Climate Change and Agriculture

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Burning of fossils fuels and eradication of forests have raised the atmospheric concentration of carbon dioxide (CO_2) by some 30 percent since the industrial revolution, and that rise continues at a rate of approximately 0.4 percent per year. Despite its seemingly minute concentration (only 0.035 percent), CO_2 inhibits the escape of longwave (thermal) radiation emitted by the earth throughout the entire atmosphere, a process known as the “greenhouse effect.” The presence of CO_2 and the more abundant water vapor naturally helps to warm our planet from a frigid -18°C to a much more hospitable 15°C. Human-driven increases in CO_2 concentration now appear to be enhancing the natural greenhouse effect, and many scientists believe that these are leading, or will lead, to surface warming and associated feedback effects on the climate system (Houghton et al. 1996).

Other so-called greenhouse gases that are present in even smaller concentrations, but which similarly tend to trap heat, include methane (CH_4), nitrous oxide (N_2O), the chlorofluorocarbons (CFCs), and tropospheric ozone (O_3). The effects of all these gases may be expressed as changes in the planet’s radiation balance in $W/m^2/yr$. Other changing atmospheric factors that affect climate include ozone, solar irradiance, tropospheric aerosols, and stratospheric aerosols. The increases in greenhouse gases may already be altering the earth’s climate. Global surface temperatures have risen about 0.7°C over the last century, leading the Intergovernmental Panel on Climate Change (IPCC) to conclude (Houghton et al. 1996): “The balance of evidence suggests a discernible human influence on global climate.” If allowed to continue, anthropogenic greenhouse-gas emissions seem bound to result in significant climate change in the coming decades.

The climatic consequences of increasing greenhouse gases are linked to far-reaching changes in agriculture, as well as in natural ecosystems. It is clear that climate change is likely to affect the regional patterns of temperature, precipitation, and evaporation, indeed the entire array of meteorological, hydrological, ecological, and agricultural relationships. Beyond what is clear, however, lie uncertainties: how much warming will occur, at what rate, and according to what geographical and seasonal patterns? And just what will be the consequences to the agricultural productivity of different countries and regions? Will some nations benefit while others suffer, and who might the winners and losers be? Finally, there are practical questions: what can and should be done in timely fashion by individual countries and by the international community as a whole to avert potential damages to life-support systems? And, to the extent that such damages are not completely avoidable, what can be done to minimize or overcome them? Upon our ability to answer such questions may rest the fate of natural and human ecosystems in the twenty-first century.

Physiological Effects of CO_2 Enrichment

The role of CO_2 in agriculture is complex in that it can be positive in some respects and negative in others. Carbon dioxide concentration affects crop production directly by influencing the physiological processes of photosynthesis and transpiration; therefore, it has the potential to stimulate plant growth. The magnitude of that stimulation will vary among species of differing photosynthetic pathway, and will depend on growth stage and on water and nutrient status. The resulting climate effects (including warmer temperatures, changed hydrological regimes, and altered frequencies and intensities of extreme climatic events) may inhibit crop production in some regions. Agricultural pests, overall, are likely to thrive under conditions of increasing atmospheric CO_2 concentrations and rapid climate change. All these changes, in concert, could have major impacts on the prospects for food security — in some cases positive and in other cases negative.

Plant responses to higher concentrations of atmospheric CO_2 may be considered on various scales, ranging from the microscopic cellular level to the macroscopic agro-ecosystem level. The scaling up of plant responses in time and space from one level to another is complicated. Photosynthesis, respiration, and transpiration are the plant processes most directly affected by changing levels of CO_2. A host of interactive changes in crop growth flow from these primary effects, some resulting in positive feed-back and others in negative (Rosenzweig and Hillel 1998).

Effects of Climate Extremes on Crops

When the optimal temperature range for a crop in a particular region is exceeded, it tends to respond negatively, resulting in less yield. The optimal temperature varies with the crop. Temperatures greater than 36°C cause the pollen of corn (*Zea mays*) to lose viability, whereas, in potato (*Solanum tuberosum*), 20°C depresses tuber initiation and bulking (Paulsen 1994).

Most agronomic crops are sensitive to episodes of high temperature. Air temperatures between 45 and 55°C that last for at least 30 minutes directly damage leaves in most environments; even lower temperatures (35 to 40°C) may be detrimental if they persist (Fitter and Hay 1987). Vulnerability of crops to damage by high temperatures varies with developmental stage. During reproductive development they are particularly injurious — for example, to corn at tasseling, to soybean (*Glycine max*) at flowering, and to wheat (*Triticum aestivum*) at grain filling. Soybean has an unusual ability to recover from heat stress, perhaps because most cultivars are indeterminate (i.e. vegetative development continues after flowering) (Shibles et al. 1975).

Precipitation, the primary source of soil moisture, is probably the most important factor determining the productivity of crops. Although climate models predict an overall increase in mean global precipitation, their results also show the potential for changed hydrological regimes (drier or wetter) in most places. A change in climate may affect total seasonal precipitation, its within-season pattern, and its between-season variability. For crop productivity, effects on patterns of precipitation events may be even more important than effects on annual totals. The water regime of a crop is also vulnerable to rises in the daily and seasonal rates of evapotranspiration, brought on by warmer temperature, drier air, or windier conditions.

Drought conditions may also be induced by less precipitation falling as snow and by earlier snowmelt. In arid regions, such as the Sacramento River basin, these effects may reduce subsequent river discharge and irrigation-water supplies during the growing season (Gleick 1987). Episodes of high relative humidity, frost, and hail can also affect yield and quality of fruits and vegetables.

Interannual variability of precipitation is a major cause of variations in yield and quality of crops. During the 1930s, severe droughts in the United States lowered yields of wheat and corn as much as 50 percent in the Great Plains. By reducing vegetative cover, droughts exacerbate erosion by wind and water, thus affecting future crop productivity.

As with high temperature, crop yields are most likely to suffer if dry periods occur during critical developmental stages. In most grain crops, flowering, pollination, and grain filling are especially sensitive to moisture stress. Accordingly, management practices have been devised to maximize crop growth in water-scarce conditions. For example, mid-season drought may be avoided by early planting of rapidly developing cultivars; fallowing and weed control can help to conserve moisture in the soil.

Heat and drought stresses often occur simultaneously, one exacerbating the effects of the other. High solar irradiance may be accompanied by high winds. When crops are subjected to drought stress, their stomata close, reducing transpiration and, consequently, raising plant temperatures.

Excessively wet years, on the other hand, may cause yield declines due to waterlogging, lodging, and increased pest infestations. High soil moisture in humid areas can also hinder field operations. Intense bursts of rainfall may damage younger plants and promote lodging of standing crops with ripening grain, as well as soil erosion. The extent of crop damage depends on the duration of precipitation and flooding, crop developmental stage, and air and soil temperatures. The costs of drying corn are higher under wetter climate regimes.

Potential Impacts on Crop Yields

Figure 1 shows projections of changes in wheat yields in the United States, for two global climate model (GCM) change scenarios; these changes are projected to occur in the 2030s if emissions of greenhouse gases continue to increase in a “business-as-usual” trajectory (~0.5 percent/yr increase). The direct effects of higher levels on crops are taken into account (higher CO_2 increases the rate of photosynthesis and improves water-use efficiency). Results show that there is still considerable uncertainty in the climate projections as described by the

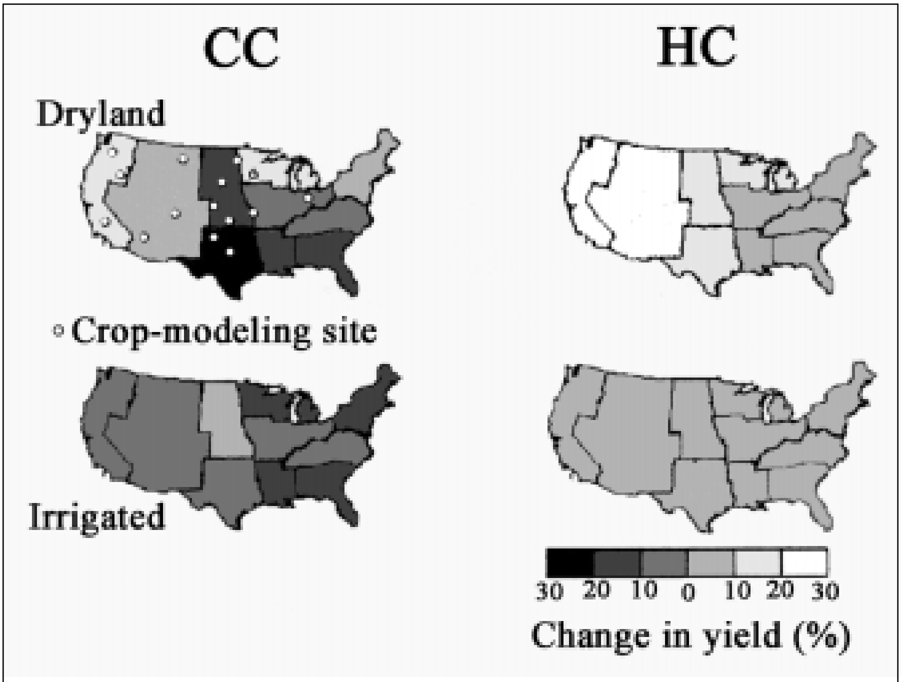

Figure 1. Projections of changes in wheat yields in the United States for the Hadley Centre (HC) and Canadian Climate Centre (CC) climate-change scenarios. Climate projections are for the 2030s and include the effects of greenhouse gases and sulfate aerosols. Crop-yield simulations take the direct physiological effects of higher CO_2 on crop yields and water use into account (Tubiello et al. 2000).

two GCMs; some regions may have improved production, whereas others will suffer yield losses. Irrigated crops may suffer greater yield losses, depending on precipitation projections. Furthermore, different crops will be affected differently. These effects are likely to bring shifts of agricultural production zones around the nation, leading to the need for on-farm adaptation, as well as changes in supporting industries and markets.

Beyond national boundaries, changes in the global patterns of supply and demand may have far-reaching consequences. Figure 2 shows projections of average national crop-yield changes around the world for the Hadley Centre climate-change scenario. At high latitudes, warmer temperature may benefit crops that are currently limited by cold and short growing seasons. In mid-latitudes, however, increased temperatures are likely to exert a negative influence on yields through shortening of crop-development stages. At low latitudes, growing periods for crops are accelerated and heat and water stresses

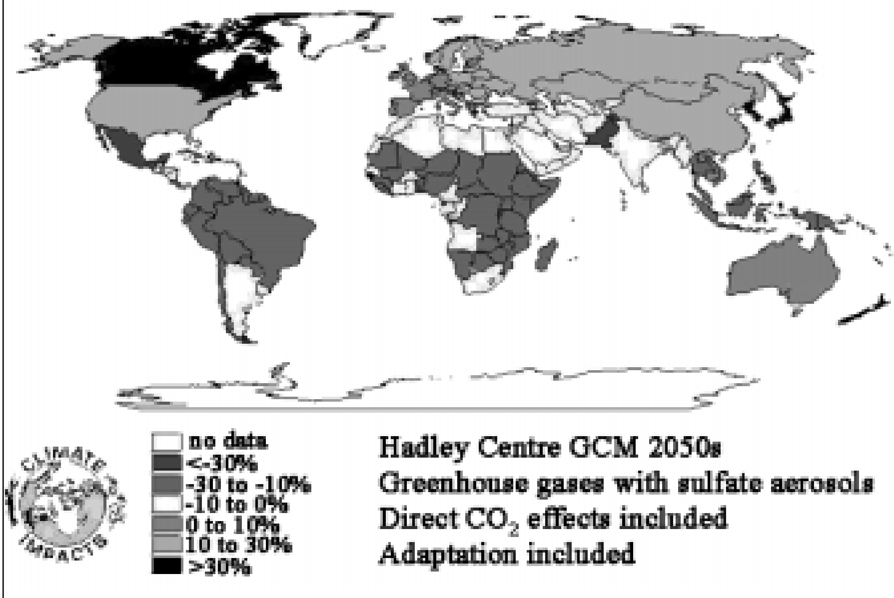

Figure 2. Projections of average national crop yield changes for the Hadley Centre HADCM2 climate change scenario. Climate projections are for the 2050s and include the effects of greenhouse gases and sulfate aerosols. Crop yield simulations take into account the physiological effects of higher CO_2 on crop yields and water use; farmer adaptation to projected climate change is also simulated (Parry et al. 1999).

are exacerbated, resulting in steeper yield decreases than at mid and high latitudes, notwithstanding the beneficial physiological effects of atmospheric CO_2 enrichment.

CHANGES IN EXTREME EVENTS

Climate change is likely to alter event patterns as well as affect mean values. If temperature variability increases, crops growing both at low and high mean temperatures may be adversely affected since diurnal and seasonal canopy temperature fluctuations often exceed optimum ranges. If temperature variability diminishes, however, crops growing near their optimum ranges might benefit. Increases in daily temperature variability can reduce wheat yields due to lack of cold hardening and to resultant winter kill. Extremes of precipitation, both droughts and floods, are detrimental to crop productivity under rainfed conditions. Drought stress increases the demand for water in irrigated regions.

To explore the effects of changes in daily climate variability, tests of changes in temperature and precipitation variability on corn have been made using crop growth models at Des Moines, Iowa (Figure 3). If variability in temperature or precipitation is doubled, decreases in corn yields and increases in corn crop

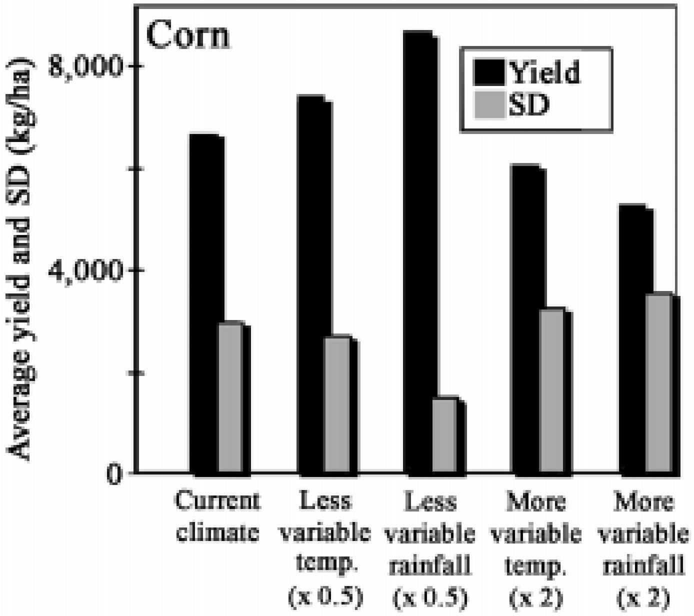

Figure 3. Effects of changes in daily temperature and precipitation variability on corn average yields and yield standard deviation at Des Moines, Iowa (Rosenzweig et al. 2001).

failure result. Such failures for doubled temperature variance are due to slower grain-filling that extended ear development into frost episodes. Doubled precipitation variance causes water-deficit failures in the crop. Halving precipitation variability increases mean yield and strongly decreases variability of the corn yields year-to-year. For soybean, results of changing the variability of temperature and precipitation are similar to those for corn in direction yet greater in magnitude.

Sequential extremes — e.g., prolonged droughts followed by heavy rains — may spawn surprises and have the severest impacts in terms of soil quality, propensity to flooding and the associated impacts for yields and pests. Droughts can reduce populations of beneficial insects (lacewings, lady bugs, etc.), spiders and birds, influencing pollination and pest infestations. The effects of several years of drought (e.g. as occurred with the "double" La Niña of 1998–99 and 1999–2000) can be additive and have longer-lasting impacts on soil quality and groundwater.

PESTS AND CLIMATE CHANGE

Climate affects not just agricultural crops, but also their associated pests as. The major pests of crops include weeds, insects, and pathogens. The distribution and proliferation of weeds, fungi, and insects are determined to a large extent by climate. Organisms become pests when they compete with, or prey upon, crop plants to an extent that reduces productivity. Not only does climate affect the type of crops grown and the intensity of the pest problems, it affects the pesticides often used to control or prevent outbreaks. The intensity of rainfall and its timing with respect to pesticide application are important factors in pesticide persistence and transport.

Because of the extremely large variation of pest species' responses to meteorological conditions, it is difficult to draw overarching conclusions about the relationships between pests and weather. In general, however, most pest-species proliferation is favored by warm and humid conditions. But crop damages by pests are a consequence of complex ecological dynamics between two or more organisms and, therefore, are very difficult to predict. For example, dry conditions are unfavorable for sporulation of fungi, but are also unfavorable for the crop; a crop weakened by drought is more likely to become infected by fungi than when it is not stressed. Pest infestations often coincide with changes in climatic conditions, such as early or late rains, drought, or increases in humidity, which in themselves can reduce yields. In these circumstances, accurately attributing losses to pests can be difficult.

Weeds. Worldwide, weeds have been estimated to cause annual crop production losses of about 12 percent (Parker and Fryer 1975; Pimentel 1992). In the United States, annual losses due to weeds have been valued at approximately $12 billion, amounting to some 10 percent of potential production (Patterson and Flint 1990). Large efforts are made to limit these damages through a variety of weed-control measures. Around the world, more human labor is expended in hand-weeding than in any other agricultural task, and most cultivation and tillage practices are designed to aid in weed control. The chemical industry manufactures herbicides, which, after fertilizers, account for the largest volume of chemicals applied to crops (Furtick 1978). Over $6 billion/yr are spent on weed control in the United States (Patterson and Flint 1990).

Insects and Diseases. Insect pests in agricultural systems are the second major cause of damage to yield quantity and quality after weeds. Insect habitats and survival strategies are strongly dependent on patterns of climate. Insects are particularly sensitive to temperature because they are cold-blooded. In general, higher temperatures increase rates of development, with less time between generations. Precipitation — whether optimal, excessive, or insufficient — is a key variable that also affects crop-insect interactions. Drought sometimes changes the physiology of perennial vegetation, affecting the insects that feed on them (Mattson and Haack 1987). Abnormally cool, wet conditions can also bring on severe insect infestations, although excessive soil moisture may drown out soil-residing insects. Climate factors that influence the growth, spread, and survival of crop diseases include temperature, precipitation, humidity, dew, radiation, wind speed, air circulation patterns, and the occurrence of extreme events

Changes in Pests. The results of most analyses indicate that, in a changing climate, pests may become even more of a problem than they are currently, thus posing the threat of greater economic losses to farmers (Watson et al. 1996). While the majority of weeds are invasive species from temperate zones, many of the most aggressive species in temperate regions originated in tropical or subtropical regions, and in the current climate their distribution is limited by low temperature. Such geographical constraints will be removed under warm conditions. Warmer temperature regimes have been shown to increase the maximum biomass of three grass weed species significantly (Figure 4).

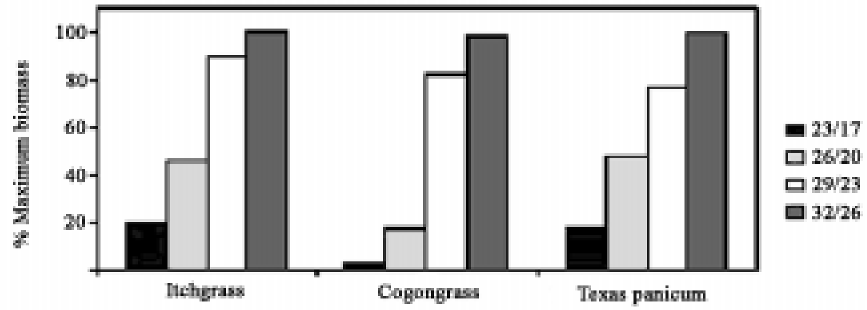

Figure 4. Effect of temperature regime on biomass of three grass weeds (Patterson and Flint 1990).

In crop monocultures, undesirable competition is controlled through a variety of means, including crop rotations, mechanical manipulations (e.g., hoeing), and chemical treatment (e.g., herbicides). The need for such measures is likely to increase in a warming climate.

With temperatures within their viable range, insects respond to warmer conditions with increased rates of development and with less time between generations. (Very high temperatures reduce insect longevity.) Warmer winters will reduce winterkill, and consequently there may be increased insect populations in subsequent growing seasons. With warmer temperatures occurring earlier in the spring, pest populations will become established and thrive during earlier, more vulnerable, crop growth stages. Additional insect generations and larger populations, encouraged by higher temperatures and longer growing seasons, will require greater efforts of pest management.

Warmer winter temperatures will also affect those pests that currently cannot over-winter at high latitudes but do over-winter in lower-latitude regions and then migrate north in the spring and summer. For example, the potato leafhopper (*Empoasca fabae*), a pest of soybean, alfalfa and other crops, may expand its over-wintering range (now limited to a narrow area along the Gulf of Mexico) and be better positioned to spread northward earlier and in greater numbers during the cropping season (Figure 5).

Some species are pests in the southern United States but not in the Midwest, because they do not migrate northward early enough or in significant numbers. Corn earworm (*Heliothus zea*) is an example of a current pest of corn in the South that is not a serious pest in field corn in the Midwest. With climate change, extension of over-wintering range may bring *H. zea* to field corn crops of the Midwest (Stinner et al. 1989).

Damage from the European corn borer (*Ostrinia nubilalis*), a major insect pest of corn in the United States and elsewhere, is limited in many regions due

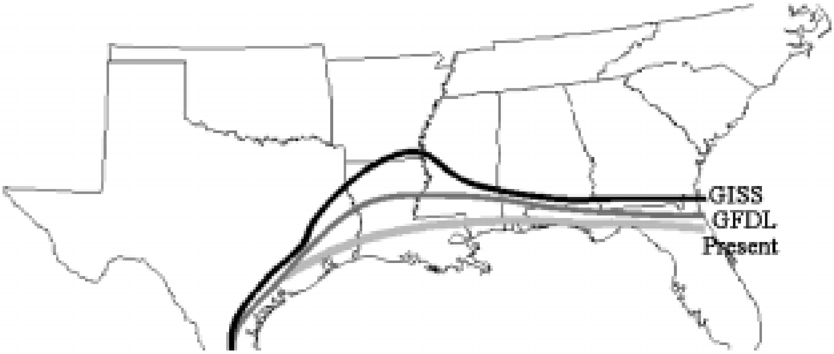

Figure 5. Over-wintering range of potato leafhopper (*Empoasca fabae*) for current climate and two climate-change scenarios (Stinner et al. 1989).

to current climate conditions. For example, in Iowa, the insect has only two generations per corn-growing season because the third generation pupae cannot complete development before winter. Warmer conditions will ensure a third generation of the insect and will significantly increase its over-wintering populations.

The Mexican bean beetle (*Epilachna varivestis*) and bean leaf beetle (*Cerotoma trifurcata*), major pests of soybean, presently have two generations in the Midwest and three in the Southeast. An additional generation may be possible in the Midwest if the growing season there lengthens (Stinner et al. 1989).

Drought stress tends to bring increased outbreaks of pests; therefore, insect damage may increase in regions destined to become more arid. If the climate becomes warmer also, the population growth rates of small, sap-feeding pests may be favored (Stinner et al. 1989). Higher temperature and humidity and greater precipitation, on the other hand, are likely to result in the spread of plant diseases, as wet vegetation promotes the germination of spores and the proliferation of bacteria and fungi, and influences the life-cycle of soil nematodes. In regions that suffer greater aridity, however, disease infestation may lessen, although some diseases (such as the powdery mildews) can thrive even in hot, dry conditions as long as there is dew formation at night.

ADAPTATION

The responses of individual producers to changes of climate regime will involve adjustments in the selection of crops and in practices of cultivation, irrigation, and pest control. Changes on the farm may, in turn, modify regional energy use, water demand, storage and transportation providers, and food processing. Improved climate forecasts can help farmers prepare for changing seasonal-to-interannual conditions. Ultimately, the ability of farmers to adapt effectively may determine the success or failure of individual farms and, by extension, may affect local, regional, national, and international economies.

Climate change will gradually (and, possibly at some point, even abruptly) affect agriculture on regional, national, and international scales. The range of options available for producers in any given region will change. Since farmers' strategies grow out of experience, they will find that the past will be a less reliable predictor of the future. Accumulated experience will be less useful as a tool for coping with what might eventually be a very different future. Under progressively changing climate conditions, adaptations will need to evolve continuously.

National farm policy is likely to be a critical determinant in the adaptation of the farming sector to changing conditions. In the United States, farm subsidies may either help or hinder necessary adaptation to the eventuality of a changing climate. An important policy consideration is the assessment of risk due to weather anomalies. If flood and drought frequencies increase as projected, the need for emergency allocations will also increase. Anticipating the probability and the potential magnitude of such anomalies may help make timely adjustments, reducing social costs.

With the advantage of extensive research and extension capacity, farmers in the United States may adapt effectively to climate change, at least initially. However, some adaptations — such as development of new irrigation systems — may be costly, while others may cause significant disruption for people in rural areas. Beyond our national boundaries, changes in the global climate may have more negative consequences. Where infrastructure for agricultural research is less effective, as in many developing countries, adaptation may be slower, leading to failure of individual farms and to losses in economies dependent on agricultural production. The vulnerability of food-deficient regions in marginal climates is likely to be exacerbated due to increased climatic extremes, including more severe and prolonged droughts alternating with floods. An overall increase in global food demand may benefit climatically favored regions, such as parts of the United States, though that advantage may be offset by intensified competition from still more favored regions (possibly Canada and Russia).

Costs of production may rise in a changing climate, as producers adjust crop varieties and species, scheduling of operations, and land and water management. Successful adaptations to climate change may imply significant alterations from current agricultural systems, and some of the required changes may be costly. There is likely to be need for investment in new technologies and infrastructure. New irrigation systems may be required where aridity or instability of precipitation ensues. Damages from flooding may increase in many areas. Costs may include greater applications of and/or development of new agricultural chemicals, particularly herbicides and pesticides.

Even without climate change, agriculture faces some serious challenges in the coming decades. Because of the growing interdependence of the world food system, the impact of climate change on agriculture in each country depends more and more on what happens elsewhere. For example, improvements in the climate of key competitive regions, such as Argentina for soybean production, may affect the United States' comparative advantage. On the other hand, the vulnerability of food-deficient regions to heat and drought may work to the advantage of major grain producers such as the United States. International trade policy issues, especially the movement to lower agricultural trade barriers, will be crucial in climate change response strategies.

Agricultural Emissions of Greenhouse Gases

The role of climate as a primary determinant of agriculture has long been recognized. Only in the last decade, however, has agriculture's reciprocal effect on climate change come to light. Clearing forests for fields, burning crop residues, submerging land in rice (*Oryza sativa*) paddies, raising large herds of ruminants, and fertilizing with nitrogen, all release greenhouse gases to the atmosphere (Rosenzweig and Hillel 1998). The main gases emitted are CO_2, CH_4, and N_2O. Emissions from agricultural sources account for about 15 percent of total anthropogenic greenhouse-gas emissions and land-use change (often for agricultural purposes) contributes another 8 percent approximately (Houghton et al. 1996). Agriculture ranks third after energy consumption and chlorofluorocarbon production as a contributor to the enhanced greenhouse effect.

Carbon in various forms (CO_2, carbonates, or organic compounds) is cycled between the atmosphere, oceans, land biota, and marine biota on short time scales and into sediment and rocks on geological time scales. Agricultural practices manipulate the vegetation and soil carbon reservoirs (Jackson 1993). As areas of natural vegetation are transformed into cultivated fields, much of the vegetative biomass originally present is converted to CO_2. Land-use change and biomass burning cause the release of carbon, in the form of CO_2 that had previously been contained in plant biomes and soil organic matter, both of which, in turn, resulted from cumulative prior photosynthesis. The aboveground material is either burned or decomposes rapidly. Declines in organic matter in agricultural soils are largely due to losses from the labile pool, also known as the “light” fraction. In contrast, the resistant pool or “heavy” fraction of organic matter in the soil, while not entirely stable, decomposes at a much slower rate.

When land supporting a natural ecosystem is first converted to agricultural use, the organic matter in the soil is gradually oxidized as the soil is cultivated and cropped. Deforestation, biomass burning, drainage, plowing, cultivation, and overgrazing all promote the decomposition of organic matter and the release of CO_2 to the atmosphere. Soil degrading processes (erosion, crusting and compaction, acidification, salination, etc.) further exacerbate losses of carbon (Lal et al. 1998). As agricultural production continues over time, soil organic matter declines still further (albeit at a slowing rate), resulting in more CO_2 releases, until a steady state is reached or until the field is abandoned (Houghton and Skole 1990). Curtailed tillage practices such as “minimum tillage” or “no-till,” efficient crop rotation, strip cropping, and fallowing tend to decrease CO_2 fluxes to the atmosphere and may sequester carbon over a period of time (Rosenzweig and Hillel 1998).

CLIMATE CHANGE AND BIOTECHNOLOGY

The prospect of a changing climate, caused by augmented atmospheric constituents, may provide motivation for the use of biotechnology in several ways. First, there may be opportunities for optimizing photosynthetic and stomatal conductance responses to higher levels of atmospheric CO_2. Second, biotechnology techniques may offer the potential for creating effective adaptations to changing climatic circumstances. Enhanced heat and drought tolerance, both of crops and livestock, are likely to be required, as are strategies to cope with shifting and newly emerging weeds, pests, and plant diseases. Finally, improved mitigation options could also be developed in regard to the ability of crops to sequester carbon, production of biofuels, reduction of CH_4 emissions from rice-paddy and ruminant-livestock systems, and management of N_2O emissions from nitrogen fertilizers.

Several caveats are in order. Genetically modified organisms may not be able to cope with all of the effects of dynamic climate changes that occur in agricultural regions. For example, severe flooding may continue to be detrimental to crop production, regardless of genetic resources. Dissemination of new and severe crop pests may be so rapid as to bring widespread damage before development of appropriately modified crops. Finally, much research and testing of genetically modified crops is required, in any case, so that potential benefits and risks are more clearly understood.

CONCLUSIONS

Providing sufficient food for the world's people is one of the great challenges of the twenty-first century. The challenge will increase as human numbers grow towards 10 billion, and as land, water, and genetic resources are progressively degraded through intensified use. There is now real concern that global warming, with its potential for affecting the climate regimes of entire regions, will exacerbate the world's food-production problems.

Indeed, if atmospheric buildup of greenhouse gases continues without limit, sooner or later it is bound to warm the earth's surface. Such a warming trend cannot but affect the regional panoply of temperature and precipitation governing natural and agricultural systems. While increased atmospheric CO_2 alone might benefit crop growth due to enhanced photosynthesis, the combination of high CO_2 and higher temperatures may not always produce greater harvests. There is a grave danger in concluding that "in general" climate change does not pose a threat to national or world agriculture.

Agricultural systems may be more adaptable, being more subject to our control, than natural systems, and may shift into regions now primarily covered by forests and other less intensively managed ecosystems. Such interactions of agriculture and the natural environment under a changing climate will have large-scale reverberations: altering rates of soil erosion, increasing competition for water resources, expanding the use of agricultural chemicals, and affecting wildlife habitats.

While global warming offers challenges to agriculture, it also offers opportunities. Many good farm-management practices also buffer against climate changes and reduce greenhouse-gas concentrations in the atmosphere. Land conversion and restoration can increase soil organic matter through sequestration (i.e., enrichment of the soil's store of organic carbon), while simultaneously reducing emissions. Improvements in fertilizer efficiency —

timely application of environmentally preferred types — can reduce N_2O emissions. Finally, the production and use of biofuels "recycles" CO_2, thus providing a direct offset to emissions from non-renewable sources. If idle land is used for biofuel production, carbon sequestration may occur as well.

Global environmental change is a deceptively simple expression for what is actually an exceedingly complex array of dynamic processes, with specific combinations of interactions in each region. Climate change, sea-level rise, and increases in CO_2, ultraviolet radiation, and tropospheric ozone are but a few of the potentially fateful factors involved. While many studies have investigated these factors singly, there is much to be gained from studying their interactions. Although unknowns still thwart our ability to predict precisely the extent of future changes in agriculture due to global environmental changes, active response and systematic preparation are clearly in order.

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