

**Climate Change and U.S. Agriculture:
The Impacts of Warming and Extreme Weather Events on Productivity,
Plant Diseases, and Pests**



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ACKNOWLEDGEMENTS:

We thank the National Environmental Trust for supporting the preparation of this report and the New York Community Trust, the Richard and Rhoda Goldman Fund and the Clarence Heller Charitable Foundation for funding this project. We are also deeply grateful to the reviewers who made many useful suggestions that helped improve the report, to José Mendoza and Rick Hartmann for their expertise in designing the graphics, and to Tracy Graham for laying out the manuscript.

PUBLISHED BY:

CENTER FOR HEALTH AND THE GLOBAL ENVIRONMENT
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May 2000

EXECUTIVE SUMMARY

This report explores some of the impacts that climate change, with warmer and more variable weather, may have on agriculture in the United States. Its aim is to elucidate how warmer temperatures and an increase in extreme weather events (including spells of very high temperatures, torrential rains and flooding, and droughts) may affect a) crop yields, b) the incidence of weeds, insects, and plant diseases, and c) the economic costs of agricultural production.

The report analyzes crop yield and production costs from 1950 to the present in an effort to understand how they have varied under current climate conditions. It focuses on the impacts of extreme weather events on U.S. agriculture, using examples from the recent past, such as the drought of 1988 and the Mississippi River Valley floods of 1993. The agricultural effects of the El Niño phenomenon, a major Pacific Ocean cycle affecting regional climates, are also described. Shifts in the ranges of major crop pests that have been noted in recent years are discussed. Finally, with current climate and agriculture scenarios serving as models, the report looks at future projections of climate change and examines the potential impacts on crop production and on pests in major agricultural regions of the U.S.

We highlight the following conclusions regarding the current state of the U.S. agricultural sector:

- ❖ Since the 1970s, U.S. agriculture has achieved enhanced productivity, but has also experienced greater variability in crop yields, prices, and farm income. The changes in variability are, in part, climate-related, either directly (through extreme weather events) or indirectly (due to agricultural pests and diseases).
- ❖ Extreme weather events have caused severe crop damage and have exacted a significant economic toll for U.S. farmers over the last 20 years. Total estimated damages, of which agricultural losses are a part, from the 1988 summer drought were on the order of \$56 billion (normalized to 1998 dollars using an inflation wealth index), while those from the 1993 Mississippi River Valley floods exceeded \$23 billion.
- ❖ Both pest damage and pesticide use have increased since 1970. Nationally, in the 1990s, pests were estimated to have destroyed about one third of our crops, in spite of advances in pest control technology over the last half century.
- ❖ The ranges of several important crop pests in the U.S., including the soybean cyst nematode [the most destructive soybean pest in the U.S.] and corn gray leaf blight [the major disease causing corn yield losses] have expanded since the early 1970s, possibly in response, in part, to climate trends.
- ❖ Pest and disease occurrences often coincide with extreme weather events and with anomalous weather conditions, such as early or late rains, and decreased or increased humidity, which by themselves can alter agricultural output. Recent climate trends, such as increased nighttime and winter temperatures, may be contributing to the greater prevalence of crop pests.

With regard to the potential future effects from climate change on U.S. agriculture, the following factors are highlighted:

- ❖ Expected temperature increases are likely to hasten the maturation of annual crop plants, thereby reducing their total yield potential, with extremely high temperatures causing more severe losses. Des Moines, Iowa, in the heart of the Corn Belt, currently experiences fewer than 20 days per year with temperatures exceeding 90°F. The number of days with temperatures above 90°F would double with a mean warming of 3.6°F.

- ❖ Climate change projections include an increased likelihood of both floods and droughts. Variability of precipitation--in time, space, and intensity--will make U.S. agriculture increasingly unstable and make it more difficult for U.S. farmers to plan what crops to plant and when.
- ❖ Higher temperatures and greater precipitation in some regions are likely to result in the spread of plant pests and diseases. Higher temperatures reduce insect winterkill, and lead to increased rates of development and shorter times between generations. Wet vegetation promotes the germination of spores and the proliferation of bacteria, fungi, and nematodes. Prolonged droughts can encourage other pests and diseases; especially those carried by insects.
- ❖ Increased crop pests may necessitate intensified use of agricultural chemicals that carry long-term health, environmental, and economic risks.
- ❖ While the majority of weeds are invasive species from temperate zones, the distribution of others, that originate in tropical and subtropical regions, may spread with warmer temperatures. In the U.S. during the 1980s, annual losses in crop production due to weeds have been valued at approximately \$12 billion, amounting to losses of some 10% of potential production.
- ❖ Climate change, with preferential warming at high latitudes, in winter and at night, is likely to shift the ranges of optimal production centers for specific crops. Such changes in agricultural zones and in productivity may lessen the comparative advantage that the U.S. now enjoys as a leading international exporter of major agricultural commodities.
- ❖ The combination of long-term change (warmer average temperatures) and greater extremes (heat spells, droughts and floods) suggest that climate change could have negative impacts on U.S. agricultural production. Economic losses in some U.S. agricultural regions could rise significantly due to greater climate variability, and to increases in insects, weeds, and plant diseases.

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I. CHALLENGES TO U.S. AGRICULTURE

The climate change issue brings the recognition that current and future levels of energy use from burning of fossil fuels and clearing of forests for cultivation can have profound effects on the global environment, and on agriculture. Producers, crop breeders, fertilizer and other input manufacturers and distributors, equipment dealers, commodity brokers, and food processors, wholesalers, and retailers, among a host of others, will ultimately be affected, not only through changes at the regional level, but also through effects on the U.S. competitive position in world commodity markets. Global warming presents a challenge to the agricultural industry to understand what is at stake and to manage its future development wisely.

In the U.S., the agricultural industry is highly productive, intensively managed, and market-based. Farms and the associated input (storage, transportation, and processing industries) provide low-cost, high-quality food for domestic consumers and contribute substantially to export earnings for the country as a whole. Although farmland has been decreasing steadily over the last several decades, especially in California and Florida, the total annual value of U.S. agricultural sector output is greater than \$230 billion. Crop production, dominated by corn, soybean, wheat, and cotton, is worth over \$100 billion (Figure 1) (ERS-USDA, 1999).

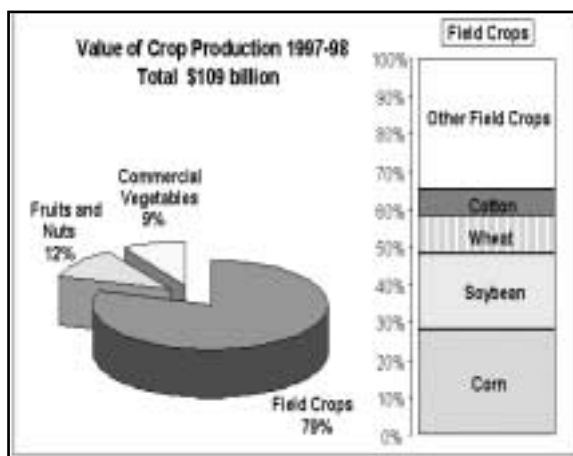


Figure 1. U.S. final agricultural sector output and final crop output, 1997. (Source: USDA).

While U.S. agriculture is a major success story, the system is still highly dependent on climate, because temperature, light, and water are the main drivers of crop growth. Plant diseases and pest infestations, as well as the supply of and demand for irrigation water, are also influenced by climate. Earlier in the century, the drought of the 1930s in the Southern Great Plains of the U.S. caused some 200,000 farm bankruptcies in the Dust Bowl; yields of wheat and corn were reduced by as much as 50% (Warrick, 1984). The drought of 1988 in the Midwest led to a 30% reduction in U.S. corn production and cost U.S. taxpayers \$3 billion in direct relief payments to farmers (Rosenzweig and Hillel, 1998). More recently, weather anomalies associated with the El Niño of 1997-98 affected agriculture adversely in California, the Southern Great Plains, and the Southeast.

Keith Collins, the Chief Economist of USDA, stated recently that “The key uncertainty for the 1998/99 crop outlook is the weather.” Despite tremendous improvements in technology and yield potential, the weather is still an important factor in U.S. agriculture.

There is now concern that weather impacts on food production and its costs will be exacerbated in the U.S. due to global warming, with its potential for affecting the climatic regimes of entire regions (IPCC, 1996b). Ranges of crop weeds, insects, pests, and diseases are projected to expand to higher latitudes (Dahlstein and Garcia, 1989; Sutherst 1990). Furthermore, such shifts in climate in other regions may have a greater effect on agricultural productivity than they will have in the U.S. There is also the possibility (although the many variables make such predictions extremely difficult) that agriculture in some parts of the world may actually benefit from global climate change, at least in the short term. As a result, the comparative advantage that the U.S. now enjoys as a leading exporter of major agricultural commodities could be at risk. On the other hand, some regions in the U.S. (e.g., North Dakota) may also benefit from warmer and longer growing seasons, where the crops are currently limited by cold but not by paucity of moisture.

This report explores some of the impacts that might alter U.S. agriculture in a greenhouse world. It focuses on the effects of extreme weather events on agriculture, looking both to examples from the recent past and to future projections. Major incidents of climate variability are contrasted: in particular the drought of 1988 and the Mississippi Valley flood of 1993. The agricultural effects of the El Niño phenomenon, a forcing mechanism in our current climate, are described. The report analyzes crop yield and price data from 1950 to the present, in order to understand the nature of agricultural variability under current climate conditions. Finally, scenarios of future climate change are used to project impacts on crop production in major agricultural regions of the U.S. Our aim is to elucidate the impacts of climate variability and change on (a) crops; (b) incidence of weeds, insects, and diseases; (c) producers; and (d) economic costs relating to the agriculture sector.

II. CLIMATE CHANGE AND VARIABILITY

The climate system consists of a series of fluxes and transformations of energy (radiation, heat, and momentum), as well as transports and changes in the state of matter (e.g., air, water, and aerosols). Received solar radiation is the major energy source that powers the entire system. The flows and transports occur between and within the main components of the system: the atmosphere, oceans, land, biota, and cryosphere (the domain of ice and snow). The system varies regularly due to the shape of the earth's orbit, its angle, and daily rotation, but also chaotically, because the atmosphere and the oceans are both fluids subject to internal movements associated with random turbulence, as energy is transported and transformed throughout the climate system. These latter variations result in climate extremes.

Climate is defined as the prevalent pattern of weather observed over a prolonged period of time. Climate variables (e.g., temperature, precipitation, wind speed) can be time-averaged on a daily, monthly, yearly, or longer basis. Associated with the average states of climate variables are indications of their oscillations or variations about their

mean values. The term climate change refers to an overall alteration of mean climate conditions, whereas the term climate variability refers to fluctuations about the mean. A changing climate is likely to bring changing patterns of climate variability.

Precipitation anomalies, for example, may occur with regard to the timing, quantity, intensity, seasonal and spatial distribution, and, type (e.g., winter rain vs. snow). Greater temperature variations may be manifested, for example, in more prolonged heat waves and sharp transitions. Greater temporal and spatial variability of meteorological conditions and storms can all affect soil conditions, water availability, agricultural yields, and susceptibility to pest and pathogen infestations.

Global Warming

Through burning of fossil fuels and eradication of forests, human activity has caused the carbon dioxide (CO₂) concentration of the atmosphere to increase by some 25% since the industrial revolution, and that increase continues. Measurements made on Mauna Loa in Hawaii since 1956 reveal the recent CO₂ trend.

CO₂ plays an important role in inhibiting the escape of the heat radiated by the earth. The sun beams short-wave radiation to the earth, which sends long-wave radiation back to space. Greenhouse gases in the earth's atmosphere (water vapor, carbon dioxide, methane, nitrous oxide, and the chlorofluorocarbons) absorb the outgoing radiation, thereby holding heat near our planet. This process occurs naturally: without the natural greenhouse effect, our planet would be near freezing. Instead, this process warms the earth to its current mean temperature of 59°F (15°C).

The concern now is that human activities are causing the natural greenhouse effect to be augmented, leading to significant changes in the temperature and related changes in the entire climate system. Has global warming actual begun? When we look at the Earth's global average temperature over the last century, we find that temperatures have risen over 1°F~ (0.7°C). The decade of the 1990s is

the warmest on record (Figure 2). While it is difficult to prove conclusively that rising CO₂ is causing the earth to warm, scientists believe that the two trends — increasing carbon dioxide and increasing temperatures — are linked (IPCC, 1996b). Furthermore, there is concern that high latitude and ocean warming could affect ice cover and thermohaline circulation (see glossary), and lead to abrupt climate change (Broecker et al., 1999).

Because the earth's climate system is too large to allow controlled experiments, scientists have been employing mathematical models, known as global circulation models (GCMs), to assess the processes known to occur and their possible interactions. Such models are used to forecast the trend of climate over the coming decades (Figure 3). Results should not be accepted uncritically, although we should pay attention to the implications of their predictions, while continuing to look for the emerging empirical evidence of changing climate.

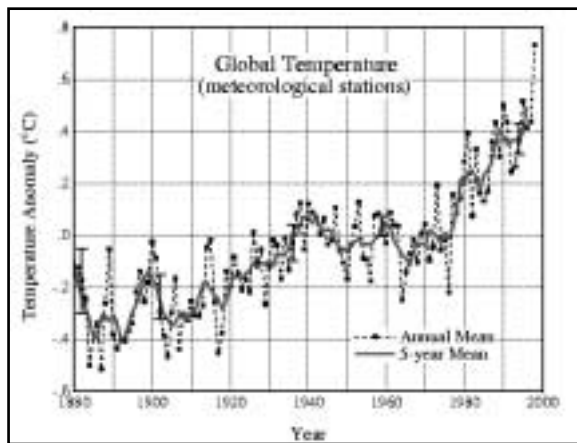


Figure 2. Global surface air temperature trend, 1880 to present. (Source: NASA/GISS).

At least ten GCMs have been developed by atmospheric scientists in various research groups and have been used to project the effects of greenhouse gas increases. Results from these simulations show a mean global warming in the range of 3 to 9°F (1.5 to 4.5°C) by the end of the next century. When the effects of sulfate aerosols are included in

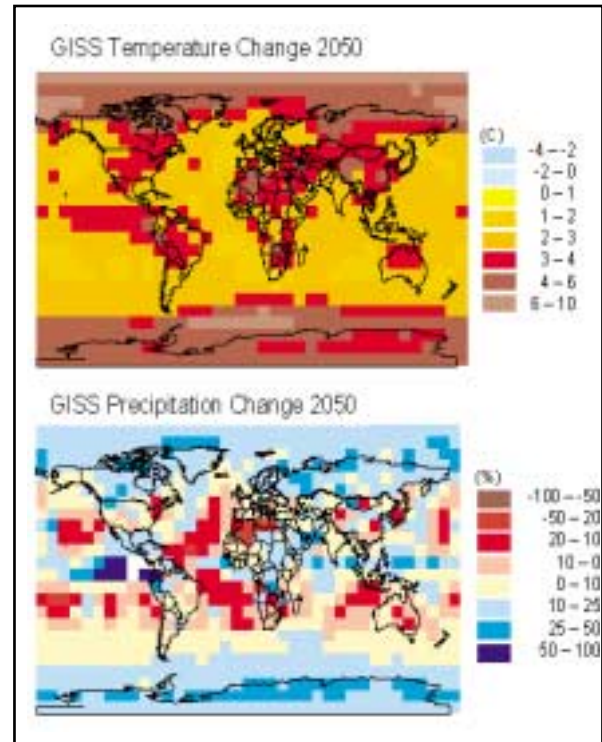


Figure 3. Global temperature and precipitation projected changes with the Goddard Institute for Space Studies (GISS) climate model for the decade of 2050s. (Source: NASA/GISS/CIG).

the projections, the estimate for 2100 is a temperature increase in the range of 2 to 7°F (1.0 to 3.5°C). The latter projections are somewhat cooler, since sulfate aerosols from industrial pollution tend to cool the earth's atmosphere by reflecting short-wave solar radiation. Global climate models also predict an increase in mean global precipitation ranging from about 5 to 15% due to the fact that a warmer atmosphere can hold more water vapor.

GCMs further predict that:

- ❖ High latitudes and high elevations are likely to continue to experience greater warming than the global mean warming, especially in winter.
- ❖ Winter and nighttime temperatures (minimum temperatures) are projected to continue to rise disproportionately.

- ❖ The hydrological cycle is likely to further intensify, bringing more floods and more droughts.
- ❖ More winter precipitation is projected to fall as rain, rather than snow, decreasing snowpack and spring runoff, potentially exacerbating spring and summer droughts.

So much has been said and written recently about the impending change in climate that many are confused by it all. The voluminous and rapidly proliferating scientific literature on this subject is highly technical, complex, fragmented, and still beset by disagreements. This much seems clear: if the buildup of greenhouse gases in the atmosphere continues without limit, it is bound, sooner or later, to warm the earth's surface. Such a warming trend cannot but affect the biophysical processes of photosynthesis and respiration, the regional infestations of weeds, insects, and diseases, and indeed the entire thermal and hydrological regimes governing our agricultural systems.

Beyond what is clear however lie great uncertainties: How much warming will occur, when and at what rate, and according to what geographical and seasonal pattern? What will be the consequences to agricultural productivity in different countries and regions? Will some areas benefit while other areas suffer? And there are the practical questions: What can be done to mitigate these changes? And to the extent that such damages may be unavoidable, what can be done to adapt our practices so as to minimize or even overcome them? The welfare of our national agriculture may well be determined by our ability to answer these and other questions related to the environment.

Weather Extremes

Extreme weather events include spells of very high temperature, torrential rains, and droughts. Under an enhanced greenhouse effect, change will occur in both the mean values of climate parameters and the frequency of extreme meteorological events. The impacts of global warming on agriculture depend on the relative magnitudes and effects of the mean and extreme event changes.

Relatively small changes in mean temperature can result in disproportionately large changes in the frequency of extreme events. Des Moines, Iowa, in the heart of the Corn Belt, currently experiences fewer than 20 days above 90°F; this would double with a mean warming of 3.6°F. For a similar level of warming, Phoenix, Arizona, where irrigated cotton is grown, would have 120 days above 100°F, instead of the 90-odd days in the present climate.

Sequential extremes can affect yields and disease patterns. Droughts, followed by intense rains, for example, can have an impact on soil water absorption, increasing the potential for flooding that creates conditions favoring fungal infestations of leaves, roots, and tuber crops. Prolonged anomalous periods - such as the five years of El Niño conditions between 1990 and 1995 - can also have destabilizing effects on agriculture.

Sequential extremes, along with altered timing of seasons, may also decouple long-evolved relationships among species (e.g., predator/prey) essential for controlling pests and pathogens, (Epstein and Chilwenhee, 1994) as well as populations of plant pollinators.

Considerations of the potential impacts of climate change on agriculture should, therefore, be based not only on the mean values of expected climatic parameters but also on the probability, frequency, and severity of possible extreme events.

Links to El Niño

Second only to the seasonal cycle, the El Niño phenomenon is a powerful force affecting the climate patterns that directly govern crop growth around the world. There is a significant difference, however, in that the seasons come regularly, year after year, while the El Niño phenomenon is inherently irregular. El Niño events, which tend to recur every two to nine years with varying intensity, are related to oceanic and atmospheric phenomena. Analysis of El Niño records shows that recent

events have been stronger and more frequent (Trenberth, 1999). While this may be suggestive of global warming (Timmermann et al., 1999; Trenberth, 1999), the connections between global climate change and the El Niño phenomenon are still uncertain.

El Niño events are characterized by increased sea-surface temperatures in the tropical Pacific Ocean, suppressed upwelling of nutrient-rich water along the coast of South America, alternation of high and low pressure in the eastern and western Pacific, disruption of the trade winds, and dramatic changes in rainfall patterns. La Niña events are the reverse. The cycle has long been known to be a

large component of climate variability in the tropics and subtropics. In recent decades, its far-reaching effects on mid-latitude regions have come to light.

Global “teleconnections” (relationships between sea-surface temperatures, most often in the Pacific Ocean, and weather anomalies across the globe) linked to El Niño include lower-than-normal precipitation in western Oceania, India, southeastern Africa and northeastern South America, and excessive precipitation in western and southeastern South America, and occasionally in North America (Figure 4). Temperatures during El Niño periods tend to be warmer in many parts of the world.

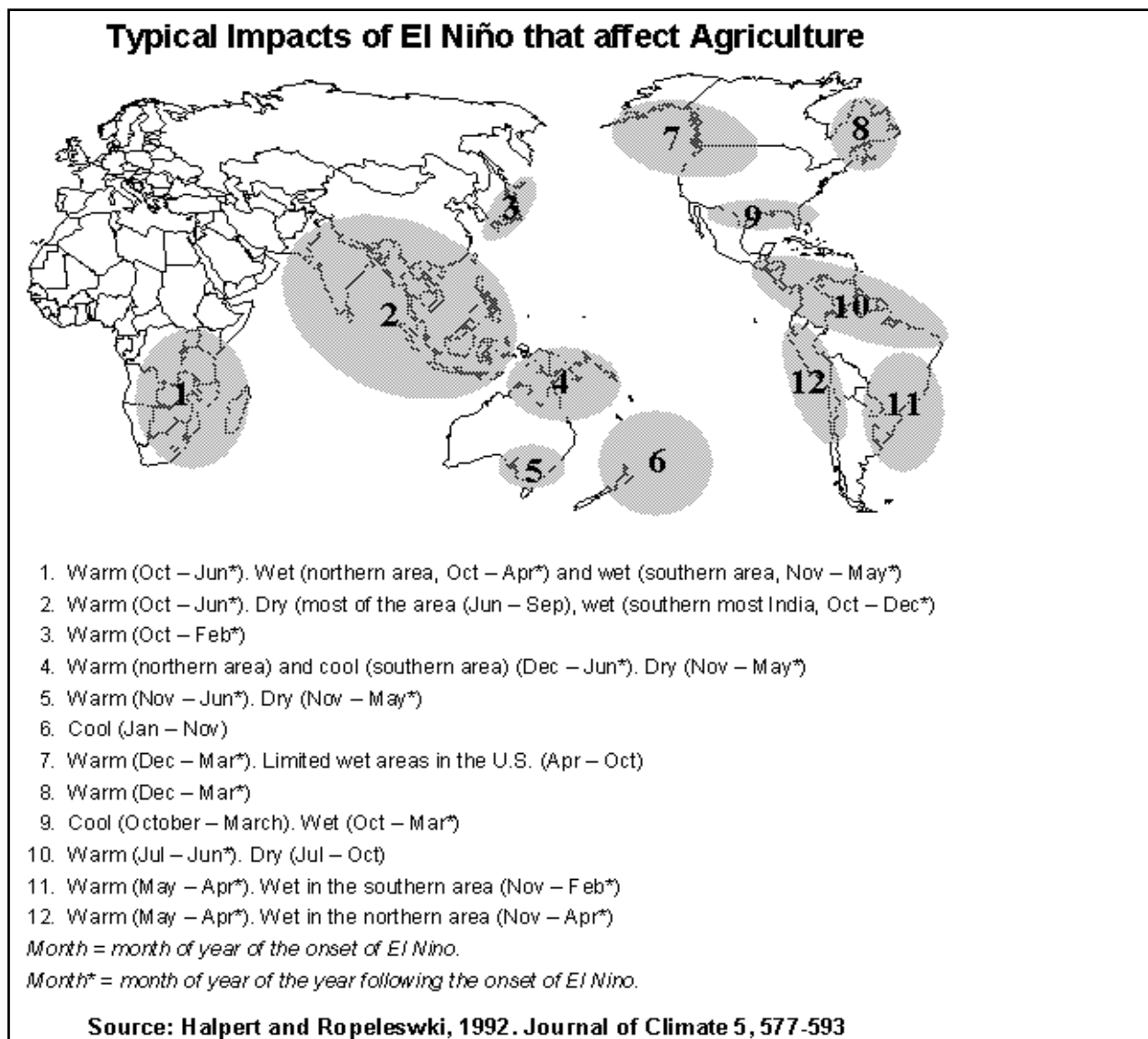


Figure 4. Typical temperature and precipitation patterns associated with El Niño that affect agriculture. (Prepared by the Climate Impacts Group NASA/GISS).

In the U.S., El Niño events often bring storms to the West Coast and rain to the South. Connections to the Midwest are generally weak, but studies have shown that during phases of the El Niño-La Niña cycle, the U.S. Corn Belt region experiences anomalies in precipitation and temperature patterns (Phillips et al., 1999; Rajagopalan et al., 2000;). These fluctuations affect crop development, which in turn can affect yields. La Niñas tend to bring drier conditions in the Corn Belt, lower general vegetation growth, and decreased crop yields (Wannebo and Rosenzweig, 2000; Figure 5). There is a significant relationship (correlation coefficient of $r = 0.45$) between aggregated Pacific sea-surface temperature (Niño3 Index, see glossary) and U.S. Corn Belt corn yields from 1961 to 1991 (Phillips et al., 1998).

El Niño connections have the strength to wreak great havoc on human activities. Indeed, it was the collapse of the anchovy fisheries off the western shore of South America that first brought the El Niño cycle to widespread public awareness in 1972-1973. Extreme El Niño events, such as those that occurred in 1982-1983 and 1997-1998, caused damage to coastal resources, agriculture, transportation, housing, and human life on five continents. El Niño impacts on agriculture, while typically negative, may actually be positive in some areas. Impacts are generally strongest in the Southern Hemisphere. Large countries, such as the U.S. and Brazil, extend over different geographical regions that experience opposite responses to El Niño events, and thus the effects of the El Niño phenomenon at the national level may cancel out other impacts. Furthermore, different crops are affected differently. In Zimbabwe, for example, corn is more strongly affected than are roots and tubers.

However, predicting climatic teleconnections and their effects is difficult: not every El Niño phase is the same in terms of strength, duration, and pattern. A strong event in the Pacific may not engender the strongest teleconnections in other regions. For example, the 1982-1983 El Niño had higher sea-surface temperatures than did the 1997-1998 event, but the climate and corn yield effects associated with the latter event in Zimbabwe were stronger. The sea-surface temperatures during the

1997-98 and 1982-1983 events were similarly high, but the resulting rainfall patterns in southeastern Africa were significantly different. In order to represent the uncertainty of the climate responses, El Niño forecasts are produced in probabilistic terms. Responses may be manifested in temperature and precipitation, and changes of the seasonal means, as well as in their patterns of variability.

Both the North Atlantic Oscillation (NAO) and the patterns in the Indian Ocean are also major components of natural climatic variability, and their climatic teleconnections affect major agricultural regions around the world. Climate variability in the eastern coast of North America depends in part on the state of the NAO. Improved accuracy in forecasts will require inclusion of these indices, local sea-surface temperatures (SSTs), decadal variability, and the anthropogenic signal.

Climate change may bring about changes in the magnitude and frequency of the key components and natural cycles of the climate system.

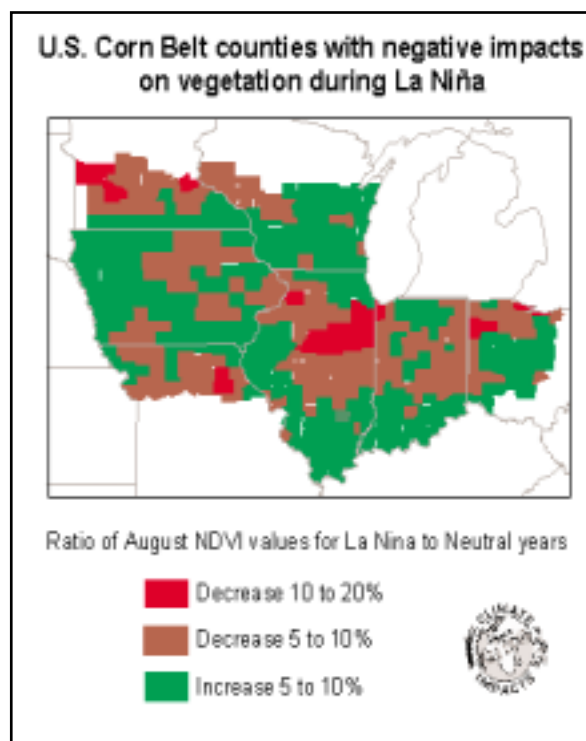


Figure 5. Ratio of August Normalized Difference Vegetation Index (NDVI) (see glossary) values from La Niña to neutral years in the U.S. Corn Belt. (Source: NASA/GISS/CIG).

III. CROP RESPONSES TO WEATHER EVENTS

Extreme meteorological events, whether related to the El Niño phenomenon, other large-scale forcing factors, or simply the chaotic nature of the climate system, can have strongly detrimental effects on crop yields (Table 1). The effects of extreme weather events on crops may be either direct or indirect, or both. Higher temperatures increase moisture stress on crops directly by increasing evapotranspiration as well as the atmospheric holding capacity for water vapor. An indirect feedback loop is created when higher temperatures hasten the breakdown of organic matter in soils, which in turn leads to lower soil organic matter

levels, culminating in less soil-moisture retention and additional crop moisture stress. Both direct and indirect effects threaten yields. Plants in the early stages of development are especially vulnerable to extreme weather events.

High Temperature

When the optimal range of temperature values for a crop in a particular region is exceeded, crops tend to respond negatively, resulting in a drop in yield. The optimal temperature varies for different crops. Temperatures greater than 36°C cause corn pollen to lose viability, while temperatures higher than 20°C depress tuber initiation and bulking in potato (Paulsen, 1994).

Table 1. High temperature and soil-moisture effects on major field crops in the U.S.

Crop	Effects
Corn	<ul style="list-style-type: none"> • Temperature higher than 36°C causes pollen to lose viability. • Extremely sensitive to soil-moisture deficits. Four days of visible wilting in (a) the period before tasseling reduces yield by 10-25%; (b) between the week before tasseling and the milk stage reduces yield by more than 50%; in (c) the soft dough stage, decreases yield by 40%. • Aflatoxin concentration rises when the crop has a water deficit. • Very intolerant to flooding except after the silking stage; the effect of flooding depends on temperature. Before the 6th leaf stage the crop does not survive more than 4 days of flooding if the temperature is less than 25°C; and less than 24 hours if the temperature is more than 25°C. When the crop is less than 6 inches high, 24 h of flooding reduces yield by 18% at any temperature. • Continuous soil saturation causes long-term problems related to rot development and increased damage by diseases (e.g., crazy top and common smut).
Soybean	<ul style="list-style-type: none"> • Soil temperature higher than 35°C at planting causes seedling death. Very sensitive to temperatures above 35°C during the first three weeks after bloom. Great ability to recover from temperature stress at other times. • Sensitive to soil moisture deficits and drought at planting and from bloom to pod-fill. Very sensitive to soil moisture deficits during pod-filling and seed enlargement. • Relatively tolerant to excess soil humidity, but saturated soils increase the risk of seedling diseases especially at temperatures above 32°C.
Wheat	<ul style="list-style-type: none"> • Temperature above 30°C for more than 8 hours can reverse vernalization. • Flowering, pollination, and grain-filling sensitive to water stress. • Excess soil moisture causes waterlogging, and increases risk of fungal infestations.
Cotton	<ul style="list-style-type: none"> • Temperature above 40°C for more that 6 hours causes bolls to abort. • Relatively tolerant to temperatures under 40°C. • Sensitive to soil moisture deficits and drought at planting and flowering. • Excess rainfall at maturity damages quality of crop.

Most agronomic crops are sensitive to episodes of high temperature. Air temperatures between 45 and 55°C that occur for at least 30 minutes directly damage crop leaves in most environments; even lower temperatures (35 to 40°C) can be damaging if they persist longer (Fitter and Hay, 1987). Vulnerability of crops to damage by high temperatures varies with developmental stage. High temperatures during reproductive development are particularly injurious – for example, to corn at tasseling, to soybean at flowering, and to wheat at grain-filling. Soybean is one crop that seems to have the ability to recover from heat stress, perhaps because it is indeterminate (i.e., grows continuously) (Shibles et al., 1975).

Precipitation

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

Drought conditions may also be brought on by lower amounts of precipitation falling as snow and by earlier snowmelt. In arid regions, such as the Sacramento River basin in California, 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 the quality of corn and other grains and fruits and vegetables.

Interannual variability of precipitation is a major cause of variation in crop yields and yield quality. During the 1930s, severe droughts reduced U.S. Great Plains yields of wheat and corn by as much as 50%. By reducing vegetative cover, droughts exacerbate wind and water erosion, thus affecting future crop productivity.

Crop yields are most likely to suffer if dry periods occur during critical developmental stages such as reproduction (Figure 11). In most grain crops, flowering, pollination, and grain-filling are especially sensitive to water stress. Management practices offer strategies for growing crops in water-scarce conditions. For example, the effects of drought can be avoided by early planting of cultivars with rapid rates of development. Fallowing and weed control can also help to conserve moisture in the soil.

Heat stress and drought stress often occur simultaneously, the one contributing to the other. These conditions are often accompanied by high solar irradiance and high winds. When crops are subjected to drought stress, their stomata close. Such closure reduces transpiration and, consequently, raises plant temperatures.

Excessively wet years, on the other hand, may cause yield declines due to waterlogging 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 waterlogging 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.

IV. WEEDS, INSECTS, AND DISEASES

Climate affects not just agricultural crops but their associated pests as well. Pests are any organism or microorganism that harms or kills crops and reduces the value of crops before and after harvest. The major pests of crops are weeds, insects, and pathogens. The distribution and proliferation of weeds, fungi, and insects are determined to a large extent by climate. Table 2 shows examples of serious crop pest epidemics that were critically influ-

enced by weather conditions. Organisms become pests when they compete with, or prey upon, crop plants or cause disease in 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 effectiveness, persistence, and transport.

Table 2. Pests, weather, and agriculture. (Sources: Munkvold and Yang, 1994; Hartman et al., 1995; Mattson and Haack, 1987; Hamilton and Stakman, 1966; Campbell and Madden, 1990; Zhao and Yao, 1989).

Event	Effects: Pest damage to crops
<i>Floods and heavy rains</i>	<ul style="list-style-type: none"> •Increased moisture benefits epidemics and prevalence of leaf fungal pathogens. <ul style="list-style-type: none"> - Rice leaf blight causes great famine in Bengal (1942), 2 million people died. - Wheat stripe rust outbreak in major production regions of China contributed to the 1960s famine. - In the U.S. Midwest (1993) fungal epidemics in corn, soybean, alfalfa, and wheat. - In the U.S. Great Plains (1993), mycotoxin produced by wheat scab (<i>Fusarium spp.</i>) reaches a record high. - Humid summers drive epidemics of gray leaf spot of maize (Iowa and Illinois, 1996). •Water-induced soil transport increases dissemination of soilborne pathogens to non-infected areas. <ul style="list-style-type: none"> - Outbreaks of soybean sudden death syndrome in the north central U.S. states (1993). •Continuous soil saturation causes long-term problems related to rot development and increase damage by diseases. <ul style="list-style-type: none"> - In maize, crazy top and common smut.
<i>Drought</i>	<ul style="list-style-type: none"> •Water stress diminishes plant vigor and alters carbon-to-nitrogen ratios, lowering plant resistance to nematodes and insects. Attack by fungal pathogens of stems and roots is favored by weakened plant conditions. Drought promotes insect outbreaks. <ul style="list-style-type: none"> - Outbreak of soybean cyst nematode correlated to drought conditions in the north central U.S. states (1990). - Summer locust outbreak correlated to drought in Mexico (1999). •Dry and warm conditions promote growth of insect vector populations, increasing viral epidemics.
<i>Storms and air currents</i>	<ul style="list-style-type: none"> •Air currents provide large scale transportation for disease agents (e.g., spores of fungi) or insects from overwintering areas to attacking areas. <ul style="list-style-type: none"> - The spread of the stem rust fungus that overwinters in Mexico and Texas is always favored by moist southern air currents. - The southern leaf blight of corn spread from Mississippi to the Midwest by air currents of a tropical storm in the Gulf of Mexico during 1970.
<i>Warm</i>	<ul style="list-style-type: none"> •Warm winters increase overwintering populations of all pests. •Data reported for the European Corn Borer; wheat scab, and wheat rust. •Increase overwintering populations of insect vectors. •Increase population of aphids that carry the soybean mosaic virus.

Crop Losses

There have been several efforts to provide a measure of global crop losses by weeds, insects, and diseases (Cramer, 1967; FAO, 1975; Pimentel, 1992; and Oerke et al., 1995). The most recent and comprehensive of these estimates are those made by Oerke et al., in 1995 (Table 3). They analyzed data on pest damage in eight important food and cash crops that together account for about one half of the world cropland area and more than US\$300 billion in annual output (data from 1988, 1989 and 1990). The estimate of pre-harvest loss caused by pests to the principal food and cash crops is 42% of potential production on a global basis (Oerke et al., 1995). This high loss to pests is not uniform over space and time, being proportionally higher in Africa and under climate conditions favorable to pests.

Crop	Actual Production	Losses due to			Total
		Pathogens	Insects	Weeds	
		(US\$ billions)			
Rice	106.4	33.0	45.4	34.2	112.5
Wheat	64.6	14.0	10.5	14.0	38.5
Barley	13.7	1.9	1.7	2.0	5.7
Maize	44.0	7.8	10.4	9.3	27.4
Potatoes	35.1	9.8	9.6	5.3	24.8
Soybeans	24.2	3.2	3.7	4.7	11.6
Cotton	25.7	4.3	6.3	4.9	15.5
Coffee	11.4	2.8	2.8	2.0	7.6
Region					
Africa	13.3	4.1	4.4	4.3	12.8
North America	50.5	7.1	7.5	8.4	22.9
Latin America	30.7	7.1	7.6	7.0	21.7
Asia	162.9	43.8	57.6	43.8	145.2
Europe	42.6	5.8	6.1	4.9	16.8
Former Soviet Union	31.9	8.2	7.0	6.7	22.1
Oceania	3.3	0.8	0.6	0.5	1.9

Table 3. Actual global production of eight major crops and estimated losses for the eight crops by pest and region, 1988-1990. (Source: Oerke et al., 1995).

In North America, the average losses to crop weeds, insects, and diseases estimated for 1988-90 are 37 percent of the potential crop value (Figure 6). Nationally, pests are estimated to destroy about one third of our crops and are an increasingly serious constraint to crop production, in spite of the advances in pest control technology over the last half century.

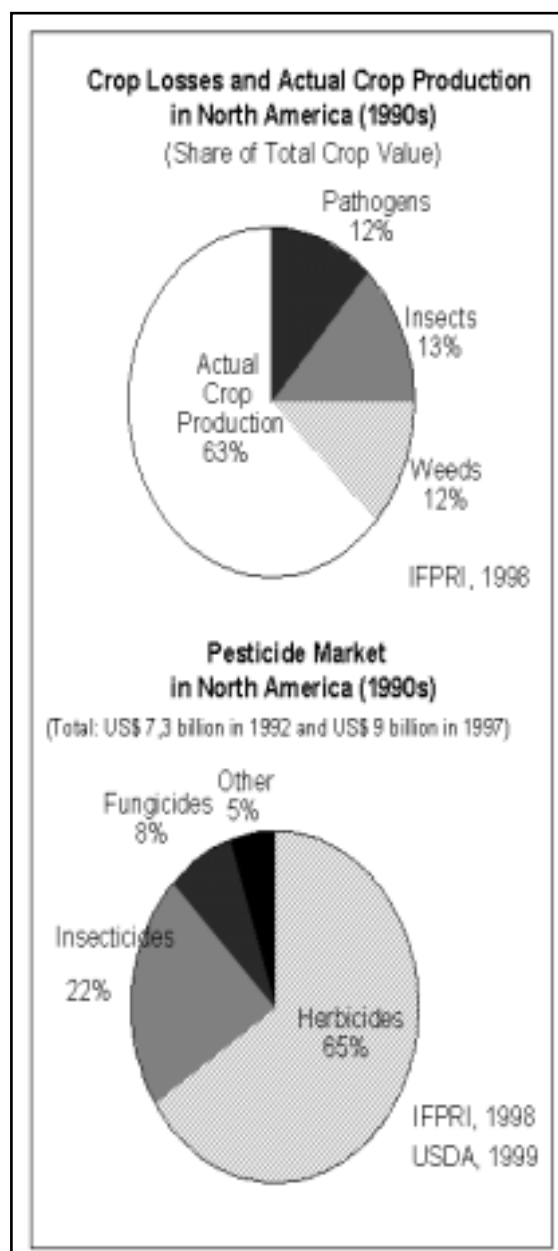


Figure 6. Crop losses (a) and pesticide use (b) in North America. (Source: IFPRI, 1998, and USDA, 1999).

The extent of crop losses to pests is determined by a combination of factors such as the size of the overwintering pest population, phenological stages of pest and host, crop management, land use, environmental conditions, etc. The total cost of pest damage to agricultural producers also depends on the value of the crop and the costs of production in a particular year.

Agricultural trends are influencing the incidence and importance of pests. First, the expansion of worldwide trade in food and plant products is spreading the impact of weeds, insects, and diseases. Second, changes in cultural techniques, particularly intensification of cropping, reduction in crop rotations, and increase in monocultures, encourages the activity of pests.

In extreme cases, pest damage can lead to severe impacts on society. In such cases, the climate conditions are conducive to widespread pest outbreaks. The late blight of potato, caused by the fungus *Phytophthora infestans*, was a major factor in the Irish famine of the 1840s. Genetic uniformity of the potatoes was also a contributing factor. Late blight is still one of the most important diseases of potato and its epidemics continue to be highly correlated to weather conditions during sporulation. This disease presents a threat in the US today (ProMED, 1995).

Almost 100 years after the potato famine in Ireland, another fungus, *Helminthosporium oryzae*, the cause of brown spot of rice, precipitated another catastrophe in Bengal (now part of India and Bangladesh). In 1943 the weather conditions were exactly right to encourage an epidemic of the disease. Losses were extreme, often rising to 90% or causing total destruction of the rice crop. Malnutrition and starvation caused the death of over 2 million people (WHO, 1996).

The southern corn leaf blight epidemic of 1970 and 1971 was the most dramatic epidemic in the history of agriculture in the U.S. Just as genetic uniformity of the potato crop in Ireland, together with the spread of a virulent pathogen, led to the Irish potato famine in the last century, a similar combination of events brought about the southern corn leaf blight epidemics of 1970 and 1971. Crop production losses were even greater but, since they

occurred in the U.S. where the agricultural industry is highly diversified, human suffering occurred.

The grayish black rot found in October 1969 on corn ears and stalks of samples from a seed field in Iowa was a fungus (*Helminthosporium maydis*). The following year, the epidemic struck.

The disease first occurred in Mississippi in May of 1970 and rapidly spread northward through the Midwest on the air currents of a tropical storm in the Gulf of Mexico (Campbell and Madden, 1990). Because 85 percent of the corn was susceptible to the pathogen and the weather conditions were favorable for pathogen reproduction and dispersal, a dramatic epidemic occurred across the Corn Belt within two months (Figure 7), causing a 15% decrease in national corn yields.

The disease was most severe in the Midwest and South of the U.S., with some areas reporting 50-100% losses. For the nation as a whole, losses were officially estimated at the time as \$1.09 billion (Campbell and Madden, 1990). Although genetic uniformity in the corn crop contributed to the widespread occurrence of this disease, favorable meteorological conditions allowed it to occur.

Aflatoxin, a compound that lowers corn quality, is related to drought conditions. The concentration of aflatoxin is raised during crop-water deficits, because drought favors the growth of the fungus *Aspergillus flavus* (the producer of aflatoxin) in the weakened crop. Similarly, wheat scab caused by *Fusarium spp.*, produces mycotoxin in contaminated grain. Mycotoxin can produce muscle spasms and vomiting in humans. The emergence of wheat scab in the Great Plains may be linked to the increase in temperatures observed in key agricultural areas of this region during the past ten years.

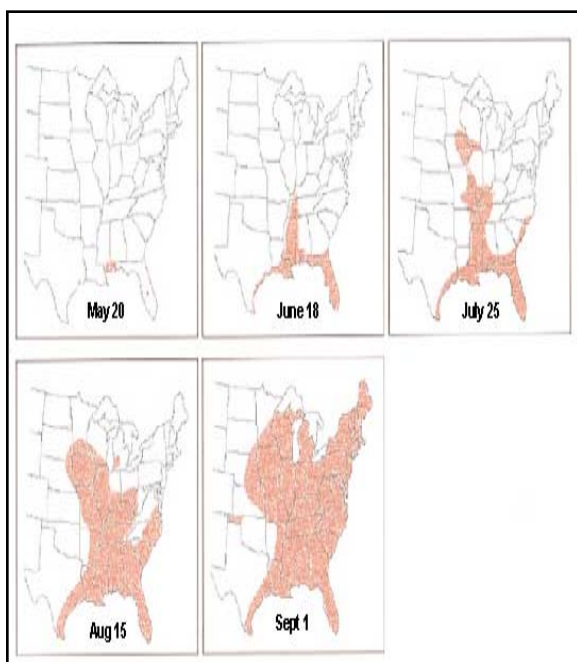


Figure 7. Spread of southern corn leaf blight of 1970. (Adapted from: Moore, 1970).

Costs of Pest Management

Farmers use a wide range of agricultural practices to limit losses from pests in crops. Strategies for pest control include cultural practices (such as crop rotations), biological control, pest-resistant crop varieties, and chemical control. Pesticide use has proved profitable for many farmers. One estimate is that, in the U.S. in 1997, each dollar invested in pesticides returned four dollars in estimated profit because of the avoidance of crop losses due to pests; so that the US\$6.5 billion invested in pesticides during 1997 saved US\$26 billion in crop losses (IFPRI, 1998).

During the 1950s, an increasing body of evidence suggested that the benefits of the pesticides introduced in the 1940s and early 1950s were obtained at a substantial cost. The costs included not only the increase in resistance to pest-control chemicals in target populations and the destruction of beneficial insects, but also the direct and indirect effects

on wildlife populations and on human health (IFPRI, 1998).

Despite this, the use of chemical pesticides continues to be important for reducing pest-induced crop losses. The world pesticide market is now around US\$30 billion a year; about 80 percent of the pesticides in use is applied in developed countries (IFPRI, 1998) and the amount has increased about US\$5 billion in the last eight years (Table 5). Herbicides account for the largest share of total pesticide sales. In 1992, herbicides made up more than 40% of all sales, followed by insecticides (30%) and fungicides (20%).

The adoption of high-yielding crop varieties during the 1960s was associated with a dramatic increase in pesticide use. When yields were low, there was little benefit from pest control. As yields rose, the economic incentive to adopt chemical pest-control technologies also rose, resulting in widespread use of chemicals to control agricultural pests. Pesticide use has risen since 1970, as measured by the economic value of pesticides sold, to a national total of US\$9 billion (Figure 8). California applies about US\$1 billion of pesticides each year to its high-value fruit and vegetable crops.

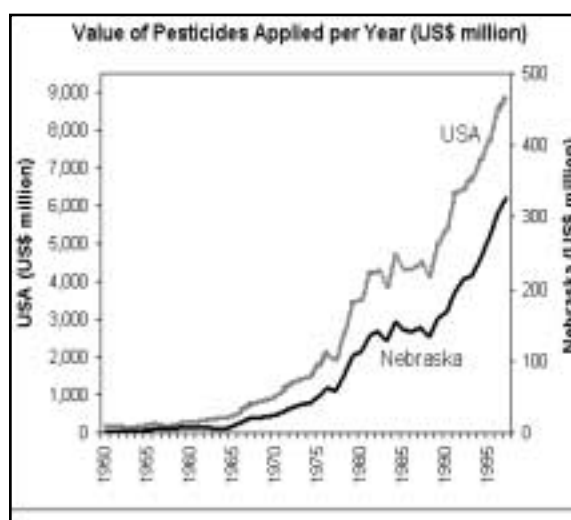


Figure 8. Value of pesticide application in the U.S. 1950-1997. (Source: USDA).

Another important issue regarding pest management in the future centers on the role of biotechnology in crop production. The next 20 years will

likely see a substantial increase in the use of genetically engineered plants. Some of these plants have been engineered so that the application of herbicides destroys weeds but not the economic crop. Other genetically engineered plants have been designed to resist pests such as stem borers and nematodes without the need for pesticides. Others are expected to combine both herbicide resistance and insect resistance in one seed.

Health concerns have been raised (Ewen and Pusztai, 1999), but require further study. Ecological concerns are another matter. Genes producing toxins provide strong evolutionary pressure and can lead to insect resistance, as well as damage to friendly insects (mosquito predators) and pollinators. Genes providing resistance to herbicides may be transferred to weeds (Butler and Reichhardt, 1999).

Policymakers interested in effective crop protection have to balance the social benefits and costs of pesticide use — including human health effects, especially on children, and the ecological risks of reducing friendly insects and birds that prey upon agricultural pests. This analysis also requires better knowledge of the causes of pest losses.

Pest Response to Climate

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 are favored with warm and humid conditions. Crop damages by pests are a consequence of the 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 weak crop during a drought is sometimes 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% (Oerke et al., 1995). In the U.S., annual losses in crop production due to weeds have been valued at approximately US\$ 12 billion, amounting to some 10% 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, next to fertilizers account for the largest volume of chemicals applied to crops (Figure 6). Over US\$ 9 billion are spent on weed control every year in the U.S. (USDA, 1999).

Insects. Insect pests in agricultural systems are the major cause of damage to yield quantity. Insect habitats and survival strategies are strongly dependent on patterns of climate. Insects are particularly sensitive to temperature because they are stenotherms (cold-blooded). In general, insects respond to higher temperature with increased rates of development and with less time between generations (Figure 9). Warmer winters reduce winterkill and consequently induce increased insect populations in the subsequent growing season.



Figure 9. Approximate distribution of European corn borer annual generations in the U.S. and Canada. (Adapted from: Mason, 1995).

Precipitation – whether optimal, excessive, or insufficient – is a key variable that also affects crop-pest interactions. Drought stress sometimes brings increased insect pest outbreaks. For long-lived species, the process is outlined in Figure 16. It is well known that drought can change the physiology of host species, leading to changes in 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.

Crop diseases. Climate factors that influence the growth, spread, and survival of crop diseases include temperature, precipitation, humidity, dew, radiation, wind speed, circulation patterns, and the occurrence of extreme events. Higher temperature and humidity and greater precipitation result in the spread of plant diseases, as wet vegetation promotes the germination of spores and the proliferation of fungi and bacteria, and influences the life-cycle of soil nematodes. In regions that suffer aridity, however, disease infestation lessens, although some diseases (such as the powdery mildews) thrive in hot, dry conditions, as long as there is dew formation at night.

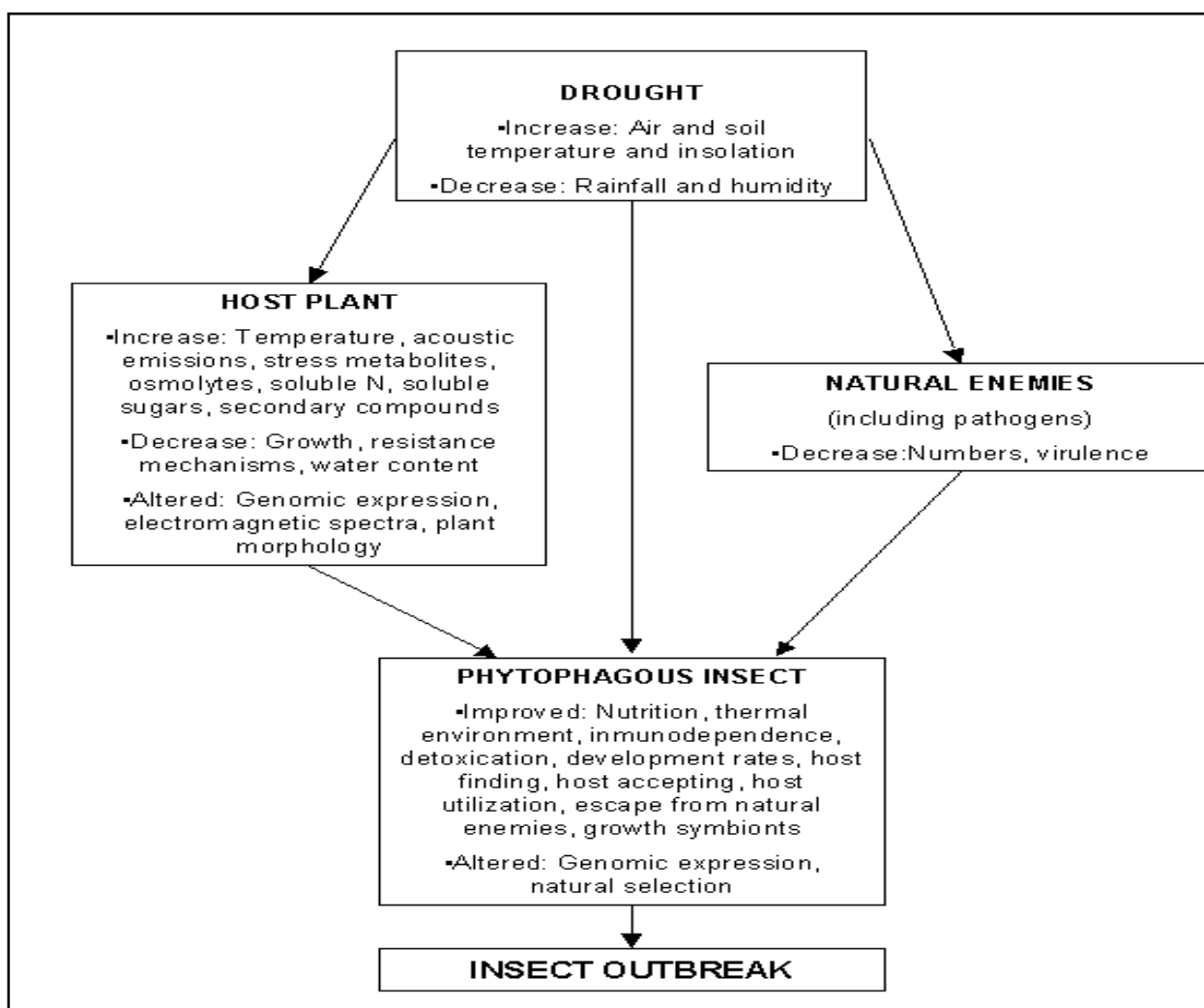


Figure 10. Drought influences on host plants, phystophagaus insects and their natural enemies leading to insect outbreaks. (Adapted from: Mattson and Haack, 1987).

V. RECENT TRENDS

We now examine trends in temperature and precipitation, floods, droughts, pests, crop yields and prices, and farm income in the major U.S. agricultural regions.

Climate

The average surface temperature of the Earth has increased by about 1.0°F over the last century (IPCC, 1996b). The warming in North America is most pronounced in the Northeast, the Lake States, and most of the Western States (Figure 11) (T. Karl, NCDC, NOAA). At the same time, the annual precipitation has increased in most of the eastern portion of the U.S. and the Pacific Northwest (Figure 11). The winter minimum temperatures have increased disproportionately since 1950 in the North Central and Southwest regions (Figure 12).

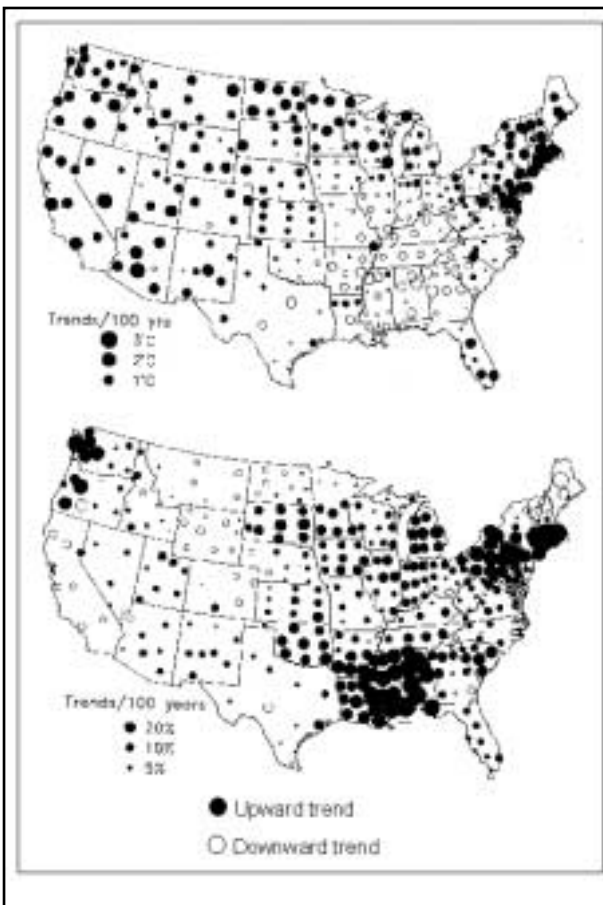


Figure 11. Trends in average annual temperature (top) and precipitation (bottom) by climate division. (Courtesy of T. Karl, NCDC, NOAA).

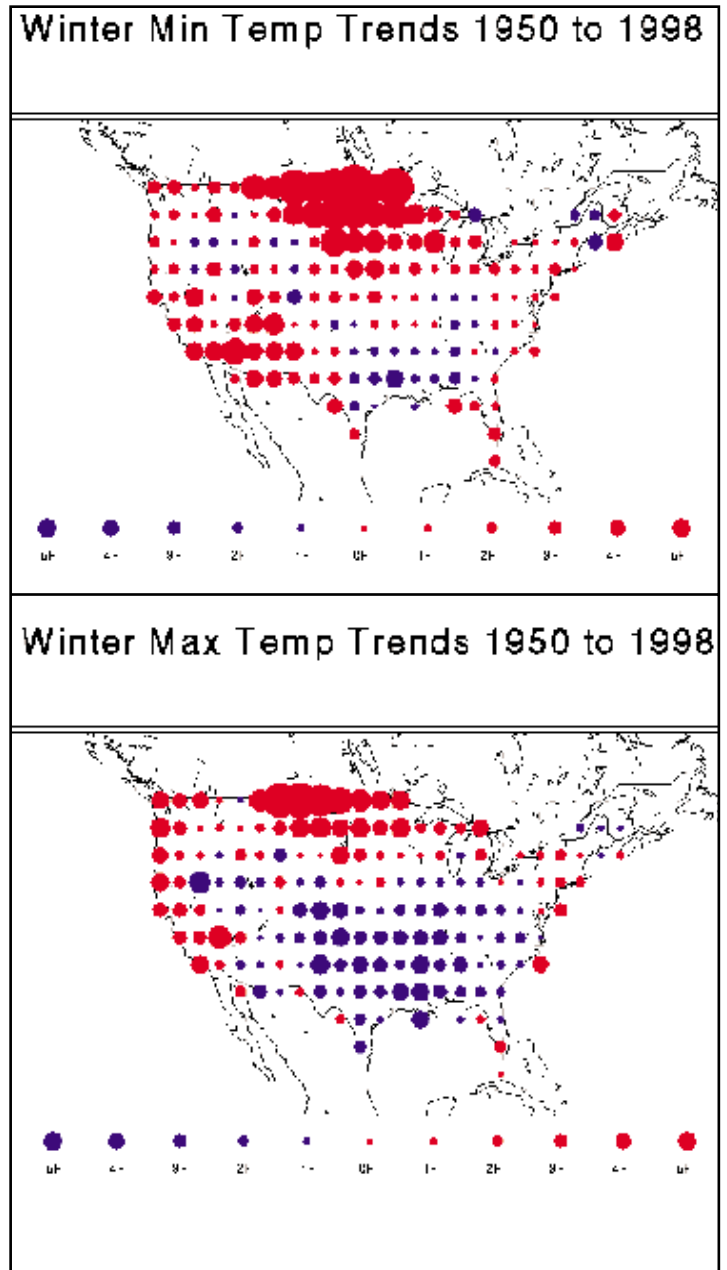


Figure 12. Trends in winter minimum (top) and maximum (bottom) temperature by climate division. (Courtesy of T. Karl, NCDC, NOAA).

In the U.S., there is a trend to more days with heavy 24-hour precipitation totals (Figure 13) (Karl and Knight, 1998). Increases are largest for the Southwest, Midwest, and Great Lakes regions of the country.

The interactions among the changes in temperature and precipitation are reflected in an increase in the area affected by severe wetness. The increase in wetness has had large impacts. Data from the National Climatic Data Center of NOAA show that the total area of the U.S. affected by extreme precipitation events has been increasing since 1910 (Figure 14). The cost of flood damage in the U.S. also appears to be increasing since 1970 (NOAA). The cost data are suggestive of changing climate regimes, but are confounded by the increasing value of built infrastructure over the same time period.

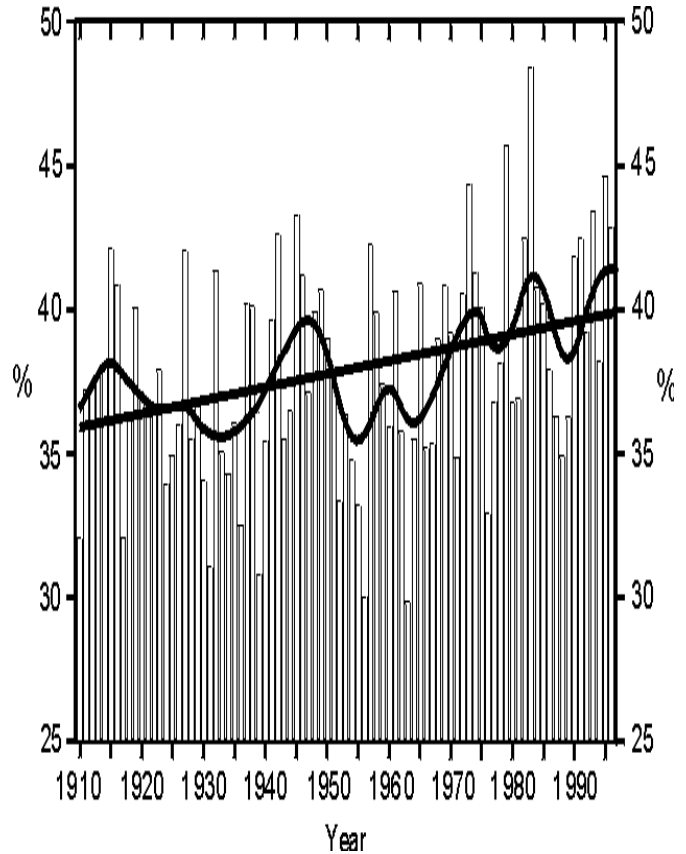


Figure 13. Percent contribution of the upper 10 percentile of daily precipitation to the total annual precipitation of the U.S. (Karl and Knight, 1998).



Area of U.S. Affected by Extreme Precipitation Events



National Climatic Data Center, NOAA

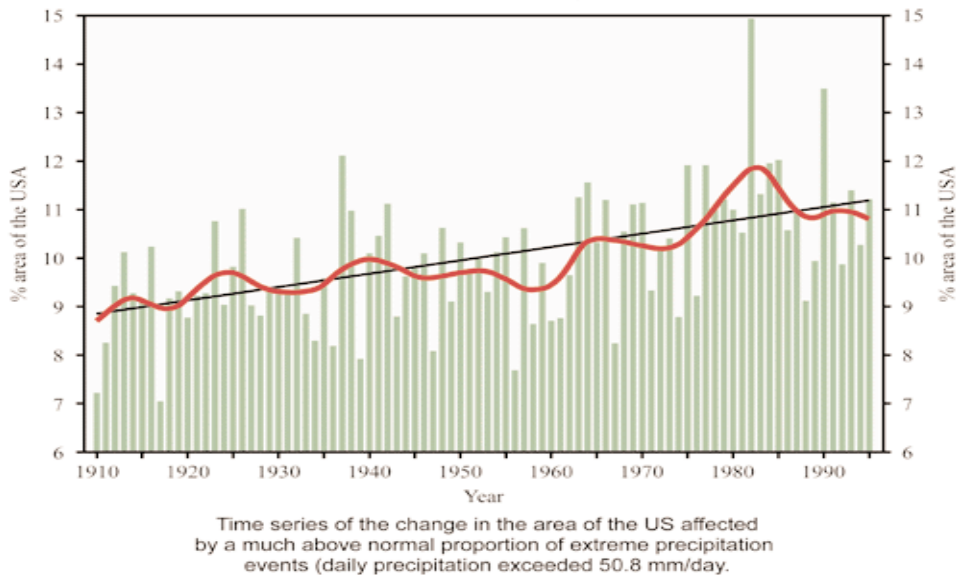


Figure 14. Area of U.S. affected by extreme precipitation events, 1910 to 1995. (Source: NOAA).

Crop Yields and Prices

The value of U.S. crop production in 1997-98 totaled \$109 billion (USDA). The top four crops, based on value of production, are corn, soybean, wheat, and cotton. In 1997-98, these crops were worth approximately \$55 billion. Over the 1950-1999 period, crop yields of corn, soybean, wheat, and cotton have risen due to steady improvements in breeding and management (Figure 15). Year-to-year variability, however, has also increased. In

order to assess the variability of yields, we compared the standard deviations of the residual values of yields after the increasing trends have been removed for two time periods — 1950 to 1970, and 1971 to 1998. The ratios of the standard deviation of the yields in the latter period to the standard deviation of the yields in the earlier period are shown in Table 4. For corn and soybean yields, the latter period is more than three times as variable as the earlier period.

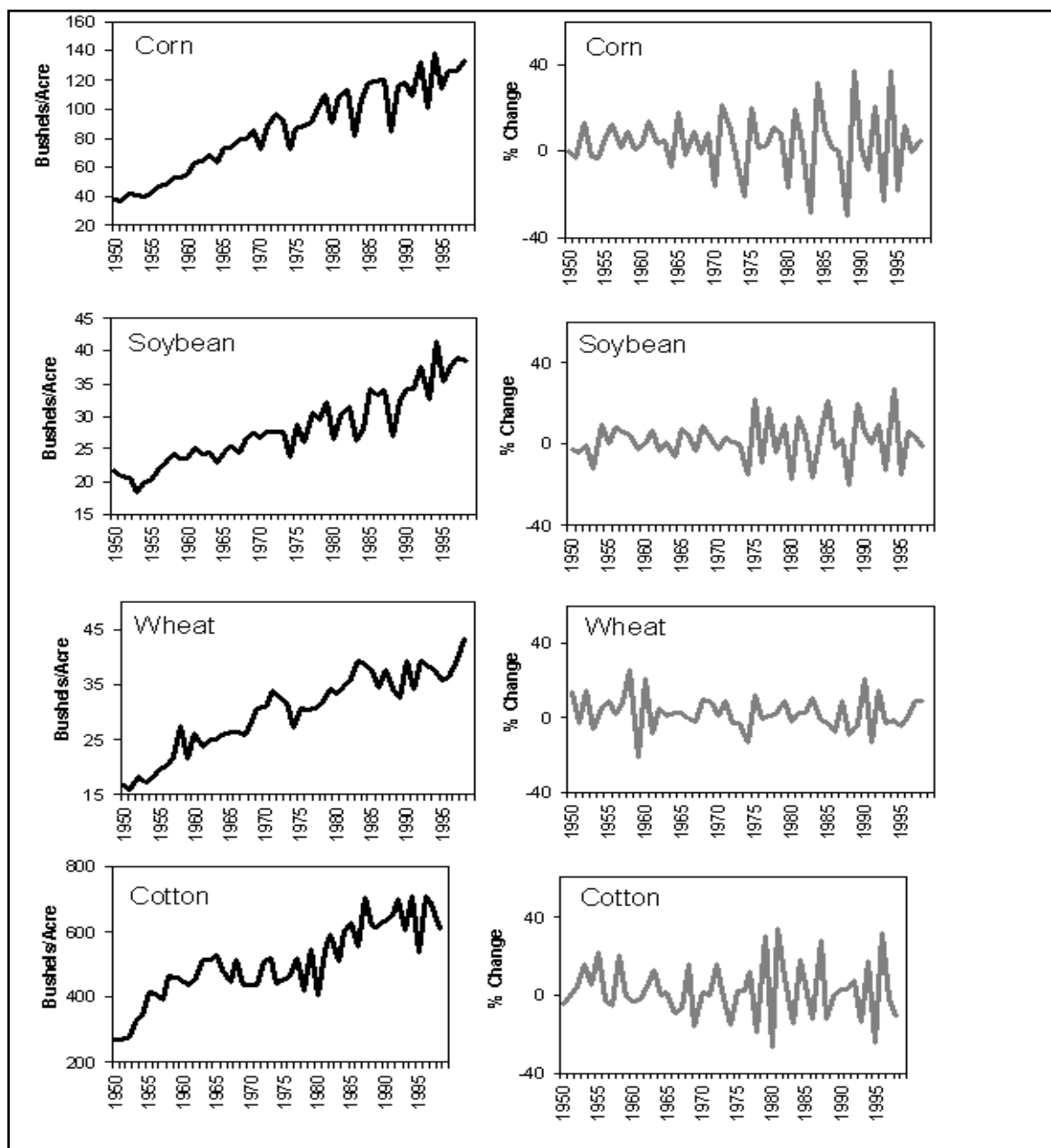


Figure 15. U.S. crop yields from 1950 to present for corn, soybean, wheat, and cotton. Right-hand column shows percent change in yield from previous year. (Source: USDA).

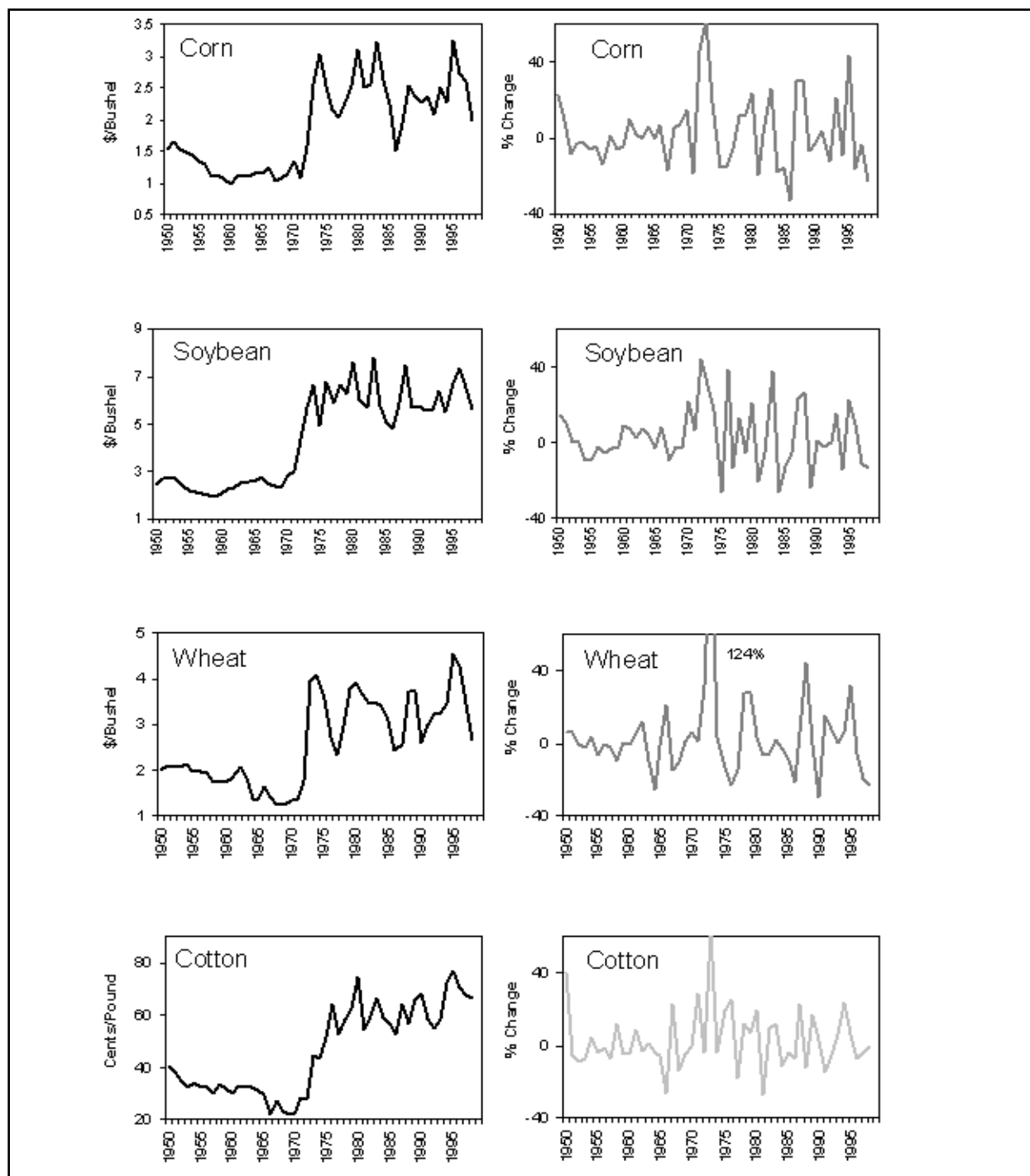


Figure 16. U.S. crop prices from 1950 to present for corn (a), soybean (b), wheat (c), and cotton (d). (Source: USDA).

Although other factors, such as levels of inputs affect yields, we know that climate remains an important determinant of agricultural outcomes, especially when climatic events are severe. The relationship between corn yield and annual temperature and precipitation in Des Moines, Iowa,

demonstrates this (Figure 17). Corn yields decline with warmer temperatures due to acceleration of the crop's development, especially during the grain-filling period. Greater precipitation (if not excessive) during the growing season tends to increase yields, as expected.

Item	Standard Deviation Variation Time Period			Standard Deviation Ratio 1971-98 to 1950-70
	50-70	71-98	50-98	
Corn yield detrended (bu/acre)	5.15	18.86	14.54	3.66*
Corn price detrended (\$/bu)	0.12	0.50	0.38	4.27*
Soybean yield detrended (bu/acre)	1.27	3.99	3.10	3.13*
Soybean price detrended (\$/bu)	0.20	1.17	0.89	6.02*
Wheat yield detrended (bu/acre)	2.36	2.90	2.66	1.23*
Wheat price detrended (\$/bu)	0.17	0.70	0.54	4.19*
Cotton yield detrended (pounds/acre)	40.56	90.46	72.73	2.23*
Cotton price detrended (cents/pound)	3.87	8.81	7.11	2.33*

*The ratios of the standard deviations (or variances) are significant at the p=0.01 significance level.

Table 4. Standard deviation of the residual values of crop yield and price during the periods 1950-71, 1971-98, and 1950-98. Ratio of the standard deviation of the period 1971-98 to 1950-70. (Source of data: USDA).

U.S. crop prices have been strongly influenced by policy, as shown by the stable yet low prices for crops during the period of price supports from 1954 to 1970, and the greater yet more variables price since price supports were removed in the early 1970s. Crop prices have risen over the period 1950-1998, but with greater year-to-year fluctuations in terms of percent change from the previous year especially since 1970 (Figure 16). Prices are more variable in the recent period, 1971-98, than in the earlier period, 1950-70. Corn, soybean, and wheat prices in the recent period are more than four times more variable than during the 1950-1970 period (Table 4.).

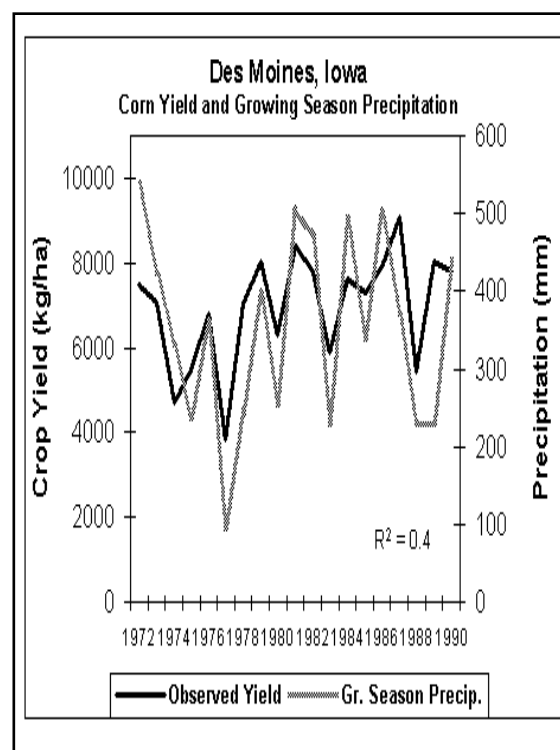


Figure 17. Relationship between corn yield and growing season precipitation in Des Moines, Iowa. (Source: NASA/GISS/CIG).

Farm Income and Direct Payments

In 1997, net farm income was highest in California, Iowa, Texas, North Carolina, Georgia, Illinois, and Nebraska, ranging from \$5.7 billion in California to \$2.0 billion in Nebraska (USDA, 1999). In general, farm income stayed relatively flat between 1950 and 1970, grew in the early 1970s, fluctuated in the late 1970s and early 1980s, and has been rising since 1985 (Figure 18). Year-to-year variability of farm income is higher in Nebraska than in California or Florida, most likely due to the predominance of rainfed agriculture in which crop production is more susceptible to variations in precipitation (Figure 18). Fluctuations in net farm income on a per acre basis were greatest in the 1970s and early 1980s, especially in Nebraska in the early 1980s.



Figure 18. Net farm income for the U.S. and Nebraska. (Source: USDA).

Direct government payments increased in the early 1980s, and are currently leveling off (Figure 19). The largest payments occurred in 1988 and in 1993, the drought and flood years described in the next section. Nebraska has received larger amounts of direct government payments than Florida and California.

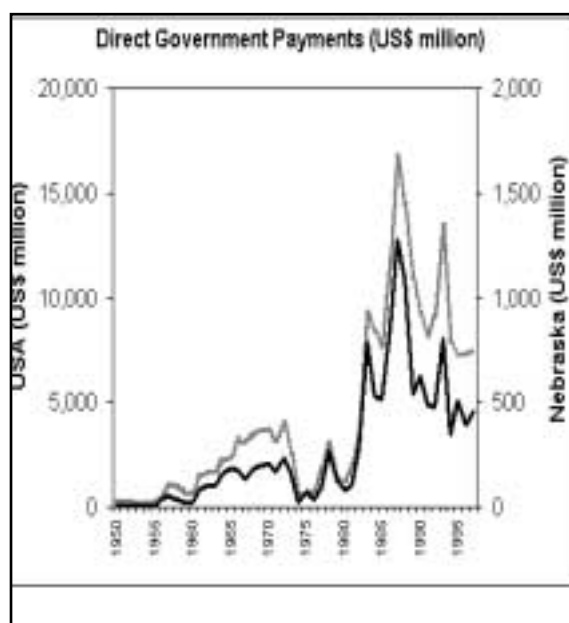


Figure 19. Direct government payments to U.S. farmers, 1950 to present. (Source: USDA).

Incidence of Weeds, Insects and Diseases

Variability in crop yields is often associated with incidence of pests and diseases, which are in turn linked to meteorological conditions. Some analyses indicate that there have been increases in the proportion of crops lost to pests since the 1940s. Data from the U.S. Department of Agriculture (USDA) show a 10-fold increase in both the amount and toxicity of insecticide use in the U.S. from the early 1940s to the 1990s (Pimentel, 1995). During the same period, crop losses from pests rose from 30 to 37 percent, losses from insects increased from 6 to 13 percent, and losses to plant pathogens rose from 10 to 12 percent. Losses from weeds decreased from about 14 percent to 12 percent (Pimentel, 1995; IFPRI, 1998).

Increases in losses from pests (with reduced crop rotation a contributing factor) in the corn crop indicate a relationship between increased use of pesticides and an increased proportion of pest-induced losses. In 1945, when very little insecticide was used, losses were estimated to be around 3.5 percent of the corn crop, but by the late 1990s when insecticide use had increased 1,000-fold to 14 million kg a year, corn crop losses were estimated to be around 12 percent (Pimentel, 1995).

This appears to be a global phenomenon. Oerke et al. (1995) compared the estimates of global pest-induced losses between 1965 and 1990 for eight major crops. The comparison showed that losses increased during the 25-year period for all crops except coffee, with wheat, potatoes, and barley suffering the largest increases in percentage lost. Given differences in assumptions and methodologies, these comparisons should not be over-interpreted; but they do suggest that the proportion of crop losses due to pests has increased during a period of time when the use of chemical pesticides has also rapidly increased.

A partial explanation for the paradox is that the industrialization of agriculture and the reliance on agrochemicals has led to changed farming systems that have produced higher yields, but have also led to an increased vulnerability of crops to pests. These changes in production systems include expansion of monocultures, increased use of fertilizers, reduction in crop genetic diversity, tillage with more crop residues left on the land surface, and the production of crops in warmer and more humid climatic regions where they are more susceptible to insect attack (Pimentel, 1995). In addition, the growth in pesticide use has resulted partly from the enhanced resistance of some pests to pesticides. A further factor contributing to the increment in pest damage is the greater rejection of pest-damaged products by consumers, as quality controls in the market place have become more demanding.

Expansion of Pest Ranges

Several detrimental pests in the U.S. and Canada have expanded their ranges since the early 1970s, possibly indicating a response to the climate trends shown in Figures 11, 12, and 13. (Table 5).

The soybean cyst nematode (caused by *Heterodera glycines*, a microscopic worm) is the cause of great economic losses to soybean producers in the U.S. The pest has been expanding since the early 1950s, but the increase has been more dramatic since the early 1970s (Figure 20) (Niblack, 1999). Before 1970, the soybean cyst was mainly distributed in the Mississippi River Delta area, northern Arkansas, southern Missouri, southern Illinois, and western Kentucky. It is now distributed throughout the main soybean production area and has become the number one soybean pest in the U.S. In Iowa alone it caused an estimated yield loss of 201 million bushels (worth about \$1.2 billion) during the 1998 growing season (USDA NCR-137 Committee, 1999). In the northern production region, the nematode has up to three generations per year, depending on planting and weather conditions during the growing season. A longer growing season, associated with a warmer climate, would result in an increased risk of losses similar to the ones reported during the 1998 year. This pest has been monitored and mapped since the 1950s.

The northward expansion of the soybean sudden death syndrome (a soil-borne fungal disease caused by *Fusarium solani* f. sp. *glycines*) is another example (Roy et al., 1997). The disease was first reported in Arkansas in 1971; in the early 1980s it was found in southern Missouri, Illinois, and Indiana; by the early 1990s it was also found in southern Iowa, northern Illinois and northern Indiana; and in 1998 it was found in Ontario, Wisconsin and Ohio (Figure 21).

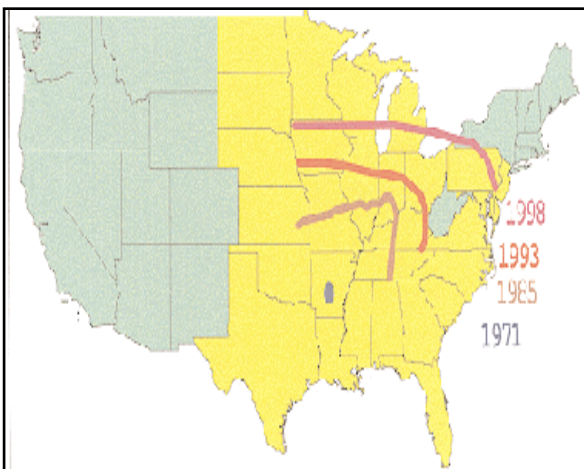


Figure 20: Range expansion of soybean sudden death syndrome (*Fusarium solani* f. sp. *glycines*) in North America. (Source: X.B. Yang).



Figure 21: Distribution of soybean cyst nematode (SCN) in the U.S. in 1973 (left) and 1998 (right). (Source: Niblack, 1999).

The gray leaf blight of corn caused by the fungus *Cercospora zea-maydis* ranks number one in causing yield losses of corn in recent years. It is also a disease whose range expansion was first noticed in the 1970s; in the last two decades, the disease has gradually developed into a major production problem in the Corn Belt. Although the increase in the abundance and epidemics of this disease may be due, in part, to the increase in the use of conservation tillage, the observed trends in minimum temperatures and precipitation in the region may also have contributed.

There have been several attempts to establish correlations between time-series of historic pest damage and climate conditions. Among the earliest attempts to relate historic records of meteorological conditions and crop pest damage were the studies of potato leaf roll outbreaks in North America and Europe (Bagnall, 1988; Bagnall, 1991). Analysis of the historic records from 1930 to 1991 led Bagnall to suggest that the outbreaks of this aphid-borne viral disease were related to drought and sunspot cycles. In the U.S., the frequency of the reported outbreaks seems to have increased since 1970 (X.B. Yang, personal communication, 2000).

Another example of the linkage between meteorological variables and pests is the wheat stem rust disease in the U.S. Great Plains. The epidemics of the disease from 1921 to 1962 seem to be related to the conditions during El Niño episodes (Yang and Scherm, 1997). In contrast, wheat stripe rust epidemics in the U.S. Northwest may be more severe during La Niña years (Scherm and Yang, 1995). Smith (1954) studied a 100-year record of grasshopper behavior as a pest in Kansas (1854-1954), showing that the most severe damage was caused during dry years (Smith, 1954).

Table 5. Major crop diseases that appeared after 1970 in the United States. (Source: Plant Pathology Department, North Carolina State University).

Crop	Disease Causal Agent	Expansion
Soybean	Sudden death syndrome <i>Fusarium solani</i> f.sp. <i>glycines</i>	Appeared in Arkansas in 1971 and has spread to the northern soybean region as far as Ontario.
	Southern stem canker <i>Diaporthe phaseolorum</i>	First observed in 1973, has developed into a devastating disease in the southern production region.
	Sclerotinia stem rot <i>Sclerotinia sclerotiorum</i>	Re-emerged as a leading disease in 1990 in the north central soybean regions.
	Soybean cyst nematode <i>Heterodera glycines</i>	Expanded to northern soybean regions.
Corn	Gray leaf spot <i>Cercospora zea-maydis</i>	First reported in the 1940s, became a concern in the 1970s in the eastern states and now is a major concern in the Corn Belt.
Potato	Late blight <i>Phytophthora infestans</i>	Re-emerged in 1990 as a new threat to potato production after a new mating type was found in Mexico.
	Powdery scab <i>Spongospora subterranea</i>	Increased damage in Washington and Oregon.
Rice	Sheath blight <i>Rhizoctonia solani</i>	Major rice disease worldwide since the 1970s.
Wheat	Wheat scab <i>Fusarium spp.</i>	Re-emerged after 1990 as a leading wheat disease in the central and north regions.
	Barley yellow dwarf Barley yellow dwarf virus	Listed by 14 wheat production states as a recently emerging disease.

V. A DECADE OF MAJOR EVENTS

Extreme weather events have caused severe crop damage (\$1 billion or more per event) in the U.S. over the last twenty years (Table 6). Extreme events happen in every agricultural region of the country, and occur somewhere in the country

almost yearly. Droughts seem to have occurred primarily in the early part of the period, with floods predominating in the 1990s. The most severe weather-related events for agriculture were the drought of 1988 and the flood of 1993.

Table 6. Extreme weather events causing severe crop damage in the U.S. (1977-1998). (Sources: NOAA, USDA, and U.S. Army Corps of Engineers).

Year	Geographical area	Extreme weather event
1977	Southern States	Drought induced high aflatoxin concentration in corn, costing producers more than \$80 million.
1977	Corn Belt	Drought disrupted domestic and export corn marketing.
1980	Central and Eastern regions	Summer drought and heat wave.
1983	Southern States	Drought induced high aflatoxin concentration in corn, costing producers more than \$97 million.
1983	Corn Belt	Drought disrupted domestic and export corn marketing.
1986	Southeast	Summer drought and heat wave.
1988	Central and Eastern regions	Summer drought and heat wave. Congress paid farmers over \$3 billion for crop losses. Total damage: order of \$56 billion.*
1990	Texas, Oklahoma, Louisiana, Arkansas	Flooding in spring.
1993	Midwest	Flooding in summer affecting 16,000 square miles of farmland, and damaging crops in over 11 million acres. Total losses: exceeded \$20 billion.
1993	Southeast	Drought and heat wave in the summer, causing the loss of 90% of corn, 50% of soybean, and 50% of wheat crops. Crop losses over \$1 billion.
1994	Texas	Severe flooding.
1995	Southern Plains	Severe drought.
1995	Texas, Oklahoma, Louisiana, Mississippi, California	Severe flooding.
1996	Pacific Northwest, Appalachian, Mid Atlantic and Northeast	Severe flooding.
1997	Northern Plains, Arkansas, Missouri, Mississippi, Tennessee, Illinois, Indiana, Kentucky, Ohio, West Virginia	Severe flooding.
1997	West Coast	Severe flooding from December 1996 to January 1997 in California, Washington, Oregon, Idaho, Nevada, and Montana.
1998	Texas, Oklahoma, and eastward to the Carolinas	Summer heat wave.
1998	Southeast	Winter and spring flooding related to El Niño.
1999	Atlantic States	Spring and summer drought; late summer flooding. Total losses: order of \$7 billion.

* Damage amounts normalized to 1998 using an inflation wealth index. (Source: National Climatic Data Center, NOAA).

The Drought of 1988

The severe drought of 1988 in the U.S. Midwest started early in the spring and continued throughout most of the summer, accompanied by higher than normal temperatures (Burnham, 1989; Halpert and Ropelewski, 1989). It spread to affect the central and southeastern parts of the nation, with consequences to agriculture, water resources, transportation, tourism, and the environment (Chagnon, 1989). Crop yields dropped by approximately 37% and required a \$3-billion bailout by Congress of affected farmers.

Crop pests were affected as well, bringing damaging outbreaks of two spotted spider mites (*T. urticae*) on soybeans throughout the entire Midwest region. The damage occurred during the critical flowering, pod-development, and pod-filling growth stages. An estimated 3.2 million hectares were sprayed with insecticides to control the mites across the region and losses to Ohio farmers were estimated to be \$15 to 20 million (Stinner et al., 1989).

The drought conditions led to decreased flows in the Ohio and lower half of the Mississippi river by the end of May (Chagnon, 1989). Mid-summer barge movement was restricted on the major rivers that drain the central U.S. The depth of the rivers near Cairo, Illinois fell to less than 8 feet by mid-June. The reduced flows caused a decrease of 25% in hydropower generation, a decrease in the recreational use of rivers and lakes of 15%, and salt-water intrusion from the Gulf of Mexico 105 miles up the Mississippi River and extending past New Orleans.

In mid-summer, Dr. James Hansen (1988) made the following statement to the U.S. Senate Committee on Energy and Natural Resources: “The global warming is now sufficiently large that we can ascribe (it) with a high degree of confidence to the (enhanced) greenhouse effect.” This statement, which raised awareness of the global climate change issue, was based on a comprehensive statistical analysis of observed land-based temperatures of the last 100 years and a comparison of the recorded warming with climate model simulations.

The Flood of 1993

Flooding in the summer months of 1993 affected 16,000 square miles of farmland, with Nebraska, Iowa, and Michigan hardest hit. In July, the flood crest at St. Louis, Missouri broke the previous record. Crops were damaged on over 11 million acres, with losses sustained of over \$3 billion (Figure 22). Emergency measures cost over \$222 million. Excess wetness presents a particularly severe problem for Iowa’s low-lying soils.

The flood of 1993 also forced a strong pulse of nitrates and other nutrients and farming chemicals into the Mississippi River and Gulf of Mexico. The runoff of nutrients may have contributed to an expansion of the “Dead Zone” in the Gulf, its size doubling in 1993 following the flood (Epstein, 1998).

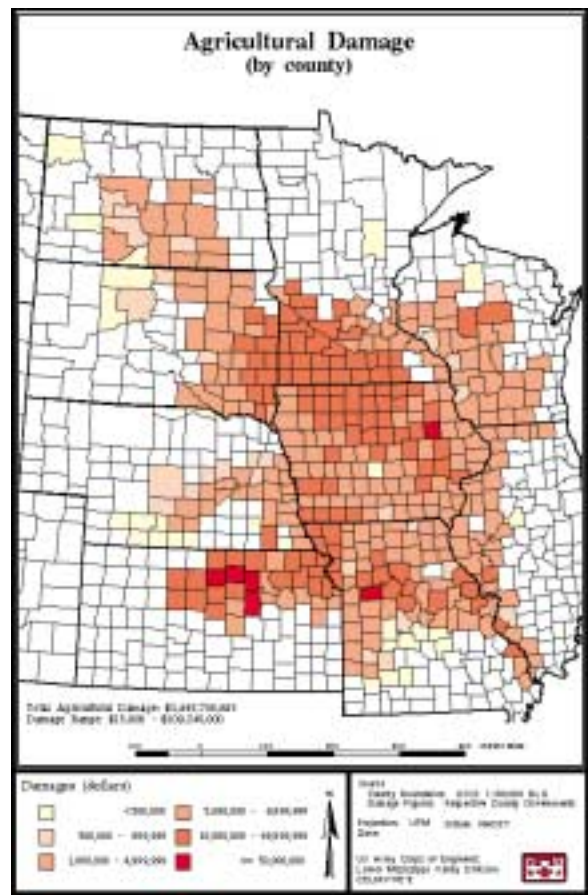


Figure 22. Damages caused by the 1993 flood; value of damage by county. (Source: U.S. Corp of Engineers)

El Niño of 1997-1998

In late 1997, the tropical Pacific witnessed the development of a major El Niño event, rivaling in strength the 1982-83 El Niño. The onset of the El Niño coincided with the occurrence of several westerly wind events in the western Pacific. Moreover, western Pacific sea levels were uncharacteristically elevated a year and a half prior to the onset, which may have helped precondition the system to a particularly strong episode. As the El Niño reached its peak in late 1997-early 1998, torrential rainfalls inundated the western coast of the Americas.

The weather impacts related to the 1997-98 El Niño had a significant effect on agriculture in some regions. As expected, droughts occurred in northeast Brazil, Indonesia, and northern Australia; wet conditions prevailed in southern Brazil and Argentina. In the U.S., wet conditions occurred on the West Coast and in southeast. Unexpectedly, drought conditions did not materialize in southwest Africa, with heavy rains failing in the north of the region, or in India, where near-normal monsoon rains occurred.

In Australia, wheat yields and production were maintained in part due to the El Niño forecast. 1988 rice production in Indonesia was below the previous year, due to late-arriving rains that delayed rice planting. In India, the near-normal monsoons helped to produce a record rice crop. In South Africa, planting was delayed due to dryness, as in a normal El Niño year, but timely rainfall during late December and mid-February accompanied by below-normal temperatures, eased crop stress and resulted in only slightly below normal corn production.

For the U.S., the El Niño was associated with several severe weather events. High rain events occurred on the West Coast from November 1997 to March 1998, bringing damage to agriculture in southern California. Extremely high temperatures in the summer following the El Niño were found in Texas and Oklahoma, causing heat stress in the elderly population and damaging crops. These conditions spread across the South to the Carolinas. In the Southeast, there was winter and

spring flooding related to the El Niño, as well as summer dryness in Florida that gave rise to forest fires.

Despite these regional impacts, the El Niño of 1997-98 did little to affect U.S. agriculture at the national scale, probably because production of the major grain crops is located in regions not strongly affected. Wheat yields were at a record high, with production the highest since 1990. Corn and soybean production were also highest on record.

On the global scale, world production of wheat and rice was at record levels in 1998, and coarse grains were only 2 percent below the previous year. Corn and soybean production were the highest on record, with yields being just above trend. In southeast South America, abundant soil moisture from the typical El Niño conditions produced a record soybean crop in Brazil and Argentina. These factors contributed to decreases in corn and soybean prices on the world market during 1998.

La Niña of 1998-2000

The La Niña event beginning abruptly in April of 1998 ushered in another year of extremes. Hurricane Mitch in Central America in November 1998 was notable for the long-term damage (Epstein, 1999). The U.S. experienced a particularly warm winter, with January rains (rather than snow) interrupted by a cold snap, resulting in a crippling ice storm in the Northeast. Decreased winter snowpack and spring runoff worsened the spring and summer drought that set in along the Atlantic states, severely impacting agricultural production in that region. Then Hurricane Floyd (September 1999) left its mark on North Carolina and New Jersey (Kilborn, 1999). North Carolina was also hit by Hurricane Dennis and Hurricane Irene, with prolonged flooding raising the risk of fungal infections affecting agriculture and human health.

Internationally, intense December 1999 rains, flooding, and landslides destroyed villages and croplands in Venezuela. Continuing into 2000, extensive flooding occurred in southern Africa, affecting agriculture and health, while severe drought affected the Horn of Africa and western states of India.

The second driest April-July period on record began in 1998 and intensified during 1999, inflicting the driest growing season in 105 years on the Northeast. A total of 109 million people and an estimated 918,960 farms suffered some drought in 1999 (USDA, 1999). The 1998-99 drought in the U.S. has had severe financial impacts on agricultural producers in the affected regions. The drought reduced commodity receipts relative to 1998 by an estimated \$1.29 billion (USDA, 1999b). Estimated farm net income losses, including yield losses, increases in expenses, and insurance indemnities, totalled \$1.35 billion, about 3 percent of 1999 U.S. net farm income (USDA, 1999; Clines, 1999; Davis, 2000).

VII. CLIMATE CHANGE PROJECTIONS

Figure 23 shows projected changes in U.S. wheat yield for the Hadley Center and Canadian Climate Centre climate change scenarios for the 2030s. Climate scenarios are based on projected mean monthly changes and not changes in variability. The direct effects of higher CO₂ levels on crops

are taken into account because higher carbon dioxide increases the rate of photosynthesis and improves water-use efficiency in crops (Acock and Allen 1985; Cure and Acock, 1986; Kimball, et al., 1995). Results show that some regions may improve production, while others suffer yield losses. This could lead to shifts of agricultural production zones around the nation. Furthermore, different crops will be affected differently, leading to the need for adaptation of supporting industries and markets.

National farm policy can be a critical determinant in the adaptation of the farming sector to changing conditions. In the U.S., 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 can help make timely adjustments that may reduce social costs.

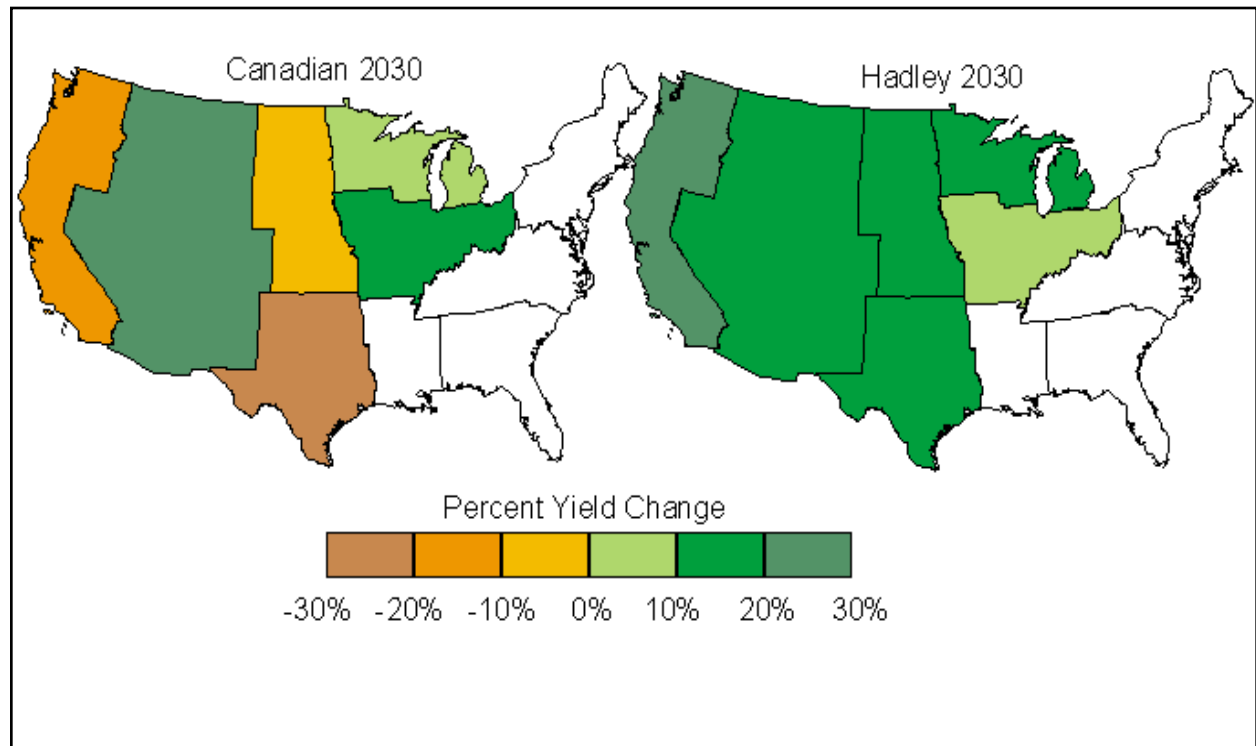


Figure 23. Projection of changes in U.S. wheat yield for the Hadley Center and Canadian Climate Centre climate change scenarios for the 2030s. Climate scenarios are based on projected mean monthly changes. (Source: NASA/GISS/CIG).

Beyond national boundaries, changes in the global patterns of supply and demand may have far-reaching consequences. Figure 24 shows projections of average national crop yield changes around the world for one climate change scenario. At high latitudes, warmer temperature may benefit crops that are currently limited by cold temperature 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. In the low latitudes, growing periods for crops are accelerated and heat and water stresses are exacerbated, resulting in steeper yield decreases than at mid and high latitudes, notwithstanding the potential beneficial physiological effects of atmospheric CO₂ enrichment.

Changes in Extreme Events

Climate change is likely to bring changes in the patterns of climate events as well as changes in the mean. If temperature variability increases, crops growing at both low and high mean temperatures could be adversely affected since diurnal and seasonal canopy temperature fluctuations often exceed the optimum range. 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 winterkill. 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.

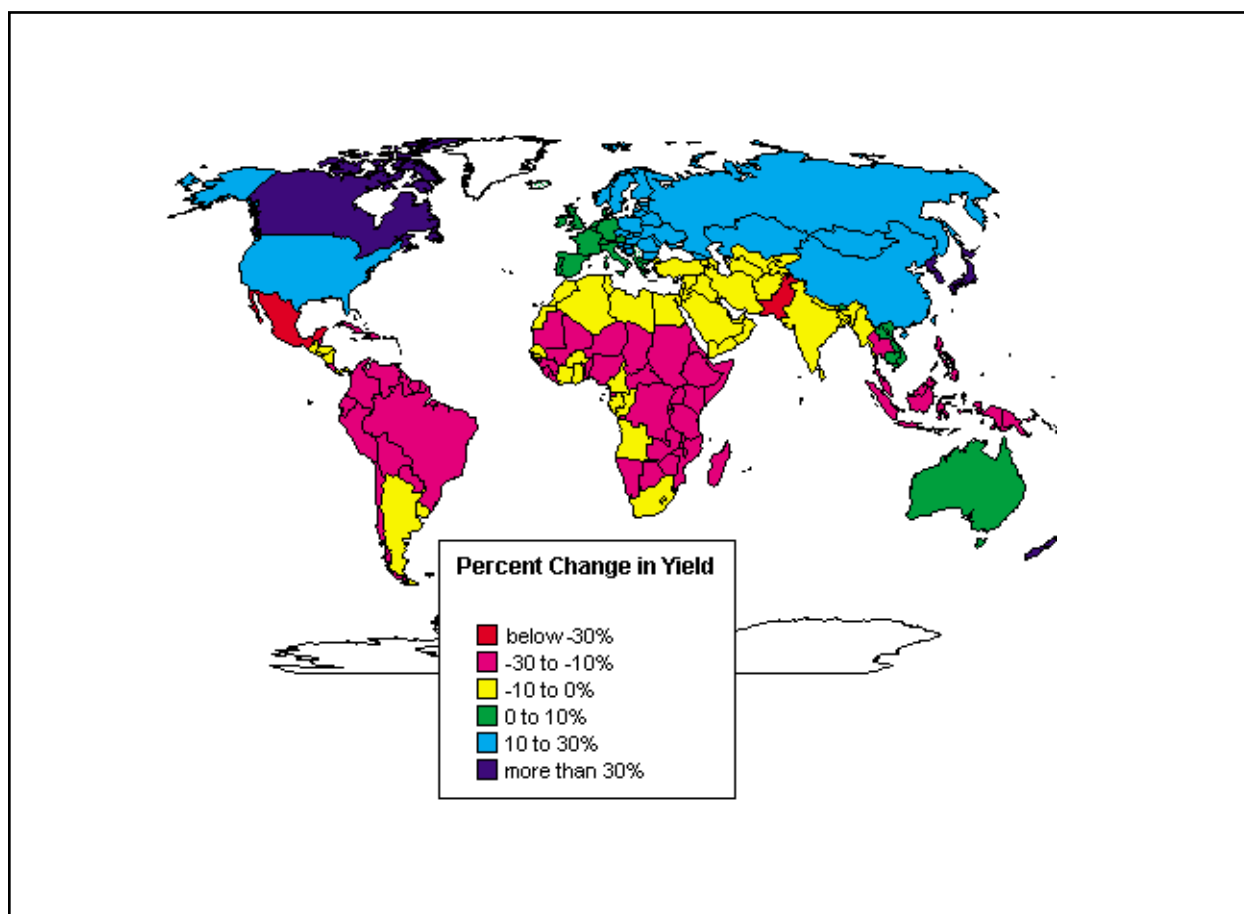


Figure 24. Potential change in yield of grain crops for the 2050s with HadCM2 scenario. (Source: NASA/GISS/CIG).

To explore the effects of changes in daily climate variability, tests of changes in temperature and precipitation variability on corn and soybean have been made using crop growth models at Des Moines, Iowa (Figure 25). If variability in temperature or precipitation is doubled, decreases in corn yields and increases in corn crop failures result. The corn crop failures for doubled temperature variance are due to slowed grain-filling that extended the corn growing period into frost episodes. Doubled precipitation variance causes water deficit failures in the corn crop. Halving precipitation variability results in an increase in mean yield and a large drop in the variability of the corn yields year-to-year.

For soybean, results of changing the variability of temperature and precipitation are similar to corn in direction yet greater in magnitude. A two-fold increase in the variability of temperature and precipitation results in large decreases in yields. Soybean crop failures increase when temperature is more variable, due to cold temperatures at the beginning and end of the crop season. When precipitation is more variable, the drop in yields is due to increased water deficits. With less precipitation variability (decreasing by half) there is a large positive effect on both corn and soybean crop yields, while the yields are less sensitive to halving temperature variability. Increased climate variability results in higher variability in crop yields.

Sequential extremes – e.g., prolonged droughts followed by heavy rains – may spawn surprises and can 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 friendly insects (lace wings, lady bugs), spiders and birds, influencing pollination and the impact of harmful pest infestations. The impacts of several years of drought (such as those associated with the “double” La Niña – 1998/99, and 1999/2000) can be additive and have longer-lasting impacts on soil quality and ground water.

Changes in Weeds, Insects, and Diseases

Most analyses concur that in a changing climate, pests may become even more active than they are currently, thus posing the threat of greater economic losses to farmers (IPCC, 1996a; Coakley et al., 1999). While the majority are invasive species from temperate zones, other weeds 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 weeds significantly (Figure 26). 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).

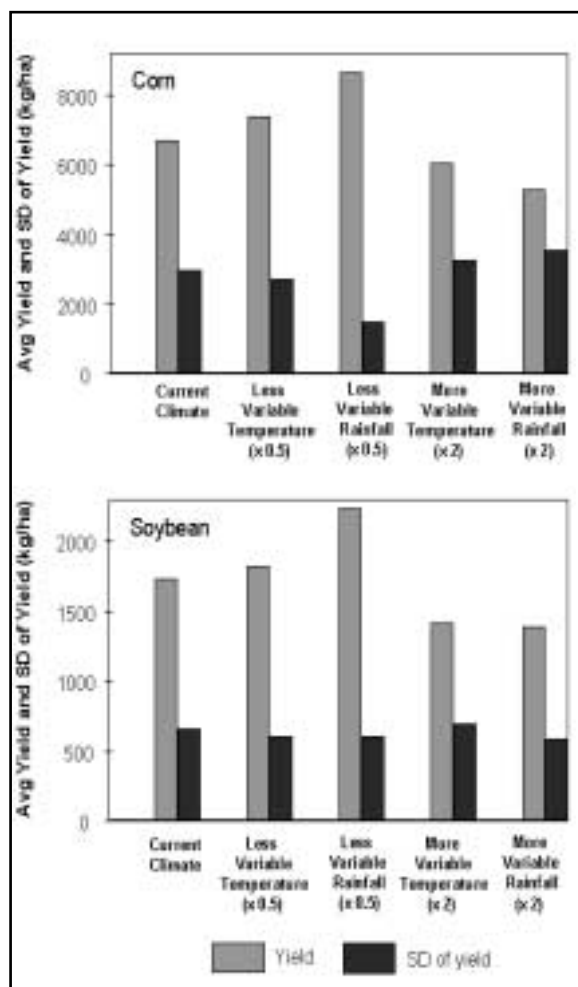


Figure 25. Change in corn (top) and soybean (bottom) yield and yield variation with changing temperature and precipitation variability at Des Moines, Iowa. (Source:Rosenzweig and Mearns, 2000).

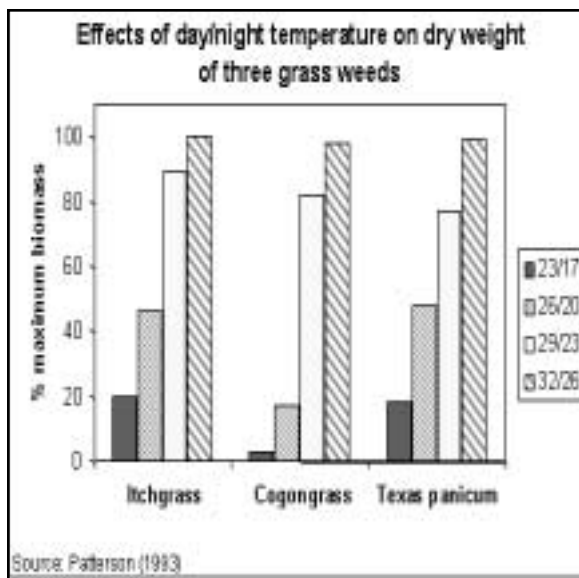


Figure 26. Effects of day/night temperature on dry weight of three grass weeds. (Source: Patterson, 1993).

With temperatures within their viable range, insects respond to higher temperature 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 can become established and thrive during earlier and more vulnerable crop growth stages. Additional insect generations and greater populations encouraged by higher temperatures and longer growing seasons will require greater efforts of pest management.

Warmer winter temperature will also affect those pests that currently cannot overwinter in high-latitude crop regions but do overwinter in lower-latitude regions and then migrate to the crops in the following spring and summer. For example, the potato leafhopper (*Empoasca fabae*), a pest of soybeans, alfalfa and other crops, may expand its overwintering range (now limited to a narrow band along the Gulf of Mexico) and thus be better positioned to travel to the U.S. Midwest earlier and in greater numbers during the cropping season (Figure 27) (Stinner et al., 1989).

Some species are pests in America’s South but not in the Midwest, because they do not migrate to the

Midwest early enough or in significant numbers. Corn earworm (*Heliothis zea* (Hubner)) is an example of a current pest of corn and soybean in the South that is not a serious pest in field corn and soybean in the Midwest. With climate change, extension of overwintering range may bring the corn earworm to field corn and soybean crops in the Midwest (Stinner et al., 1989).

The damage of the European corn borer (*Ostrinia nubilalis*), a major insect pest of corn in the U.S. and elsewhere, is limited in many regions due to current climate conditions. For example, in Iowa the insect has only two generations per corn-growing season because the third generation pupa can not complete development before the winter. Warmer conditions will ensure a third generation of the insect and would make its overwintering population significantly larger.

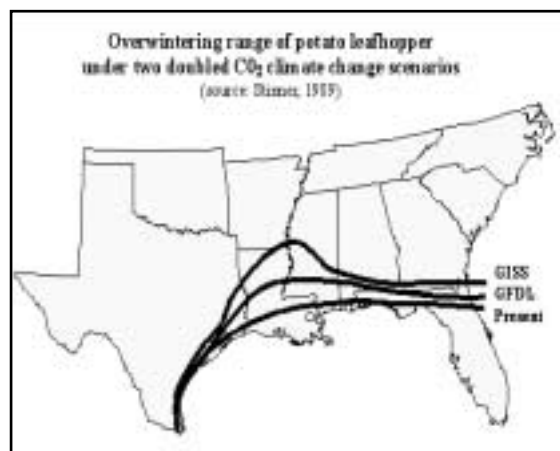


Figure 27. Overwintering range of potato leafhopper under two doubled CO₂ climate change scenarios. (Source: Stinner et al., 1989).

Since warmer temperature will bring longer growing seasons in temperate regions, this should provide opportunity for increased insect damage. A longer growth period may allow additional generations of insect pests and higher insect populations. The Mexican bean beetle and bean leaf beetle, both major pest of soybeans, presently have two generations in the U.S. 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 sometimes tends to bring increased insect pest outbreaks; insect damage may increase in regions destined to become more arid. If climate becomes warmer and drier as well, 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.

Costs of Production and Comparative Advantages

Costs of production are likely to 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 changes to current agricultural systems, and some of the required changes may be costly. There will likely be a 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 regions. Costs may include greater applications of and/or development of new agricultural chemicals, particularly herbicides and pesticides.

Even without climate change, U.S. agriculture faces some serious challenges in the coming decades. The most striking of these are moderating domestic demand, a potential loss of comparative advantage vis-à-vis international growers, and the need for environmental protection. Competition for international markets will intensify. Countries such as Brazil, Argentina, and Thailand, whose labor and other production costs are lower than those of the U.S., may well increase their market share.

When climate change is taken into account on a global basis, the U.S. role as a major provider of food for export may be affected. The heavy dependence of world grain demand on North

America (on the order of 80% of the global marketable surplus) has increased the sensitivity of world food supply to the climate of the region. The U.S. ranks first in world corn and soybean production (accounting for half the world's total) and third in wheat production.

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 U.S. 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 U.S., but the intensified competition from still more favored regions (such as Canada and Russia) may limit that advantage. International trade policy issues, especially the movement to lower agricultural trade barriers, will be crucial in climate change response strategies.

On the other hand, the economic value of U.S. crops value is heavily dependent on trade. More than one-quarter of U.S. corn and more than one-half of U.S. soybeans move overseas either directly in bulk, as an intermediate product (soybean meal or oil), or indirectly through livestock and associated products. If comparative advantage shifts with climate change and other regions become more conducive for crop growth, the favorable position the U.S. enjoys as a leading agricultural exporter may suffer.

DISCUSSION AND CONCLUSIONS

Since the 1970s, there have been significant increases in the variability experienced by U.S. farmers in terms of crop yields, prices, and farm incomes. Climate variability has also increased. Over the same period, several important crop pests and diseases of major U.S. field crops (corn, soybeans, and wheat) have expanded their ranges in the Corn Belt and Great Plains. Crop losses from extreme weather events have substantial costs: estimated damages from the 1988 summer drought were \$56 billion, while those from the 1993 floods exceeded \$23 billion. These damage amounts are normalized to 1998 using an inflation wealth index (National Climatic Data Center, NOAA).

If these trends continue, and are exacerbated by warming temperatures and a more variable climate, as predicted by climate change projections, the livelihoods of many U.S. farmers may be substantially altered. The impacts of these trends may lessen the comparative advantage that the U.S. now enjoys as a leading international exporter of major agricultural commodities.

The response of individual producers to changes of the climate regime will need to involve changes 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. Advances in cli-

mate forecasting may improve preparations and help prevent some of the projected losses. Ultimately, the ability of farmers to adapt effectively can decide the success or failure of individual farms and, by extension, can affect regional, national, and international economies. Under progressively changing climate conditions, adaptations will need to evolve continuously, and may be increasingly difficult to plan.

The impacts of trends in climate extremes and disease patterns in poorer and more vulnerable regions of the world could be substantial. Given the growing interconnectedness of world economic and ecological systems, decreased agricultural yields in underdeveloped nations could affect the U.S. via demands on relief efforts and international trade, as well as through impacts on political stability and the international movement of populations.

Climate change will gradually (and, at some point, maybe even abruptly) affect U.S. agriculture. Warming temperatures and a greater incidence and intensity of extreme weather events may lead to significant reductions in crop yields. Expanded ranges of crop pests and altered transmission dynamics of insect pests and plant diseases may exacerbate these reductions. Since farmers' strategies grow out of experience, they may find that the past will be a less reliable predictor of the future.

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GLOSSARY

adaptation strategies—a type of adjustment or response to climate change that is based on adapting to changing conditions in the environment usually through some type of technological or institutional innovation. An example of a technological innovation would be the development of new crop varieties or farming techniques. Institutional innovations involve changes in underlying economic, political, and social structures.

advection—the process of transport or flow of an air parcel; related to wind speed.

aerosol—solid or liquid particles in the Earth's atmosphere having sizes on the order of 0.01-10 microns (1 micron = 0.0001 centimeter). Aerosols have a variety of sources: natural sources include salt particles ejected from the ocean, organic molecules, wind-blown dust, pollen, desert sand particles; anthropogenic sources include carbon-based soot particulates from fossil fuel burning, SO₂ emissions from industry that undergo a gas-to-particle conversion. Aerosols are important in the radiative balance of the atmosphere, as they tend to cool the Earth's surface by scattering incoming solar radiation back to space.

analogue climate—climate modeling technique that uses known climate conditions of the past to forecast future conditions that are expected to have similar characteristics. It is assumed that if certain essential conditions in the forecast scenario are similar to the past conditions, then the resulting climate will compare favorably. See the control climate entry in this glossary.

carbon dioxide (CO₂)—a greenhouse gas whose atmospheric concentrations have been continually increasing from its pre-industrial (1750-1800) levels of 280 parts per million (ppm). It is currently increasing at a rate of 1.3-1.6 ppm per year, with a concentration (1995) ranging from 356-360 ppm, depending on location. There is a natural seasonal cycle in carbon dioxide levels in the atmosphere; CO₂ decreases in summertime when plant productivity consumes CO₂, and an increase in winter when biota are less active and respiration exceeds photosynthesis. The main source of carbon dioxide increase in the atmosphere has been fossil fuel consumption, with biomass burning becoming more significant over the past few decades, currently contributing approximately 30% as much as fossil fuel emissions.

CO₂ fertilization effect—the theory that forests and vegetation will experience enhanced growth or increased net primary productivity under elevated atmospheric carbon dioxide levels.

control climate—a control climate is a set of climate conditions drawn from the climate record (generally a three decade period) that is used as a point of departure for assessing model or analogue climate results. The control climate is generally assumed to represent “normal” or “average” climate. See analogue

climate in this glossary.

correlation coefficient— statistical figure indicating the strength of association between two variables.

coupled atmosphere/ocean model—a general circulation model (GCM) that integrates atmosphere and ocean components, which may or may not allow for feedbacks between the model components, depending on the complexity of the particular model.

damages—includes all monetary losses due to climate change impacts, less the amount that can be averted by adaptive measures, and less the economic gains that may be realized by the adaptive measures. This implies that net damages may, in some cases, take on negative values that reflect monetary gains when all factors are considered.

dynamical model—a model that calculates climatic variables at discrete time intervals during a simulation by using input values that change with time, as compared to a static model simulation such as a “doubled CO₂” scenario that calculates climatic variables at a final endpoint without considering how CO₂ or temperature changes over time.

evaporation—loss of water from a system by a change of phase from liquid to vapor. Evaporation leads to latent heat transfer, which is important in energy balance calculations.

feedbacks (positive, negative)—an effect that tends to amplify (+) or reduce (-) a particular process. Warmer temperatures will cause greater evaporation of water from the oceans, for example, potentially leading to greater low cloud formation. Increased low cloud cover would reflect more solar radiation back to space, thus cooling the surface, implying a negative feedback to increased surface temperatures from global warming.

flux—a generic term having different meanings in different fields of study. In radiation studies, it can refer to the amount of radiant energy passing through a unit area (i.e., watts per square meter); in biogeochemical cycles, it may indicate the time rate of change of a given species such as carbon into or out of a particular reservoir (i.e., teragrams of carbon per year).

general circulation model (GCM)—a general circulation model is a generic term used to describe a computer model that simulates how climatic variables such as temperature and precipitation change over time. These models range in complexity from 0-dimensional models to 3-dimensional models, and are typically used to address the issue of global warming potential due to increasing atmospheric concentration of greenhouse gases.

geographical information system (GIS)—a system of computing tools and procedures designed for capturing, managing, analyzing, modeling, and displaying spatially-referenced data. (<http://www.census.gov/geo/gis/gis-faq.html#part2>).

GISS—Goddard Institute for Space Studies. A research institute of the National Aeronautics and Space Administration located in New York, NY. A subdivision of the NASA Goddard Space Flight Center Earth Sciences Directorate, GISS is primarily engaged in studies of global change. (<http://www.giss.nasa.gov>).

gross national product (GNP)—a measure of the market value of goods and services that were produced during a specific period of time, typically measured in terms of an annual rate.

heating/cooling rates—a parameter describing the radiative characteristics of a particular atmospheric constituent such as carbon dioxide or ozone that indicates whether it tends to heat or cool a particular region of the atmosphere. Values are typically given in units of degrees per day. Used extensively in radiative transfer models and general circulation models.

hectare—unit of area equal to 10,000 square meters. Equivalent to 2.471 acres.

IPCC—acronym for Intergovernmental Panel on Climate Change. An international organization that has

published comprehensive analyses on the scientific assessment of global climate change used for many policy applications and considerations.

market goods—in general, market goods and services are those that are produced, and are generally subject to the economic tenets of supply and demand. See the non-market goods entry in this glossary for a comparison.

mitigation strategies—a type of adjustment or response to climate change that generally involves limiting the emission of greenhouse gases. A tax on the carbon content of fossil fuels that is designed to reduce the use of high carbon fuels such as coal would be an example of a mitigation strategy. Mitigation strategies are aimed at slowing the potential rate of climate change or preventing it before it occurs.

Niño3 index- sea surface temperature anomalies in the western Pacific Ocean from 5S-5N latitude (spanning the equator) and 150W-90W longitude.

non-market goods—in general, non-market goods and services are of natural origin, and are not traded in the marketplace, such as ecosystems.

North Atlantic Oscillation (NAO) — One of the large-scale modes of variability coupling ocean temperatures and sea level pressures, centered on the North Atlantic Ocean basin. The atmospheric circulation normally displays a strong meridional (north-south) pressure contrast, with low pressure in the northern edge of the basin, centered close to Iceland, and high pressure in the subtropics, centered near the Azores.

NDVI—Normalized Difference Vegetation Index, a measure of “greening” derived from red and infrared signals from satellite instruments on the Advanced Very High Resolution Radiometer.

relative humidity—the amount of water vapor (vapor pressure) in a given parcel of air divided by the maximum amount of water vapor the parcel of air could contain at a given temperature (saturation vapor pressure) before it would begin to condense into water droplets.

sensitivity study—model scenarios in which one variable is typically modified while all other variables are fixed, to investigate the effect of changing a single variable on the climate system.

teleconnections- the linkages between sea surface temperatures (principally in the Pacific Ocean) and weather anomalies across the globe.

thermohaline circulation—the ocean “conveyor belt,” with vast currents transferring heat throughout the globe. The Gulf Stream is the Northern Atlantic component.

terrestrial radiation—the radiation emitted by the surface of the Earth. This falls into the infrared (IR) portion of the spectrum.

USGCRP—United States Global Change Research Program. This program was created through the Global Change Research Act, adopted by the United States Congress in 1990. Its purpose is to establish research program “aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment, [and] to promote discussions toward international protocols in global change research...” (Our Changing Planet, The FY 1995 U.S. Global Change Research Program, p1).

vernalization — in some crops derived from winter grasses (e.g., winterwheat), full flowering does not occur unless the plant experiences a period of cold temperature.

water vapor (H₂O)—an important greenhouse gas in the troposphere that also plays a role in ozone depletion chemistry in the stratosphere.

wetlands—an area of land whose water table is at or near the surface. Typically inundated with water, these shallow water regions cover approximately 6% of the Earth’s surface and have high levels of net primary productivity. Wetland emission of methane is an important source of this greenhouse gas.



PUBLISHED BY:

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<http://www.med.harvard.edu/chge/>**

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May 2000**