Global Climate Change: Its Impacts on Food and the Environment

By Dr. David Pimentel

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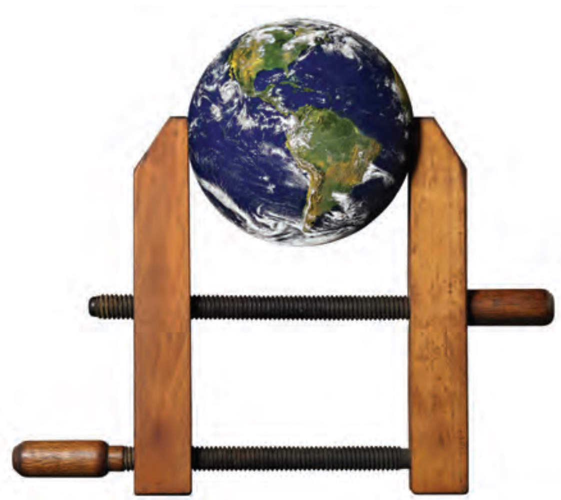
Introduction

The projected changes in climate associated with global CO_2 increases are expected to alter world food production and the environment *(Brown, 1988; Sinha, et al., 1988)*. Although present agricultural production provides food for more people than ever before, the number of malnourished humans (3.7 billion) is also greater than ever *(WHO, 2000)*; in addition, FAO (2009) reports there are an additional 1.02 billion who are protein/calorie malnourished. Demographers project that the world population will rise from the present 6.9 billion (PRB, 2010) to approximately 9.2 billion by 2050 *(UN, 2008)*. Equally alarming is the current 1.2% annual population growth rate—a rate about 1,200 times greater than during the first million years of human existence *(PRB, 2010)*. More than a quarter of a million people are added each day, and each individual requires food, shelter, and fuel.

Terrestrial ecosystems supply more than 99.7% of all world food, while fish in aquatic ecosystems supply the remaining 0.3% *(FAO, 2006)*. Each year the portion available from the aquatic ecosystem shrinks because of over-fishing and pollution; global warming and ozone depletion may further reduce this food source.

At present, declining supplies of freshwater and arable land per person, increased soil erosion, deforestation, loss of biological diversity, and food losses to pests contribute to food supply problems. The pressure of population escalation, when coupled with anticipated climate changes, can only exacerbate the task of providing adequate food for humans. This problem is especially acute in third world and eastern bloc countries where malnutrition and poverty are growing as a result of world and internal economic conditions, internal government policies, explosive population growth, severe environmental degradation, and limited access to technology *(Pimentel and Pimentel, 2008)*.



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World agriculture already exploits most arable land, and millions of hectares of marginal land are now being forced into production *(Buringh, 1989)*. In addition, soil degradation is resulting in the abandonment of about 20 million hectares of land annually *(Pimentel, 2006)*, which is replaced by clearing valuable forests.

As the buildup of CO_2 and other greenhouse gases in the atmosphere continues, the impacts of this "greenhouse effect" will be felt worldwide. The reduction of fossil fuel use and planting of additional trees can help slightly to counter the greenhouse effect. In some areas temperature and rainfall levels will increase and in others moisture levels will decrease. Coastal flooding is expected to diminish land available for society *(Oppenheimer, 1998)*. These changes, including extreme climatic events, are expected to bring about many shifts in world food production. In general, food crops are sensitive to changes in climatic conditions, including alterations in temperature, moisture, and carbon dioxide levels. Furthermore, major climatic changes influence populations of beneficial organisms and pests and alter their roles in the agricultural ecosystem. Overall, effects on human society are likely to be negative *(Hansen, et al., 2006)*. The anticipated global climatic change is projected to reduce cropland by about 33% *(Schneider, 1989)*, but this figure may be as low as 10% or as high as 50% *(Stevens, 1989)* depending on the specific effects of high temperatures, coastal flooding and reduced rainfall.

Our investigation considers how global warming is expected to alter the production of five major crops (rice, wheat, corn, soybean, and potato) grown in North America and Africa. These crops provide the staples for billions of humans. Also, North America and Africa are selected because they highlight the regional differences that are projected to occur as climate changes. This analysis includes an assessment of the effects of carbon dioxide buildup, changes in temperature and rainfall, and ozone depletion on the production of these agricultural staples and on the abundance of pests. In addition, we examine several agricultural policies and technologies for their capacity to offset the potential negative effects of global climatic change on food production.

Increase in CO_2 and Other Gases in the Atmosphere

Assessing the impact of CO_2 and other greenhouse gases such as the chlorofluorocarbons (CFCs), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) on the world's climate is difficult because scientists, at this juncture, have not fully defined the size of atmospheric, biotic, and oceanic reservoirs as sources and sinks of CO_2 and other greenhouse gases *(Hansen, et al., 2006)*. Nonetheless, burning fossil fuels and removing and burning forests increase the levels of atmospheric CO_2 and other gases. Levels of CO_2 have risen from 280 ppm in the 1850s to nearly 400 ppm today. Without changes by society, atmospheric CO_2 and other gases will continue to increase.

Absolute elimination of the atmospheric CO_2 problem appears to be difficult if not impossible even if all the sources and sinks were identified. Fos-

Our investigation considers how global warming is expected to alter the production of five major crops sil fuel burning has contributed 50% to 66% of the more than 175 billion tons of anthropogenic CO_2 released into the atmosphere since the Industrial Revolution *(Woodwell, et al., 1983; Hansen, et al., 2006)*. Of this amount, approximately two-thirds of the total human contribution has been released in just the past 45 years. In fact, the present releases of CO_2 from fossil fuels amount to approximately 5-6 billion tons per year. The United States consumes and burns about 22% of all the fossil fuel burned in the world *(USCB, 2007)*. Other developed nations are also major contributors because, like the United States, their transportation, industry, agriculture, and citizens use enormous amounts of energy.

Standing forests help diminish atmospheric CO_2, but, when removed and burned, they release not only CO_2 but CH_4, CO, and N_2O, thereby adding to the accumulation of the greenhouse gases in the atmosphere *(MacDonald, 1988)*. About 20 million hectares of forests are cleared and burned throughout the world each year, while only 1 million hectares are reforested. Deforestation today contributes about 30% of the CO_2 released to the atmosphere by human activities each year, and accounts for 40-50% of the CO_2 buildup that has occurred since 1800 *(Myers, 1989)*. The decline in forests is striking. Within the past two centuries, Central and South America have lost about 37% of their original tropical moist forests, Southeast Asia about 38%, and Africa almost 52% *(UN, 2006)*. At present, only about 1 billion hectares of tropical forest remain. At this rate of forest destruction *(Myers, 1989)*, only a few large parcels of forests will remain after the turn of the century.

Approximately 80% of annual forest removal occurs worldwide because new land is needed for agriculture *(Pimentel and Pimentel, 2008)*, both for expansion and to replace land that is lost during rapid erosion *(Pimentel, 2006)*. More specifically, topsoil is being removed from cropland about 30 times faster than soil is being formed *(Pimentel, 2006)*. To compound the problem, soil erosion contributes directly to the CO_2 problem because it increases the rate of oxidation of soil organic matter, thereby emitting CO_2 into the atmosphere.

Another major factor that contributes to the worsening CO_2 problem is the rapid growth of the world population. Most of the quarter million people added daily to the population require fossil fuel for tillage, for other operations associated with food production and for other purposes; most require some wood and other biomass resources for fuel; all require more cropland for food and fiber production; and all contribute to the reduction of the plant and animal reservoir. In these ways, population growth intensifies the pressure on all the

support systems vital to human life, and these systems respond by expelling increasing amounts of CO_2 into the atmosphere.

Reducing the rate of increase of CO_2 concentration and other atmospheric gases will be extremely difficult. Fossil fuel is used to produce food and provide services, especially in industrialized nations, but several opportunities exist for conservation *(U.S. Congress, 1990; Pimentel and Pimentel, 2008)*. Worldwide, forests are being rapidly removed for agricultural expansion. Soil degradation continues, with little governmental concern evidenced in the United States or elsewhere in the world. Unfortunately, no political or social approach has been developed that limits rapid world population growth. Also, some politicians and others argue that we should not act to remedy climate change without further research of the global warming problem.

Projected Climate Changes

In 2008 a group of climatologists and other scientists brought together by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) concluded that, if present trends continue, the combined effect of carbon dioxide and other greenhouse gases (CFC, CH4, N2O, and O3) would warm the earth from 1.5 to 4.5°C before the middle of the next century, with warming most pronounced in the Arctic (Green Economics Institute, 2008). The Intergovernmental Panel on Climate Change (IPCC), consisting of approximately 250 respected scientists worldwide, completed their scientific assessment of climate change, and agreed that global temperatures would rise 1.5-4.5 °C if present trends continue. Investigations by many scientists and predictions from the general circulation models strongly support the conclusion that the atmosphere is now warming and will continue to do so *(Hansen, et al., 2006)*.

Hansen, et al. *(2006)*, have reported that average global temperatures have already risen approximately 0.5°C in the past century. This evidence of warming is supported by the fact that six of the warmest years on record occurred during the past 20 years. Furthermore, others have found that the permafrost surface in the Arctic had warmed 2-4°C during the last few decades of the 20th century. Although the temperature increase seems indicative of global climate change, others question whether the significant global temperature increase has occurred attributing the warming to natural climate variability.

Exactly when and how much the climate will change depends on the complex interactions of the atmosphere, oceans, and biosphere. The changes will not be uniform over the earth. Winter temperatures in the middle and high latitudes can be expected to rise by more than twice the world average. Summer temperatures will also rise, but less severely than during other seasons. Further, rainfall is expected to increase above present levels in some regions, such as Africa, especially the eastern portion, and decrease in others such as the central portion of the United States *(Hansen, et al., 1989; Hansen, et al., 2006)*.

Although all of the projected climate changes appear small based on averages, such small changes can have a major impact on the world's ecosystem. For example, during the most recent ice age (more than 10,000 years ago) the earth's average temperature was only about 5°C cooler than it is now. But this relatively minor alteration brought about major changes over the entire earth. Even an average global temperature decline of 1°C could have major ecological impacts. For example, in 1816 when global temperature declined less than one degree, frosts were reported in June in New England, resulting in

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widespread crop failures *(Stommel and Stommel, 1979)*.

About 6,000 years ago average temperatures were about 1°C warmer than they are now and, as a result, the climate was markedly different. In the tropics and subtropics, such as in Africa and India, rainfall was from 50% to 100% higher than current levels; the Sahara was not a desert but a savannah with significantly more vegetation *(UNEP, 1987)*. In contrast, the U.S. Corn Belt was a dry prairie during this period.

For this study the author assumes that, by 2030, CO_2 will nearly double from preindustrial concentrations, other greenhouse gases will increase substantially, and temperatures will rise approximately 2°C in North America and Africa. Projections are that rainfall patterns in the central portion of North America will average about 10% lower than present levels. Rainfall patterns, especially in eastern and northern Africa, are projected to average about 10% higher than present.

In Africa, this could lead to a slight improvement of agriculture over the current situation, but higher temperatures may decrease soil moisture conditions throughout the region *(Schwartz and Randall, 2003)*. In fact, the Food and Agriculture Organization projected in 1986 *(FAO, 1986)* that many African countries were too dry to attain food self-sufficiency by 2000, even when irrigation projects were taken into account. Also, the usefulness of any small increase in rainfall in Africa depends on timing, intensity, and distribution.

The changes in climatic patterns in Africa and North America will have a wide array of effects on the entire ecosystem. The higher temperatures, for example, will change the thermodynamics of the entire global climate system. The warmer temperatures will increase evaporation and increase transpiration rates in plants. Increased wind speeds will accelerate evaporation and transpiration rates and soil erosion, resulting in less soil moisture *(Houghton and Woodwell, 1989)*. Crops grown under hot, arid conditions use 20% to 40% more water than those grown under normal moist conditions *(Arkley, 1963; Swindale, 1980)*, and per unit of biomass produced may require as much as five times more water *(Falkenmark, 1990)*. Therefore, regions that experience some increased rainfall may not end up with more available soil moisture for crops because of higher evaporation and transpiration rates *(Houghton and Woodwell, 1989)*.

Relatively high levels of atmospheric carbon dioxide will increase growth rates in some crops *(UNEP, 1987)*, but such an increase may be more than offset by reduced rainfall projected for areas such as North America, Europe, and Siberia *(Schwartz and Randall, 2003)*. Whether or not crop production will increase depends not only on CO_2 and rainfall but also on the temperature of the region, cropping patterns, available nutrients, and other factors including the presence of pests.

A major concern for future agricultural production is the rate of climate change. If the change is gradual, farmers and society will have time to reorganize and adjust. Similarly, with slow climate changes natural biota will have time to adapt. However, even a relatively minor change, such as 0.1 degree per decade, will create immense difficulties not only for agriculture and forestry but also for all species in the natural ecosystem.

Temperature and rainfall patterns vary from year to year and from region to region throughout the

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world. Small changes in mean climatic conditions may result in relatively large changes in the frequency of climatic extremes, including heat waves, floods, and droughts. If global warming increases variability in weather patterns, agriculture, forestry and the entire natural ecosystem will suffer *(Schwartz and Randall, 2003)*.

Effects of Temperature Rise on Crops

Any attempt to project the influence of global warming on crops relies on many assumptions, including that central North America will be hotter and more dry while Africa will be warmer and more moist. Assessing the impact of temperature and moisture changes on crops also depends on the degree of change and the stage of growth during which the crop is exposed to drought or overheating. Flowering and fruiting stages are often quite sensitive. In addition, temperature and rainfall timing and intensity vary from year to year and from region to region, and the expected increase in variability can have unfavorable impacts on crop production. Furthermore, temperature and rainfall patterns associated with climate change are expected to interact in a complex manner with atmospheric gases, fertilizers, soil organic matter, as well as with beneficial and pest organisms.

Earlier it was mentioned that lowering the average global temperature by less than 1 degree was associated with June frosts and widespread crop losses, whereas raising the temperature by only 0.6°C would extend the frost-free growing season in the U.S. Corn Belt by two weeks. However, if temperatures continue to increase beyond a threshold specific to each crop, the growing season of the crop will tend to become shorter and yields will be reduced.

Each crop has optimal microclimate temperatures and an optimal length of growing season for maximum production, as summarized in Table 1. Although rice, for example, grows best at 30-33°C during fruiting and requires a minimum daily average of at least 18°C, some varieties can tolerate relatively high temperatures of 40°C with minimal adverse effects.

In contrast, the potato is a cool-weather crop that grows best at temperatures between 15°C and 20°C. Accordingly, when temperatures average above 28°C, potato yields decline significantly *(Table 1)*. Corn, wheat, and soybean also have optimal microclimate temperatures as well as maximum and minimum temperatures for production. Recognition of these specific optimal levels will enable farmers to manipulate the mix of crops that they grow in response to the changing temperature conditions of their region. However, modifying the types of crops cultivated will not guarantee that the same amount of food will be produced or that farmers will receive the same profits as before the change.

Effects of Changing Moisture Levels on Crops

Rainfall is the major limiting factor in crop and natu-

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ral plant growth and plant production worldwide *(Pimentel, et al., 2004)*. Adequate moisture is critical for plants, especially at seed germination and during fruit development. Irrigation water for crops is pumped from rivers, lakes, and aquifers. Of all the water pumped in the United States, about 80% is pumped for irrigation in agriculture. When rainfall is insufficient, irrigation may deliver the needed water, but this may be expensive ($450 per hectare per year for pumping costs) *(Pimentel, et al., 2004)*. In the United States on average about 10 million liters per hectare of water are applied while irrigating various crops during the growing season. This is in addition to the natural rainfall for the region.

Moisture is extremely important because crops transpire enormous amounts of water. For example, during the growing season high-yielding corn (9 tons per hectare per year) will transpire about 5 million liters (1 million liters = 100 mm water depth) of water per hectare.

In addition to the 5 million liters of water that corn transpires when yielding about 9 tons per hectare of grain each growing season, corn needs considerably more water from either rainfall or irrigation because some water evaporates, some percolates through the soil out of reach of plant roots, and some is lost through runoff. In general, corn does best with about 1,260 mm (about 50 inches) of rainfall per year under relatively moist conditions.

Rice transpires about 6 million liters of water per hectare and usually produces the highest yields under flooded conditions. Although sprinkler-irrigated rice requires up to 1,400 mm less water per growing season than flooded cultivation, water use efficiency of wetland paddy is often higher because of the higher yields of paddy rice.

Table 1
Favorable temperatures (in degrees C) for five crops and their growing seasons

Crop	Optimal Temperatures	Growing Season (days)
Corn	22-25	100-130
Wheat	20-25	95-110
Rice	30-33	98-107
Potato	15-20	120-125
Soybean	25-28	90

Fortunately, both wheat and soybeans can be grown with relatively little rainfall, ranging as low as 300-400 mm per year. However, both crops do best and produce maximum yields when rainfall levels are higher. Potatoes in particular require the largest amount of water *(Table 3)*. Because of its high energy usage, irrigation is costly in terms of both energy and dollars. For example, pumping costs for rice irrigation in California costs from $500 to $1,000 per hectare depending on the dimensions of the well and the power source employed. Note that irrigation depends not only on fossil fuels but also on adequate supplies of water, which in turn depend on

Irrigation water for crops is pumped from rivers, lakes, and aquifers. Of all the water pumped in the United States, about 80% is pumped for irrigation in agriculture.

Table 2
Moisture requirements and rainfall levels for five crops

Crop	Yield (t/ha)[a]	H_2O/ kg dry[b]	Annual Rainfall (mm) Range cultured[b]	Annual Rainfall (mm) High yields[b]
Corn	9	700	300-4,000	1,260
Wheat	4	600	300-2,500	870
Rice	6	1,000	500-4,200	1,000-1,800
Potato	40	1,000	300-4,600	2820
Soybean	3	2,000	400-4,100	1.000

[a] USDA 2009
[b] Pimentel, et al., 2004.

rainfall.

Another factor that influences the moisture requirements of a given crop is the level of fertilization used. High rates of fertilizer application increase moisture requirements for rice. Rice is particularly sensitive to moisture stress during the tillering (sprouting from the main stalk) stage (0-20 days after transplanting) and during flowering (40-60 days after transplanting). Heavily fertilized rice will suffer more if moisture is insufficient during these periods than if water levels are adequate. In general, fertilization tends to reduce the amount of water needed per unit of yield, but increases the total amount of water transpired by the crop.

Benefits of Increased Carbon Dioxide

Carbon dioxide is an essential compound in photosynthesis and increases water use efficiency in plants *(Goudriaan and Unsworth, 1990)*. Therefore, increasing levels of CO_2 in the atmosphere should improve the rates of growth and utilization of water by many crops, other factors being equal. Doubling the preindustrial CO_2 level (to about 600 ppm) in the atmosphere as an isolated factor is projected to increase crop yields significantly, based on laboratory studies of crops cultivated under favorable controlled conditions *(Table 3)*. Under field conditions, however, such CO_2 increases probably will not result in a major increase in crop yields because the mixing of all the dominant air components surrounding the plants diminishes the CO_2 photosynthesis enhancement *(Martin, et al., 1989)*. This will reduce the beneficial effects of CO_2; thus, the estimated increase in yields would be only one-quarter to one-third that of the controlled greenhouse conditions potential, without considering the other deleterious climate changes under field conditions *(Table 3)*.

Although some plant species benefit greatly from high levels of CO_2 in the atmosphere, other plant species benefit much less. As expected, C4 plants (e.g., corn) would not benefit as much as C3 plants (e.g., soybean) from increased levels of CO_2 *(Carbon Dioxide Review, 1982)*. Under high levels of carbon dioxide, C3 plants may achieve photosynthetic rates equal to those typical of C4 plants.

Sixteen out of 20 of the most important world food crops have C3 photosynthetic pathways; thus increased CO_2 levels would benefit these crops. However, 14 out of 18 of the world's most noxious weeds have C4 pathways and therefore should be at a slight disadvantage compared with C3 crops.

Increased CO_2 levels reduce the nitrogen-nutrient concentration while increasing the carbon-nutrient concentration in plants, thereby altering insect herbivore feeding responses *(Strain and Bazzaz, 1983)*. For example, the soybean looper con-

Table 3
Percentage increase in crop yields from doubling carbon dioxide to 600 ppm under greenhouse and field conditions

Crop	Greenhouse Conditions	Field Conditions
Corn	16[a]	5[b]
Wheat	30-43[a,c]	10[b]
Rice	9[a]	3[b]
Potato	2[a,d]	0[b]
Soybean	32[e]	10[b]

[a] UNEP (1987).
[b] Estimated.
[c] Wiks (1988).
[d] Wheeler and Tibbitts (1989).
[e] Allen (1989).

sumed more soybean leaf material when soybean plants were grown under high CO_2 concentrations *(Lincoln, et al., 1984, 1986)*. A similar higher feeding rate occurred with other lepidopterans, including *Trichoplusia ni* feeding on lima beans *(Osbrink, et al., 1987)*, *Spodoptera eridania* feeding on peppermint *(Lincoln and Couvet, 1989)*, and *Junonia coenia* feeding on *Plantago lanoeo-lata (Fajer, et al., 1989)*. Although the larvae ate more plant material, they grew significantly slower, and mortality in young larvae was nearly three times higher than the larval group raised on control plants. Thus, the higher mortality in young larvae may more than offset the effect of their increased feeding rate. For sucking insects, such as whiteflies that feed on sap, there appears to be no effect when fed cotton grown under high levels of CO_2 *(Butler, 1985; Butler, et al., 1985)*.

High levels of CO_2 may compensate for other environmental deficiencies. Plants grown under high CO_2 can tolerate greater water stress conditions. For instance, under controlled greenhouse conditions, increasing CO_2 levels may completely compensate for limited water stress *(Martin, et al., 1989)*. For some crops like wheat, high levels of CO_2 may compensate for limited amounts of soil nitrogen.

Although the projected increase in yields associated with CO_2 increases in at least two of the crops (soybean and wheat) appears to be encouraging, the situation with corn, rice, and potatoes does not *(Table 3)*. Then too, the beneficial effect of CO_2 increase with soybean and wheat may be more than offset by the related increase in moisture stress caused by low rainfall, high temperatures, and increased pest attack associated with global warming. Also, the increase in cloud cover because of higher global temperatures is projected to limit photosynthesis and result in reduced crop production *(Allen, et al., 1990)*.

Pest Attack and Projected Climate Change

Worldwide pre-harvest crop losses to pests are currently estimated to be about 40%, with about 13% lost to insects, 12% to diseases, and 12% to weeds. Crop losses to pests in the United States average 37%, with about 13% lost to insects, 12% to diseases, and 12% to weeds. Although the U.S. average for crop losses to pests is 37%, the average crop loss to pests for U.S. corn, potato, rice, soybeans, and wheat is 32% and ranges from 25% for soybeans to 39% for wheat *(Table 4)*. The average loss for the same crops in Africa is 45%, ranging from 37% for rice to 55% for potato *(Table 4)*. The cooler and higher rainfall climate and improved pest control in the United States are probably the primary reasons for the current significantly lower crop losses to pests compared with Africa.

If global warming raises the temperature 2°C in the United States and somewhat less in Africa, ecological conditions for insect growth and abundance are expected to improve. During a growing season some insect pests produce 500 progeny per female every two weeks, whereas others produce up to 3,000 progeny in only a single generation during the growing season *(Metcalf, et al., 1962)*. Raising the temperature by 2°C will lengthen the breeding season and increase the rate of reproduction, and in turn the

Table 4
Current losses to pests in North America and Africa with projected losses for corn, potato, rice, soybean and wheat after global warming
Projected percentage crop losses are estimates.

Crop	North American Current (%)	North American Projected (%)	African Current (%)	African Projected (%)
CORN				
Insects	12	15	27[a]	27
Diseases	10	7	10[a]	11
Weeds	10	15	14[a]	15
Total	**32**	**37**	**51**	**53**
POTATO				
Insects	6	10	20[b]	21
Diseases	20	15	25[b]	25
Weeds	7	10	10[b]	12
Total	**33**	**35**	**55**	**58**
RICE				
Insects	4	5	14[a]	15[c]
Diseases	6	6	10[a]	9[d]
Weeds	19	20	14[a]	14[e]
Total	**29**	**31**	**38**	**38**
SOYBEAN				
Insects	3	6	10[b]	7[f]
Diseases	7	6	12[b]	13
Weeds	15	17	15[b]	17
Total	**25**	**29**	**37**	**37**
WHEAT				
Insects	6	8	16[a]	13
Diseases	20	15	6[a]	14
Weeds	13	15	24[a]	24
Total	**39**	**38**	**46**	**51**

[a] Azraq (1987). [b] Cramer (1967). [c] Singh and Chandra (1967); Alam (1971).
[d] Ou (1985); Azraq (1987); Kato, (1976); Asai, et al. (1967).
[e] Schiller and Indhapun (1979); Seaman (1983); Tanaka (1976); Pons (1982); Nussbaum, et al. (1985).
[f] International Centre of Insect Physiology and Ecology (1987, 1988).

total number of insects attacking the crop, and subsequently increase crop losses. In addition, some insects, such as the southwestern corn borer, will be able to extend their range northward because of the warming trend *(Chippendale, 1979)*.

Overall losses due to insects are higher in the warmer regions. For example, losses to potato insects in northern Maine average only 6%; however, in Virginia under warmer conditions potato losses to insects average about 15%, despite the fact that more insecticide is applied in the southern region *(Zehnder, 1989)*. Under the projected warming trend in the United States, we can expect an increase anywhere from 25% to 100% in losses to insects depending on the crop *(Table 4)*. Because crop losses to insects are already relatively high, the projected changes in losses to insects for different crops in Africa range from —30% for soybeans to +7% for rice *(see Table 4 for explanation)*. The warm, moist conditions of West Africa are ideal for insect pests and crop diseases *(Virmani, et al., 1980)*.

Under the warmer but drier climatic conditions projected for North America, crop losses due to plant diseases are expected to decline as much as 30% below current levels *(Table 4)*. However, under the wetter conditions projected for Africa, the expectation is that crop losses to diseases will increase up to 133% above current levels for some crops *(Table 4)*.

Although most weeds are C4 types (eg. corn), the projected warmer/drier conditions in the United States are expected to increase losses caused by weeds because of increased competition by weeds for moisture, nutrients, and light *(Table 4)*. This is anticipated because the climatic change will stress crops and will intensify competition from weeds, which are better adapted to arid conditions than crops. In addition, herbicidal controls are less effective under hot/dry conditions than the usual cool/wet conditions; however, mechanical cultivation is more effective under hot/dry conditions.

Another problem associated with herbicides applied under arid conditions is that they accumulate in the soil, which can lead to serious environmental and agricultural problems *(Ward, et al., 1989)*. Overall, U.S. crop losses to weeds are projected to rise between 5% and 50% for the selected crops, depending on the crop *(Table 4)*. Similarly, the warm/moist conditions projected for Africa are expected to increase crop losses to other pests, like insects and plant pathogens *(Table 4)*. Some insect, plant pathogen, and weed pests are expected to increase, whereas others are expected to decrease *(Table 4)*. The projected warm/moist conditions for Africa will probably increase some insect pests, some plant pathogens, and some weeds.

In addition, the increase in atmospheric carbon dioxide is expected to alter the nutritional makeup of crops, as mentioned, thereby affecting the severity of attack from insects and disease organisms. While the impact of this alteration has not been quantified, some studies document that certain caterpillars eat more but have a higher mortality on plants grown under high CO_2 conditions (see the section on $CO_2$and plants). Plant pathogens can be expected to react in a similar manner because pathogens respond with increased vigor to improved nutrition in

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the plant. Therefore, increases in crop losses from insects and diseases because of nutritional changes in host crops are projected to be minimal.

In summary, crop losses to pests in North America under warmer/drier conditions and higher carbon dioxide conditions are projected to increase pest losses from an average of 32% to 34% for the five selected crops (corn, potato, rice, soybean, and wheat) *(Table 4)*.

Although the projected climatic conditions in Africa are different from those in North America, crop losses to pests are expected to increase from an average of 45% to 46% under the projected warm/moist conditions and higher carbon dioxide conditions. The high percentages of crop losses to pests are expected to be sustained in Africa because effective pest control technologies are not extensively in use nor are they expected to improve appreciably in the future.

Conclusion

The extensive burning of fossil fuels and forests appears to be increasing the level of CO_2 and other greenhouse gases in the atmosphere, and this raises several ethical issues. Clearly there is an urgent need to reduce fossil fuel consumption and deforestation to slow global warming. Reducing fossil fuel will at the same time conserve this vital resource and controlling deforestation has other benefits, including conserving biological diversity.

Most meteorologists and physical scientists conclude that the continued increase in CO_2 and other greenhouse gases will warm the earth from 1.5°C to 4.5°C by the middle of the next century. The precise rate, extent, and regional variations are difficult to predict; however, negative impacts are generally projected. Further, alterations in the ozone layer will have negative impacts on some crops. Thus, the projected climate changes are expected to have major impacts on crop production.

The overall changes in temperature, moisture, carbon dioxide, insect pests, plant pathogens, and weeds associated with global warming are projected to reduce food production in North America. The extent of alterations in crop yields will depend on each crop and its particular environmental requirements. However, the implementation of improved agricultural technologies could partially offset this anticipated decrease in yields.

In Africa, the projected rise in rainfall associated with global warming is encouraging, especially since Africa already suffers from severe shortages of rainfall. Therefore, the 10% increase in rainfall will help improve crop yields to a limited extent, but it will not solve Africa's food problems. Water shortages are projected to persist and serious crop losses to pests are expected to continue. In addition, development in Africa is expected to continue to remain slow because of rapid population growth and serious economic and political problems.

Further research is needed on the potential impacts of global climate change on crop production in North America, Africa, and other regions of the world. Additional research is needed on the rate of degradation of soil, water, and biological resources

The extensive burning of fossil fuels and forests appears to be increasing the level of CO_2 and other greenhouse gases in the atmosphere, and this raises several ethical issues.

and their potential impact on crop production and the interrelationship with global warming. In addition to the projected global warming, there is need for agriculture in North America and Africa to adopt sound ecological resource management practices, especially soil and water conservation. This would benefit agriculture, the environment, farmers, and society as a whole. Sustainable agricultural policies will not only enable agriculture to remain productive, it will help offset some of the negative impacts that global warming is projected to have on food production and the quality of life.

Related to both global warming and world environmental degradation, the adoption of sound ecological practices in agriculture is imperative. Therefore, we should take steps to improve production and conserve vital soil, water, energy, and biological resources. Fortunately, there is a growing interest in sustainable agriculture by farmers, scientists, and society as a whole *(Paoletti, et al., 1989)*. At the same time, more research is needed concerning the complex effects of potential global climate change on a wide variety of crops under a wide range of environmental conditions and on new technologies that might be utilized in agricultural production.

To even attempt to feed the world population an adequate diet in the future and maintain the integrity of the natural ecosystem, we must conserve resources, reduce deforestation, halt human population growth, and protect soil, water, and biological resources. Numerous ethical issues are related to these needed changes for improved food production and environmental protection.

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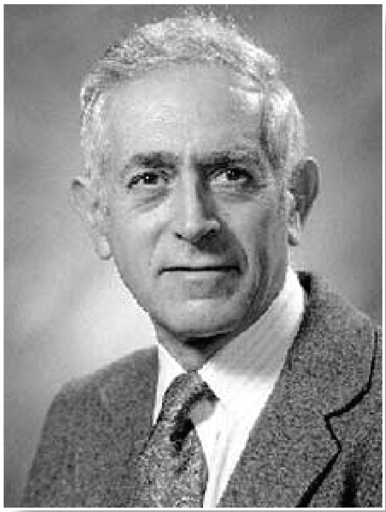

Dr. Pimentel writes and lectures extensively on ecology and ecological economies, as well as on the impacts of chemical pesticides. He has acted as an advisor in the public and private sectors both here and abroad and has served on numerous boards of the National Academy of Sciences. He has served as President of the Rachel Carson Council.

RACHEL CARSON COUNCIL, INC.
8600 Irvington Avenue
Bethesda, MD 20817
Phone: 301-214-2400
E-mail: office@rachelcarsoncouncil.org
www.rachelcarsoncouncil.org

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