meterological Office
UN	United Nations
U.S.	United States
USDA	United States Department of Agriculture
WUE	Water Use Efficiency
WUEi	Irrigation water use efficiency

Frequently Used Symbols

C	Carbon
°C	Degrees Celsius
CH_4	Methane
CO_2	Carbon dioxide
Gt	Gigaton (10^9 metric tons)
ha	Hectare
kg	Kilogram
kWh	Kilowatt hour
mm	Millimeter
Mt	Megaton (10^6 metric tons)
N	Nitrogen
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_3	Nitrate
N_2	Nitrogen gas
N_2O	Nitrous oxide
O_2	Oxygen gas
P	Phosphorus
ppb	Parts per billion
ppm	Parts per million
t	Ton (metric)

Appendix 2 Units

The Omnibus Trade and Competitiveness Act (OTCA) of 1988 amends the Metric Conversion Act of 1975 directing each Federal agency to convert to the metric system by a date certain and to the extent economically possible by the end of 1992. The President's Executive Order 12770 of 25 July 1991 on Metric Usage in Federal Government Programs required Federal Agencies to draft their metric transition plans by 30 November 1991 for the Department of Commerce. New national science publications to be released in 1992 should be in metric units.

This report has been prepared in consistent metric units based on the *Le Système International d'Unités* (SI). Some important features of the SI are summarized in this appendix along with a summary of factors to enable readers to convert to English units.

Table A-1. SI base units

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
(Alternative for common use)	deg Celsius	^{0}C
Amount of substance	mole	mol

Table A-2. SI derived units

Quantity	Unit	Symbol	Formula
Force	newton	N	kg m/s^2
Pressure	pascal	Pa	N/m^2
Energy, work, heat[a]	joule	J	N m
Power, radiant flux	watt	W	J/s
Electric potential	volt	V	W/A
Electric resistance	ohm	R	V/A
Conductance	siemans	S	A/V

[a] An energy unit accepted for limited use is the kilowatthour (KWh). 1 kWh = 1,000 Wh = 3.6 MJ.

Table A-3. SI prefixes

Multiplication factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ

Table A-4. SI miscellaneous units

Quantity	Unit	Symbol	Formula
Area			
Square meter	1 m^2	m^2	
Hectare	10,000 ^{2}	ha	
Million hectares	10^6 ha	Mha	
Volume			
Liter	0.001 m^3	L	
Cubic meter	1 m^3	m^3	
Cubic dekameter (megaliter)	10^6 m^3	ML	
Time			
Minute	60 s	min	
Hour	3,600 s	h	
Day	86,400 s	day	
Year	365 days	yr	
Mass			
Metric ton	10^3 kg	t	
Million metric tons	10^6 t	Mt	
Giga ton	10^9 t	Gt	
Mass per unit volume			
Kilogram per cubic meter (density)	kg/m^3		kg/m^3
Volume per unit time			
Cubic meter per second (flow)	m^3/s		m^3/s
Volume per unit volume			
Parts per million	$m^3/10^6$ m^3	ppm	
Parts per billion	$m^3/10^9$ m^3	ppb	

Table A-5. Conversion of metric units to English units

To convert from	to	multiply by
Basic units		
Length		
millimeters (mm)	inches	0.0394
centimeters (cm)	inches	0.3937
meters (m)	feet	3.281
kilometers (km)	miles	0.6214
Area		
square meters (m^2	square ft	10.764
hectares (ha)	acres	2.471
square km (km^2)	square miles	0.3861
Volume		
liters (L)	gallons	0.2642
liters (L)	cubic ft	0.03531
cubic meters (m^3)	cubic ft	35.31
megaliter (ML)	acre-feet	0.8107
Mass		
grams (g)	pounds (mass)	0.002205
kilograms (kg)	pounds (mass)	2.205
metric tons (t)	short ton (2,000 lb)	1.102
Energy		
kilojoules (kJ)	British thermal units (Btus)	0.9478
exajoules (EJ)	quad (10^{15} Btus)	0.9478
Special units		
Carbon		
kg carbon (kg C)	lb CO_2	8.084
Crop production		
metric t (corn)	bushel (56 lb)	39.37
metric t (soybeans)	bushel (60 lb)	36.74
metric t (wheat)	bushel (60 lb)	36.74
Crop yield		
kg/ha	lb/acre	0.8922
metric t/ha	short ton/acre	0.4461
metric t/ha (corn)	bushels (56 lb)/acre	15.93
metric t/ha (soybeans)	bushels (60 lb)/acre	14.87
metric t/ha (wheat)	bushels (60 lb)/acre	14.87
Evaporation/precipitation		
mm/day	inch/day	0.03937
Volume/time		
m^3/s	cubic feet/second	35.31
m^3/s	billion gallons per day	0.02282
ML/yr	acre-feet/year	0.8107

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Task force reports are CAST's principal publications. Reports are prepared by groups of eminent scientists working in various disciplines related to the subject. Task forces write reports intended to be sound statements on the scientific aspects of subjects concerning food and agriculture, and do not take advocacy positions.

Ionizing Energy in Food Processing and Pest Control: I. Wholesomeness of Food Treated With Ionizing Energy
R109, July 1986, 50 pp., $4.00

Diet and Health
R111, March 1987, 62 pp., $5.00

Effective Use of Water in Irrigated Agriculture
R113, June 1988, 64 pp., $5.00

Long-Term Viability of U.S. Agriculture
R114, June 1988, 48 pp., $4.00

Ionizing Energy in Food Processing and Pest Control: II. Applications
R115, June 1989, 98 pp., $10.00

Mycotoxins: Economic and Health Risks
R116, November 1989, 91 pp., $10.00

Ecological Impacts of Federal Conservation and Cropland Reduction Programs
R117, September 1990, 28 pp., $6.00; Summary, 8 pp., $1.00

Food Fats and Health
R118, December 1991, 96 pp., $12.00; Summary 4 pp., $1.00

Preparing U.S. Agriculture for Global Climate Change
R119, June 1992, $15.00; Summary, 8 pp., $3.00

Special Publications

***Alternative Agriculture*: Scientists' Review**
SP16, July 1990, 182 pp., $15.00; Summary, 8 pp., $3.00

Comments from CAST

Timely letters and other comments of broad interest, written by one or more authors.

Pesticides, Cancer, and the Delaney Clause
CC1987-2, May 1987, 15 pp., $2.00

Perspectives on the Safety of 2,4-D
CC1987-3, December 1987, 16 pp., $2.00

Reducing American Exposure to Nitrate, Nitrite, and Nitroso Compounds: The National Network to Prevent Birth Defects Proposal
CC1989-1, June 1989, 16 pp., $3.00

Antibiotics for Animals: The Antibiotic-Resistance Issue
CC1989-2, June 1989, 12 pp., $3.00

Pesticides and Safety of Fruits and Vegetables
CC1990-1, December 1990, 15 pp., $4.00

Herbicide-Resistant Crops
CC1991-1, May 1991, 28 pp., $8.00

Food Safety: The Interpretation of Risk
CC1992-1, March 1992, 23 pp., $8.00

Pesticides: Minor Uses/Major Issues
CC1992-2, May 1992, $8.00

Science of Food and Agriculture

Science of Food and Agriculture is a newsletter for high school science teachers and students. A four-issue subscription is $10.00.

AU Lean: low-fat hamburger, rhizotron, herbicide-resistant crops, soap as a bee killer, science briefs, food and nutrition news.
SFA3-2, July 1991, 16 pp., $2.50

Rolling beans cuts losses, low-palmitic acid soybeans, CO_2 levels affect plant growth, landscape contracting careers, science briefs, food and nutrition news.
SFA4-1, January 1992, 16 pp., $2.50

Forthcoming Reports

Animal Well-Being

Biological Pest Control in Agriculture: Opportunities and Challenges

Consequences for Food and Fiber (Plant and Animal) Production and Processing from Reduced or Less Reliable Western U.S. Water Resources

Contribution of Animal Products to Healthful Diets

Development of Host Plant Resistance to Pests

Household Waste Disposal through Agricultural Recycling

The Impact of Alternative Agricultural Practices on the Environment

Impact of Pests on Food Quality

Integrated Animal Waste Management

Naturally Occurring Antimicrobials in Food

Possible Geographical Redistribution of Food and Fiber (Plant and Animal) Production and Processing as a Consequence of More Free Trade

Public Land Grazing: Social, Economic, and Regulatory Issues

Public Perceptions of Agricultural Drugs and Chemicals

Quality of U.S. Agricultural Products

Relationship of Value-Added Activities on Agricultural Products and the U.S. Trade Balance

Risk/Benefit Assessment of Antibiotics Use in Animals

Risks Associated with Foodborne Pathogens

Waste Management and Utilization in Food Production and Processing

Water Quality: Agriculture's Role

Wetlands: Impact and Regulation

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