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IMPLICATIONS OF POLICIES TO PREVENT CLIMATE CHANGE FOR FUTURE FOOD SECURITY

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ABSTRACT

Implications of Policies to Prevent Climate Change for Future Food Security

Measures to reduce the use of fossil fuels, suppression of on-farm emissions of methane (CH_4) and nitrous oxide (N_2O), afforestation, and geoengineering "fixes" have been proposed to mitigate or eliminate greenhouse-forced climate change. These measures will impact agriculture and other sectors of the economy.

Mandatory reductions in the use of carbon dioxide (CO_2)-emitting fossil fuels and/or carbon taxes will make energy more expensive. Profitability in agriculture will be affected as costs rise for on-farm traction, refrigeration, crop drying and irrigation pumping, and for off-farm transport of inputs and commodities produced. Additionally, demands for the low carbon intensity fuels--natural gas and petroleum--are likely to increase and their prices to rise. Hydroelectric generation emits no CO_2 and will be used whenever possible to replace fossil fuels. Hydropower will compete more strongly with irrigation for available water than it does now. Water for agriculture will be in shorter supply and will be more costly.

CO_2 is not the only greenhouse gas now accumulating in the atmosphere. Methane and N_2O are greenhouse gases generated on the farm: the former in rice paddies and in the digestive tracts of ruminant animals; the latter by denitrification and nitrification in all soils, but most in soils to which nitrogen fertilizer is applied. New technologies and higher levels of management will be needed to reduce agricultural emissions of CH_4 and N_2O. If not too costly, some of the technologies proposed, such as the use of feed supplements that reduce methanogenesis in ruminant animals and chemical coatings that reduce the rate at which nitrogen fertilizers are converted to N_2O or otherwise lost from the soil, could actually improve production efficiencies and profitability.

Afforestation on a massive scale has been proposed as a means of reducing the accumulation of CO_2 in the atmosphere. One estimate suggests that an area of new forest as large as the contiguous United States west of the Mississippi would be needed to remove the 45 or so percent of the annual CO_2 emissions that remain in the atmosphere, about 3-4 gigatons (GT or 10^9 tons) C per year. Whether for permanent or rotational forests harvested for biomass, it is clear that afforestation on the requisite scale will create considerable competition with agriculture for good land.

Geoengineering, the *advertent* manipulation of geophysical processes, has been proposed as a strategy to counteract *inadvertent* climate change caused by the accumulation of greenhouse gases in the atmosphere. Not all of the geoengineering schemes proposed have obvious linkages to agriculture, but some may have. For example, space mirrors that shade some portions of the earth permanently or all portions periodically will impact photosynthesis and net primary productivity. Generally speaking, less sunshine means less crop.

There is another side to the climate change coin, the side with a smiling face. CO_2 enrichment of the atmosphere is known to increase photosynthesis, decrease evapotranspiration and improve water use efficiency (crop yield per unit of water consumed). Mitigation of climate change by reduction of CO_2 emissions means that these benefits must be foregone.

In this paper we speculate about whether the mitigation measures described above alter comparative advantage of developed and developing country agricultures, how this might happen, and how these changes might affect regional food security. Those mitigation measures that increase demands for water and land and make it more difficult for agriculture to compete for these resources pose the greatest threats to global food security.

IMPLICATIONS OF POLICIES TO PREVENT CLIMATE CHANGE FOR FUTURE FOOD SECURITY

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1. INTRODUCTION

There have been a number of comprehensive and detailed studies on the question of what climate change might do to agriculture (Parry et al. 1988; Smith and Tirpak, 1989; Rosenberg, 1993; Council on Agricultural science and Technology (CAST), 1992; Intergovernmental Panel on Climate Change (IPCC), 1990, 1992; National Academy of Sciences, 1992; and others). The potential for adaptation of agriculture to climate change has been evaluated in a number of these studies and in Rosenberg (1992). There has been, however, little if any systematic analysis of how attempts to mitigate or avoid climate change might affect agriculture. Our aim in this paper is to explore this question. Data and analyses on which to draw are limited, so the results of our exploration are preliminary, at best.

Strategies to mitigate or avoid climate change due to greenhouse forcing focus, for the most part, on reducing or eliminating emissions of greenhouse gases into the atmosphere and recapturing them for recycling or sequestration. The gases of greatest concern are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), all of which have both industrial and biogenic, or natural, sources. Fossil fuel combustion and the conversion of forests to other uses emit about 6 GT of carbon in the form of CO_2 into the atmosphere. Industrial sources of CH_4 include coal mines and natural gas installations. Methane is also emitted from wet soils, including rice paddies, and is also a by-product of ruminant digestion. Industrial sources of N_2O are relatively minor; this substance is emitted from all soils as the result of both anaerobic and aerobic processes. The use of nitrogen fertilizers has greatly increased the emissions from agricultural soils.

Several strategies have been proposed to mitigate climate change. First and foremost is reduction of fossil fuel combustion. Another strategy is cessation of the conversion of tropical forest conversion to other uses. There are ways that on-farm emissions of CH_4 and N_2O can be reduced. Carbon dioxide can be withdrawn from the atmosphere through the plantation of new forests and the regrowth of those already harvested. Since dry soil is a strong sink for CH_4, the

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drainage of wetlands is a possible mitigation strategy. Geoengineering strategies of various kinds have been proposed to facilitate the capture of CO_2 and/or to counteract the greenhouse warming by decreasing the penetration of solar radiation into and through the atmosphere. In this paper, we examine a number of these strategies and speculate on how, if put into effect, they might impact on agriculture. We also attempt to estimate the magnitude of such impacts, although, for reasons that will be obvious, this is somewhat more difficult. Where possible, we attempt to differentiate the impacts of particular climate change mitigation strategies on developing and developed agricultures.

In this paper, we also consider the possibility that mitigation of climate change could have at least one negative impact on agriculture. Because elevation of atmospheric CO_2 concentration increases photosynthetic rate and reduces plant water use, attempts to hold concentrations to current levels will eliminate an opportunity for improving global agricultural productivity.

Many examples used in this paper are drawn from the Missouri-Iowa-Nebraska-Kansas (MINK) study (Rosenberg, 1993), an analysis of the possible effects of a 1930s-like "dustbowl" climate on the agriculture of the Missouri-Iowa-Nebraska-Kansas region, as it is now and as it might be forty years from now, by which time climate change may actually be observed. The MINK study dealt not only with climate change effects on agriculture but also on forestry, water resources, and energy. What happens to these sectors under climate change bears on agriculture, and what happens to all of these sectors bears on the total regional economy.

The authors of this paper will be neither surprised nor offended if our good readers identify other, more interesting or imaginative ways in which climate change mitigation strategies might affect agriculture. Nor will we be surprised if the weights we have assigned to items on our "laundry list" are disputed.

2. ENERGY COSTS FOR AGRICULTURE

Attempts to reduce emissions of CO_2 and other greenhouse gases from energy production should increase the unit costs of energy production from fossil fuels. This could have a detrimental effect on the costs of energy used in agriculture, would likely increase the overall costs of agricultural production, and, in some cases, could lead to changes in the comparative advantage of some production regions over others.

To understand whether these effects are likely to be important in terms of world food security, it is necessary to understand the following: (1) how much the cost of energy is likely to increase as a result of greenhouse-limitation policies; (2) how dependent agriculture is on purchased energy; and (3) how the production of crops will be affected.

To address the first question, we assume a $100 per ton tax on carbon contained in fossil fuels.[2] We then calculate the probable changes in fuel prices that would occur as a result of a U.S. carbon tax assessed on fossil fuels. It is also possible to estimate the impact on prices of energy, fertilizers, and other agricultural chemicals. This is illustrated in Figure 1, where a regression equation on fuel prices was used to "predict" fertilizer prices. We then took the estimate of a carbon emission tax of $100 per metric ton of carbon equivalent (mtce) and estimated its future consequences for fuel and farm chemicals prices. Extrapolation of the regression relationship for energy and chemicals costs into the future yields an estimated increase of about 30% for fuels and about 15% for fertilizers and other farm chemicals.

The dependence of U.S. agriculture on fossil fuels is illustrated with data from the MINK study. The energy costs of the various on-farm uses of energy include direct uses of petroleum, natural gas, and electricity in end uses such as plowing, planting, trucking, and harvesting; fertilizer and pesticides application; lighting and ventilation for animals; irrigation; and crop drying. In addition, the applied fertilizers and pesticides embody a significant amount of energy used in their production. Natural gas, for example, is a major input to nitrogenous fertilizer production. Energy used in the four-state region declined significantly during the 1980s. Table 1 indicates the total amount of energy used and the change for the agricultural census years of 1978 to 1987.

Figure 2 provides estimates of the changes in the prices of energy and farm chemicals, and in the intensity of their use in U.S. agriculture that have occurred since the late 1970s. In general, the prices of fuels and agricultural chemicals trended upward, relative to farm output prices, until 1982 and have since declined. Both direct energy use and agricultural chemicals use increased until 1982, declining thereafter in the MINK states and the nation as a whole.

Farmers will respond to higher fuel and chemicals prices by economizing on their use. A $100 per ton carbon tax would cause total fuel and chemical costs per acre to rise by less than 30% for fuels and 15% for chemicals. Based on recent U.S. history of energy use in agriculture, it appears that a 1% increase in price of fuels in agriculture results in a reduction of 0.3% in their consumption (in economic jargon, a "price elasticity" of -0.3), while in agricultural fertilizers and chemicals, a 1% increase in price leads to about a 0.6% decrease in use. With a carbon tax of $100/ton, farmers can be expected to reduce fuel use by about 10% and fertilizer use by about 8%. The "future" situation for total energy costs per acre, given these price increases and substitutions, is shown in Table 2. Year-to-year variability in fuel and fertilizer use has been greater than 10% during the last 20 years. The change likely would have little impact on agricultural output in the United States.

Table 2 estimates "current" (1989) values for direct and indirect energy expenditures per acre in the MINK states and energy expenditures per acre at future prices with the $100 per ton carbon tax. Because irrigated farms dominate the total in Nebraska and Kansas but are rare in Missouri

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[2] A $100 per metric ton of carbon equivalent (mtce) carbon tax is about the amount necessary to keep carbon emissions at 1990 levels through the year 2030. See Bradley, Watts, and Williams, 1991, pp.xvi-xvii.

and Iowa, the values in Table 2 for "all farms" are close to those for irrigated farms in Nebraska and Kansas, whereas they are close to those for the non-irrigated farms in Missouri and Iowa. Table 2 assumes that prices for direct energy rise by 30%, prices for agricultural chemicals rise by 15%, and farmers react to this price rise by reducing energy use according to historical U.S. patterns. As is clear from Table 2, total energy expenditures per acre in this region would likely rise by about 10 to 15% if carbon taxes were assessed, even with the estimated reduction in the use of energy.

The impact of the increased energy expenditures on U.S. agricultural productivity is likely to be slight, however. In the last 15 years, the amount of energy used in agriculture has declined by over 20%, while the amount of agricultural chemicals used has also declined slightly. During the same period, output of agricultural crops has grown by more than 20% (U.S. Department of Agriculture, 1991).

Although the prospective impact of increased energy prices is small, U.S. agricultural production and competitiveness could be adversely affected, even if technical substitution out of energy continues at the pace experienced in the 1980s. How much any country's agricultural sector is affected, however, depends in part on its comparative advantages. If elsewhere in the world there are regions even more energy intensive, the United States would be rendered more competitive by a general increase in energy prices. Conversely, the United States would be rendered less competitive with international competitors that are less dependent on fossil energy for maintenance of their productivity. Unfortunately, existing international data bases on energy consumption published by bodies such as the Organization for Economic Cooperation and Development and United Nations do not adequately or consistently distinguish energy consumption in agriculture from energy consumption in other sectors. Therefore, only limited international comparisons of energy intensity in agriculture are possible.

We offer one such limited comparison, that of the United States and India. Energy is a significant cost component of U.S. agriculture, and although we think of energy as a key element in the worldwide Green Revolution, recent data indicates that neither in the United States nor in India (one of the Green Revolution countries), is the cost of energy an overwhelming component of total costs (Figure 3). In the United States in 1989, the combined costs of petroleum, fertilizers, and farm chemicals were about 10% of the total value of farm output. In India, these costs were about 5.5% (United States Department of Agriculture, 1990; and Center for Monitoring the Indian Economy, 1992). Thus, a major increase in energy costs to prevent global warming would increase the costs of energy used in agriculture in both countries; this could increase the costs by more in the relatively energy-dependent U.S. production system than it would in India. However, in neither country is the increase significant when compared with the effects of technological change by which total factor productivity (the ratio of the value of output to the cost of all inputs to production) has been increased in both countries in the last 10 years by 25% or more. Crop production per acre has increased by 20 to 25% (U.S. Department of Agriculture, 1990; Centre for Monitoring the India Economy, 1992).

To summarize, the effect of an increase in energy prices to combat global warming would increase the price of energy used in agriculture by about 30% and the overall costs of energy used in agriculture by perhaps 15%. The consequent decrease in energy use is not expected to significantly affect costs, productivity, or food security in the developed countries or even in some of the agriculturally more-advanced developing countries, such as India. However, when we consider the developing countries as a group, the outcome is less certain.

The Green Revolution has been energy-intensive. In the process of joining the Green Revolution, India began to use much more mechanical energy, fertilizers, and agricultural chemicals than it had previously. Between the growing seasons 1974-75 and 1989-90, for example, yields per acre of food crops in India increased by about 60%. Some of this increase was due to improved crop strains; however, consumption of commercial fertilizers per hectare increased 4.8 times, the number of tractors per hectare increased 4.7 times, and the consumption of electric power per hectare increased 5.1 times. Thus, some of the increase in yield undoubtedly was due to increased application of energy in agriculture. We note that these increases took place against a background of steep energy price increases, so increased application of energy in Indian agriculture was profitable, even with high and rising fuel prices. As we noted earlier, the prospective increase in energy prices due to imposition of carbon taxes would not critically increase the costs of Indian agriculture.

However, consider a less developed country attempting to follow in India's footsteps. Here the result of future increases in energy prices is less obvious. Such a hypothetical country likely would be using less mechanical energy, fertilizers, and agricultural chemicals per hectare than India does now and, theoretically, should be less affected. However, rising energy prices might be more likely to discourage the adoption of energy-intensive techniques, because farmers in these countries (being less productive, poorer, and with less access to borrowed capital than those in India) would be less likely to be able to afford to purchase the necessary energy inputs. Thus, ironically, the poorest and least energy-intensive countries might be the very ones most disadvantaged in attempting to join the Green Revolution.

3. HYDROPOWER

The movement toward reduction of fossil fuel usage will increase demand for sources of energy that do not release CO2 to the atmosphere or that, at the least, add only CO_2 that has recently been removed from the atmosphere by photosynthesis. Candidate energy sources that meet this criterion are nuclear fission, wind, solar, geothermal, biomass, and hydroelectricity. Wind, solar and biomass (especially the latter) require large land areas and could, therefore, compete for land with agriculture. This matter is reviewed in a later section. In the remainder of this section we deal with the competition between hydroelectric generation and irrigation for water resources.

Despite the good they have done or were intended to do, dams on large rivers throughout the world has been a mixed blessing. The Aswan High Dam, for example, traps the sediment that from time immemorial has replenished the soils of the Nile Valley. Damming the Columbia River in the U.S. Pacific Northwest has interfered with the natural salmon spawning cycle. Many other examples can be given. For these and other reasons, old dams are viewed unfavorably by many in the environmental movement, and because few rivers remain in the "wild" (uncontrolled) state, new dams are actively opposed. Whether or not pressures to reduce fossil fuel use will cause environmentalists to reconsider their opposition to the construction of new dams to provide hydropower remains to be seen.

Developed river basins are managed for many purposes, of which hydroelectric generation is only one. Other purposes include navigation, recreation, fish and wildlife habitats, the provision of cooling water for thermoelectric plants and other industrial processes, the transport and dilution of sewage and industrial wastes, irrigation, and the transport of saline drainage waters from irrigated lands. These various uses often are in conflict throughout the entire year or in particular seasons.

Environmental concerns are driving the movement for reduction in fossil fuel use and, hence, are increasing the desirability of hydropower. However, environmental uses are often in conflict with hydropower. Frederick (1991) describes one instance of such conflict. The least tern and the piping plover are designated as endangered and threatened species. These birds nest on low lying sandbars and islands downstream of three of the upper Missouri River basin dams. The Corps of Engineers is required at times to alter reservoir releases (and hence, hydropower production) during the May through mid-August nesting season to avoid jeopardizing the habitat of the tern and plover.

Surface runoff into streams, rivers, and reservoirs is finite, depending on the vagaries of seasonal and annual precipitation and evaporative demands--that is, on the weather and climate. Decades of research into various methods of weather modification have yet to provide evidence of an operational capacity to augment precipitation. Therefore, supply remains finite, if variable, while demands for water for all purposes increase. Will pressures to reduce use of fossil fuels increase the value of water used for power generation? Will such increased value result in increased allocations of water to hydropower despite growth in competing demands?

What impacts do irrigation and hydropower have on one another? Butcher et al. (1986) explain the competition in these terms:

> 1) irrigation changes the seasonal pattern of electricity demand, streamflow, and hydropower supply
>
> 2) irrigation consumes large amounts of electricity for pumping
>
> 3) irrigation depletes streamflows and thus reduces downstream hydropower.

The loss of hydropower when water is withdrawn and consumed for irrigation depends on the quantity of water diverted and consumed and the amount of developed head that the water would fall through if left in the stream.

Currently, hydropower is one of the higher value uses of water. Irrigation is one of the lowest, particularly when the water is applied to low-value, extensive crops such as alfalfa and pasture. Electricity generation is a non-consumptive use of water and irrigation is one of the most consumptive uses. Economics in most developed river basins currently favors hydropower generation over irrigation. The difference in economic value of water can only grow as the demand for CO_2-clean energy grows and as the costs of fossil fuels rise when anti-climate change policies take effect.

Hydroelectricity is typically the least expensive form of electricity to produce, and regions receiving a large proportion of their electric power from this source enjoy significantly lower costs for electricity. For example, in 1989 the average cost of electricity provided to residential consumers in the United States was $25.67 per million Btu; in gas- and nuclear-dominated California it was $31.71; in hydroelectric-dominated Washington State, it was $14.54 (DOE, 1991). Most of the trans-Mississippi west except for the southwest in the lower forty-eight states, the Tennessee Valley and Alaska derive more than a quarter of their power from hydroelectricity and, therefore, would be particularly vulnerable to desiccation due to natural droughts and/or climate change (Gleick, 1990). The primary users of water for irrigation in the United States are the seventeen western states. In the United States, the west is the region in which the most severe conflicts between hydropower and irrigation are likely to occur.

In many regions, tensions already exist between irrigation and hydroelectric use of water. A case study of the Snake River by Miller (1990) is instructive. Fostered by growing demands for power and by occasional droughts that impair the water security of hydroelectric facilities, the Snake River basin has had to explore institutional changes. Withdrawals for irrigation have reduced the potential for generating low-cost electricity further downstream. Through a series of negotiations and litigation, water security and transferability of water rights have been arranged within the basin. Compacts have been arranged "to limit future encroachment on in-stream water rights for hydropower generation by irrigation depletions." A water bank was created that initially permitted single-year transfers. This system now permits purchases of water rights for up to twenty-five years. While the Snake River case actually may be the exception rather than the rule in the relatively water-abundant Columbia River basin, competition among hydropower, irrigation, and water users is common in most western U.S. river basins, with the Colorado and Missouri being prime examples.

The trend of transferring water away from agriculture and to higher value uses is likely to accelerate for many reasons. This is particularly true if demand for CO_2-clean hydropower increases because of public policy aimed at diminishing the likelihood of climate change. Climate change of the kind that general circulation models predict for North America, i.e. warmer and drier (less runoff and diminished stream flow) would make these transfers even more urgent.

To give the latter statements some dimension, we refer again to the MINK study. In the water resources portion of that study, Frederick (1991; Rosenberg, 1993) compared current (1951 to 1980) streamflow at 15 gaging stations in the Missouri, Upper Mississippi, and Arkansas-White-Red River basins with flows at the same stations during the dry years of the 1930s. The 15 stations selected were in watersheds in which no man-made changes (e.g., diversions, dams) had been made in the intervening years. The ratios of the 1930s to current flows were applied to the subbasins represented in order to scale up to the entire river basin. The calculations show that if the climate of the 1930s were to recur today, flows would be reduced from the long-term means by 28%, 28% and 7% in the Missouri, Upper Mississippi, and Arkansas basins, respectively (Figure 4).

Frederick (1991) also observed that were the large reservoirs on the upper Missouri to continue operating under current Corps of Engineers assumptions, it would be necessary to curtail hydropower production by about 50%. Of course, the demand for irrigation water would be increasing at the same time: first, because of greater evaporative demand due to higher temperatures and drier air and second, because the profitability of irrigated agriculture would increase as dryland production falls. The assumption of no change in irrigated acreage and irrigation water applied in amounts determined by climatic conditions leads to an increased demand of 39% in Nebraska and 12% in Kansas, the two MINK states with significant irrigated acreage today.

One may argue with the assumptions on which the latter calculations are based, but the picture emerging will not be greatly changed by more rigorous assumptions. The picture is one of much less water available for all purposes, a premium placed on power supplies not derived from the combustion of fossil fuels, and increased demand for water to maintain or even enlarge the irrigation enterprise. We venture on the basis of the foregoing to assert that hydropower is likely to out-compete irrigation for increasingly scarce water supplies.

4. FARM EMISSIONS OF METHANE AND NITROUS OXIDE

Methane and nitrous oxide are greenhouse gases. While less potent than CO_2 because of their far smaller concentrations in the atmosphere, they nevertheless contribute significantly to current greenhouse warming potential (IPCC, 1990; 1992). Methane has industrial and biogenic sources; N_2O is primarily biogenic. Of the many natural sources of CH_4 on the farm, sources of greatest importance are ruminant animals (via enteric fermentation) and animal wastes. Methane is also emitted under anaerobic conditions from wet soils, although emissions vary greatly depending on soil conditions. Paddy rice is one very important source. Soil is also a sink for CH_4 in which it is oxidized under dry conditions. Nitrous oxide is formed in soils under both aerobic and anaerobic conditions. Nitrogenous fertilizers greatly increase the volume of N_2O emitted from agricultural lands.

Climate forcing by any greenhouse gas is a complex function of its infrared absorptive power (radiative forcing per unit mass), its mean lifetime in the atmosphere, and the quantities emitted. The radiative forcings of CH_4 and N_2O per unit mass are, respectively, about 60 and 200 times that of CO_2. The mean lifetime of a CO_2 molecule in air is about 120 years. Methane and N_2O have lifetimes of roughly 10 and 150 years. For the same unit mass, CH_4 and N_2O have, respectively, cumulative lifetime global warming potentials 21 and 290 times that of CO_2. Nonetheless, CO_2 is the predominant greenhouse gas because so much more of it than of CH_4 and N_2O is emitted into the atmosphere: from all sources, over 22 billion tons of CO_2; about 500 million tons of CH_4, and about 20 million tons of N_2O. Mitigation of greenhouse warming requires that the net emissions of all of these gases be reduced. In this section, we deal only with suppression of CH_4 and N_2O emissions. Management to decrease agricultural emissions of CO_2 and increase capture and sequestration of carbon are dealt with peripherally in a later section.

More specifics on methods for reducing CH_4 and N_2O emissions are given below. However, before dealing with the means of reducing greenhouse gas emissions from agriculture it is useful to gain some perspective about how much agriculture contributes to overall global emissions. Figure 5, drawn from a report of the CAST (1992), shows that CO_2 emissions from U.S. agriculture contribute about 0.4% to the total global climate forcing potential of that gas; U.S. agriculture contributes about 1% to the global CH_4 and N_2O forcing. At least in the United States, major efforts to reduce or eliminate agricultural emissions of the three gasses would have little global impact; their total elimination would, of course, require total elimination of U.S. agriculture.

The picture for global agriculture is different. According to IPCC (1992), global agriculture (rice paddies, enteric fermentation, and animal wastes) accounts for about 32% of all CH_4 emissions (Table 3). Biomass burning, most of which is attributable to agricultural practices, accounts for an additional 8%. Twenty-two percent is emitted from wetlands, much of which could, conceivably, be drained for agricultural uses other than paddy rice, although there are strong ecological reasons for not doing so. Table 3 indicates that current best estimates of CH_4 sources and sinks fall within very broad bands of uncertainty.

No "best estimates" of N_2O sources and sinks are given in Table 4, only the range of reported estimates. Agricultural sources may be as small as 0.05% of the lowest estimate of all natural plus anthropogenic sources (5.18 Tg N/annum) or as high as 25% of the highest estimate. Biomass burning is again included in this estimate as an agricultural source. Thus, it appears that on the global scale (assuming the highest estimates of agricultural emissions of CH_4 and N_2O hold true), the reduction of CH_4 and N_2O through changes in agricultural practice could significantly reduce the potential for greenhouse warming.

We now turn to the questions of how to reduce agricultural emissions of the subject greenhouse gases. CAST (1992) provides details on ways in which the total emissions of CH_4 from agriculture might be reduced. Net CH_4 emissions can be reduced by improving the feed utilization efficiency of ruminant animals, by proper treatment of animal manures, by increasing the efficiency of paddy rice production and by draining wetlands that naturally emit CH_4. Methane emission is unavoidable in paddy rice production. The appropriate strategy for meeting growing demands for rice is to increase productivity per unit of land, rather than to put more land into paddy. Deep placement of nitrogen fertilizers stimulates production and decreases the ratio of CH_4 emitted per unit of rice produced. Improvements in biological efficiency of rice to produce higher yields should also reduce the amount of CH_4 per unit of rice. An absolute reduction in CH_4 production per unit land area can be achieved by reducing the amount of organic residue returned to the soil. If the residue were burned, however, the benefits of carbon sequestration would be lost. Residue management that includes rotation of paddy with dryland crops would reduce CH_4 production per unit area, but then rice would have to be produced on more acres to make up for the production shortfall. Another suggested approach is to invest more effort in improving the productivity of upland rice and encouraging the adoption of other cereal grains into the diet of nations in which rice is the staple food.

It is difficult to see where any of the methane-reducing practices described here would greatly strain agricultural economies. The proposed practices that lead to greater productivity of rice production could enable a reduction of area planted to that crop. A reduction in the amount of organic matter incorporated into paddy soils could, over time, lead to a reduction in soil fertility, however. None of the proposed practices appear likely to alter the supply of rice radically or to greatly affect world prices for this commodity.

With respect to CH_4 emissions from ruminant animals, the CAST report concludes that significant reductions are possible through improvements in the biological efficiency of the animals. This can be accomplished through conventional breeding programs, improvements in feed formulations and pharmaceuticals, and the use of additives such as somatotropin to increase feed efficiency and animal gains. CAST suggests, as well, that decreased human consumption of animal products would contribute to reduction of agricultural CH_4 emissions.

Historically, manure and legumes have been used to provide nitrogen for crop production. Use of nitrogenous fertilizers has been widespread since the 1950s. Nitrogen fertilizers are costly, and farmers have a natural interest in using them efficiently. The desired outcome with respect to climate change is to reduce both the quantity of nitrogen lost as N_2O and its share of the total gaseous nitrogen emissions, of which N_2O is the greatest in quantity. The CAST report provides details on ways to decrease N_2O emissions.

Both the "natural" and manufactured nitrogen fertilizers undergo chemical processes in the soil that result in the synthesis of N_2O and other nitrogen compounds. The amounts and the rates are determined by management practices, biogenic processes, soil properties, and climate. Soil management offers opportunities to improve the effectiveness of applied nitrogen, maximizing the amount taken up by the crop, thus minimizing both volatilization and escape to the atmosphere and leaching to depths below the root zone.

Net N_2O emissions can be reduced by improved timing and placement of nitrogen fertilizers and by encapsulating the fertilizers to slow the release of nitrogen. It can also be accomplished through use of nitrification inhibitors. Nitrification is the process whereby fertilizers applied in the relatively immobile forms of NH_3 or NH_4^+ are converted to the NO_3^- ion, which is readily denitrified or leached. Since denitrification occurs primarily under anaerobic conditions, irrigation practices that reduce the number of wet/dry cycles can also aid in decreasing N_2O emissions and potentially improve water use efficiency.

All of the practices described above as being helpful in reducing N_2O emissions also contribute to improving the efficiency of fertilizer use and decreasing costs of crop production. This is one case in which strategies for mitigating greenhouse warming should be acceptable in the agricultural sector.

5. COMPETITION FOR LAND: AFFORESTATION AND HERBACEOUS BIOMASS

It is generally held that the best lands for growing crops are those already growing crops. Much of that land was originally forested and until recent times was cleared for agriculture with great exertion by man and beast. Forest conversion for cropping and grazing continues to this time and at rates in the tropics far exceeding historical experience. Equipment powered by internal combustion engines can remove forests much more rapidly than human and animal power ever could.

Afforestation and the application of management to existing forests, now mostly unmanaged, have been proposed as ways of helping to mitigate greenhouse warming. The aim is to capture through photosynthesis a large portion of the carbon emitted into the atmosphere by fossil fuel combustion, deforestation, and biomass burning. The captured carbon either can be sequestered in the roots and boles of trees and in soil organic matter, or the wood can be burned or otherwise converted to provide energy as a substitute for fossil fuels.

Estimates have been made of the amount of land required for afforestation to significantly reduce net carbon emissions to the atmosphere. The estimates vary widely as the result of varying assumptions about the species to be planted, the biological limits of carbon fixation of the various candidate species, climatic and soil conditions, and time required for a planted stand to reach maturity. Three of these estimates are given in Table 5. Two of the estimates take a global view of the problem and one focuses on the United States.

Sedjo and Solomon (1989) calculated that, in order to offset the 2.9 GT C that accumulate in the atmosphere each year after natural scavenging, some 465 million hectares must be planted with trees having production equivalent to that of plantation forests in the U.S. southeast. Marland (1988) calculated that, depending on the productivity of the forests planted, between 500 and 700 million hectares would be needed for the more ambitious goal of removing 5 of the 6.3 to 8.5 GT C that are emitted into the atmosphere yearly. A notion of the scale of land diversion being discussed can be gotten from Figure 6, which shows how large an area is encompassed in Sedjo and Solomon's estimate of 465 million hectares.

Afforestation for sequestering carbon easily captures the imagination. Not as much prominence has been given, however, to the potential for recycling carbon through production of herbaceous biomass crops. These crops would be grown as feedstocks for chemical manufacture of substances to replace petroleum-derived liquid fuels and natural gas, or for direct combustion as boiler fuel in energy generation. Although possibilities exist for the production of non-woody biomass on marginal lands, at least in the United States, the better agricultural lands will be needed to produce biomass competitively (Tyson, 1990). A study of the potential for biomass to provide a significant share of the energy needs of the Netherlands (NOVEM, 1992) concludes that if all of that nation's land were devoted to biomass, about 22% of its energy needs could be met. However, at the most, 0.5 million hectares of land could be diverted for biomass, which would provide only about 5% of the Netherlands' energy requirements.

In a sense, the production of non-woody biomass is agriculture; the inputs and management required to grow "energy sorghum" differ little from those for corn. Sylviculture, on the other hand, involves different planting and harvesting methods and much longer rotations. There are two questions to explore: 1) the social effects of carbon-sequestration practices (i.e., what happens to the farmers), and 2) the effects on food security.

What would be the overall effect of large scale land diversions away from food production to the sequestering and/or recycling of carbon to mitigate climate change? In calculating the costs of carbon fixation through afforestation, Moulton and Richards (1990) and Adams et al. (1993) have shown sharply rising costs with each increment of additional carbon capture. Adams et al. calculated, for example, that the first 10% of U.S. emissions can be captured at a cost of about $18 per ton. To sequester 50%, however, would cost $55 at the margin. The steeply rising cost of sequestration reflects rising opportunity costs of agricultural land, as more land of better quality is diverted from cropping. Commodity costs would necessarily rise with reduced production. Of course, U.S. emissions need not be offset by plantings only in the United States. Investment in tropical forest plantations may make more sense, but impacts on food-producing potential in the tropics would likely not be small.

Moulton and Richards (1990) focused on opportunities for afforestation in the United States to offset portions of that nation's net emissions of carbon to the atmosphere. A goal of offsetting 10% of the net U.S. emissions of 1.27 GT C (1,270 Tg C) per annum could be accomplished on 28.7 million hectares of economically marginal pasture lands, crop lands, and forest lands where productivity could be improved by management. If more than 15% of the net U.S. emissions are to be offset, better agricultural lands must be diverted. To increase carbon sequestration from 15 to about 50% (725 Tg C/yr), for example, would require 224 million acres (90.7 million hectares), or about 48% of all U.S. cropland (Moulton and Richards, 1990).

Figures on the uses of U.S. cropland suggest that about two-thirds is devoted to the growing of wheat, corn (maize), and soybeans, with each crop occupying about one-third of that area. Assuming that the land removed from agriculture is proportionately distributed among all crops and has average productivity, we can calculate an approximate maximum amount of lost farm production of these three major crops.[3] The loss of 48% of U.S. production would be about 40 million tons of wheat, 70 million tons of corn and 26 million tons of soybeans (7%, 15%, and 25%, respectively, of world production). While clearly an overestimate of the impact, these values are quite significant, and would be a matter of some concern for world food security.

It is beyond the scope of this paper to attempt a nation-by-nation or region-by-region analysis to identify the best places for afforestation and non-woody biomass production. It is sufficient to say here what was--obvious to the reader before--that in any real world efforts at afforestation lands of marginal value to agriculture (i.e., highly erodible lands, wetlands, etc.) will be the first committed to this purpose, but if a significant impact is to be made, highly productive agricultural lands will also be required. Diversion of the highly productive lands will make feeding the world that much more difficult. Of all the climate change mitigation strategies covered in this paper, it seems likely that afforestation and biomass production will have the greatest impacts on global food security.

6. GEOENGINEERING

Geoengineering consists of several approaches intended to offset climate change, or its impacts, through intentional control of climate or of the concentrations of greenhouse gases. The interventions fall under five general categories: 1) collecting and disposing of CO_2 from flue gas streams; 2) increasing net uptake of CO_2 into the terrestrial biosphere; 3) increasing net uptake of CO_2 into the oceans; 4) changing the Earth's energy balance by altering the albedo (the fraction of incident solar energy scattered or reflected back to space without being absorbed); and 5) altering internal processes in the climate system. Actions that might be taken under categories 2 and 4 could, conceivably affect agriculture in a direct way.

A balance between incoming short-wave solar radiation and outgoing long-wave infrared radiation maintains the global heat balance, which energizes the climate system. A doubling of atmospheric CO_2 (or its equivalent, with other greenhouse gasses included) would increase the global average radiation flux at the top of the troposphere by 4.4 W/m^2 (IPCC, 1990). On average, the Earth absorbs about 240 W/m^2 of the 340 W/m^2 solar energy flux. Thus, a 2% decrease in sunlight penetrating to the lower atmosphere could approximately offset the effects of an equivalent CO_2 doubling. Intentional manipulation of the Earth's albedo could help to limit global warming.

[3] This is a maximum for two reasons: 1) the land most valuable for agriculture would likely remain in agriculture, meaning that average yield would overstate average loss in production on the average hectare diverted into forests; and 2) farmers would likely farm remaining land more intensively, resulting in higher yields.

Our goal in this section in to describe a few of the albedo manipulations that have been proposed to mitigate climate change in terms of how they might affect agriculture. The issue of carbon sequestration through afforestation has already been mentioned in Section 5.

Modifications of planetary albedo can be made in space. One plan proposed by NASA involves the use of 55,000 orbiting mirrors of 100 km^2 in near-Earth orbit. If arrayed parallel to the Earth's surface, 1% of the incoming solar radiation could be reflected; if arrayed perpendicular to the incoming radiation, 2% could be reflected. Shadows cast on the surface by these mirrors would be roughly similar to those of an eclipse. Photosynthesis would be affected, but by how much and where would depend on orbiting characteristics of the mirrors.

It has also been proposed that clouds of soot particles be lofted into space to absorb and scatter solar radiation. Backscattering would effectively reflect some of the radiation into space. It has been calculated that 500 million kg of soot in a cloud 5 million km^2 would be needed to absorb 1% of the incoming radiation. Again, the impact of this type of solar shield would affect photosynthesis, the effect depending on the orbiting characteristics of the cloud and its durability.

Albedo modification can also be done within the atmosphere. It has been suggested that insertion into the stratosphere of small, thin-skinned, helium-filled aluminum balls could be effective in reflecting solar radiation. Corner reflectors could be attached to the spheres to enhance the overall efficiency of the balloons. The balloons would not cast large shadows, so their effect on plant growth would probably be no greater than would be caused by any transitory 2% reduction in insolation.

Injection of various aerosols into the atmosphere provides other ways of reducing absorbed insolation. Current SO_2 emissions and aerosols associated with burning biomass are believed to already exert a cooling effect by increasing reflectivity of the atmosphere (Charleson et al., 1992; Penner et al., 1992). In the stratosphere, injected sulphates would have a reflective effect; injected soot would absorb radiation and prevent it from reaching the lower atmosphere.

Modification of albedo is most easily accomplished at the surface, although it is least effective there, because only about half of the incoming solar radiation reaches the ground. Increasing snow and ice cover (or preventing its loss) provides one way of increasing surface albedo. Turning forests and grasslands into desert would also raise albedo, but it would hardly do much for agriculture. Experiments have been performed to increase the albedo of soils and vegetation. Their aim has not been to protect the planet from climate change but, rather, to decrease the radiant energy load on transpiring surfaces, thereby reducing plant water use. In a series of such experiments in Nebraska from the late 1970s to mid-1980s, soybean plants were maintained with coatings of kaolinite clay and a diatomaceous earth (Baradas et al., 1976a,b). Reflectance in the visible portion of the spectrum was tripled; reflectance increased by 25% in the near infrared. Overall, it was found that the coatings increased crop albedo by about 8 to 10%. Water use was reduced and photosynthesis barely affected, so overall water use efficiency was improved. In later studies, the Nebraska researchers tested cultivars of soybeans that had been bred to increase their leaf pubescence. Pubescent isogenes had at least triple the number of hairs per unit area than normal. Albedo was greater, water savings occurred, and photosynthesis was essentially unchanged in plots of "hairy" soybean plants (Baldocchi et al. 1983). Although far-fetched, if prospects for severe climate change warrant, it might be possible to breed and introduce highly reflectant varieties of all cultivated crops and managed forests species. Biotechnology might be used to speed plant breeding if the task becomes urgent enough. The water-saving effects shown in the few field studies described above suggest that the overall impact of breeding for reflectance would be beneficial to agriculture.

To our knowledge, little thought has yet been given to the biological implications of the various geoengineering schemes to reduce insolation from space or from the atmosphere. Direct shading of the surface means that the plants receive only diffuse solar radiation. Diffuse and direct beam solar radiation differ somewhat in spectral composition. It has been shown that the photosynthetic mechanism of many C_3 plants is light-saturated; thus. these plants are not adversely affected by moderate shading. Additionally, crops with dense canopies may benefit from the greater penetration of diffuse radiation (Rosenberg et al., 1983). On the other hand, most C_4 plants are not light-saturated, even at full sunlight, and do show reduced photosynthesis under shade. However, C_3 rice is often limited by cloudy conditions during rainy seasons in Asia, and this crop might suffer still more if sunshine were further reduced. On the positive side, reduced solar radiation would decrease the energy load on plants, with consequent reductions in evapotranspiration. Would any of the proposed geoengineering fixes alter the quantity or quality of solar radiation enough to make a difference? Possibly so, but the effects would no doubt differ by crop species and by the latitude, altitude and natural cloudiness of the sites affected by the mirrors, dust palls, or whatever the geoengineers somehow convince us to deploy.

7. THE CO_2 FERTILIZATION EFFECT FOREGONE

It is a well-known and demonstrable fact that plants exposed to higher-than-normal concentrations of CO_2 respond with an increased rate of photosynthesis. Such increases in photosynthesis normally lead to larger and more vigorous plants, to higher yields of total dry matter (roots, shoots, and leaves), and often, to higher yields of harvestable products--fruits, grains, etc. (Rosenberg, 1981, 1992; CAST, 1992). The behavior described here is demonstrated particularly in plants of the C_3 category which includes most of the world's small grains, legumes, root crops, cool-season grasses, and trees. Another category of plants, the C_4 or tropical grasses such as corn, sorghum, millet, and sugar cane, are naturally more efficient photosynthesizers than the C_3 plants. They also respond, but less markedly, to increases in atmospheric CO_2. Remarkably, elevating CO_2 concentrations can increase photosynthetic rates in C_3 plants to levels approaching those achieved by C_4 plants at current ambient concentrations. This effect is illustrated schematically in Figure 7.

The magnitude of this CO_2 fertilization effect is not known precisely because it varies with species, weather conditions, soil fertility, and other factors. Kimball (1983a,b, 1986) helped to estimate the effect through extensive reviews of agronomic, greenhouse, and growth chamber research in which plants were grown in various concentrations of atmospheric CO_2. The literature shows that, on average, a doubling of CO_2 from its recent concentration (340 to 356 ppmv), all else constant, will increase growth and yield in C_3 plants by about 34% (+/-6%) and about 14% (+/-11%) in C_4 plants.

Carbon dioxide enrichment also leads to another interesting response in both the C_3 and C_4 plants. Their consumption of water by transpiration is reduced because of partial closure of the leaf stomata (pores) induced by high CO_2 concentration. Reviews of experimental evidence for a wide range of agricultural, woody and weed species have shown that doubling ambient CO_2 from recent levels reduced transpiration by an average of 34% (Kimball and Idso, 1983) and increased stomatal resistance to vapor transport out of the plant by from 51% (Cure, 1985) to 67% (+/-14%) (Morison, 1987). The reduction in transpiration is not accompanied by any significant loss in instantaneous photosynthesis and usually results in greater total photosynthesis where moisture savings occur. Water use efficiency (production per unit of water consumed) increases because of reduced transpiration and increased photosynthesis.

If the findings from the laboratory, greenhouses, and open chambers upon which the above statements are based can be extrapolated to open-field agriculture, we may expect important benefits from the increasing concentration of CO_2 in the atmosphere--increased photosynthesis in many important species and decreased water consumption in most species. We still do not know whether these laboratory-demonstrable CO_2 effects on photosynthesis and transpiration do now or will occur in the future in the field where temperature, moisture, and nutrients are the factors that normally limit plant productivity. In developing countries, where limited economic resources and access to technology make it difficult to overcome these limiting factors, it will be more difficult to realize the benefits of CO_2 fertilization. However, laboratory, controlled environment, and open-top chamber experiments have shown that CO_2 enrichment of the atmosphere can actually reduce the impacts of moisture and salinity stress on plants (Rosenberg et al., 1990). A summary by Allen et al. (1990) shows that high temperature stress is also alleviated by CO_2 fertilization. The effects on nutrient stress remain unclear at this writing.

Carbon dioxide enrichment of the atmosphere could also lead to a number of troublesome effects for agriculture as well as for unmanaged ecosystems. Because of the special benefit that C_3 plants derive from elevated CO_2, infestations of C_3 weeds may become worse where they grow in association with C_4 plants. Additionally, the carbon-to-nitrogen ratio increases in leaves of plants fertilized with CO_2. Some short-term studies show that herbivory increases as insects consume more vegetation to satisfy their nutritional needs (Lincoln et al., 1984). Later studies suggest more complicated outcomes, however. Over longer periods, the population of insects feeding on plants stimulated by higher CO_2 would likely decline in response to the diminished proportion of nitrogen in the plant tissues. As pest populations decline, so would the populations of their predators (Fajer et al., 1989). The long-term ecological changes that may follow from increasing CO_2 concentration in the atmosphere are difficult to predict (Bazzaz and Fajer, 1992). However, the impacts of changes in weed competition and insect activity on agriculture would probably be less profound than they would be in ecosystems that are unmanaged (Rosenberg, 1992).

Because of the many complicating factors induced by the artificiality of experimental environments it will be some time before we have definitive answers on whether CO_2 fertilization will actually affect photosynthesis in totally natural open-air environments. Attempts to measure open-air responses began in the 1970s in experiments where CO_2 was released directly into fields of selected crops (see Harper et al., 1973a, 1973b for cotton; Allen et al., 1974 for corn). These experiments failed to provide definitive results, primarily because of the difficulty of maintaining elevated CO_2 concentrations in the air surrounding plants in the face of normal atmospheric turbulence, which tended to remove it rapidly.

Since these experiments were conducted, technological advances have made open-air CO_2 enrichment research possible. In a program called FACE (which stands for Free Air Carbon Dioxide Enrichment), sponsored by the U.S. Department of Energy and conducted by the U.S. Department of Agriculture, equipment has been developed to maintain an elevated level of CO_2 in the air within and above crops for the duration of entire growing seasons (Hendrey and Kimball, 1990). The FACE system was originally tested in a Mississippi cotton field using industrial by-product CO_2 and is now working in a field near Phoenix, Arizona. Cotton crops have been grown for two years with CO_2 held at a concentration of about 550 ppmv.[4] Cotton growth and yield has been about 40% greater with CO_2 enrichment. Seasonal water use may not have been affected, although use appears to have been greater early in the season because of more rapid crop growth while the stomatal closure effect reduced use later in the season. Water use efficiency was improved in direct proportion to the increase in yield.

How can we quantify the impacts of a CO_2 fertilization effect foregone because of concern for the more negative possibilities that rising atmospheric CO_2 concentrations may cause in climate? One attempt (perhaps the only one thus far) to estimate the economic impacts of CO_2 fertilization was made as part of the MINK study. The results of Erosion Production Impact Calculator (EPIC) crop model simulations that allow consideration of the direct (non-climatic) effects of elevated CO_2 on crop yield are shown in Table 6. Yields were simulated on some 50 representative farms exposed to a permanent 1930s "dustbowl" climate under conditions of current CO_2 and elevated CO_2 concentrations (350 and 450 ppmv). Resulting yields were aggregated to the state and regional level.

At ambient CO_2 concentrations the dustbowl climate lowered simulated yields of all crops studied. Elevated CO_2 concentration diminished the yield losses for corn, sorghum, and soybeans and produced an increased yield for wheat and hay. The elevated CO_2 concentration reduced the regional loss to regional producers from approximately $2.7 billion to $1.3 billion (in 1982 dollars). A regional input-output model IMPLAN (Alward, 1986) was used to track the overall effect on

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[4]Personal communication, February 1992, Dr. Bruce Kimball, USDA/Water Conservation Laboratory, Phoenix, AZ.

the regional economy. Table 7 shows that adaptations (earlier planting, longer season cultivars, moisture conserving tillage practices) reduced the loss to the regional economy from $4.37 to $3.76 billion. CO_2 enrichment and adaptations together reduced the loss to $1.85 billion. Thus, in this input-output calculation, the regional economy was spared the loss of nearly $2 billion by the direct effects of CO_2 and its interactions with adaptations.

These calculations assume that the shortfall of feedgrains is absorbed entirely by the regional animal feeding industry and by the meat packing industries, its suppliers, the transporters of its products, etc. In this case the loss to the regional economy would be about 10%. The interacting effects of CO_2 enrichment and on-farm adaptations in response to climate change might reduce this loss to about 6%. These numbers are "worst case," because it is unlikely that the animal feeding industry would not import some feedgrains to make up for the within-region shortfall. Nonetheless, these input-output calculations put credible order-of-magnitude numbers on the benefits that could be foregone if CO_2 enrichment of the atmosphere ceases.

It is difficult to conclude from the scanty analysis described above that we really know how important the economic consequences of the CO_2 fertilization effect will be. Will the positive benefits of CO_2 fertilization outweigh the negative effects of greenhouse warming globally or for specific regions? Probably not, but we cannot know for sure. At the least, however, it seems fair to say that attempts to mitigate greenhouse warming may cause us to forego one possibly benign effect of the consumption of fossil fuels.

8. SUMMARY AND CONCLUSIONS

Strategies to avoid or mitigate climate change could affect global food security. Increases in the cost of energy will affect all sectors of the economy, with agriculture included. The major effect we see is one in which intensification of developing country agriculture is impeded by rising energy costs. Because it is a carbon-free source of energy, hydropower will be at a premium and will compete more strongly for water supplies at the expense of irrigation.

Strategies that have been proposed for the suppression of on-farm emissions of CH_4 and N_2O need not be very costly. These strategies involve increasing ruminant feed efficiency, increasing the productivity of paddy rice production, and increasing conservation of nitrogen fertilizers--all of which should be environmentally benign and should increase the profitability of farming.

Geoengineering to reduce insolation will be complicated and accomplished only at great cost. Impacts on food security of the various methods proposed would likely be small, although significant effects on particular crops and/or places cannot be ruled out.

Afforestation and production of herbaceous biomass to sequester and/or recycle carbon in significant amounts will require vast areas of land, only a small portion of which can be provided by agriculturally marginal land. Thus, afforestation and biomass will have to compete with agriculture for the use of productive land.

The possibility that significant benefits due to CO_2 fertilization will not be realized because of limits on fossil fuel use must be considered in any accounting of the possible impacts of climate change mitigation strategies on agriculture and food security. We think benefits of CO_2 fertilization foregone would not be small.

Crosson and Rosenberg (1989) argue that the capacity of world agriculture to support a growing population can be accomplished only if the land, water and genetic resources on which agriculture depends are protected. Several strategies to mitigate climate change could make agricultural access to two of these resources (land and water) more difficult. Whether afforestation (or perhaps geoengineering) will negatively alter genetic diversity is a question we have not attempted to examine here, but one that may well warrant study.

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Predicted vs Actual Fertilizer Prices, U.S. , 1976-1989

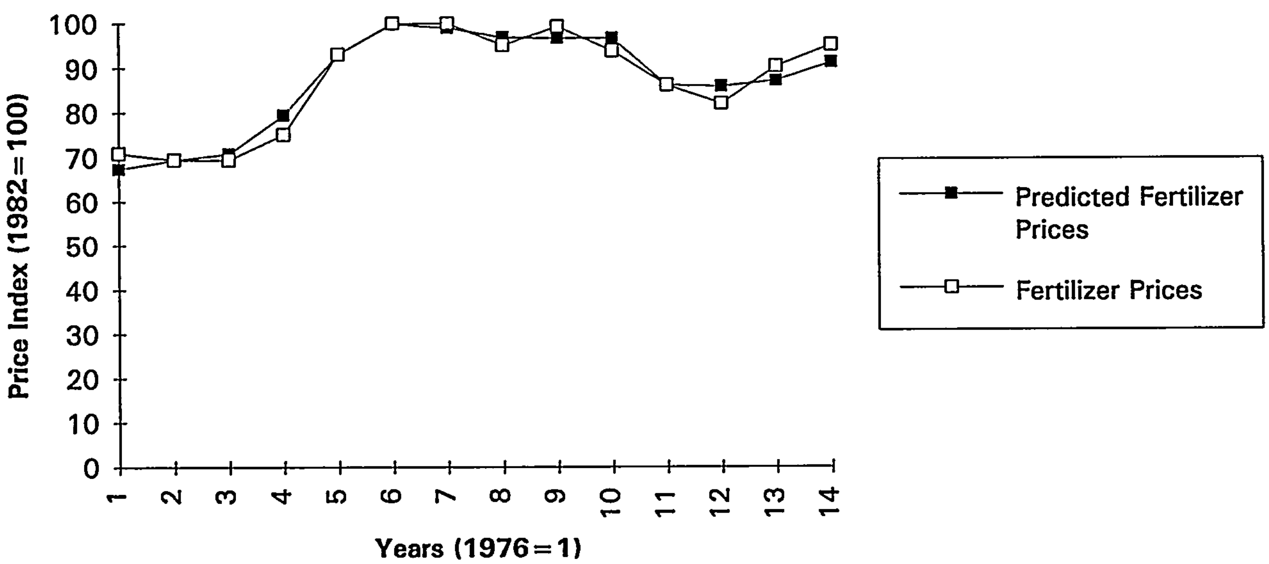


Figure 1. Predicted vs. Actual Fertilizer Prices, United States, 1976 to 1989.

Table 1. Direct and Indirect Energy Used per Dollar of Farm Output in Missouri-Iowa-Nebraska-Kansas, Selected Years, MINK Study

	Direct Energy		Fertilizers and Pesticides		Total Energy	
Year	Trillion BTU	1000 BTU/1982$ Value of Crop Production	Trillion BTU	1000 BTU/1982$ Value of Crop Production	Trillion BTU	1000 BTU/1982$ Value of Crop Production
1978	253.8	10.3	166.7	6.8	420.5	17.1
1981	229.1	9.2	197.6	7.9	426.7	17.1
1987	182.1	6.8	180.8	6.7	384.6	13.5

Sources: Author estimates based on data from Darmstadter 1991 and the 1987 Census of Agriculture.

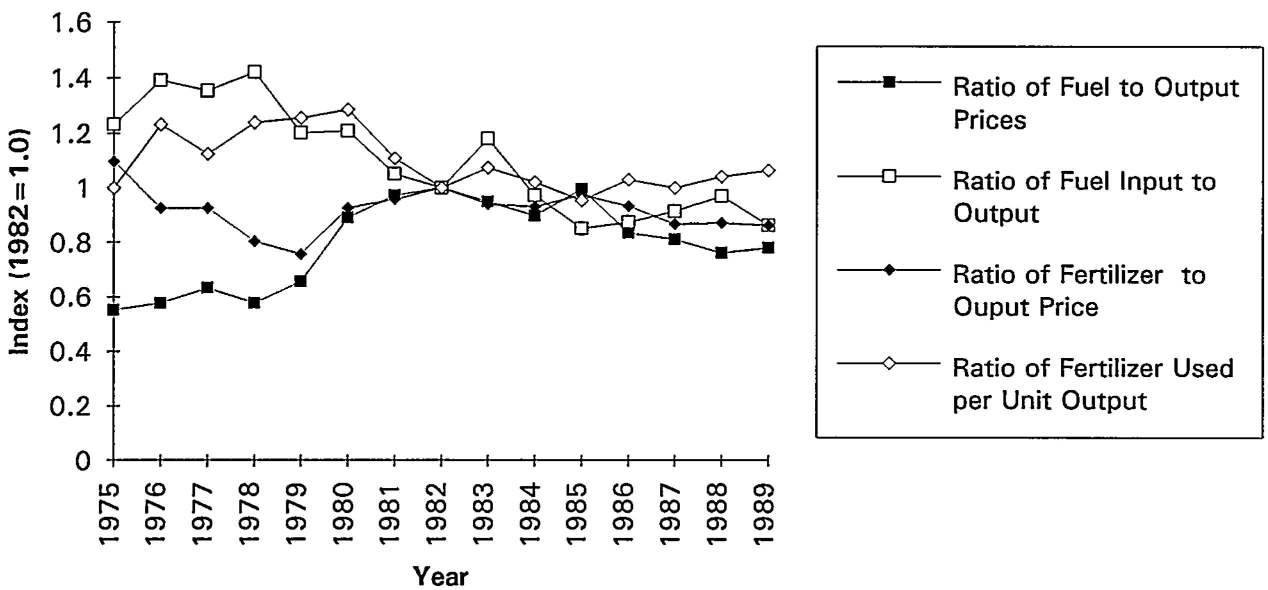

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Index (1982=1.0)
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
Year
Ratio of Fuel to Output Prices
Ratio of Fuel Input to Output
Ratio of Fertilizer to Ouput Price
Ratio of Fertilizer Used per Unit Output

Figure 2. Impact of Prices on Agricultural Use of Fuels and Chemicals in the United States, 1975 to 1989.

Table 2. Per-Acre Direct and Indirect Costs of Energy in Agriculture, Missouri-Iowa-Nebraska-Kansas, MINK Study (1982), 1989 (Author Estimate), and with Future Carbon Tax of 100$ per Ton (Forecast)[a]

Per Acre Expenses ($)	Missouri			Iowa			Nebraska			Kansas		
	1982	1989	Future	1982	1989	Future	1982	1989	Future	1982	1989	Future
Direct Energy												
All Farms	14	11	13	23	18	21	19	15	18	12	10	12
Irrigated	69	55	65	83	66	78	50	40	47	51	41	49
Non-Irrigated	13	10	12	22	18	21	9	7	8	9	7	8
Commercial Fertilizer												
All Farms	21	23	24	25	25	27	18	20	21	11	12	13
Irrigated	78	85	90	78	85	90	42	46	49	36	39	42
Non-Irrigated	19	21	22	25	27	28	7	8	9	8	9	10
Other Agricultural Chemicals												
All Farms	15	19	20	15	19	20	9	11	12	6	8	9
Irrigated	45	57	61	48	61	65	19	24	26	18	23	24
Non-Irrigated	14	18	19	15	19	20	5	6	6	4	5	5
Total Energy												
All Farms	50	53	57	63	62	68	46	46	51	29	30	34
Irrigated	192	197	216	209	212	233	111	110	122	105	103	115
Non-Irrigated	46	49	53	62	64	69	21	21	23	21	21	23

Sources: Darmstadter, 1991; U.S. Department of Agriculture, 1990; U.S. Department of Agriculture, 1991; and Author Estimates

[a]Calculated with the following assumptions: fuels increase approximately 30% in price, with a price elasticity of -0.315; and fertilizer and chemical prices rise by about 15%, with a price elasticity of -0.598. Price elasticities were calculated from U.S. price and use data for the period 1975 to 1989.

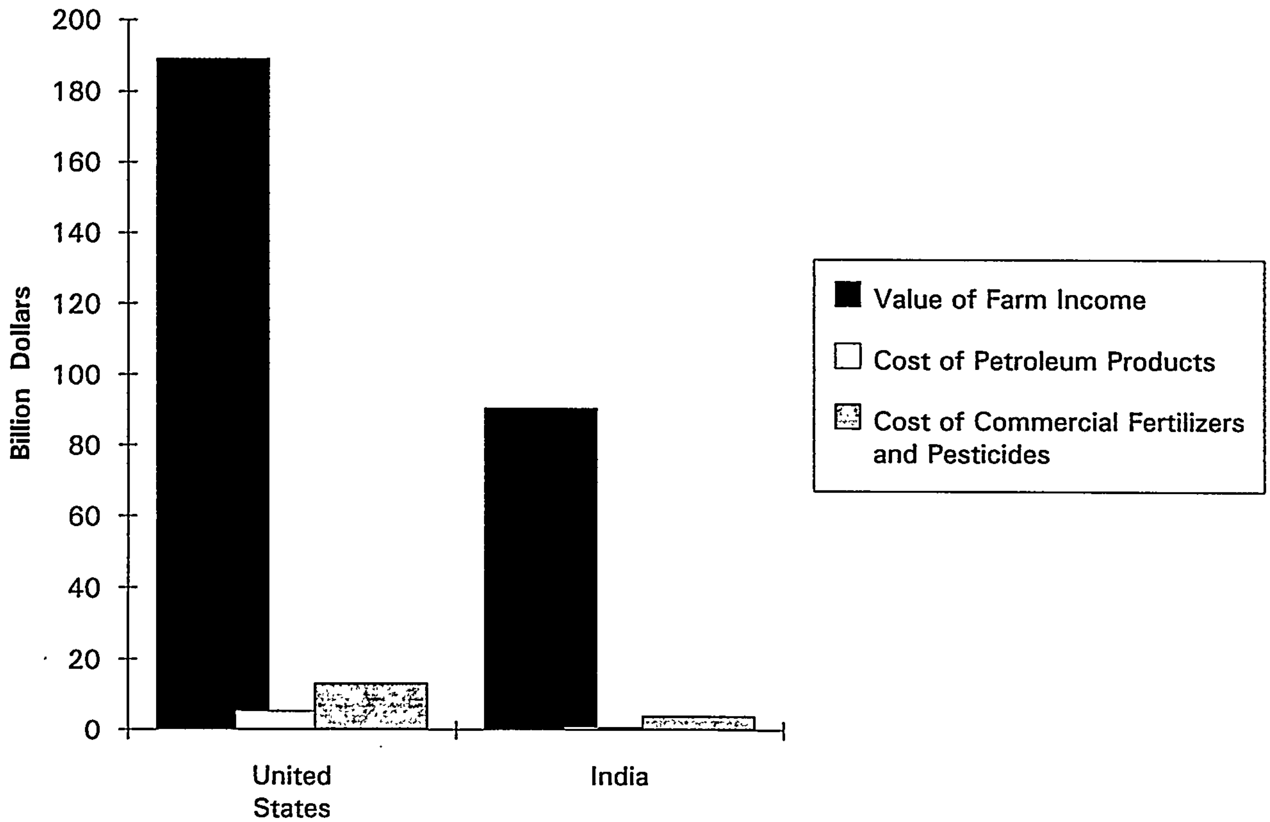
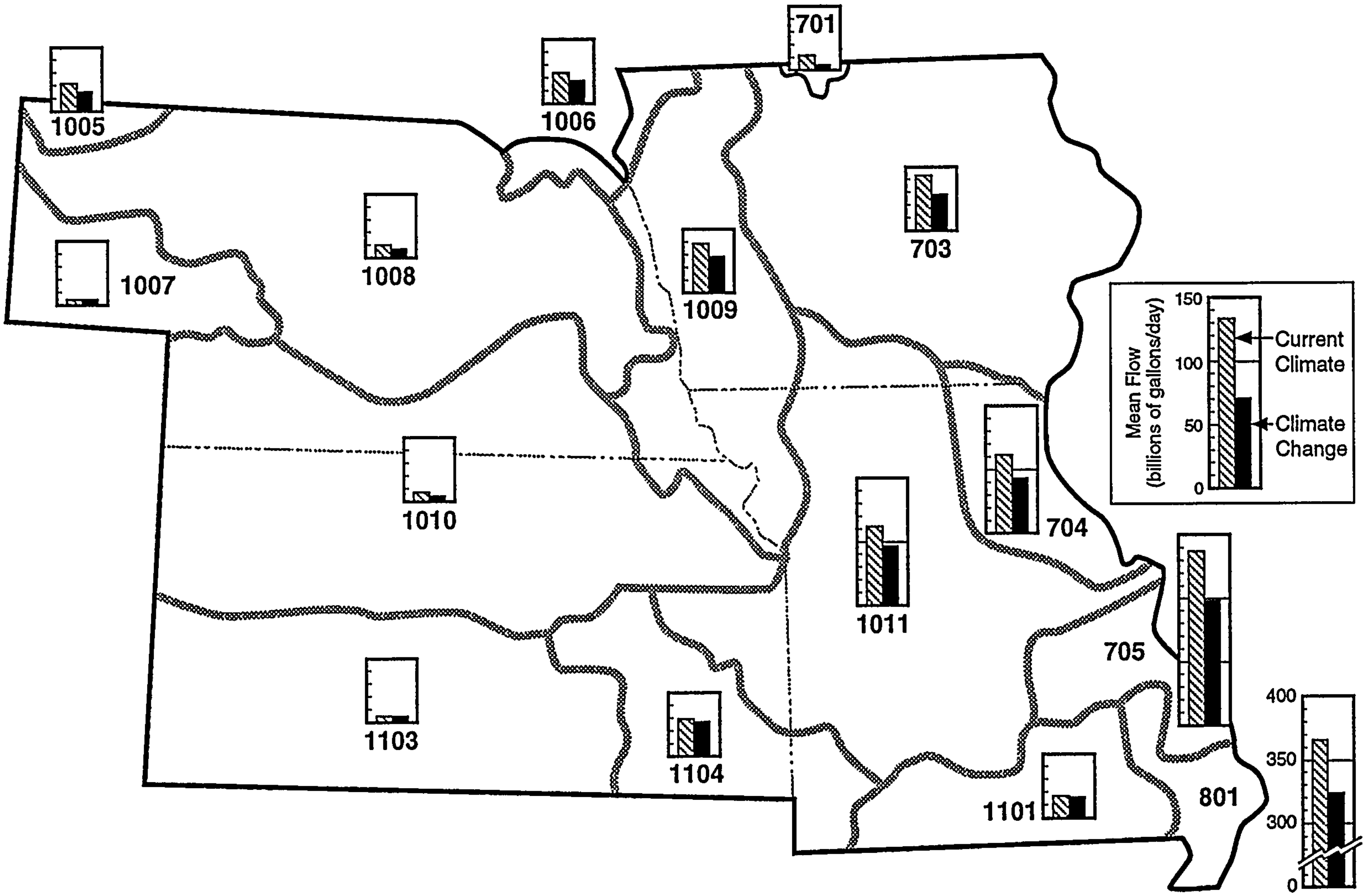

200
180
160
140
120
100
80
60
40
20
0
Billion Dollars
United States
India
Value of Farm Income
Cost of Petroleum Products
Cost of Commercial Fertilizers and Pesticides

Figure 3. Cost of Petroleum Fuels and Farm Chemicals Compared with the Value of Production in U.S. and Indian Agriculture, 1989.



701
703
704
705
801
1005
1006
1007
1008
1009
1010
1011
1101
1103
1104
Mean Flow (billions of gallons/day)
150
100
50
0
Current Climate
Climate Change
400
350
300
0

S9306013.1

Figure 4. Impact of Climate Change on Mean Natural Stream Flows in Selected Subbasins of the Missouri, Upper Mississippi, and Arkansas-White-Red River Systems (billions of gallons/day).

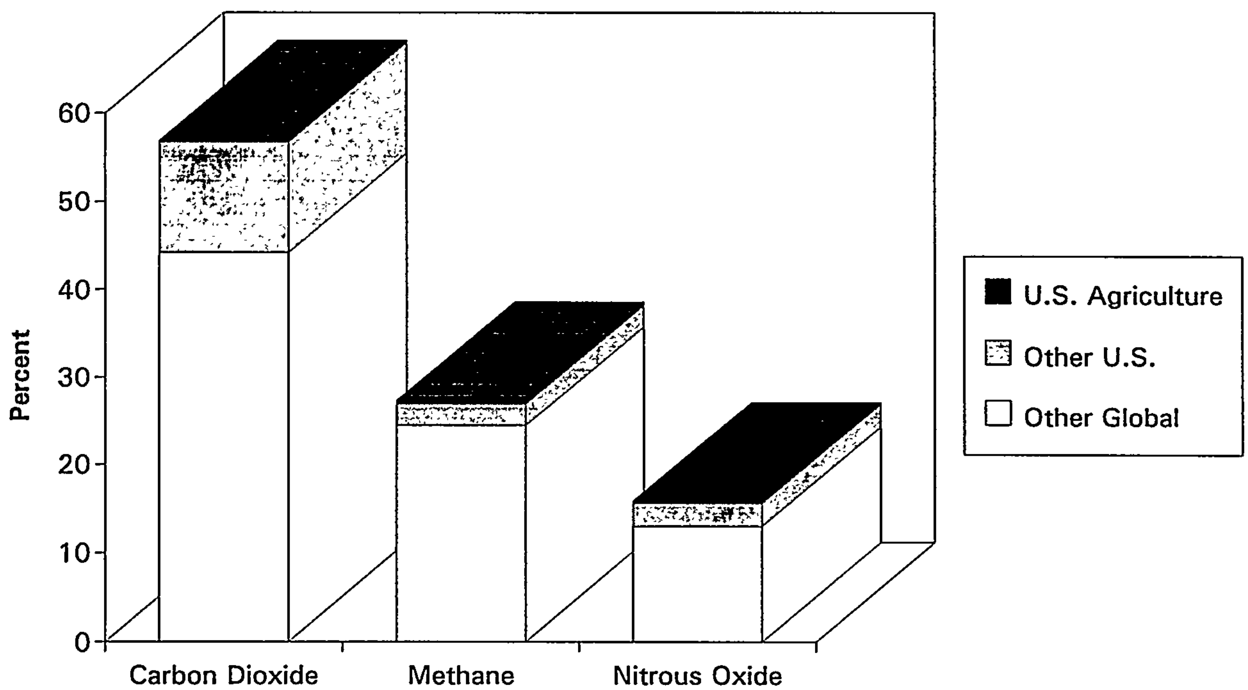

60
50
40
30
20
10
0
Percent
Carbon Dioxide
Methane
Nitrous Oxide
U.S. Agriculture
Other U.S.
Other Global

Figure 5. Climate Forcing by Carbon Dioxide, Methane and Nitrous Oxide Driven by Global Emissions, US Emissions and US Agriculture. (Source: CAST, 1992, Figure 4.1.1)

Table 3. Estimated Sources and Sinks of Methane (Tg CH_4 per year)

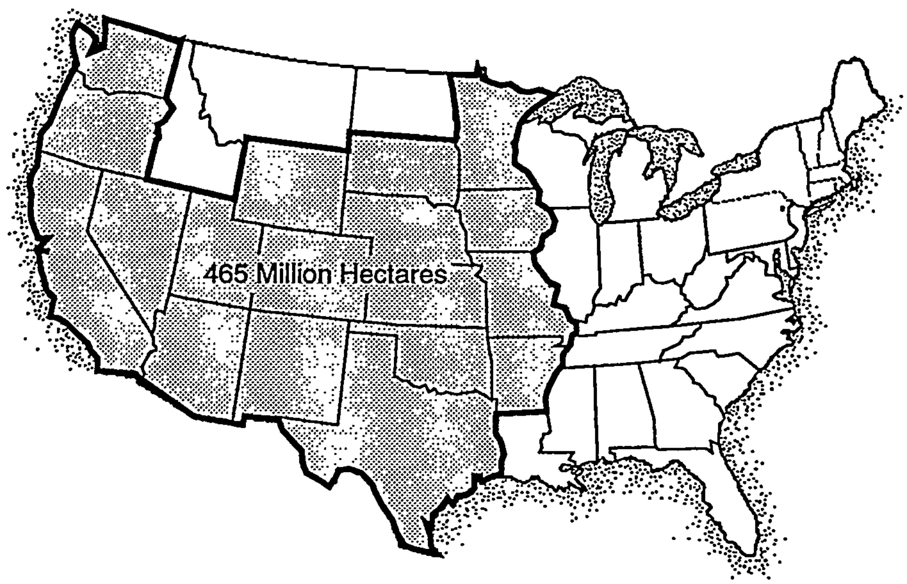
	Best Estimate	Possible Range
SOURCES		
All sources		
Natural + anthropogenic	515	331-850
Agricultural sources		
Rice paddies	60	20-150
Enteric fermentation	80	65-100
Animal wastes	25	20-30
Biomass burning	40	20-80
Total agricultural	205	125-360
Wetlands	115	100-200
SINKS		
All sinks	500	420-520
Atmospheric increase	32	28-37
Removal by soil	30	15-45

After IPCC, 1992, Table A1.3.

Table 4. Estimated Sources and Sinks of Nitrous Oxide (Tg N per year)

	Range
SOURCES	
All sources	
Natural + anthropogenic	5.18 - 16.1
Agricultural sources	
Cultivated soils	0.03 - 3.0
Biomass burning	0.2 - 1.0
SINKS	
Photolysis in stratosphere	7 - 13
Atmospheric increase	3.0 - 4.5
Removal by soils	?

After IPCC 1992, Table A1.5.



S9306013.2

Figure 6. An Area of Approximately 465 Million Hectares (after Sedjo and Solomon, 1989).

Table 5. Estimates of Land Required for Afforestation to Capture Specified Portions of the Annual Net CO_2 Emissions to the Atmosphere.

Source	Total C Removal (GT/yr)	Total Land Area Required (millions of hectares)	Assumptions
Marland, 1988	5.0	500	Production equivalent to best tropical forests
Marland, 1988	5.0	700	Production equivalent to short rotation sycamores in southeastern U.S. (Georgia)
Sedjo & Solomon, 1989	2.9	465	Production equivalent to tree plantations in U.S. southeast and northwest
Moulton & Richards, 1990		28.7[a]	Net U.S. carbon emission = 1.27 GT/yr 10% reduction

[a]Economically marginal and environmentally sensitive croplands, pasture lands, and forest lands on which growth rate of trees could be enhanced. Beyond a 15% reduction in net carbon emissions would require croplands almost exclusively.

Table 6. Loss in Value of Feedgrain Production (Corn, Sorghum, and Soybeans) and of Total Regional Production under the Dustbowl Climate and 1980s Agricultural Conditions in the MINK Region.

Situation	Millions of 1982 $
(1) Climate change	4374
(2) Adaptation only	3755
(3) Adaptation + CO_2	1847
(4) Reduction in losses attributable to CO_2 effects (2) - (3)	1908

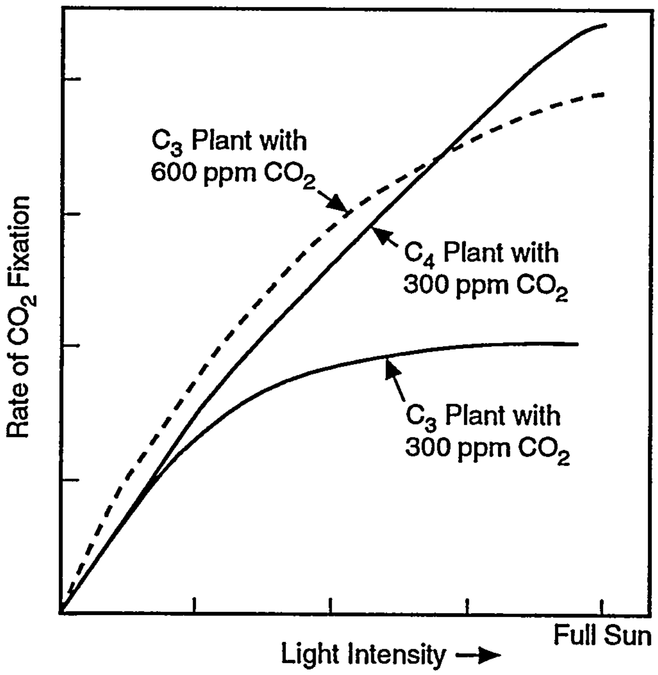
After Bowes and Crosson, 1991, Table 4.5.

Table 7. Changes in Crop Production and Value in the MINK States Due to Imposition of a Dustbowl Climate and the Ameliorating Effects of CO_2 Enrichment

	Production (million tons)		Value (millions of 1982 $)	
Crop	Current[a] CO_2	Elevated[b] CO_2	Current[a] CO_2	Elevated[b] CO_2
Corn	-15.03	-9.46	-1644	-1035
Wheat	-0.10	+1.14	-14	+150
Sorghum	-2.15	-1.18	-215	-118
Soybeans	-3.77	-2.09	-789	-438
Hay	-0.80	+1.90	-47	+112
Total			-2709	-1329

[a]Current CO_2 = 350 ppmv
[b]Elevated CO_2 = 450 ppmv

After Crosson, Katz and Wingard, 1991, Table 1.11.



C_3 Plant with
600 ppm CO_2
C_4 Plant with
300 ppm CO_2
C_3 Plant with
300 ppm CO_2
Rate of CO_2 Fixation
Light Intensity →
Full Sun

S9306013.3

Figure 7. Response of a C_3 Plant to Doubling of Ambient CO_2 Concentration over a Range of Illumination from Darkness to Full Sunlight.