Ethical Issues Concerning Potential Global Climate Change on Food Production

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Abstract *Burning fossil fuel in the North American continent contributes more to the CO_2 global warming problem than in any other continent. The resulting climate changes are expected to alter food 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. However, in Africa, the projected slight rise in rainfall is encouraging, especially since Africa already suffers from severe shortages of rainfall. For all regions, a reduction in fossil fuel burning is vital. Adoption of sound ecological resource management, especially soil and water conservation and the prevention of deforestation, is important. Together, these steps will benefit agriculture, the environment, farmers, and society as a whole.*

Keywords: climate change, food, agriculture, ethics, technologies.

Introduction

The projected changes in climate associated with global CO_2 increases are expected to alter world food production (Brown, 1988; Sinha et al., 1988). Although present agricultural production provides food for more people than ever before, the number of malnourished humans (1.6 billion) is also greater than ever (Kates et al., 1989). Demographers project that the world population will rise from the present 5.4 billion (Population Reference Bureau, 1991) to approximately 9.4 billion by 2025, and might reach 15 billion by 2100 (Population Crisis Committee (PCC), 1989). Equally alarming is the current 1.8% annual population growth rate — a rate about 1800 times greater than during the first million years of human existence. More than a quarter of a million people are added each day and each individual requires food, shelter, and fuel.

Terrestrial ecosystems supply about 98% of all world food, especially protein, while aquatic ecosystems supply the remaining 2% (Waggoner, 1984). 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 (Grissim, 1989).

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 (World Resources Institute (WRI), 1992; Worldwatch, 1992). The pressure of population escalation, when coupled with anticipated climate changes, can only exacerbate the task of providing adequate food for humans (Daily and Ehrlich, 1990). 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 (George, 1984; Ehrlich et al., 1989; Durning, 1990; World Bank (WB), 1990).

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 15 million hectares of land annually (Pimentel et al., 1992), which is replaced by clearing valuable forests (Pimentel et al., 1986; Lal, 1992).

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 (Schneider, 1989a) and planting of additional trees (Trexler et al., 1989) 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 in other areas. These changes, including extreme climatic events, are expected to bring about many shifts in world food production (Mearns, 1989). 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 will probably be negative (Department of Energy (DOE), 1989; Hansen et al., 1989; Schneider, 1989a,b; Ward et al., 1989). The anticipated global climatic change is projected to reduce cropland by about 33% (Flavin, 1989; Schneider, 1989a) 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 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 (National Academy of Sciences (NAS), 1989a; Schneider, 1989a; Tans et al., 1990). 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 more than 350 ppm today and are expected to reach 400-600 ppm by the year 2035 (NAS, 1983; Ramanathan, 1988; Schneider, 1989a,b). However, 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 (Abrahamson, 1989). Fossil fuel burning has contributed 50–66% of the more than 175 billion tons of anthropogenic CO_2 released into the atmosphere since the Industrial Revolution (Woodwell et al., 1983). Of this amount, approximately two-thirds of the total human contribution has been released in just the past 35 years (DOE, 1989). In fact, the present releases of CO_2 from fossil fuels amount to approximately 5-6 billion tons/yr (Woodwell et al., 1983; MacDonald, 1988). The United States consumes and burns about 31% of all the fossil fuel burned in the world (US Bureau of Commerce, 1990). Other developed nations are also major contributors because, like the United States, their transportation, industry, agriculture, and citizens use enormous amounts of energy. The Toronto conference urged a 20% reduction in CO_2 emissions by 2005. Public policy must bring about fossil fuel conservation if we are to avert catastrophic climate changes (Postel, 1990).

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 ha of forests are cleared and burned throughout the world each year, while only 1 million ha are reforested (Myers, 1989; WRI, 1990). 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; Postel and Heise, 1988). 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% (Milne, 1988). Presently, only about 1 billion hectares of tropical forest remain (Henderson-Sellers et al., 1988). At this rate of forest destruction (Myers, 1988, 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 et al., 1986), both for expansion and to replace land that is lost during rapid erosion (Pimentel et al., 1987). More specifically, topsoil is being removed from cropland about 30 times faster than soil is being formed (Pimentel et al., 1987). 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 (Kellogg and Schware, 1981; NAS, 1983).

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 and for other operations associated with food production and for other purposes; most require some fuelwood 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 (Kellogg and Schware, 1981; Schneider, 1989a). 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, but it must be done. Fossil fuel is used to produce food and provide services, especially in industrialized nations, but several opportunities exist for conservation (Energy Research Advisory Board, 1982; Pimentel and Hall, 1989; NAS, 1990; US Congress, 1990). Worldwide, forests are being rapidly removed for agricultural expansion (Henderson-Sellers et al., 1988). Soil degradation continues, with little governmental concern evidenced in the United States or elsewhere in the world (Office of Technology Assessment, 1982; Pimentel, 1992). Unfortunately, no political or social approach has been developed that limits rapid world population growth (Keyfitz, 1989; PCC, 1989). Also, some politicians and others argue that we should not act to remedy climate change without further research of the global warming problem (Rogers and Fiering, 1989; Bush, 1990a,b; Lindzen, 1990).

Projected Climate Changes

In 1985 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-11, CFC-12, CH_4, N_2O, O_3) 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 (Bolin et al., 1986). 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 (IPCC, 1990). 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 (Holdren, 1990; IPCC, 1990).

Jones et al. (1986), Hansen and Lebedeff (1987), Ramanathan (1988), Schneider (1989a), Nierenberg et al. (1989), Abelson (1990) and the IPCC (1990) 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 during the century were in the 1980s (Kerr, 1990). Furthermore, Lachenbruch and Marshall (1986) have found that the permafrost surface in the Arctic had warmed 2–4 °C during the last few decades of the century. Although the temperature increase seems indicative of global climate change, others question whether a significant global temperature increase has occurred attributing the warming to natural climate variability (DOE, 1989; Nierenberg, 1990; Watt, 1990).

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 (Houghton and Woodwell, 1989). 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 (IPCC, 1990), especially the eastern portion (Kellogg and Schware, 1981; IPCC, 1990), and decrease in others such as the central portion of the United States (Hansen et al., 1989; Waggoner, 1990).

Although all of the projected climate changes appear small based on averages, such small changes can have a major impact on the world ecosystem (Stommel and Stommel, 1979). 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 (UNEP, 1987). 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 widespread crop failures (Stommel and Stommel, 1979).

About 6000 years ago average temperatures were about 1 °C warmer than they are now, and as a result the climate was markedly different (UNEP, 1987). 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 (Kellogg and Schware, 1981; UNEP, 1987). In contrast, the US corn belt was a dry prairie during this period (Kellogg and Schware, 1981).

For this study we assume 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 (Kellogg, 1977; Gribbin, 1981; Wisconsin Energy News, 1988; Keepin, 1989). Rainfall patterns, especially in eastern and northern Africa, are projected to average about 10% higher than present (Gribbin, 1981; Kellogg and Zhao, 1988).

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 (IPCC, 1990). In fact, the Food and Agriculture Organization (1986) projects that many African countries are too dry to attain food self-sufficiency by

2000 even when present irrigation projects are 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 (Rind, 1988) and increase transpiration rates in plants (Janick, 1986). Increased wind speeds will accelerate evaporation and transpiration rates and soil erosion (Hansen et al., 1989; Mabbutt, 1989), resulting in less soil moisture (Houghton and Woodwell, 1989). Crops grown under hot, arid conditions use 20–40% 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 (Manabe and Wetherald, 1986; 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 (MacDonald, 1988; Ward et al., 1989). 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 (Rosenzweig and Daniel, 1989).

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 for all species in the natural ecosystem (Jaeger, 1988; Woodwell, 1989a,b).

Temperature and rainfall patterns vary from year to year and from region to region throughout the world. Mearns et al. (1984) and Revelle (1989) reported that 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 (White, 1985; Sahn, 1989).

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 drier while Africa will be warmer and wetter. 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 we mentioned that lowering the average global temperature by less than one degree was associated with June frosts and widespread crop losses (Stommel and Stommel, 1979), whereas raising the temperature by only 0.6 °C would extend the frost-free growing season in the US corn belt by 2 weeks (Malone, 1974). 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 (Monteith, 1981).

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 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 natural plant growth and primary production worldwide (Falkenmark, 1989a). Adequate moisture is critical for plants, especially at seed germination and during fruit development (Shaw, 1980). Irrigation water for crops is pumped from rivers, lakes, and aquifers. Of all the water pumped in the United States, 15% is consumed by industry and the public (NAS, 1989a). The remaining 85% is consumed by agricultural irrigation, even though only 12% of US cropland is irrigated. When rainfall is insufficient, irrigation may deliver the needed water, but this may be expensive ($450/ha/yr for pumping costs) (Pimentel et al., 1982). In the United States on average about 10 million liters/ha of water are applied while irrigating various crops during the growing season (Postel, 1989). 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 will transpire about 4.2 million liters (1 million liters = 100 mm) of water per hectare (Leyton, 1983; Tripathi et al., 1986). The production of 1 kg of the following food and fiber products under irrigation in California requires: 1400 liters for corn; 4700 liters for rice; and 17,000 liters for cotton (Ritschard and Tsao, 1978).

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

	Temperatures (C)			Growing season (days)
	Optimal	Maximum	Minimum	
Corn	22-25[a,b,c,d]	32-34[a,e]	<20	100-130[f,g]
Wheat	20-25[h,i,j]	38[k]	5[k]	95-110[g,l]
Rice	30-33[m,n,o]	37-40[n,p]	18-22[m,n,q]	98[r]-107[m]
Potato	15-20[s,t,u]	28-34[t]	12[t]	120-125[v]
Soybean	25-28[w,x,y,z]	37-40[y,a′]	10-14[b,x,b′]	90

[a]Shaw (1980).
[b]Thompson (1975).
[c]Lee and Estes (1982).
[d]Willis et al. (1957).
[e]Walker (1969).
[f]Brown (1976).
[g]Ladd et al. (1902).
[h]Fabriani and Lintas (1988).
[i]Cloele and Kritzinger (1984).
[j]Cao and Moss (1989).
[k]Brown and Cocheme (1969).
[l]Kettunen et al. (1988).
[m]Adair et al. (1962).
[n]De Datta (1981).
[o]Nuttonson (1965a,b).
[p]Copeland (1924).
[q]Yoshino et al. (1988).
[r]Tropical Agricultural Research Center (1987).
[s]Yamaguchi and Spurr (1964).
[t]Ng and Loomis (1984).
[u]Menzel (1983).
[v]World Potato Facts (1982).
[w]Trang and Giddens (1980).
[x]Seddigh and Jolliff (1984).
[y]Mederski (1983).
[z]Raper and Kramer (1987).
[a′]Temu (1980).
[b′]Munevar and Wolum (1982).

In addition to the 4.2 million liters (420 mm) of water that corn transpires when yielding about 7 t/ha 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 1260 mm of rainfall per year under relatively moist conditions. However, under arid conditions up to five times more water would be needed to produce the same amount of biomass (Falkenmark, 1990) (Table 2).

Rice transpires about 6.2 million liters of water/ha (Leyton, 1983) and usually produces the highest yields under flooded conditions. Depending on the quantity of water used, the incidence of pests, and soil conditions, rice yields are on average up to 50% higher under flooded conditions than rice grown under sprinkler irrigation (McCauley et al., 1985; Westcott and Vines, 1986). Although sprinkler-irrigated rice requires up to 1400 mm less water per growing season than flooded cultivation (Dabney and Hoff, 1989), water use efficiency of wetland paddy is often higher because of the higher yields of paddy rice (Prasad and Sharma, 1984). A 15% decline in rainfall is reported to reduce rice yields from 3% (paddy) to 30% (upland) below current production levels (Van Dat, 1986).

Fortunately, with irrigation, both wheat and soybeans can be grown with relatively little rainfall, ranging as low as 300–400 mm per year (Table 2). However, both crops do best and produce maximum yields when rainfall levels are higher. Potatoes in particular require the largest amount of water (Table 2).

Applying large amounts of water by irrigation requires the expenditure of large amounts of fossil energy. For example, to irrigate one hectare of corn, while pumping water from a depth of only 30 m, requires more than twice as much energy as

Table 2
Moisture requirements and rainfall levels for five crops

	Yield (t/ha)	H_2O (mm) requirements†	Annual Rainfall (mm) Range cultured	High yields‡
Corn	7	420[a]	300-4000[b]	1260[a]
Wheat	4	290[a]	300-2500[b]	870[a]
Rice	6	620[a]	500-4200[b]	1000-1800[cde]
Potato	35	940[a]	300-4600[b]	2820[a]
Soybean	3	360[a]	400-4100[b]	1000[f]

[a]Calculated based on data from Leyton (1983).
[b]Duke (1978).
[c]Grist (1986).
[d]Grummer (1970).
[e]De Datta (1981).
[f]Estimated.
†Water required during growing season under relatively moist conditions. Under arid conditions water requirements may be 2–5 times higher.
‡Minimum rainfall for high crop yields. Under arid conditions water requirements may be 2–5 times higher.

producing the same amount of corn using rainfed agriculture (Pimentel and Burgess, 1980). Because of its high energy usage, irrigation is costly in terms of both energy and dollars. For example, pumping costs for rice irrigation in Louisiana range from $68 to $239/ha depending on the dimensions of the well and the power source employed (Salassi and Musick, 1983). Note that irrigation depends not only on fossil fuels but also adequate supplies of water, which in turn depend on 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 (Cherian et al., 1968). Rice is particularly sensitive to moisture stress during the tillering stage (0–20 days after transplanting) and during flowering (40–60 days after transplanting) (Prasad and Sharma, 1984). 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 (Singh and Mehta, 1938; Wilson et al., 1971).

Effects of Ultraviolet Radiation on Crops

The ozone layer is being diminished particularly by the release of chlorofluorocarbon chemicals (Beggs et al., 1986). Generally, for each 1% decrease in the ozone layer, there is a 2% increase in ultraviolet radiation reaching the earth (Murali and Teramura, 1986). Investigations on the effect of ultraviolet-B (UV-B) radiation indicate that approximately two-thirds of 300 species and cultivars examined in a recent study appear to be susceptible to damage from increased UV-B radiation (Teramura and Sullivan, 1989). Yields of soybeans, the most susceptible of the crops investigated were reduced 20% with a 25% ozone depletion (Teramura and Sullivan, 1989). As expected, different varieties of soybeans respond differently to ultraviolet radiation (Teramura and Murali, 1986).

Although both wheat and rice produce significantly more grain under elevated CO_2 conditions, when both crops were grown under combined elevated UV-B and CO_2 no increase in grain yield occurred (Teramura et al., 1990). Increased UV-B thus negates any positive response to high CO_2. Surprisingly, soybean produces net gains under conditions of both elevated CO_2 and UV-B radiation (Teramura et al., 1990).

Although some crops may tolerate UV-B radiation in terms of growth, they may become more susceptible to plant pathogens. For example, although wheat seems to be relatively tolerant to ultraviolet-B radiation, Red Hard disease infection rates in wheat increased from 9% to 20% when experimental UV-B is increased from 8% to 16% above ambient levels (Biggs and Webb, 1986). Disease rates in rice have also been reported to increase when rice is exposed to higher UV-B radiation than normal (Holman, 1990). Also, cucumbers exposed to UV-B were found to be more susceptible to fungal diseases (*Colletotrichum lagenarium* and *Cladosporium cucumerinum*) than those grown under ambient UV-B levels (Orth et al., 1990).

Benefits of Increased Carbon Dioxide

Carbon dioxide is an essential compound in photosynthesis and increases water use efficiency in plants (Martin et al., 1989; 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; we thus estimate an increase in yields to 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, C_4 plants (e.g., corn) would not benefit as much as C_3 plants (e.g., soybean) from increased levels of CO_2 (Carbon Dioxide Review, 1982). Under high levels of carbon dioxide, C_3 plants may achieve photosynthetic rates equal to those typical of C_4 plants.

Sixteen out of 20 of the most important world food crops have C_3 photosynthetic pathways; thus increased CO_2 levels would benefit these crops (Strain and Cure, 1985). However, 14 out of 18 of the world's most noxious weeds have C_4 pathways and therefore should be at a slight disadvantage compared with C_3 crops.

Increased CO_2 levels reduce the nitrogen-nutrient concentration while increasing the carbon-nutrient concentration in plants (Strain and Cure, 1985)

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

	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).

thereby altering insect herbivore feeding responses (Strain and Bazzaz, 1983). For example, the soybean looper consumed 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 (Carbon Dioxide Review, 1982; Martin et al., 1989).

For some crops like wheat, high levels of CO_2 may compensate for limited amounts of soil nitrogen (Tolbert, 1983). However, high levels of carbon dioxide do not compensate for reduced availability of phosphorus or potassium (Estes et al., 1973; Goudriaan and de Ruiter, 1983).

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 preharvest crop losses to pests are currently estimated to be about 35%, with about 12% lost to insects, 12% to diseases, and 11% to weeds (Pimentel et al., 1987). Crop losses to pests in the United States average 37%, with about 13% lost to insects, 12% to diseases, and 12% to weeds (Pimentel et al., 1991). Although the US average for crop losses to pests is 37% (Pimentel et al., 1991), the average crop loss to pests for US 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 2 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 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 anywhere from a 25% to a 100% increase 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 C_4 types, the projected warmer/drier conditions in the United States are expected to increase losses caused by weeds because of increased competition for moisture, nutrients, and light by weeds (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

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

	North America		Africa	
	Current[†]	Projected	Current	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[c]	14[a]	15[d]
Diseases	6	6[e]	10[a]	9[c]
Weeds	19	20[d]	14[a]	13[e]
Total	29	31	38	37
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]	16
Total	39	38	46	43

[a]Azraq (1987).
[b]Cramer (1967).
[c]Ou (1985), Azraq (1987), Kato (1976), Asai et al. (1967).
[d]Singh and Chandra (1967), Alam (1971).
[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).
[†]Pimentel et al. (1991).

conditions (Pimentel et al., 1991). 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, US 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 pests (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 (Metcalf et al., 1962; Singh and Chandra, 1967), some plant pathogens (Agrios, 1988) and some weeds (NAS, 1968).

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 has not been quantified, some of our 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 the plant (Oka and Pimentel, 1976). 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 losses from an average of 32–34% for the five selected crops (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.

Improved Agricultural Technologies

Several agricultural technologies have already been developed that would help farmers reduce the expected negative impacts of the projected global climate change on crop production in both North America and Africa. If these technologies were put into common use in agriculture, some of the negative impacts of global warming could be offset (Easterling et al., 1989). In addition, the yields of some crops might be increased, especially in Africa. These beneficial technologies include:

Soil and Water Conservation

The high rate of soil erosion now typical of North America and African agricultural land emphasizes the urgency of stemming this loss, which in itself is probably as threatening to sustained levels of continued food production as the projected climatic change. For example, along with the typical 20–30 tons/ha/yr of soil loss in North America and Africa, respectively, substantial amounts of nitrogen and other vital nutrients are also lost (WB, 1989a). Further, optimum soil organic matter, topsoil depth, water-holding capacity (Cornell University, 1987), and soil biota are reduced as soil erodes. Perhaps most important is the loss of 25–33% of rainfall due to increased water runoff and reduced soil water-holding capacity that is associated with erosion (Hoogmoed and Stroosnijder, 1984; Elwell, 1985). Taken together or separately, these factors limit the productivity of the soil and as a result can reduce crop yields from 15% to 30% (Follett and Stewart, 1985; McDaniel and Hajek, 1985; Pimentel, 1992).

A technique that will slow water runoff sufficiently to enhance water infiltration is the placement of lines of rocks across slopes (Falkenmark, 1989a). This technique, plus others including crop rotations, contour planting, strip cropping, polyculture, grass strips, no-till, and agroforestry help prevent erosion and increase soil productivity (Follett and Stewart, 1985; Kidd and Pimentel, 1992).

When sound soil and water conservation practices are followed, erosion rates can be reduced to about 1 ton/ha/yr, which is roughly the rate at which soil is reformed under normal agricultural conditions (Hudson, 1981; Lal, 1984a,b; Elwell, 1985). Adopting soil and water conservation practices would increase crop yields 2–15% in North America and 5–15% in Africa (Table 5). Thus, the adoption and practice of reliable soil and water conservation practices would help make agriculture sustainable and productive in the future (Falkenmark, 1989a; NAS, 1989b).

Improving and Changing Crop Varieties/Biotechnology

Some crop varieties have a slightly greater tolerance of moisture stress than current dominant crops and these might be tested as substitutes for the commonly used varieties. For example, switching from spring to winter wheat in Canada has been suggested as a practical way to deal with increased moisture stress (Parry et al., 1985, 1988).

If a crop like corn can no longer be grown in a region because of low rainfall, it would be possible to substitute crops like sorghum, millet, cassava, sweet potato, or wheat that have lower moisture requirements than corn (Jung, 1978). However, the yield in kilograms of food produced per hectare would probably be lower because substitute crops usually produce less harvestable food than corn. The crop may also be less nutritious as is cassava compared with corn and soybeans.

Plant breeding is expected to improve yields about 1% during the next half century (Table 5). Biotechnology could also be used to develop new crop varieties that require slightly less water, but success will be exceedingly difficult because drought tolerance is a multigenic character and basic photosynthesis requires enormous amounts of water (see the section on moisture and crops). Overall, in North America, we project about a 1% increase in crop yield based on the anticipated contributions of biotechnology during two decades (Duvick, 1989). However, no increase was projected for Africa because no major advances in biotechnology are expected to be applied in Africa in the near future (Table 5).

Crop Rotations

A return to the use of crop rotations in all cropping systems would substantially reduce soil erosion and water runoff and also improve the control of insects, disease, and weeds (Pimentel et al., 1991) (Table 5). Overall, crop rotations have proved to be sound agricultural practices and they should be widely utilized in agriculture (NAS, 1989b).

Table 5
Improved agricultural technologies that might help farmers offset the negative impacts of global climate warming on crop production. (Estimated percentage increase in crop yields because of the adoption of new agricultural technologies by 2030)

	Soil + water conserv.	Improved crop varieties	Improved irrigation	Improved pest control	Bio-technology
			North America		
Corn	15[ab]	2[c]	1[d]	7[e]	1[f]
Wheat	15[ghi]	1[c]	0[dj]	1[e]	1[f]
Rice	2[k]	0[c]	0[d]	0[e]	1[f]
Potato	10[g]	1[c]	1[d]	5[e]	1[f]
Soybean	10[a]	1[m]	1[d]	2[e]	1[f]
			Africa		
Corn	15[ghi]	0[n]	0[op]	5[q]	0[r]
Wheat	15[ghi]	0[o]	0[p]	0[q]	0[r]
Rice	5[s]	2[o]	0[o]	0[q]	0[r]
Potato	15[t]	0[u]	0[p]	0[q]	0[r]
Soybean	10[v]	2[wxy]	0[p]	5[q]	0[r]

[a]Mannering et al. (1985), American Society of Agricultural Engineering (ASAE) (1985), Olson and Nizeyimana (1988), WB (1989b).
[b]Langdale et al. (1985), ASAE (1985), WB (1989b).
[c]CIMMYT (1981).
[d]Pimentel et al. (1982), Salassi and Musick (1983).
[e]Allen (1987).
[f]Based on information from Duvick (1989) and Brown et al. (1990).
[g]Bradle (1984) Benefits of shelterbelts.
[h]US Department of Agriculture (USDA) (1978), WB (1989b) Benefits of soil erosion control including crop rotations.
[i]Papendick et al. (1985), WB (1989b), Hoogmoed and Stroosnijder (1984), Elwell (1985).
[j]The mining of water in several aquifers will have a negative impact on future irrigation.
[k]Rice is grown primarily as paddy rice, therefore the erosion is minimal.
[l]Follett and Stewart (1985), ASAE (1985).
[m]Lal (1976).
[n]Myers (1985).
[o]Dalrymple (1986).
[p]Water shortages will probably continue in Africa.
[q]ICIPE (1987, 1988).
[r]African biotechnology benefits will lag behind efforts in North America.
[s]In contrast to the United States, 70% of Africa's rice is grown as upland rice, therefore rice culture in Africa will benefit from soil and water conservation including crop rotations.
[t]Lal (1992), Hurni (1992).
[u]Beukema and Van der Zaag (1979).
[v]Adisarwanto (1986), Hoogmoed and Stroosnijder (1984), Elwell (1985).
[w]Lawn et al. (1984).
[x]Lal (1984c).
[y]Jackai et al. (1984).

Improved Pest Control

Because insects, diseases, and weeds destroy about 35% of potential crop production in the world, the implementation of appropriate technologies to reduce pest losses would increase crop yields. In addition to the prudent application of pesticides, increased use of a wide array of nonchemical pest controls would help minimize crop losses to pests (Bottrell, 1979; Pimentel et al., 1991). The nonchemical controls include: host plant resistance, crop rotations, biological controls, altering planting dates, altering fertilizer and irrigation applications, soil management and tillage, polyculture, trap crops, and others. One or more of these technologies could help control the projected increase in pest losses and thereby help maintain or increase crop yields in North America and Africa (Table 5).

Irrigation

Irrigation can be used to substitute for reduced rainfall, but only if abundant water and abundant energy resources are available to implement irrigation programs (Batty and Keller, 1980). Excessive overdraft, especially of groundwater, is already a serious problem in many important food producing regions, including the western United States, northern China, parts of India and Mexico (US Water Resources Council, 1979; FAO, 1986; Postel, 1989). Other serious problems associated with irrigation are salinization and waterlogging of the soil (Postel, 1989). All these factors combine to limit increased irrigation from being a sustainable solution to water shortages. In fact, world net irrigated area per capita has been declining since 1978 (Postel, 1990).

Other Technologies

Several other technologies, such as increasing soil organic matter, making effective use of livestock wastes, increasing crop diversity, employing ridge-planting, and use of wind breaks, are feasible ways to reduce the negative impacts of global climate change on agriculture (NAS, 1989b). The technologies listed in Table 5 are those that overall are considered to be most beneficial in minimizing the effects of projected climate change associated with global warming.

Changes in Food Crop Production

In North America the projected alterations in temperature, soil moisture, carbon dioxide, and pests associated with global warming are expected to decrease food crop production as much as 27% (Table 6). The implementation of improved agricultural technologies could partially offset this problem (US Environmental Protection Agency, 1988; Miller and Senft, 1988) (Table 6). Because each of the five crops analyzed varied in their response to climate, pests, and the different technologies considered to offset climate change (Table 6), generalizations are difficult. Therefore, a crop-by-crop analysis is a more valid way to investigate the problem. However, since moisture is vital in all crop production, its decrease is certain to be a major limiting factor in many regions and for many crops grown in North America. Also, heat stress may be a problem for some crops such as corn and potatoes.

Table 6
The overall increase or decrease in crop yields due to temperature, moisture, carbon dioxide, and pests resulting from global warming plus improved technologies

	Current (kg/ha)	Temperature	Moisture	UV-B	CO_2	Pests	Improved technology	Total
			North America					
Corn	7,500[a]	−3%[b]	−20%[b]	− 2%[c]	+ 5%[d]	−5%[e]	+26%[f]	+ 1%
Wheat	2,400[a]	−5[b]	−10[b]	0[c]	+10[d]	+1[e]	+18[f]	+14
Rice	6,300[a]	+5[b]	− 3[g]	− 2[c]	+ 3[d]	−2[e]	+ 3[f]	+ 4
Potato	32,700[a]	−5[b]	−20[b]	− 2[c]	+ 0[d]	−2[e]	+18[f]	−11
Soybean	2,300[a]	+2[b]	−15[b]	−11[h]	+10[d]	−4[e]	+15[f]	− 3
			Africa					
Corn	1,500[i]	0%[b]	+ 5%[b]	− 2%[j]	+ 5%[d]	−2%[e]	+20%[f]	+26%
Wheat	1,700[i]	0[b]	+ 5[b]	− 2[j]	+10[d]	+3[e]	+15[f]	+31
Rice	1,700[i]	0[b]	+10[b]	− 2[j]	+ 3[d]	+1[e]	+ 7[f]	+19
Potato	8,800[i]	−5[b]	+ 5[b]	− 2[j]	+ 0[d]	−3[e]	+15[f]	+10
Soybean	1,100[i]	0[b]	+ 5[b]	−11[h]	+10[d]	−0[e]	+17[f]	+21

[a]USDA (1989).
[b]Estimates based on review of the data in Table 1 and data in Department of Transport (1975), Williams (1978), Waggoner (1983), National Defense University (1986), Smit et al. (1988), and Rosenberg et al. (1989).
[c]Estimated.
[d]See Table 3.
[e]See Table 4.
[f]See Table 5.
[g]Van Dat (1986).
[h]Teramura and Sullivan (1989).
[i]FAO (1988).
[j]Estimated.

In Africa, the picture is different because of projected increased rainfall, at least in East Africa. The analysis of the five crops suggests an increase in yields, if rainfall increases and improved agricultural technologies are adopted (Table 6). Even this projected increase in crop yields from 10% to 31% (Table 6) will not be sufficient to provide adequate food for the African population in the future with current climate and resource management technologies (Ogallo, 1984; FAO, 1986; Stiles and Brennan, 1986; Brown and Thomas, 1989; Falkenmark, 1989a,b). In addition, providing adequate food supplies per capita in several African countries will be exceedingly difficult because of the self-serving political and economic policies of some African and western nations vis à vis food production, food aid, and the plight of the rural poor (George, 1984; Durning, 1990).

Table 6 contains estimates based on available data concerning five crops and based on various assumptions concerning projected temperature and moisture patterns in North America and Africa. In addition, no attempt was made to factor in periodically extreme climatic events, which generally have a negative impact on crop production and can be severe. For example, either or both temperature and moisture stress of a crop at fruiting can significantly reduce yields, even if average temperature and moisture conditions appear favorable. Also, assessing the synergistic interactions of temperature, moisture, UV-B, CO_2, pests, and technological change is most difficult and no attempt was made to investigate the potential interactions.

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 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 (WB, 1990).

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 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 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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