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Climate change and extreme weather events - Implications for food production, plant diseases, and pests

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Challenges to Food Production and Nutrition

Current and future energy use from burning of fossil fuels and clearing of forests for cultivation can have profound effects on the global environment, agriculture, and the availability of low-cost, high-quality food for humans. Individual farmers and consumers are expected to be affected by changes in global and regional climate. The agricultural sector in both developing and developed areas needs to understand what is at stake and to prepare for the potential for change wisely.

Despite tremendous improvements in technology and crop yield potential, food production remains highly dependent on climate, because solar radiation, temperature, and precipitation are the main drivers of crop growth. Plant diseases and pest infestations, as well as the supply of and demand for irrigation water are influenced by climate. For example, in recent decades, the persistent drought in the Sahelian region of Africa has caused continuing deterioration of food production[1,2]; the 1988 Midwest drought led to a 30% reduction in U.S. corn production and cost taxpayers $3 billion in direct relief payments to farmers[3] and, weather anomalies associated with the 1997-98 El Niño affected agriculture adversely in Nordeste, Brazil and Indonesia[4]. Earlier in the century, the 1930s U.S. Southern Great Plains drought caused some 200,000 farm bankruptcies in the Dust Bowl; yields of wheat and corn were reduced by as much as 50%[5].

The aim of this article is to discuss the effects of climate variability and change on food production, risk of malnutrition, and incidence of weeds, insects, and diseases. It focuses on the effects of extreme weather events on agriculture, looking at examples from the recent past and to future projections. Major incidents of climate variability are contrasted, including the effects of the El Niño-Southern Oscillation. Finally, projected scenarios of future climate change impacts on crop production and risk of hunger in major agricultural regions are presented.

Altered weather patterns can increase crop vulnerability to infection, pest infestations, and choking weeds. Ranges of crop weeds, insects, and diseases are projected to expand to higher latitudes[6,7]. Shifts in climate in different world regions may have different and contrasting effects. Some parts of the world may benefit from global climate change (at least in the short term), but large regions of the developing world may experience reduced food supplies and potential increase in malnutrition[2,3]. Changes in food supply could lead to permanent or semi-permanent displacement of populations in developing countries, consequent overcrowding and associated diseases, such as tuberculosis[8].

Climate Change and Variability

Considerations of the potential impacts of climate change on agriculture should be based not only on the mean values of expected climatic parameters but also on the probability, frequency, and severity of possible extreme events. Temporal and spatial variance of meteorological conditions and storms can affect soil conditions, water availability, agricultural yields and susceptibility to pest and pathogen infestations.

Global Warming

Global climate models (GCMs) have projected the effects of increasing atmospheric concentrations of greenhouse gases. Recent simulations predict a mean global warming of between 1.5 to 5.8°C (2.7 to 10.4°F) by the end of the century for varying scenarios of population growth, economic development, energy use, and land-use change[1,9]. Because a warmer atmosphere can hold more water vapor, they also predict an increase in mean global precipitation of 5 to 15%.

GCMs further predict that:

- The 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 springs and summer droughts.

It seems clear that 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 can be expected to 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.

However, there are a number of 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 who may the winners and losers be? And, there are the practical questions: What can be done to mitigate these changes? To the extent that such damage may be unavoidable, what can be done to adapt practices so as to minimize or even overcome them? The welfare of agriculture in many regions and countries may rest on our ability to answer these and related questions.

Weather Extremes

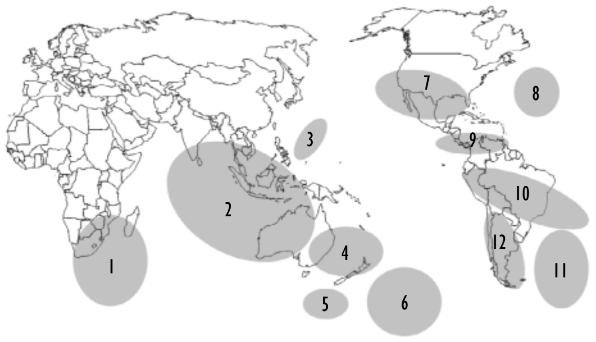
Extreme weather events include spells of very high temperature, torrential rains, and droughts. Under an enhanced greenhouse effect, change can occur in both mean climate parameters and the frequency of extreme meteorological events.

Relatively small changes in mean temperature can result in disproportionately large changes in the frequency of extreme events. Des Moines, in the heart of the U.S. Corn Belt, currently experiences fewer than 20 days above 32°C (89.6°F); this would double with a mean warming of 2°C (3.6°F). For similar warming, Phoenix, where irrigated cotton is grown, would have 120 days above 37°C (98.6°F), instead of the current 90-odd days.

Sequential extremes can affect yields and diseases. Droughts, followed by intense rains, for example, can reduce soil water absorption and increase the potential for flooding, thereby creating conditions favoring fungal infestations of leaf, root and tuber crops in runoff areas. Prolonged anomalous periods – such as the five years (1990-1995) of El Niño conditions -- can have destabilizing effects on agriculture. Sequential extremes, along with altered timing of seasons, can decouple long-evolved relationships among species (e.g., predator/prey) essential for controlling pests, pathogens, and populations of plant pollinators.

El Niño-Southern Oscillation

The El Niño-Southern Oscillation (ENSO) phenomenon is second only to the seasonal cycle as a powerful force affecting climate patterns that directly govern crop growth around the world. There is a significant difference, however, in that growing seasons come regularly, year after year, while the El Niño phenomenon is quasi-regular, tending to recur every two to nine years with varying intensity. Analysis of El Niño records shows that events have been stronger and more frequent since the 1980s, a pattern possibly linked to global warming[1,10,11].



1 Warm (Oct - Jun*), wet (northern area, Oct - Apr*) and wet (southern area, Nov - May*)
2 Warm (Oct - Jun*), dry (most of the area (Jun - Sep) and wet (southern most India, Oct - Dec*)
3 Warm (Oct - Feb*)
4 Warm (northern area) and cool (southern area) (Dec - Jun*), dry (Nov - May*)
5 Warm (Nov - Jun*) and dry (Nov - May*)
6 Cool (Jan - Nov)
7 Warm (Dec - Mar*), limited wet areas in the U.S. (Apr - Oct)
8 Warm (Dec - Mar*)
9 Cool (Oct - Mar), wet (Oct - Mar*)
10 warm (Jul - Jun*), dry (Jul - Oct)
11 Warm (May - Apr*), wet in the southern area (Nov - Feb*)
12 Warm (May - Apr*), wet in the southern area (Nov - Apr*)
Month = month of year of the onset of El Niño
Month = month of year of the year following the onset of El Niño*

Figure 1 *Typical temperature and precipitation patterns associated with El Niño that affect agriculture. (Source: Ropelewski and Halpert, 1987, 1989)*

El Niño events result in 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 generate reverse effects. Temperatures during El Niño periods tend to be warmer in those areas affected by drought. These fluctuations affect crop development and pest infestations, which, in turn, affect yields (Fig. 1).

The manifestations of El Niño have wrought great havoc on food production. The collapse of the anchovy fisheries (used to derive fishmeal, an animal feed supplement) off the western shore of South America first brought the El Niño cycle to widespread public awareness in 1972-1973. El Niño impacts on agriculture, while typically negative, are actually positive in some areas. Its effects are generally strongest in the Southern Hemisphere. Large countries, such as the U.S. and Brazil, extending over different geographical regions, may experience opposite responses to El Niño events. And, different crops are affected differently. In Zimbabwe, for example, corn is more strongly affected than roots and tubers.

Predicting climatic teleconnections and their effects is difficult as responses may be manifested in temperature and precipitation, and changes of the seasonal means as well as in their patterns of variability. Not every El Niño phase has the same 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 those of the 1991-1992 event whose associated climate and corn yield effects in Zimbabwe were stronger. The sea-surface temperatures during the 1982-1983 and 1997-98 events were similarly high, but the resulting rainfall patterns in southeastern Africa were significantly different.

The North Atlantic Oscillation (NAO) and the patterns in the Indian Ocean are also major components of the natural climatic variability. Their climatic teleconnections affect 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 requires inclusion of these indices, local sea surface temperatures (SSTs), decadal variability and the anthropogenic signal.

Recent Climate Events Affecting Agriculture

Extreme weather events, which occur in every agricultural region of the world, cause severe crop and livestock damage. The persistent drought in the Sahel region of Africa has arguably had the greatest human impact. In the U.S., economic damages from single events can exceed $1 billion (Table 1). The most severe recent weather-related events for U.S. agriculture were the drought of 1988 and the flood of 1993. Recent El Niño and La Niña events have also affected agriculture.

Drought in the Sahel

The Sahel region has undergone a general decline of rainfall since the late 1960s[2], and since 1975, has experienced warming of up to 1.5°C (2.7°F)[3]. There have been several unusually prolonged and severe droughts over this period, in marked contrast with the preceding twenty relatively wet years[3,12]. Gonzalez[13] found declines in forest species richness and tree density related to rainfall and tem-

Table 1 Extreme weather events causing severe crop damage in the U.S. (1977-1998)

Year	Geographical area	Extreme weather event
1977	Eight 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	Eight 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
1990	Texas, Oklahoma, Louisiana, Arkansas	Flooding in May
1993	Midwest	Flooding in the summer affecting 16,000 square miles of farmland, and damaging crops in over 11 million acres; Crop losses over $3 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, Appalachia, 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

Sources NOAA, USDA, and U.S. Army Corps of Engineers.

perature trends in the West African Sahel during the last half of the twentieth century. The changes have also decreased human carrying capacity below actual population densities: the rural population of 45 people per square kilometer exceeded the 1993 carrying capacity of firewood from shrubs of 13 people per square kilometer. Semiarid ecosystem degradation has been linked to migrations that may have displaced ~3% of the population of Africa since the 1960s[14].

The U.S. Drought of 1988

The severe drought of 1988 in the U.S. Midwest, accompanied by higher than normal temperatures, began early in the spring and continued throughout most of the summer[15,16]. It spread to the central and southeastern parts of the nation, affecting agriculture, water resources, transportation, tourism, and the environment[17]. Crop yields dropped by approximately 37% and required a $3-billion Congressional bailout for farmers.

Crop pests were also affected, with outbreaks of two-spotted spider mites (*T. urticae*) damaging soybeans throughout the entire Midwest region. The damage occurred during the critical flowering, pod-development, and pod-filling growth stages. Approximately 3.2 million hectares were sprayed with insecticides to control the mites across the region, and estimated losses to Ohio farmers were $15 to 20 million[18].

The drought led to decreased flows in the Ohio and lower half of the Mississippi Rivers by the end of May[17], restricting barge movement, and extending salt-water intrusion from the Gulf of Mexico 105 miles up the Mississippi River, past New Orleans.

The 1988 mid-summer statement by Dr. James Hansen to the U.S. Senate Committee on Energy and Natural Resources that "The global warming is now sufficiently large that we can ascribe (it) with a high degree of confidence …. to the (enhanced) greenhouse effect" raised awareness of the global climate change issue. It 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 Mississippi River 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 Mississippi River flood crest at St. Louis, Missouri broke the previous record. Over 11 million acres of crops were damaged, with losses of over $3 billion (U.S. Army Corp of Engineers). Excess water presents a particularly severe problem for Iowa's low-lying soils, and increased pathogen outbreaks[19]. Emergency measures cost over $222 million.

The flood of 1993 generated 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 the doubling of the Gulf's "Dead Zone" in 1993, following the flood[20].

El Niño of 1997-1998

In late 1997, the tropical Pacific witnessed the development of a major El Niño event, rivaling the strength of 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, the western Pacific's uncharacteristically elevated sea levels a year and a half prior to the onset 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-related effects of the 1997-98 El Niño had a significant impact on agriculture. 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 the southeast. Unexpectedly, drought conditions did not materialize in southwest Africa, where heavy rains fell in the north, nor in India, where near-normal monsoon rains occurred.

In the U.S., the El Niño was associated with several severe weather events. From November 1997 to March 1998, high rain events occurred on the West Coast, damaging infrastructure in southern California. In the summer following the El Niño, there were extremely high temperatures in Texas and Oklahoma, causing heat stress among the elderly population and damaging crops. These conditions spread across the South to the Carolinas. In the Southeast, there was El Niño related flooding in the winter and spring, and, in Florida, summer dryness triggering forest fires.

Despite these regional effects of the 1997-98 El Niño, there was little impact on U.S. agriculture nationally, probably because major grain crop production is in regions not strongly affected. Wheat yields were at a record high, with the highest production since 1990; corn and soybean production were also the highest on record.

World production of wheat and rice was at record levels in 1998, and coarse grains were only two percent below the previous year. Corn and soybean production were the highest on record, with yields slightly above the expected trend. In southeast South America, abundant soil moisture from the typical El Niño conditions produced a record soybean crop in Brazil and Argentina, contributing to decreases in corn and soybean prices on the world market during 1998.

In Australia, wheat yields and production were maintained, due, at least in part, to strategic responses to the El Niño forecast. In Indonesia, the 1998 rice production was below the previous year's, 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 during late December and mid-February, timely rainfall, accompanied by below-normal temperatures, eased crop stress and resulted in only slightly below normal corn production.

Climate Extremes of 1998-2000

The abrupt April 1998 La Niña ushered in another year of extremes. In November, 1998, Hurricane Mitch caused long-term damage in Central America[8]. 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.

The decreased winter snowpack and spring runoff exacerbated the spring and summer drought throughout the U.S. Atlantic states, severely affecting agricultural production. 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[21]. The 1998-99 drought in the U.S. resulted in reduced commodity receipts (from 1998) by an estimated $1.29 billion[22]. Estimated farm net income losses, including yield losses, increased expenses and insurance indemnities, totaled $1.35 billion, approximately 3 percent of 1999 U.S. net farm income[22,23,24].

Then, Hurricane Floyd (September 1999) flooded coastal regions in North Carolina and New Jersey[25]. North Carolina was also hit by Hurricane Dennis and Hurricane Irene, causing prolonged flooding and increasing the risk of fungal infections to agriculture and human health.

Intense December 1999 rains caused flooding and landslides, destroying villages and croplands in Venezuela; windstorms damaged or destroyed an estimated 270 million trees in France. Continuing into 2000, extensive flooding occurred in southern Africa, bringing loss of life and crop failure. In early 2000, La Niña brought severe drought to agricultural production in southeastern Brazil and Uruguay, leading to government subsidies to affected areas[26].

Food Production Vulnerability to Weather Events

Extreme meteorological events related to the El Niño cycle, other large-scale forcing factors, or simply the chaotic nature of the climate system can have severe detrimental effects on crop yields, and therefore, food production. Most food crops are sensitive to direct effects of high temperature, decreased precipitation, and flooding. Other effects on crops are indirect, through influence on soil processes, nutrient dynamics, and pest organisms.

Crop Responses

Precipitation, the primary source of soil moisture, is probably the most important factor determining the productivity of crops. Interannual precipitation variability is a major cause of variation in crop yields and yield quality.

Drought stress and heat stress frequently occur simultaneously, exacerbating one another. They are often accompanied by high solar irradiance and high winds. Under drought stress, the crop's stomata close, reducing transpiration and, consequently, raising plant temperatures. Flowering, pollination, and grain-filling of most grain crops are especially sensitive to water stress. By reducing vegetative cover, droughts exacerbate wind and water erosion, thus affecting future crop productivity.

Excessively wet years 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, promote ripening-grain lodging in standing crops, and cause soil erosion. Episodes of high relative humidity, frost, and hail can affect yield and quality of fruits and vegetables. And, the costs of drying corn are higher under wetter climate regimes.

Greater precipitation (if not excessive) during the growing season tends to increase yields, as illustrated by the relationship between corn yield and annual precipitation in Des Moines, Iowa, (Fig. 2). Corn yields decline with warmer temperatures due to acceleration of the crop's development, especially during the grain-filling period.

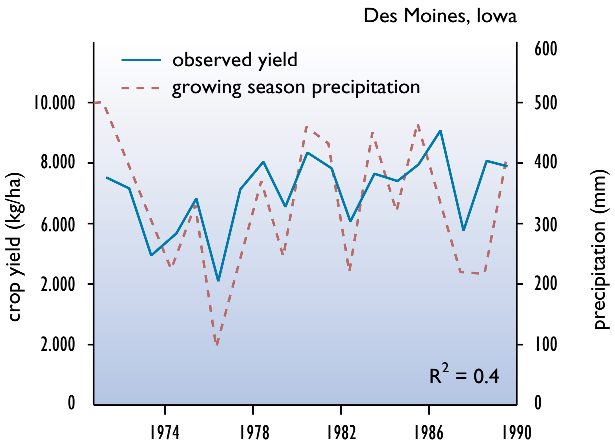


Figure 2 *Relationship between corn yield and growing season precipitation in Des Moines, Iowa. (Source: Rosenzweig et al., 2000)*

The extent of crop damage depends on the duration of stress and crop developmental stage. Crop yields are most likely to suffer if the adverse weather conditions, especially high temperature and excess or deficit precipitation, occur during critical developmental stages such as the early stages of plant reproduction.

Juvenile stages. Soil temperature higher than 35°C (95°F) causes seedling death in soybeans. Air temperature above 30°C (86°F) for more than 8 hours can reverse vernalization in wheat. Saturation of soil increases the risk of seedling diseases, especially at air temperatures above 32°C (89.6°F). Flooding causes seedling death in corn and soybean; the combination of flooding with high temperature accelerates death.

Reproductive stages. Air temperatures higher than 36°C (96.8°F) cause pollen to lose viability in corn and reduce grain yield in post-blooming soybean. Soil temperature higher than 20°C (68°F) depresses potato bulking. Soil moisture deficits are very detrimental to corn -- four days of soil moisture stress reduces yields up to 50% -- and other grain crops. Grain crops are also highly vulnerable to flooding.

Mature stages. Soil saturation causes long-term problems related to rot and fungal development and increased damage by diseases (e.g., crazy top and common smut in corn). Water deficits increase aflatoxin concentration in corn.

All stages. Extremely high air temperatures (>45°C; 113°F) persisting for at least 30 minutes directly damage crop leaves in most environments; even lower temperatures (35-40°C; 95-104°F) can be damaging if maintained for longer periods.

Crop Weeds, Insects, and Diseases

Climate also affects agricultural pests. The spatial and temporal distribution and proliferation of insects, weeds, and pathogens is determined, to a large extent, by climate, because temperature, light, and water are major factors controlling their growth and development. Table 2 shows the 1998-1990 global production of eight major crops and their estimated losses by pest and by region. Climate also affects the pesticides used to control and/or prevent pest outbreaks: the intensity and timing of rainfall influence pesticide persistence and efficiency; temperature and light affect pesticide per-

Table 2 Global production of eight major crops and estimated losses for the eight crops by pest and region, 1988-1990.

Crop	Actual Crop Production (billions of US$)	US$ (billions) Losses due to Pathogens	Insects	Weeds	Total
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
N. 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

Source: Oerke et al., 1995.

sistence through chemical alteration. Most analyses show that in a warmer climate, pests may become more active than currently and may expand their geographical range, resulting in increased use of agricultural chemicals with accompanying health, ecological and economic costs[3,6,18,27-29].

Because of the great variation of pest species' responses to meteorological conditions, the relationships between pests and weather are not susceptible to overall characterization. Crop damage by pests is a consequence of complex ecological dynamics between two or more organisms, and therefore, is difficult to predict. For example, dry conditions are unfavorable for sporulation of fungi, but are also unfavorable for the crop; during a drought, a weak crop is more likely to become infected by fungi than when it is not stressed.

Precipitation – whether optimal, excessive, or insufficient – is probably the most important variable affecting crop-pest interactions. Many pest species are favored by warm and humid conditions. Both direct and indirect effects of moisture stress on crops make them more vulnerable to damage by pests, especially in the early stages of plant development. 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, attributing specific losses to pests can be difficult. Table 3 shows key weather conditions that critically influence major pest epidemics and examples of resulting crop damages.

Insects flourish in all climates. Their habitats and survival strategies are strongly dependent on local weather patterns, and are particularly sensitive to temperature because they are cold-blooded. Insects respond to higher temperature with increased rates of development and with less time between generations. However, very high temperatures reduce insect longevity. Warmer winters reduce winterkill, and consequently, increase insect populations in subsequent growing seasons. Drought changes the physiology of host species, leading to changes in the insects that feed on them, and can reduce populations of friendly insects (such as predators or parasitoids), spiders and birds, influencing the impact of pest infestations. Abnormally cool, wet conditions can also bring on severe insect and plant pathogen infestations, although excessive soil moisture may drown soil-residing insects.

Weeds compete with crops for soil nutrients, light, and space. Drought conditions increase the competition for soil moisture; humid conditions increase the proliferation of weeds; and warmer temperatures increase the maximum biomass of grass weeds.

Temperature, precipitation, humidity, dew, radiation, wind speed, and circulation patterns influence the growth, spread, and survival of crop pathogens. Increased temperature and humidity result in the spread of diseases as wet vegetation promotes the germination of spores and the proliferation of fungi and bacteria. Enhanced soil moisture encourages the spread of nematodes, roundworms that inhabit water films or water-filled pore spaces in soils.

Some pathogens (e.g., powdery mildews) thrive in hot, dry conditions as long as there is dew formation at night. Climate conditions also influence post-harvest pest damage. For example, the concentration of mycotoxin (produced by *Fusarium spp.*) is favored by high humidity and temperature at harvest. Mycotoxin, ingested with the food crop, can induce muscle spasms and vomiting in humans. The emergence of wheat scab in key agricultural areas of the U.S. Great Plains may be linked to the increased temperatures during the past ten years. In contrast, aflatoxin rises during crop-water deficits because the growth of *Aspergillus flavus*, which produces the fungus in the weakened crop, is favored by drought.

Recent Trends

Over the last five decades, crop yields have risen due to steady improvements in breeding and management. Year-to-year variability, however, has also increased in many regions. For example, in the U.S. during the period 1971-1998, the variability of corn

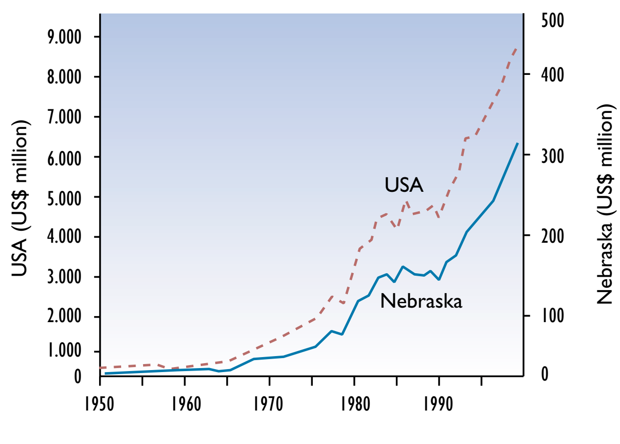


Figure 3 *Value of pesticide applied in the U.S. 1950-1997. (Source: USDA)*

yields was significantly higher than during the period 1950-1971: The standard deviation of the yields was more than three times higher in the later period[30].

There have been global increases in pest-induced losses of crops in all regions since the 1940s[31,32]. During the same period, there was a more than 33-fold increase in both the amount and toxicity of pesticide used[31]. The dramatic increase in U.S. dollars spent on pesticides in the U.S. (Fig. 3) has raised many environmental and public health issues. (Increased U.S.$ spent does not necessarily (although actually may) reflect increased pesticide use)

Increased pest damage arises from changes in production systems, enhanced resistance of some pests to pesticides, and the production of crops in warmer and more humid climatic regions where crops are more susceptible to pests. Changes in crop management techniques, particularly the intensi-

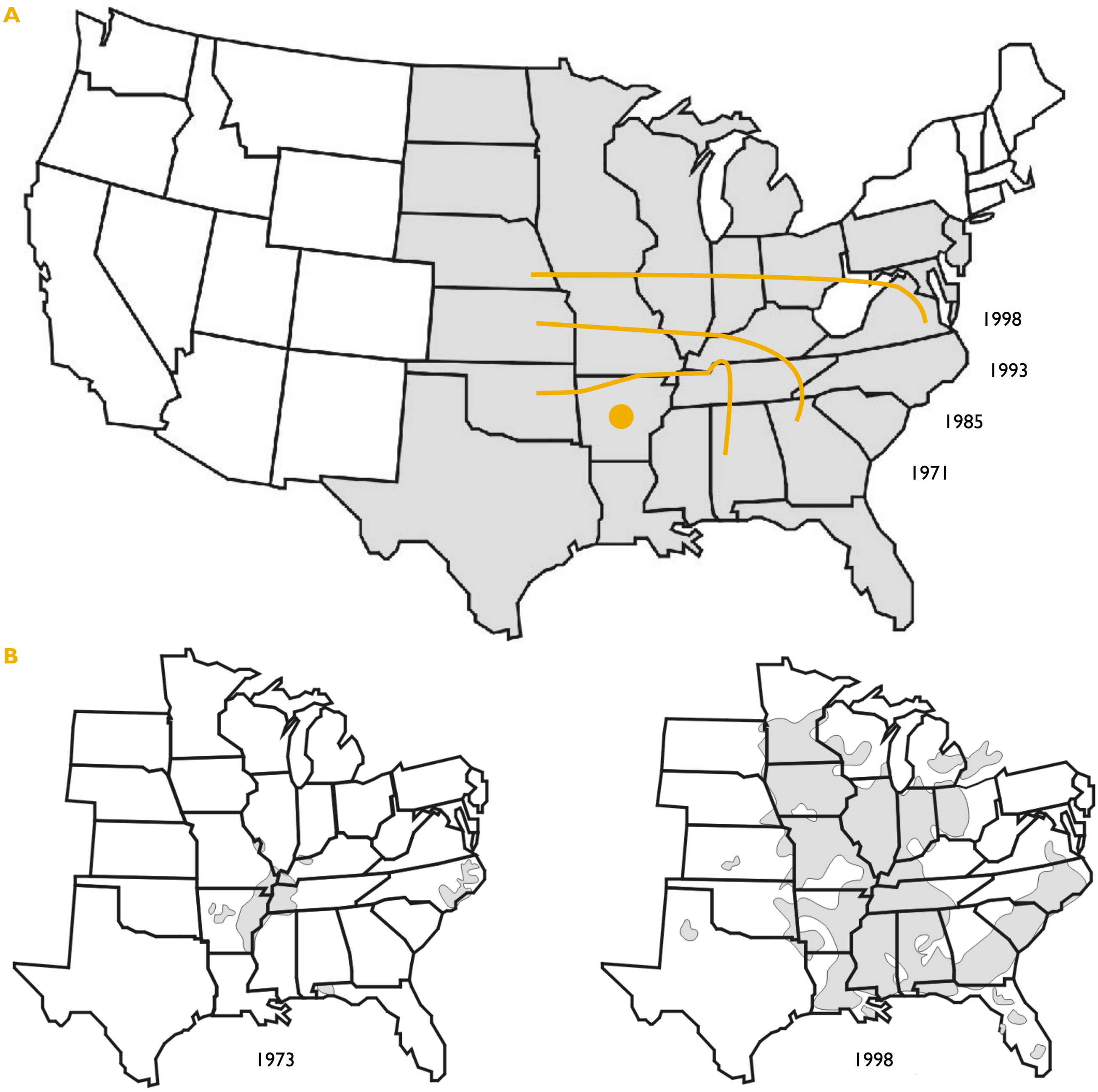


Figure 4 *Range expansion of soybean cyst nematode (Heterodera glycines) from 1971 to 1998 (A) and soybean sudden death syndrome (Fusarium solani f. sp. glycines) from 1973 to 1998 (B) in North America. (Source: Niblack, 1999; X. B. Yang)*

fication of cropping, reduction in crop rotations, and increase in monocultures, have increased the activity of pests. The expansion of worldwide trade in food and plant products has also increased the impact of weeds, insects, and diseases on crops.

The geographical ranges of several important insects, weeds, and pathogens in the U.S. have recently expanded, including soybean cyst nematode (*Heterodera glycines*) and sudden death syndrome (*Fusarium solani* f. sp. *glycines*) (Fig. 4)[30,33,34]. Recent climate trends and extreme weather events may be directly and indirectly contributing to the increased pest damage[30,35]. It is not known whether the change in global climate has contributed to these trends.

There have been several attempts to establish associations between historic pest damage and climate conditions[30,35]. Major pest outbreaks have occurred during favorable regional weather conditions (Table 3). Records of potato leaf roll in North America from 1930 to 1991 suggest that the outbreaks of this aphid-borne viral disease are related to drought conditions[36,37]. A 100-year record of the grasshopper behavior in Kansas (1854-1954) shows that the most severe damage was caused during dry years[38]. Climate conditions during El Niño and

Table 3 Effect of weather events on pest damage and key observed examples.

Floods and heavy rains

- Increased moisture benefits epidemics and prevalence of leaf fungal pathogens.
  - Rice leaf blight caused great famine in Bengal (1942), 2 million people died.
  - Wheat stripe rust outbreak in major production regions of China contributed to the 1960s famine.
  - Fungal epidemics in corn, soybean, alfalfa, and wheat (U.S. Midwest, 1993).
  - Mycotoxin (produced by *Fusariun spp.*) reached a record high (U.S. Great Plains, 1993); mycotoxin increases are related to high humidity during harvest (East Africa and South America, 1990s).
  - 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.
  - Outbreaks of soybean sudden death syndrome in the north central U.S. (1993).
- Continuous soil saturation causes long-term problems related to rot development and increased damage by pathogens.
  - In maize, crazy top and common smut

Drought

- Water stress diminishes plant vigor and alters C/N lowering plant resistance to nematodes, and insects.
  Attack by fungal pathogens of stems and roots are favored by weakened plant conditions.
  Dry and warm conditions promote growth of insect vector populations, increasing viral epidemics.
  - Outbreak of soybean cyst nematode correlated to drought conditions in north central U.S. (1990).
  - Summer locust outbreak correlated to drought in Mexico (1999).
  - Increased incidence of *Aspergillus flavus* (producer of aflatoxin) in southern U.S. (1977 and 1983).

Air currents

- Air currents provide large-scale transportation for disease agents (e.g., spores of fungi) or insects from overwintering areas to attacking areas.
  - The spread of the stem rust that overwinters in Mexico and Texas is 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.

Warm winters

- Increase overwintering populations of all pests and insect vectors.
  - Data reported for the European Corn Borer; wheat scab; wheat rust; and potato leafhopper.
  - Increase population of aphids that carry the soybean mosaic virus.
  - Increase population and number of generations of Mexican bean beetle and bean leaf beetle in the U.S.

Source: Rosenzweig et al., 2000.

Figure 5 *Spread of southern corn leaf blight (Helminthosporium maydis) of 1970. (Source: Moore, 1970)*

La Niña years have been correlated to pest damage in some regions (e.g., wheat stem rust damage in the U.S. Great Plains; wheat stripe rust epidemics in the U.S. Northwest)[39,40]. Insect damage to soybeans increased during the severe drought of 1988 in the U.S. Midwest[18]. An estimated 3.2 million hectares were sprayed with insecticides to control spotted spider mites across the region; drought-related losses to Ohio farmers were estimated as 15 to 20 million dollars.

The southern corn leaf blight epidemic of 1970 and 1971 was the most dramatic epidemic in the history of agriculture in the U.S. (Fig. 5). 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, as they occurred in the U.S. where the agricultural industry is highly diversified, human suffering was far less. 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 disease spread rapidly northward through the Midwest on the air currents of a tropical storm in the Gulf of Mexico[41]. The disease was most severe in the Midwest and southern U.S., with some areas reporting 50-100% losses. Losses were officially estimated as $1.09 billion for the nation as a whole. Although genetic uniformity in the corn crop laid the groundwork for the fungus, favorable meteorological conditions were instrumental to the outbreak and spread of the disease.

Projections of Food Supply

Global climate models are used to develop scenarios of the potential impact of climate change on world food supply. Climate change is expected to alter global patterns of food supply and demand, and may have far-reaching consequences. Figure 6 shows projections of average national grain crop yield changes throughout the world for the Hadley Center climate change scenario HadCM2 for the 2020s, 2050s, and 2080s[30,42]. The direct effects on crops of higher CO_2 levels are taken into account as higher CO_2 increases the rate of photosynthesis and improves their water-use efficiency[43-46].

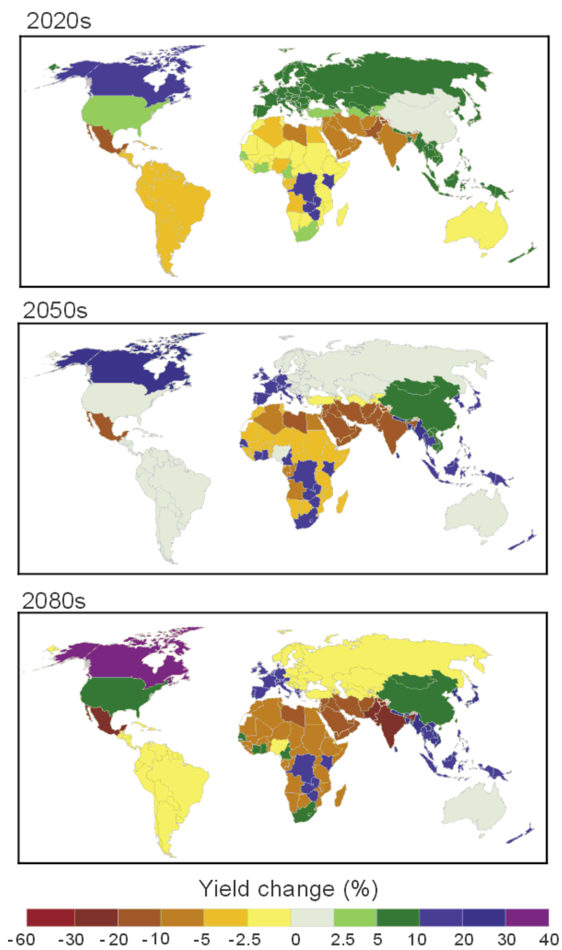


Figure 6. *Percentage change in crop yields for the Hadley Center global climate change scenario, HadCM2. Direct physiological effects of CO_2 and crop adaptation are taken into account. Crops modeled are: wheat, maize, and rice. (Source: NASA/GISS)*

Some regions may improve production, while others suffer yield losses. For example, for regions at high and mid-latitudes, yield increases lead to production increases, a trend that may be enhanced by the countries' greater adaptive capacity as in Canada and Europe. In contrast, yield decreases at lower latitudes, and especially in the arid and sub-humid tropics, leading to production decreases with increases in the risk of hunger. These effects may be exacerbated where adaptive capacity is lower than the global average. Demand for world grain from North America (on the order of 80% of the global marketable surplus) has increased the sensitivity of world food supply to climate. Different climate models project similar changes in the shifts of agricultural production zones around the world.

Risk of Hunger and Malnutrition

Reduced crop production, as expected with projected climate change, could lead to increased vulnerability to malnutrition and hunger in some regions. A model of the world food trade system, the Basic Linked System (BLS) was used to test the socio-economic effects of food production estimates[47]. In dynamic simulations of the world food system, response to climate-induced shortfalls of cereals result in higher commodity prices due to increases in production factors (cultivated land, labor, and capital) and inputs such as fertilizer. Simulations show that production in the developed countries benefit from the projected climate change, whereas production in developing nations declines. World cereal prices in developing countries are projected to increase in most scenarios, including those with farmer adaptation[47]. Assumptions of lower and higher rates of economic development and population growth have demonstrated little effect on the geopolitical patterns of relative climate change effects in the simulations.

The population with an insufficient income to either produce or procure their food requirements is used as the indicator of number of people at risk of hunger in the economic model of developing countries (excluding China). The measure is derived from the United Nations Food and Agriculture Organization (FAO) estimates and methodology for developing market economies[48]. The FAO estimates stipulate that a country's calorie consumption is skewed and can be represented by a beta distribution. The parameters of these distributions were estimated by FAO for each country based on country-specific data and cross-country comparisons. The estimate of the energy requirement of an individual is based on the basal metabolic rate. FAO presents two estimates of undernourished people, based on minimum maintenance requirements of 1.2 and 1.4 (the latter, the more appropriate) basal metabolic rate. The BLS estimate for 1990, based on a 1.4 basal metabolic rate requirement, is 521 million undernourished people in the developing world, excluding China.

Figure 7 shows significant global increases in people at risk of hunger in the future. However, the global estimates mask important regional differences. For example, in Africa, it is estimated that cereal productivity, under the HadCM2 greenhouse gas only scenario, will be reduced by about 10% from the reference case by 2080; the consequent risk of hunger in the region would increase by 20%.

The Influence of Extreme Events

Climate change can change the patterns of climate events. If temperature variability increases, crops growing at both low and high mean temperatures could be adversely affected as diurnal and seasonal canopy temperature fluctuations often exceed the optimum range. 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.

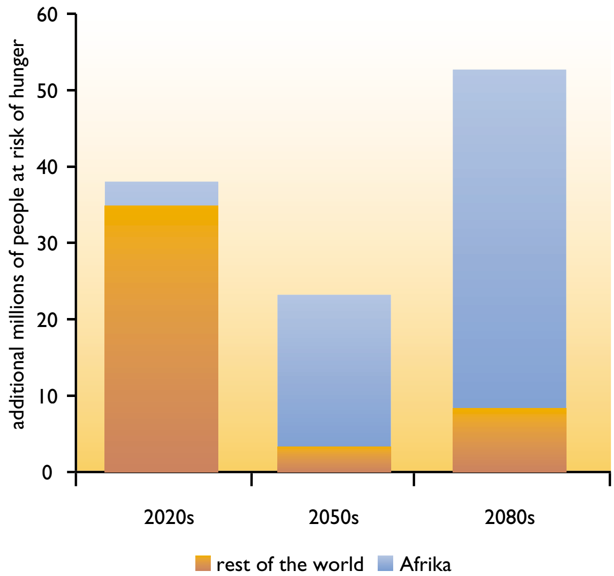


Figure 7 *Projected additional numbers of people at risk of hunger under the HadCM2 climate change scenario (0 = Projected global reference case). (Source: Parry et al., 1999).*

Sequential extremes – e.g., prolonged droughts followed by heavy rains – can have the severe effects on soil quality, propensity to flooding and their associated changes in yields and pests. Droughts can reduce populations of friendly insects (lace wings, lady bugs), spiders and birds, influencing pollination and pest infestations. The impact of several years of drought (such as those associated with the "double" La Niña – 1998/99, and 1999/2000) can be additive and have long-lasting impacts consequences on agricultural regions.

Changes in Crop Insects, Weeds, and Diseases

The warming trend and changes in extremes can be expected to affect the regional incidence of weeds, insects, and crop pathogens. A change in the patterns of precipitation for crop-pests interactions may be even more important than a change in the annual total. The water regime of pests is vulnerable to a rise in the daily rate and seasonal pattern of evapotranspiration resulting from warmer temperature, dryer air, or windier conditions. Projected temperature increases can be expected to induce earlier and faster development of crops, and cause increased pest damage at the sensitive earlier stages of crop development. Disproportionate warming at high latitudes and high elevations in winter and nighttime can affect crop development, bringing re-patterning of the geographical distribution of production activities, and alter the ecological balance between the crops and its associated pests.

Even without climate change, pest management faces some serious challenges in the coming decades. The most striking are the increasing dependence on chemical treatments, and rising costs of environmental protection and public health policies. Improved climate forecasts can help farmers prepare for changing seasonal-to-interannual conditions, and optimize pesticide management while minimizing environmental damage.

Options and Costs of Adaptation

Growing population, potential changes in comparative advantage of different international producers, and the overall need for non-destructive land and water management pose serious challenges in the coming decades. National and regional farm policies can be a critical determinant in the adaptation of the farming sector to changing conditions, in both developed and developing countries. Assessment of risk due to current and future weather anomalies is an important policy consideration. If, as projected, flood and drought frequencies increase, the need for emergency allocations will also increase. Assessment of the probability and potential magnitude of such anomalies can aid in making timely adjustments so as to reduce social costs.

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 adaptation to climate change may involve significant changes to current agricultural systems, some of which may be costly: there will probably be a need for investment in new technologies and infrastructure; new irrigation systems may be required for aridity or precipitation instability; damages from flooding may increase in many regions; there may be greater applications and/or development of new agricultural chemicals, particularly herbicides and pesticides.

Because of the growing interdependence within the world food system, the impact of climate change on agriculture in each country depends increasingly on what happens elsewhere. For example, climate improvements of competitive regions, such as Argentina for soybean production, may affect existing U.S. comparative advantage. On the other hand, the vulnerability of food-deficient regions to heat and drought may provide an advantage to major grain producers, such as the U.S., but intensified competition from more favored regions (possibly Canada and Russia) may limit that advantage. International trade policy issues, especially the movement to lower agricultural trade barriers, will be crucial to climate change response strategies.

Conclusion

Human activities are causing the augmentation of the natural atmospheric greenhouse effect. Future climate models (which should not be accepted uncritically) predict that anthropogenic forcing will bring about changes in the magnitude and frequency of all key components and natural cycles of the climate system. Climate change will gradually (and, at some point, maybe even abruptly) affect regional and global food production. 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 the reductions. Given the growing interconnectedness of world economic and ecological systems, decreased agricultural yields in underdeveloped nations could affect the more developed countries via demands for relief efforts and international trade, as well as through impacts on political stability and the international movement of populations.

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