MARES' TAILS AND MACKEREL SCALES

The stormy prospect of global warming...
What it means to farming in the Middle Border...
And what farmers and farm policy can do about it.

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Marty Strange

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Walthill, NE 68067

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Foreword

The old timers used to say that when clouds took the shape of mares' tails or mackerel scales, a storm would soon strike. Although weather forecasting is more technical today, it might not be much more accurate, especially if so-called "greenhouse gas" emissions destabilize the climate and increase the uncertainty of weather events. The prospect of more erratic and perhaps more violent weather patterns is especially troublesome to farmers, whose livelihoods are traumatized by unstable agronomic conditions. Mares' tails and mackerel scales spell trouble on the farm.

That is especially true out here in the region novelist Hamlin Garland referred to as the "Middle Border," where the subhumid Corn Belt gradually gives way to the semi-arid Great Plains. Here, the weather is already so volatile and so severe that it has always been a source of desperate, self-defensive humor. There's the one about the Nebraska farmer who died and was cremated, but after four hours in the furnace he suddenly sat up and observed, "If this weather don't let up, I don't believe we're gonna get a corn crop this year." Or the one about the farmer who lamented during a drought, "I don't care whether it ever rains again -- *I've* seen rain before -- but my ten year old son, well..."

Everywhere farming is important, the weather is, too.

So, farmers and those who live in farming areas should be especially concerned about the widely reported prospect that human activity causes the release of gases into the atmosphere that will change the climate. These greenhouse gases may cause a global warming effect that permanently and substantially alters agriculture as we know it, threatening to dislocate and ruin many farmers.

We have set out to understand and explain the global warming and climate change issue as it affects agriculture especially in the American Midwest. Specifically, the task before us has been fourfold:

1. To summarize the findings of available studies that predict how the climate in the American Midwest might change due to the greenhouse and how agriculture in the region might be affected by those changes;

2. To estimate the major sources of U.S. agricultural greenhouse gas emissions, with special attention on sources related to Midwestern agriculture;

3. To evaluate the potential for U.S. agriculture to reduce its emissions and to "cleanse" the atmosphere of carbon dioxide, the most prominent greenhouse gas.

4. To recommend appropriate policies.

This report is divided into four parts. Part I introduces the reader to the greenhouse phenomenon and the scientific basis for predicted climate change. It also provides general background about each of the greenhouse gases most closely associated with agriculture -- carbon dioxide, methane, and nitrous oxide.

Part II reviews extensive scientific literature on how climate change is likely to affect agriculture, with special emphasis on predicted impacts in the Middle Border, or the mid-section of the North American continent generally.

Part III analyzes American agriculture's contributions to greenhouse gas emissions, again with special emphasis on farming systems typical of our region, and proposes both management strategies and policy reforms that might lessen agriculture's contribution to the problem. This part also demonstrates the importance of considering the impact of farming systems as a whole on emissions of all greenhouse gases, rather than the impact of specific management practices on emissions of a single gas.

Finally, Part IV sums up our findings and recommendations.

We are not climatologists. Indeed, in preparing this report, we have brought a layperson's innocence to the challenge of trying to sort out the complexities of global warming and climate change. If we have understood the issues confronting agriculture in our society and communicated them to farmers, farm leaders, and farm policy makers in this report, we have accomplished our most important goal.

Acknowledgements

We have been aided in our work by the patient counsel of many scientists who submitted to lengthy interviews, collected difficult-to-find pieces of datum for us, and both scientists and non-scientists who patiently reviewed early drafts. Among those who gave generously of their time and whom we want especially to thank are: Basil Acock, Laure Benzing-Purdie, Jim Brandle, Gary Breitenbeck, William Easterling, Gary Evans Paul Faeth, Don Johnson, Mark Johnson, Bruce Kimball, Terry Klopfenstein, Paul Kruse, Linda Mearns, William Parton, Mac Post, Paul Rasmussen, Cynthia Rosenzweig, L.M. Safley, Jr., Michael Thompson, and Justin Ward. Many others also gave of their time in informational interviews. They are noted in the bibliography.

Of course, neither these nor others with whom we consulted are responsible for the opinions expressed nor any errors in our work. Only we are.

Finally, we also want to thank the Joyce Mertz-Gilmore Foundation and the Joyce Foundation for providing major funding for this project.

WHAT IS THE GREENHOUSE EFFECT?

Summary: The "Greenhouse Effect" is a natural and beneficial process by which the gases in the earth's atmosphere trap solar energy to warm the planet. However, human activity has increased the level of greenhouse gases in the atmosphere by causing them to be released from fossil fuels, vegetation, and soil.

The most "agricultural" of these gases are carbon dioxide, methane, and nitrous oxide. Each is increasing in the atmosphere, according to a large body of scientific research. If these gases continue to increase at current rates through the year 2020, their warming effect would be double that of carbon dioxide alone prior to the industrial revolution 200 years ago. Most climatologists agree that such an increase eventually would warm average surface temperature by about 1 to 6 degrees (F) compared with current temperatures.

Such a temperature increase would shift agronomic zones, alter precipitation patterns, raise the sea level, and especially important for agriculture, increase the variability, instability, and unpredictability of weather, and increase weather related disasters, including droughts.

Complex, but not necessarily very reliable, computer models are used to make such predictions. These models have difficulty accounting for many "interactive feedbacks," such as the role of oceans and clouds, in moderating or exacerbating the effect of greenhouse gases in the atmosphere.

Although much maligned, the "greenhouse effect" is actually essential to the continuing existence of life on earth. If all the solar energy that the earth absorbs were reflected back into space as infrared radiation with nothing to stop it, the earth would be too cold to support much life. What keeps the heat within the earth's atmosphere are clouds and certain gases that allow the sunlight in, but trap the heat that otherwise would radiate back out from the earth.

Besides water vapor, the greenhouse gases that provide this essential service are primarily carbon dioxide, methane, nitrous oxide, and ozone. Together, they have kept the earth some 60 degrees (F) warmer on average than it would be without them (Schneider 1989).

Atmospheric scientists have been able to confirm by several means that these chemicals form a greenhouse. First, satellite measurements of the amount of radiation the earth emits back into space compared to the radiation received by the earth confirm the greenhouse effect. Second, the greenhouse theory effectively explains the difference in the surface temperatures of Venus, Mars and Earth in light of their different atmospheres. Third, evidence of changes in the concentrations of carbon dioxide and methane in the atmosphere over the past 160,000 years shows a close correlation to changes in the earth's temperature (IPCC 1990a).

Earth's atmosphere is roughly 78 percent nitrogen and 20 percent oxygen. While the greenhouse gases (including mostly water vapor) mentioned above make up only about one percent of earth's atmosphere (Schneider 1989), that's adequate to trap just enough heat for our moderate global temperatures. Because such a small fraction of the atmosphere's gases provides the crucial level of greenhouse warming, even small changes in the level of these critical greenhouse gases can have a big effect on our climate.

What Is Going Wrong With the Greenhouse Effect?

The level of atmospheric greenhouse gases has increased significantly since the beginning of the industrial era, due largely to the activities of people. We are concerned primarily with the three greenhouse gases most closely associated with agriculture: carbon dioxide, methane, and nitrous oxide. A brief case-by-case review of these gases follows.

Carbon Dioxide

Carbon dioxide is the most prevalent of the greenhouse gases. At current levels of concentration, (350 parts per million in 1988) it is 200 times as concentrated as methane and over 1,000 times as concentrated as nitrous oxide. Moreover, it is growing rapidly. The atmospheric concentration in 1988 was 25 percent higher than it was at the beginning of the Industrial Revolution (280 ppm), and higher than at any time in the past 160,000 years. In fact, carbon dioxide concentrations have risen by more than 35 ppm in just the past 30 years (WRI 1990), and at the current growth rate of 0.5 percent per year, atmospheric carbon dioxide will double from pre-industrial levels by about 2055 (IPCC 1990a).

Although it is the most voluminous of the greenhouse gases, carbon dioxide is not the most potent. It has less than 2 percent of the warming effect of methane, and less than 0.5 percent the warming effect of nitrous oxide. Moreover, carbon dioxide is constantly being absorbed from the atmosphere by the oceans, soils, and photosynthesis. In fact, so much carbon dioxide is removed that less than half of the gas that is known to have been released shows up in atmospheric measurements.

Nonetheless, due to its sheer volume and longevity (at least 100 years) in the atmosphere, scientists estimate that it accounts for over half of the warming effect.

The burning of fossil fuels (for electricity, heat, industry and transportation) is the largest source of carbon dioxide emissions. A second major source is deforestation, most extensive in the tropics, though the United States has contributed its share of carbon dioxide from deforestation since its founding (Houghton and Woodwell 1989; IPCC 1990a).

Any land use change which decreases the amount of plant life also releases carbon. The principal example is deforestation, but this can also occur when agricultural lands are left bare, or organic matter in the soil declines. Soil erosion also is a considerable source of carbon dioxide emissions. Carbon dioxide is also released through the manufacture of cement (WRI 1990).

Because carbon dioxide is by far the most prevalent of the greenhouse gases, the other gases are frequently measured in terms of their ''equivalent warming effect'' -- the amount of those gases that would produce the same warming effect as one molecule or gram of carbon dioxide.

Methane

At 1.72 ppm in 1990, methane is much less prevalent than carbon dioxide. Moreover, it breaks down in only 8-12 years, meaning that less than one fifth of the methane released increases its total level in the atmosphere. For these reasons, it may be the most ''manageable'' of the greenhouse gases.

However, its growth rate of 0.9 percent per year makes it the fastest growing of the three ''agricultural'' gases, and its warming effect makes it one of the most potent. Over a 100 year period, methane exerts about 20 times greater global warming potential as compared to carbon dioxide (IPCC 1990a). Atmospheric methane concentrations have increased more than 100 percent over preindustrial levels. Currently the second most important greenhouse gas, within 50 years methane could be the most important.

Scientists are still working to discover all the sources of increased methane in the atmosphere. About 20 percent of the methane currently in the atmosphere was previously trapped in the earth. It has been seeping from coal seams, oil wells, natural gas pipelines, and melting permafrost (as a result of the warming that has already occurred). Methane is produced by bacteria in the absence of oxygen. The more prominent sources of its production are biomass burning, rice paddies, ruminant digestion, animal manure, land-fills, bogs, wetlands, and termite mounds. It is also possible that methane is being released from hot asphalt roads and roofs (Ciborowski 1989; Pearce 1989).

The increase of total methane in the atmosphere is also due to the fact that it is staying around longer because the things that break it down are increasingly prevented from doing their job.

Hydroxyl (OH) is primarily responsible for removing methane in the atmosphere, but hydroxyl also oxidizes carbon monoxide, so the more carbon monoxide in the atmosphere (from automobile exhaust and other fossil fuel combustion, land clearing, and wood or other biomass burning [Ciborowski 1989]), the less hydroxyl there is to work on methane. In fact, atmospheric levels of hydroxyl have declined about 25 percent since 1950. One researcher believes that cars are therefore indirectly a more important contributor to increased methane than either cows or rice paddies (Pearce 1989).

Changes in soil conditions, for example acid rain and the application of nitrogen fertilizers, may be reducing the ability of bacteria to break down methane in soils (Pearce 1989).

Nitrous Oxide

At a concentration level of only 0.31 ppm, nitrous oxide is the least prevalent of the gases we are considering. Moreover, it is increasing at the slowest rate, about 0.25 percent per year. However, once in the atmosphere, it is also very persistent, lasting as long as 150 years. It is also one of the most potent, with nearly 300 times the global warming potential of carbon dioxide over a one hundred year period (IPCC 1990a). Because of its durability and potency, preventive action to keep nitrous oxide out of the atmosphere before it gets there is particularly important.

Unfortunately, that is not happening. Although nitrous oxide has increased by only about 0.02 parts per million (ppm) over the past century, it is now increasing at a much faster rate and is projected to reach 0.34 ppm by the year 2030 (U.S. Congress 1991).

Nitrous oxide is released from natural processes in the soil, from nitrogen fertilizer, fossil fuel combustion (especially coal), animal and human wastes, bodies of water, and biomass burning and land clearing (Ciborowski 1989, Ciborowski and Abrahamson 1984).

What is the Evidence That Global Warming is Already Underway?

What does it mean that these gases, which are known to trap heat, are increasing in concentration? The widely accepted theory is that they will intensify the "greenhouse effect", leading to an increase in the earth's average surface temperature. There is a broad, but not complete, consensus that some warming of the climate is inevitable and that this warming will both alter and redistribute the world's "climatic resources."

Because of their different properties as absorbers of infrared radiation, the contribution of each of these gases to the increased greenhouse effect is not directly proportional to its abundance in the atmosphere. Based on atmospheric concentration and relative heat-trapping potential, it has been estimated that carbon dioxide is contributing 55 percent of the warming effect, chlorofluorocarbons, 24 percent, methane, 15 percent, and nitrous oxide, 6 percent.[1] Tropospheric ozone (smog) may also be significant, but its contribution cannot currently be quantified (IPCC 1990a).

But so far, it has not been possible for scientists to prove unequivocally that the increasing greenhouse gas concentrations have already caused the climate to warm. First is the question of whether average global temperature has in fact risen. The second question is whether a warming trend, if it can be detected, results from rising greenhouse gases in the atmosphere, or is merely a (relatively) short-term aberration.

The available evidence is that average global temperature has risen about 0.9 degrees Fahrenheit over the past century (IPCC 1990a). The measurements that form the basis of this observed increase have been challenged as being unrepresentative of actual average global temperatures, due to the lack of weather stations over the oceans, and the artificial effects of urban areas, which by storing heat in concrete and asphalt and concentrating combustion, become "heat islands" that distort temperature readings.

But in an article published in the August 1990 Scientific American, two British scientists reported on ten years of work systematically analyzing all available temperature records and eliminating uncertainties. They assert unequivocally that "the world's climate, although highly variable over periods of decades or less, has become generally warmer during the past century," by about a half a degree Centigrade (0.9° F) (Jones and Wigley 1990:84). Nearly half the actual temperature increase of the past 100 years has occurred since 1965 (WRI 1990). In addition, the six global-average warmest years on record were in the 1980s and 1990 (Schneider 1989, IPCC 1990a, IPCC 1992). Further evidence of the warming is a marked recession of the majority of mountain glaciers over the past century (IPCC 1990a).

According to the models used by scientists, increasing levels of carbon dioxide and other gases should have increased the average temperature about 0.9 to 1.8 degrees Fahrenheit over the past 100 years, or about the amount the atmospheric temperature actually did increase.

The actual increase probably would have been even greater over the past century if not for the moderating effect of the ocean. Oceans have a very large heat storage capacity, and they warm more slowly than the atmosphere (MacDonald 1989), creating a kind of "thermal delay" as increased air temperature is gradually transferred to the ocean.

Because of the influence of the oceans, as greenhouse gas concentrations rise, the actual global temperature will be less than the ultimate "equilibrium temperature", which will be realized more slowly and over a longer period of time. This means that even if net greenhouse gas emissions were stopped today, we would still experience an upward climb in average global temperatures by more than a third of a degree Fahrenheit per decade for several decades (IPCC 1990a).

In fact, the greater the warming caused by greenhouse gases, the longer the ocean thermal delay. Since the ocean thermal delay may significantly mask the warming as it occurs, it is difficult to say whether the small degree of warming observed up until now means that the atmosphere isn't really warming as much as the increased greenhouse

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[1] These figures were developed prior to very recent findings that chlorofluorocarbons may exert a cooling as well as a warming effect (Easterbrook 1992).

gases indicate it should, or that it is warming, but the ocean is absorbing more of the increase in temperature than scientists thought it would (Abrahamson 1989).

It also isn't clear whether the actual increase signifies an enhanced greenhouse. Are these changes part of a long term trend, or just short-run aberrations?

Standard statistical tests can be used to determine the probability that the warming is real and not just short term variation, but at this point it's still a close scientific call. Two scientists might reach different conclusions from the same data (Schneider 1989). A few prominent atmospheric scientists assert confidently that the evidence of warming over the last century means that the greenhouse is already here. But most scientists have been much more circumspect in their public statements, even though privately they may agree.

It comes down to whether we can afford to wait for conclusive evidence before acting to curb greenhouse gases. Especially when many of the measures that can and ought to be taken now to reduce our contribution to global warming (such as energy conservation), are measures that ought to be taken anyway for other reasons.

How Much Will It Warm, and What Are the Consequences?

A number of models, varying in their complexity, have been developed to predict the effects of a changing atmosphere, in particular the extent of warming we can expect over the next 30 to 40 years. At current rates of increasing greenhouse gas concentrations, by about 2020 we would reach a warming commitment[2] equal to that which would occur if carbon dioxide levels doubled from pre-industrial levels (IPCC 1990a).

The available models predict that doubled carbon dioxide levels would eventually warm average surface temperatures 2.7 to 8.1 degrees Fahrenheit (1.5 to 4.5 degrees Celsius) compared to the pre-industrial period.[3] The Intergovernmental Panel on Climate Change (IPCC), a panel of several hundred scientists charged by the World Meteorological Organization and the United Nations Environment Programme to assess the science of climate change, potential impacts and response strategies, estimates the average global temperature already has increased about 1.8°F (1°C) since 1765. If greenhouse gas emissions rates are not curbed, IPCC's best estimate is that by 2030 the average global temperature will have risen about 3.6°F (2°C) since 1765 (IPCC 1990a). And it will increase an additional 3.6 degrees Fahrenheit before 2100. That translates into a warming of nearly 2 degrees Fahrenheit above the current average within 40 years, and 5.4 degrees Fahrenheit within one hundred years (IPCC 1990a).

The consequences of such a rapid and dramatic temperature increase are numerous and potentially devastating for many parts of the world. Almost every ecological system would be affected, and in turn, economic activities dependent on those systems would be disrupted (Abrahamson 1989).

One consequence will be a shift in temperature zones. One degree Celsius of warming (1.8°F) is equivalent to moving south about 100 miles (Abrahamson 1989). Such a shift would have many implications, including a shift in agronomic zones. Though average global precipitation would increase, several of the models predict that in the mid- to higher latitudes and the middle of large continents--areas such as the Midwest--a drier climate will be likely. The combination of higher temperatures and reduced precipitation would threaten the viability of forests, freshwater ecosystems, and aquatic species, as well as established agricultural systems. The ability of streams to dilute pollutants would also be compromised. A further consequence of this ecological disruption would be an increase in the rate at which species (biological diversity) are lost (Brown et al. 1989).

Another consequence of global warming will be a rise in the sea level. The IPCC report predicts that sea level will rise nearly 8 inches by 2030 and 26 inches by the end of the next century (IPCC 1990a). The sea level rise would be

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[2] "Warming commitment" refers to the total extent of warming that can be expected from a given combined level of greenhouse gases. Extent of warming is usually figured in terms of CO_2 concentrations, with the understanding that the concentrations of the other greenhouse gases can be translated into equivalent levels of CO_2.

[3] In the remainder of this report, temperatures in almost all cases will be given in degrees Fahrenheit only, though the reader should understand that these figures are our conversions for the degrees Celsius provided by the sources cited. Our assumption is that most of our readers have much more experience with Fahrenheit than Celsius. Our purpose is to simplify the text for greater ease in reading

caused by the ocean's thermal expansion, and by melting mountain glaciers and perhaps the eventual melting of polar ice sheets. This increase in sea level would threaten low-lying areas, drown coastal marshes and swamps, erode beaches, and dump ocean salt water into rivers, bays, and aquifers throughout the world (Titus 1989).

Weather related disasters, including droughts, heat waves, and hurricanes would also be more common in a warmer world (Brown et al. 1989). Mearns, Katz and Schneider (1984) have shown that even small changes in mean temperature can result in a much higher probability of "extreme temperature events", e.g. five consecutive days with maximum temperatures above 95 degrees (F). Regardless of whether the global climate changes as predicted by scientists, more frequent weather extremes seem inevitable, particularly because during the last 50 years the weather has been unusually stable (Schneider 1989).

Variability in the weather--from year to year and day to day--is a key question in current research on the implications of an increase in the mean temperature. For example, it's quite possible that an increase in average *amount* of precipitation also means an increase in the *variability* of precipitation. On the other hand, scientists are not as sure that an increase in the average temperature level will also be accompanied by an increase in temperature variability.

It could be, therefore, that the heat and drought experienced in much of the Midwest in 1988 and 1989, followed by an excessively wet and relatively cool spring and summer in 1990 represent a pattern of extreme variation that may become more common as global warming increases (Mearns 1990).

There are other factors, too. Air pollution may be worsened by rising temperatures that would increase the reactivity of chemical pollutants, and potentially extend their seasonal effects. Many cities would experience higher levels of ozone pollution and other constituents of smog (Smith and Tirpak 1989) In addition to the health effects of increased pollution, worsened heat waves are likely to result in more heat-related deaths, particularly among the elderly. A study by Dr. Gene Tackle at Iowa State University found that only a modest increase in mean summer temperatures could triple air conditioning demand. Thus global warming could increase energy demand, which in turn could further contribute to increased greenhouse gas emissions.

The most extreme possible outcome of a warmer world might be a shift in ocean currents. Ocean currents and the mixing of ocean layers affect the rate at which oceans transport heat to and from the atmosphere. Currents are caused by geographical differences in salinity and water temperature, and these could be altered by rising polar temperatures and the melting of polar ice. Even small changes in the relative saltiness of the Atlantic and Pacific oceans from melting ice could conceivably cause ocean currents to shift. According to the historical evidence, such a shift probably did occur in the distant past, and Europe, no longer warmed by the Gulf Stream, was covered by glaciers (Schneider 1989).

Both the volume of greenhouse gases and their rate of increase in the last 160,000 years are unprecedented. This has prompted Stephen Schneider (1989), a leading climatologist, to assert,

> the bottom line is that if we disturb the climatic environment by as much as nature has from the last ice age to the present interglacial, and we do it some ten to fifty times faster, then nasty surprises, such as a radical and potentially catastrophic shift in ocean currents, are plausible. And the faster we alter the climate, the greater the likelihood of surprises.

It may be the potential for "nasty surprises" that should concern us most.

How Do Scientists Predict Global Warming?

One source of information to help scientists evaluate the impacts of a changing atmosphere is geologic history. Scientists have correlated carbon dioxide levels with global temperatures and climate patterns over the past 160,000 years. While temperatures have varied widely, carbon dioxide levels have varied with them. Most of the temperature changes, however, occurred gradually, and it is difficult to know with certainty whether increased carbon dioxide levels were a cause or an effect of warming trends.

Another approach increasingly used by scientists involves model building. The climatological effects of increasing carbon dioxide concentrations are predicted using computer models built to represent current climatic conditions.

To develop and refine climate models, scientists need a world-wide system of data gathering. First, they need continuously updated information on the factors affecting earth's climate currently. These include atmospheric circulation, ocean currents, and solar radiation, measured by an international effort called the World Weather Watch which is set up to enable daily weather forecasting.

But long-term climate change modeling requires other specialized monitoring systems as well, covering factors that are not important for short-term weather forecasting. Together, the World Climate Research Programme, and the International Geosphere-Biosphere Programme have in place or are undertaking research and monitoring programs to evaluate the control of greenhouse gases by the oceanic and terrestrial biosphere; the control of radiation by clouds; precipitation and evaporation; ocean transport and storage of heat; and ecosystem processes (IPCC 1990a). Also, volcanic aerosols (primarily sulphates that cause cooling), solar radiation cycles, afforestation or deforestation, and the increase or decline of polar ice are all being monitored (WRI 1990). These programs are complemented by the substantial U.S. Global Change Research Program which studies the various processes affecting global climate change and seeks to improve the ability to make scientifically reliable projections of greenhouse effects (Evans 1992).

All the information generated by these research programs will help climatologists refine the predictive ability of computer models. General Circulation Models (GCMs) are those computer models which aim for a relatively complete representation of all relevant atmospheric processes. They are designed to provide information that will help society deal with global warming, such as the distribution of regional, seasonal, and daily temperatures and the extent of soil moisture and surface runoff (MacDonald 1989). With the help of computers, the models apply the laws of physics to interactions among the climate's various subsystems: atmosphere, oceans, land, biota, and glaciers (Schneider 1989). The equations that make up the models represent, for example, the laws of motion (e.g. for atmospheric winds) and the laws of thermodynamics (conservation of thermal energy). The models include equations for atmospheric water and hydrodynamics. They also represent the radiative properties of the various chemical constituents of the atmosphere and of land surfaces (e.g. snow and ice), and the role of other land-surface processes, such as soil moisture and evapotranspiration (Dickinson 1986).

Because of the large number of variables involved, predicting climate change using GCMs requires the most powerful computers available to solve about 200,000 equations, each requiring extensive calculations (MacDonald 1989). A single "run" of a model's projections (for example to a doubling of atmospheric carbon dioxide) can require several days.

GCMs are limited, however, by the fact that climate occurs and changes simultaneously everywhere on earth. The data entered into the computer only represent widely spaced points on the earth's surface. The models treat large areas of the earth's surface as a single climatic zone. In a typical model, over 2,000 grids of about 100,000 square miles each -- roughly the size of Wyoming -- are laid out for this purpose. Each grid, in turn, might have nine vertical layers, yielding about 20,000 grid-layers from which to analyze the earth's atmosphere (MacDonald 1989). In the newer models the grid size is decreasing and the number of layers increasing, but they still can represent only large-scale features of the climate (IPCC 1990a).

The result of the large size of the grid is that regional climate phenomena cannot be precisely accounted for. The models therefore attempt to estimate the collective effect of these local phenomena. They provide a very rough measure.

In general, the various models that have been developed differ in their results because scientists do not have complete descriptions of some climatic processes and because they do not agree on which kinds of approximations provide the most reliable model. They have therefore developed different modeling approaches (Dickinson 1986). The result is that the GCMs yield different predictions of the regional effects of climate change, as well as variation in the predicted degree of average global warming. Regional predictions are not yet reliable (IPCC 1990a).

One of the big sources of difference among the GCMs has to do with how they treat clouds (Schneider 1989). Clouds affect the distribution of radiative energy, and both cloud coverage and cloud height vary within the regions represented by the grids (MacDonald 1989). Cess et al. (1989) compared fourteen GCMs and found that most of the three-fold variation in predicted warming was due to differences in how the effects of clouds were incorporated into the models.

There are several ways to test the reliability of climate models (Schneider 1989). For example, models have been successful in reproducing climatic conditions on Venus and Mars, and their representations of past climatic states are also consistent with the hard evidence available to scientists. They have also successfully simulated the earth's seasonal weather cycles well. This is important because seasonal differences are much greater than the changes that are likely to result from the greenhouse effect. In addition, the models can be tested by comparing in the present whether a particular component, such as cloudiness, matches the actual cloudiness in a given grid.

Two of the most widely cited models have been produced by the Goddard Institute for Space Studies (GISS) in New York, and the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey. Many of the findings concerning impacts on Midwestern agriculture rely on climatic projections of these two models. These models differ in their respective representations of convection (the transport of heat and moisture by vertical displacement of air) and other processes. In the "runs" we refer to, the GFDL model shows a slight increase in annual precipitation in the Midwest, including a marked increase in summer; whereas the GISS model shows a decrease in annual precipitation, especially in winter, summer and fall, with much greater precipitation in spring than the GFDL. Table 1 in the Appendix provides the figures for temperature and precipitation.

Transient and Equilibrium Models

Until recently, most GCMs undertook the task of predicting how climate would change if the level of carbon dioxide were doubled all at once. These are called "equilibrium response" models because they move from one stable climate condition to another.

More recently, scientists have attempted to address how climate will change with a gradual increase in greenhouse gas concentrations. These models are called "transient response" models, and their major difference is that they try to incorporate ocean dynamics and "thermal delay." This makes them more complex and more difficult to construct.

So far the results from these models are roughly in agreement with the equilibrium models about predicted average global temperature increases. However, since the oceans influence the atmosphere, ocean currents can redistribute greenhouse warming around the earth, resulting in evolving regional effects different from those projected by equilibrium models. Recent studies have projected, for example, an inconsistent warming pattern in the higher latitudes of the Northern Hemisphere including a possible period of cooling in the North Atlantic and Northwest Pacific; or a faster rise in temperature in the Northern than Southern Hemisphere (IPCC 1990a).

Climate Predictability

This brings us to the question of just how predictable climate change is in response to an enhanced greenhouse. Eventually, if we stop net greenhouse gas emissions a new equilibrium will result. But as the climate in any particular region changes toward that equilibrium, it may not change in a straight line progression, even accounting for normal variability from year to year. There may even be more than one possible equilibrium climatic state that could result from an atmosphere with doubled carbon dioxide (Schneider 1989). This suggests that as the climate responds to new atmospheric conditions from one year to the next or from one decade to the next, the changes that occur in a given region (such as the Midwest) may not all seem to be headed toward a single climatic pattern.

Weather forecasters know that small changes in one part of the system can have a large effect on how the system develops. That's why they're limited to forecasting about a week in advance, and it's why they're not always right. This could also mean that long-range climate change is less predictable than we'd like.

Based on the observation that the climate and ocean systems do have stable components such as predictable cycles, the IPCC considers the predictability of the changes in the system as a whole a "reasonable working hypothesis (IPCC 1990a)." But notice it's still a hypothesis.

The final test of the climate models, of course, will be what happens to our climate in the years to come. Indeed, the 0.9 degree Fahrenheit increase we have experienced over the past century may well be a confirmation of the warming predicted by the models, though we may not know for sure until at least the turn of the century.

Interactive Feedbacks That Might Alter the Predictions of Warming.

There are a number of interactions and feedback processes that will affect global warming. A "feedback" is a secondary effect caused by an initial change in climate. It's a "positive" feedback if it reinforces the change that has already taken place. It's a "negative" feedback if it tends to offset the change that has taken place. Just to give an indication of how complex the issues that climate modelers have to deal with are, we offer a brief overview of some expected feedbacks.

Oceans

As discussed earlier, the oceans may be buffering the climatic effects of increasing carbon dioxide by absorbing some heat from the atmosphere, delaying warming. In addition, the oceans are directly absorbing some carbon dioxide emissions (WRI 1990). Changes wrought by warming, such as shifts in winds, ocean chemistry, the biology of the oceans, and the mixing of layers and general ocean circulation, could all alter the oceans' role as a sink for both heat and carbon dioxide. Whether these changes would cause the oceans to absorb more or less cannot now be readily predicted (Schneider 1989, WRI 1990). Many experts believe, however, that a rise in ocean temperatures is likely to decrease carbon dioxide uptake (Lashof 1989, Mearns 1990).

A change in ocean temperature and circulation also could release ancient methane from the ocean bottom. Solid methane hydrates form a shell up to a quarter mile thick at the bottom of the ocean, and cracks in it could release large amounts of both methane and carbon (Pearce 1989). Increased ocean water temperature would also reduce the water pressure which keeps hydrate stable. Lashof (1989) has speculated that the release of methane from hydrates may be the most important biogeochemical feedback.

Clouds

Clouds play an important, if not fully understood, role in shaping climate. Clouds both reflect solar radiation away from the earth, and trap heat radiating from the earth. Thus they can play a role in both heating and cooling.

Which role a cloud plays depends on its type and altitude. High cirrus clouds tend to trap heat, whereas lower level stratus and cumulus clouds tend to reflect the sun's radiation. Currently, the net effect of clouds is to make the earth cooler than it would otherwise be. Global warming will likely affect cloud area, altitude, and water content, which in turn will shift the net effect of clouds. But it is not yet possible to predict whether the change will help keep the earth cool, or make it even hotter (WRI 1990). However, even if they act to cool the earth, clouds could not entirely cancel the effect of increased greenhouse gases (Dickinson 1986).

Ice and Snow

The effects of warming on ice and snow will also have a feedback effect. As the warming melts the ice and snow cover, the capacity of the planet to reflect heat (its albedo) will be reduced. Moreover, the melting of sea-ice will increase the heat transfer from the ocean to the air. In the short run increases in precipitation could counter-act this by increasing snow cover, but in the long run melting ice and snow will tend to amplify the warming trend.

The significance of the albedo effect is limited, however, because vegetation and clouds mask the reflectivity of much of the earth's surface (Lashof 1989).

Living Organisms and Ecosystems

Living organisms and ecosystems could also play an important role in shaping the climatic effects of the greenhouse. Many, though not all, species of plants increase their rate of photosynthesis in response to carbon dioxide enrichment. The effect of increased temperature on this increased rate of photosynthesis may be negligible, negative, or positive, depending on the plant species and the extent of warming (Rose 1989). Increased plant growth due to carbon dioxide "fertilization" may be limited by the availability of water and nutrients. However, there is evidence that carbon dioxide enrichment may help some plants to significantly reduce transpiration (the evaporation of water through the pores of leaves).

The increased uptake of carbon dioxide by photosynthesis may be more than offset, especially in the higher latitudes, by greater rates of plant respiration and decay which release carbon dioxide (WRI 1990). Both respiration and decay increase rapidly with a rise in temperature. Respiration is the process by which cells break down carbohydrates to obtain energy. Currently, the annual absorption of carbon dioxide by plants through photosynthesis is approximately equal to the release of carbon through respiration. Small shifts in the balance between photosynthesis and respiration could have a substantial impact on greenhouse gas concentrations (Lashof 1989), and the rate of respiration by plants can increase 10-30 percent or more with an increase of 2 degrees (F) in temperature (Woodwell 1989).

The rate of warming could determine the feedback effects of plants. If the rate of warming is slow, it could contribute, for example, to the expansion of forests, and greater carbon dioxide uptake, though forest expansion may be limited by many other factors such as seed dispersal and nutrient availability, and the rate at which new forest areas can be planted by people. For example, the prairie/forest border in Minnesota could migrate northward by nearly 100 miles per decade (Houghton and Woodwell 1989). If the warming is faster, however, it could lead to widespread mortality of plants due to respiration out-pacing photosynthesis (Houghton and Woodwell 1989). It is likely that the more rapid the warming, the more severe will be the net release of carbon into the atmosphere from dying forests. That will further exacerbate the warming (Woodwell 1989).

In addition, the movement or demise of vegetation could alter the planet's reflectivity. If forests expanded, less heat would be reflected off the earth's surface, resulting in a warming. However, if grassland or desert areas increase, that could counteract the effect. The potential significance of these surface changes is still debated.

A warming of less than 2 degrees (F) in the high latitudes (where warming is expected to be relatively greater) could release large amounts of carbon from the tundra. Tundra contains about 14 percent of all the carbon stored in the world's soils (Woodwell 1989).

A warming of even this limited extent could also increase methane emissions from the tundra by 20 or 30 percent (Abrahamson 1989). Higher temperatures increase the rate of anaerobic decay which releases methane. Anaerobic decay (decay in the absence of oxygen) occurs in swamps, bogs, or moist soils, such as the tundra, where large amounts of dead plant matter have been preserved by cold temperatures (WRI 1990).

Research on permafrost suggests that it has warmed between 3.6 and 7.2 degrees (F) in the past century (cited in Pearce 1989). Some researchers have suggested that because methane releases from northern bogs are so sensitive to temperature, they may provide the first clear sign of greenhouse warming (Pearce 1989). It seems significant that carbon dioxide releases have surged during the warmer 1980s (Houghton and Woodwell 1989).

On the other hand, warmer and moist conditions in the tundra could result in increased carbon storage through peat production or the northward migration or planting of coniferous forests. The net effect of warming on the tundra, between methane and carbon emissions and carbon uptake, would depend on water availability for increased peat productivity (Woodwell 1989).

Atmospheric Chemistry

Another potential positive feedback on global warming is how increased temperatures could affect lower atmosphère chemistry. Higher temperatures could increase the amount of ground-level ozone (smog) which absorbs heat, and could accelerate warming (Oppenheimer and Boyle 1990). Higher temperatures would also increase significantly the amount of water that evaporates into the atmosphere. Water vapor is a strong greenhouse gas itself, and can double the heating effect of the increased trace gases. But, it could also increase the quantity of hydroxyls formed when water vapor reacts with oxygen. An increase in hydroxyls would reduce methane and ozone in the atmosphere, causing a negative feedback effect (Lashof 1989, Raval and Ramanathan 1989).

Summing Up the Effect of Feedbacks

Confused? Don't feel alone. There is a lot more unknown than known about climatic feedbacks and the greenhouse. Some have already been incorporated, however crudely, into the models, while others have not.

Still, the IPCC report (1990a) concludes that the net effect of these feedback effects likely will be to increase greenhouse gas abundance and result in greater climate change than is currently predicted. In a comprehensive review of feedback effects on climate change, Lashof estimated that if the carbon dioxide level doubled, the net effect of all the feedbacks would be positive, resulting in an increase in global temperature of up to 11.3 degrees (F).

Now, a "likelihood" is far from certainty, and some would challenge the notion that we should be concerned about the prospect of global warming. They (including the Bush administration) argue that until we know of real danger with more certainty, there's little reason to act. On the other hand, if we fail to act now, to what kind of world might we be condemning our children? Stephen Schneider (1987) cogently expresses the predicament:

> Climate models do not yield definitive forecasts of what the future will bring: they provide only a dirty crystal ball in which a range of plausible fortunes can be glimpsed. They therefore pose a dilemma: we are forced to decide how long to keep cleaning the glass before acting on what we think we see inside.

It is important to remember that the changes in climate, in a practical time frame, will be irreversible. Even if we act to reduce emissions immediately, we should still experience a moderate warming as the greenhouse gases already present exert their full effects. Moreover a doubling of carbon dioxide is not the outer limit of the potential from greenhouse gas warming. The recoverable fossil fuels still in the ground could increase the atmospheric carbon dioxide by five to 10 times (Houghton and Woodwell 1989).

We think that some significant warming is bound to occur, and that it will have a largely detrimental impact on the global economy and ecology, society and politics. We know enough to know that we would be better off not blindly changing the chemistry of the atmosphere, if only because we don't understand its full ramifications. Even the Intergovernmental Panel on Climate Change, the most authoritative consensus position published to date, states that our imperfect understanding makes us vulnerable to surprises (1990a).

There are many sensible ways that we as a society could

temperatures and changes in rainfall patterns and weed and insect populations may lower yields. A study by the Environmental Protection Agency projects moderate yield reductions and greater year-to-year yield variation.

Looking on the Bright Side

One perspective holds that global warming is really nothing farmers need worry about--not yet anyway. This point of view is well represented in the United States Department of Agriculture, where the sun always seems to shine whatever the climate outside. Much of this soothing message is based on some basic facts:

> (1) plant growth can benefit from increased levels of carbon dioxide because carbon dioxide enhances photosynthesis and reduces water loss from plant leaves (transpiration), improving water use efficiency;
>
> (2) farmers and farm researchers have proven remarkably adaptable for many generations;
>
> (3) even if crop yields do decline, the agricultural economy will likely benefit from higher crop prices.

Many USDA scientists are confident that if conditions become less favorable for some crops in some regions, adaptation will be rapid and unproblematic. The geography of crop choices will shift, and scientists will maintain a steady flow of new crop varieties and new technologies to help farmers adapt to new conditions and cropping regimes. For example, if less rain or soil moisture is available in the Midwest, farmers will have to switch to crops that require less water. The production of crops requiring large amounts of water will shift to regions--such as the coastal states--where rainfall may increase. According to W. Doral Kemper, former head of the Agricultural Research Service's Climate Impact Program, ''it [global warming] shouldn't be much of a problem for U.S. farmers....They're fairly versatile and have demonstrated an ability to change (Bahls 1989).''

While there is a recognition that researchers need to study the implications for agriculture of rising greenhouse gas concentrations, and work to shape constructive responses, the atmosphere at USDA is one of optimism here as well. Kemper seemed to be quite sanguine that adequate help will be forthcoming:

> Our plant physiologists and crop breeders will help, if necessary, to select crop varieties tolerant of high temperatures. And the fact that the changes will be so gradual means there is plenty of time for our food production complex to adapt (Miller and Senft 1989:9).

It is fairly typical that Kemper and the authors of the article discuss the potential threat of global warming in terms of how crops and the ''food production complex'' will do. There's little mention in these discussions of how climate change will impact real farmers and real communities, except to celebrate their versatility.

This optimism springs not only from a tendency to think about plants rather than people, but from USDA's institutionalized myopia in the past about what aspects of rising greenhouse gas concentrations are worthy of study. Until recently, nearly all of USDA's research attention has been focused on the effects of carbon dioxide on crop plants. The rationale for this narrow focus is again expressed by Kemper:

> There is one major area of consideration as far as agriculture is concerned. That is how a continued build up of CO_2 could affect crop growth and yield. The question of temperature increases must be addressed, of course, but the main concern is how doubled CO_2 will affect agriculture....While other groups of scientists are writing disaster scenarios about drought, decreased yields, and rising sea levels, our data indicate benefits. And there is little doubt that wheat, rice, and corn -- the three major foods for Earth's population -- will benefit from extra CO_2 (Miller and Senft 1989:6-7).

Such optimism about an enhanced greenhouse effect is flawed in two fundamental ways. First, although we frequently talk about the ''greenhouse effect'' in terms of a doubling of carbon dioxide by the year 2030, that warming projection is based on an assumption that ***all greenhouse gases*** will accumulate in the atmosphere in sufficient quantity to have the warming effect ***equivalent*** to a doubling of carbon dioxide. The actual level of carbon dioxide alone will not be doubled (at current emission rates, from preindustrial levels of 280ppm) until at least 2055 (IPCC 1990a). The rest of the climate change is attributed to other greenhouse gases which do not have the beneficial effects on plants that carbon dioxide does.

Secondly, while carbon dioxide increases ***alone*** may have a beneficial effect on plants (as laboratory studies irrefutably establish), the combined and interactive effect of higher carbon dioxide levels ***and*** higher temperatures, changed precipitation patterns, altered pest environments, and other factors, are not nearly so benign.

As the studies we are about to review in this section have accumulated, even the USDA has sobered up about greenhouse gases. In its 1990 Global Change Strategic Plan, the agency addresses the need for studies on the interactions of carbon dioxide and various climate and atmospheric factors such as increased UV-B radiation from ozone depletion. It also supports research on the effects of climate and chemical stresses on ecosystems, and on how agriculture's contribution to greenhouse gases can be reduced. Under "Human Interactions" the plan calls in part for research on how agricultural management decisions and rural communities will be affected by "Earth system changes." And the development of management options to respond to "environmental changes" is on the agenda. These are all steps forward for USDA.

Curiously, however, the plan overall still subtly avoids the specific notion of a global *warming* and its potential significance to farmers. Apparently the Department continues to reject the broad consensus among climatologists that warming very probably will occur as a result of greenhouse gas accumulation in the atmosphere, and that it will be significant. The agency's preference is to emphasize the continuing uncertainties in whether and how the climate may change. To its credit, buried in the middle of the Plan is a call for the study of environmental and economic impacts of "climate and biophysical changes." But the Plan avoids the question of how climate change will affect the conditions of farming as a livelihood and occupation, and its possible impact on current trends in the social structure of agriculture. Many USDA scientists and administrators continue to believe the impact of rising greenhouse gases on agriculture could just as well be positive as negative (see, for example, Rawlins 1991).

A Different Perspective: Focusing on the Potential Impacts of Global Warming

Many don't agree that the outlook is either quite so benign, or quite so uncertain. From this perspective, global warming looks like a significant threat, and one that demands a response. The major study in 1989 by the Environmental Protection Agency, or the 1990 study by the Intergovernmental Panel on Climate Change are representatives of this perspective.

The study by the Environmental Protection Agency (EPA), called The Potential Effects of Global Climate Change on the United States (Smith and Tirpak 1989), addresses both socioeconomic and environmental implications for forests, agriculture, sea level rise, biological diversity, water resources, electricity demand, air quality, human health and urban infrastructure for the U.S. as a whole and for selected regions. The section on agriculture considers the effects of both climate change and rising carbon dioxide (Smith and Tirpak 1989). On the basis of its wide-ranging research, the study warns of significant negative impacts on agriculture.

The EPA recognizes that as climate change affects crop yields and causes a northward shift in cultivated lands, the result would be significant regional dislocations in the agricultural economy (which means hard times for farmers and rural communities). There would be greater pressure on sources of water for irrigation, livestock would be stressed by increased temperatures and livestock pest populations, and plant pests and diseases would become more significant problems. All of these effects would impact the Midwest, particularly where the supply of irrigation water is already an issue.

According to the study, the direct effect of carbon dioxide on crop photosynthesis and transpiration will tend to ameliorate the impact of climate change on crop yields in some locations and on some crops, but EPA found little reason to think that yields will actually go up. We should note, however, that the study was limited by not considering the potential for continued improvements in agricultural productivity, and the adjustments farmers may make in response to climate change.

Nevertheless, three out of four scenarios EPA modeled estimated a moderate reduction in U.S. agricultural output--not enough to threaten U.S. food needs, but enough to decrease exports. Perhaps more importantly, the EPA finds that yield stability may decrease with changes in climatic variability and the frequency of drought.

The EPA study suggests that environmental issues involving agriculture may intensify with increased demand for irrigation water and greater pressure to use pesticides to deal with both crop and livestock pests. More weather extremes could also lead to intensified soil erosion.

The IPCC study confirms that these types of impacts on agriculture might be expected under climate change.

The farming community may be surprised to learn that the EPA may be a greater friend than USDA in its willingness to take a hard look at how farming could be affected by the extent of climate change discussed in Part I of this report.

Nevertheless, there is at least one thing that USDA's plan and EPA's study agree on -- considerable uncertainty remains about the specifics of what we can expect for Midwestern agriculture under a changing climate. But it seems clear that the agricultural community should be educated--not pacified--about the real potential consequences of increasing greenhouse gases in our atmosphere. In the rest of Part II we will consider the evidence available about the specific effects of potential climate changes. First, let's look at how climate in the Midwest is most likely to change.

FIGURE 1

Frequency of Extreme Temperature Events

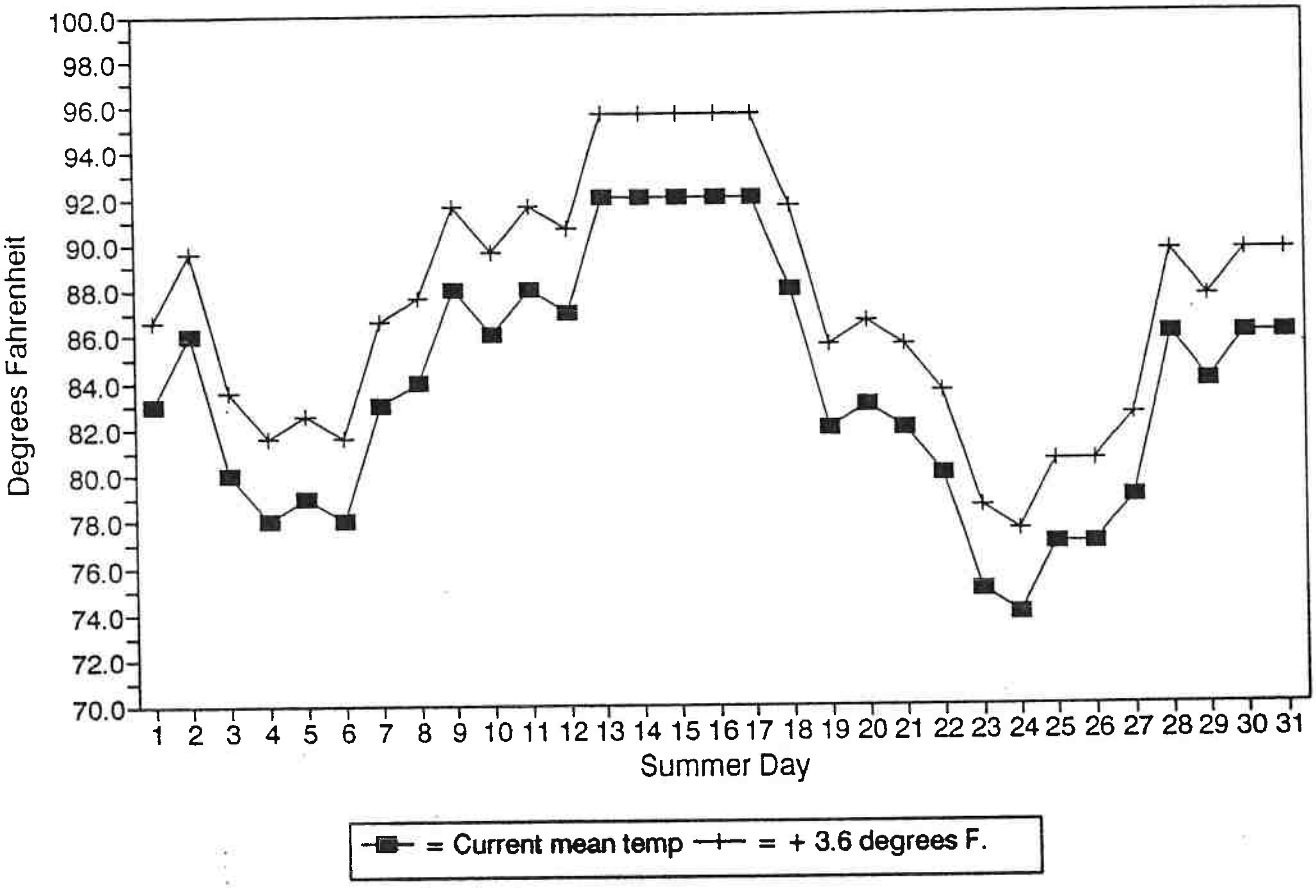

Figure 1 shows a hypothetical example of current summer temperatures ("Current mean temp"), and the same variation in temperatures but 3.6 degrees (Fahrenheit) hotter ("+ 3.6"). It shows how increasing the mean temperature can also increase the probability of an "extreme temperature event," that is, five or more days in a row above 95 degrees Fahrenheit. With the higher average temperature, an extreme temperature event occurs during days 13-17, where none had occurred under "current mean temperatures."

(variability) and the predictability of weather actually pose a much greater risk for farmers than a gradual rise in average temperature. Greater interannual (year-to-year) variability may make it harder for farmers to select crops or varieties from one growing season to the next. There has been an increase in interannual variability in the central U.S. since the mid 1970s (Decker, Jones and Achutuni 1985).

Changes in the weather from one day to the next (daily variability) can affect farmers' ability to complete field work on schedule, and may affect the growth cycle of crops. Moreover, the highest yields occur when weather is near normal or slightly cooler. When weather deviates from normal, yields decline (Thompson 1975).

Changes in the range of temperatures over the course of a day (diurnal variability) are also important. As the range between the maximum and minimum temperatures during a day decreases, crop growth may be stunted since higher minimum temperatures increase the nighttime respiration rate of plants and may disrupt the diurnal patterns to which plants are adapted. A rise in winter minimum temperatures (especially in the more southerly latitudes) could adversely affect winter chilling needed to produce viable seeds in crops such as winter wheat. There is some evidence that winter temperatures have been more mild in the past several decades and average nighttime temperatures have increased more than average daytime temperatures (Michaels 1990; Easterbrook 1992). If the latter pattern continues, it could mean that daytime temperature stress on crop growth will be less severe than average temperature increases might indicate.

The few climate modeling studies of variability done to date agree that both daily and interannual variability of precipitation will go up (especially if average precipitation increases). There is disagreement, however, about how temperature variability may be affected. Rind, Goldberg and Ruedy (1989) found that interannual, daily and diurnal temperature variability went down in a climate shaped by a doubling of carbon dioxide. Research by Mearns et al. (1989) suggests that increases or decreases may occur depending on the region and season.

A change in variability will also affect the frequency of extreme events (Smith and Tirpak 1989). If daily temperature variability does decline, this may increase the likelihood of extended periods of high temperature stress on crop plants because temperature may stay at high levels for a longer period of time before it shifts. For example, Mearns, Rosenzweig and Goldberg (1991) found that with a 3 degree (F) rise in mean maximum July temperature around Des Moines, the probability of five or more consecutive days above 95°F increased from 6% to 21%. Adding to this effect a decrease in variability, the probability increased to 37%. Assuming current varieties, this means that in at least one year out of three corn crops around Des Moines could suffer serious damage to pollination. An increase in the variability of precipitation would probably increase the frequency of droughts or floods (Mearns 1992).

Perhaps most important, there is evidence that precipitation and soil moisture levels may vary even more unpredictably *as climate is changing* than they will after a climate change is completed and a new, stable climate is in place with higher levels of greenhouse gases (Harvey, cited in Parry 1990; also see discussion of Climate Predictability in Part I). Of course, as long as greenhouse gases continue to accumulate, climate will not stabilize, and unpredictability may become "normal".

The Potential Agricultural Impacts of Rising Carbon Dioxide Levels

Summary: Higher carbon dioxide levels in the atmosphere will increase photosynthesis and reduce moisture stress on plants. Studies in ideal laboratory conditions indicate that with a doubled level of carbon dioxide, crop yields will increase by an average of 33 percent, with the greatest increases coming for cotton, sorghum, wheat, and barley, and lowest increases for corn, soybeans, and rice. Generally, plants that do not use carbon dioxide very efficiently will benefit most from increases in carbon dioxide levels, while those that already use carbon dioxide efficiently will benefit little.

However, other factors may offset the higher carbon dioxide levels. For example, if carbon dioxide increases the total leaf surface area of a plant, the plant may require more total water even though its water loss per square inch of leaf area is smaller. Temperature increases caused by greenhouse gases may more than offset the benefits of higher carbon dioxide levels, because the more carbon dioxide in the atmosphere, the less tolerant plants seem to be to high and low temperatures. Moreover, plants will require about one-third more nitrogen fertilizer to make use of increased carbon dioxide levels. Plants may also adapt to higher levels of carbon dioxide and revert to lower photosynthesis rates after a period.

Finally, increased carbon dioxide may affect the quality of food and feed produced, increasing carbohydrate content, reducing protein, palatability, and storage potential. Pests may require more plant material to meet their

own nutritional requirements, and weeds, like crops, will grow more vigorously under higher carbon dioxide levels.

Much of the optimism about minimal adverse impacts of an enhanced greenhouse atmosphere depends on studies of the direct effects of rising carbon dioxide levels on agriculture. In this section we will consider these direct effects on crop yield, crop quality and nutrient cycling, and in the following sections take up the impacts of the climate changes described above.

The Effects of Increased Carbon Dioxide on Crop Yield

There have been a number of crop growth studies that show that increased carbon dioxide concentrations can enhance yields by increasing rates of photosynthesis and reducing transpiration. As noted above, this at least partly offsets the negative effects of climate change. Let's look a lot more closely at the issue, since it is at the core of the argument made by some that agriculture has little to fear from an enhanced greenhouse effect.

Not all plants are equally able to take advantage of available carbon dioxide in the atmosphere. Some plants (called "C3" plants) are relatively less efficient in taking advantage of carbon dioxide. These plants speed up photosynthesis when carbon dioxide is made more available. Examples are wheat, soybeans, and small grains. In addition, some plants (soybeans are a good example) reduce the openings of the pores (stomata) in their leaves in response to higher carbon dioxide, and this allows less water to escape through transpiration.

On the other hand, other plants (called "C4" plants) are already very efficient users of carbon dioxide, and they don't benefit as much from increased levels of that gas in the atmosphere. They benefit some, mainly because increased carbon dioxide decreases their transpiration rate. Examples are corn, sorghum, and millet.

Studies of the potential interactions between carbon dioxide and other climate variables have begun only recently. The jury is still out on the extent to which increased carbon dioxide will mitigate the potential negative effects of climate change on agriculture (Rosenzweig 1989). For example, Schneider and Rosenberg (1989) argue that salinization, pests and changes in solar radiation, temperature, moisture, and windiness could all combine to negate the beneficial effects of carbon dioxide in one region, while climate changes could enhance those beneficial effects in another region.

Kimball's review of laboratory studies (1985) concludes that doubled carbon dioxide could increase crop yields by an average of 33 percent. However, even without climate change, it is not yet clear whether the benefits of carbon dioxide will be as apparent in farm fields as it is in laboratories (IPCC 1990b).

Because C3 crops benefit more than C4 crops do from increased carbon dioxide, farmers may eventually find greater advantage in growing wheat, rice, soybeans, barley and oats than corn, sorghum and millets.[2] Of potential importance to some Middle Border states like Nebraska, Colorado, Wyoming, and Minnesota, it may reduce the value of sugar cane (a C4 species) relative to sugar beets (C3) (IPCC 1990b).

According to Parry (1990), rangelands may not benefit substantially from increased carbon dioxide because many pasture and forage grasses are C4 plants. Moreover, a preliminary study has found that the carbon dioxide response was no greater for the C3 than the C4 species (Hunt et al. 1990). On the other hand, Hunt et al. (1991) found that doubling carbon dioxide did increase productivity of temperate grasslands.

Table 1 shows summary projections of doubled carbon dioxide levels on yields under optimal conditions (Remember, a climate that is ***equivalent*** to that which would occur with doubled carbon dioxide will have less than twice as much carbon dioxide because part of the warming effect will be accomplished by increases in other greenhouse gases). The figure shown for sorghum may be an experimental anomaly since C4 crops as a group are shown to exhibit much lower yield effect.

It is easy to see from these results why some people are sanguine about the implications for agriculture of rising carbon dioxide levels. It certainly helps that crops can take advantage of carbon dioxide fertilization. Even so, there may be less than meets the eye to the yeild benefits of increased carbon dioxide.

First, studies supporting a high yield response to increased carbon dioxide have been criticized for methodological weaknesses, and many crops have received little or no study of carbon dioxide response (Rose 1989).

Second, it is important to remember that when scientists talk about a doubled carbon dioxide climate change, they are

---

3. More moisture in winter and spring and less in summer could also favor a shift to "cool season" C3 crops such as oats, wheat, rye, and barley.

TABLE ONE:

DOUBLED CO_2 (660 ppm) EFFECTS ON YIELD

Note: Most of these experimental results derive from studies conducted under ideal enclosed conditions.

Source	Plants	Increased yield
Kimball (1983 and 1986, cited in Schneider & Rosenberg)	C3	+ 28-40%
	C4	+ 4-24%
Kimball (1983 -- cited in Acock and Allen, 1985)	rice	+ 9%
	wheat	+ 38%
	barley	+ 36%
	corn	+ 16%
	sorghum	+ 79%
	soybean	+ 17%
	cotton	+104%
	clover	+ 4%
	tomato	+ 13%
Kimball (1985)	wheat	+ 27-80%
	soybeans	+ 46%
	pea	+ 33%
	tomato	+ 14-23%
Rawlins and Kemper (1988)	small grains	+ 23-37%
	corn	+ 10-20%
	soybeans	+ 14-27%
	cotton	+ 50-100%
Kimball (direct communication -- *experiment under field conditions*)	cotton	+ 60%

really talking about an overall level of increase in all greenhouse gases that, taken together, equals the warming effect a doubling of carbon dioxide alone would have. At the current rate of growth in emissions, carbon dioxide levels won't reach 660 ppm before 2075 (IPCC 1990a), while the climate could change significantly decades earlier.

But perhaps the most serious limitation is that few of these studies have addressed the interactions between the direct effects of carbon dioxide on growth and yield, and air temperature, precipitation, total demand for water by the crop, rising leaf temperatures due to relatively more closed leaf pores, respiration, and pest and weed effects. Since the potential of the plant to respond to carbon dioxide may be limited by these other factors, an increase in photosynthesis or a decrease in transpiration will not necessarily result in a yield increase (Acock and Allen 1985). Some of what is known about these interactions is discussed in the following sections.

CO_2 and Water Use by Plants

On the positive side, increased concentrations of carbon dioxide in the atmosphere will also tend to increase the efficiency with which a plant uses water. That is, carbon dioxide will help plants withstand drought stress. Higher carbon dioxide levels cause plants to partially close their stomata which reduces transpiration and increases the ability of the plant to withstand water stress. Plants stressed by too little water will increase photosynthesis and increase yields when carbon dioxide is increased. In fact, drought-stressed plants in general benefit more from carbon dioxide than do well-watered plants. Some plants can maintain higher yields under conditions of water-stress and high carbon dioxide than under conditions of no stress and current carbon dioxide levels (Rose 1989).

On the other hand, carbon dioxide enrichment may not be able to overcome a long or severe water stress for at least some species. One study of soybeans found higher yield response, while another found that high carbon dioxide was not enough to make up for severe drought stress (Rose 1989). Studies indicate that winter wheat yield may decline under drought stress even with very high carbon dioxide, although spring wheat may be able to compensate (Rose 1989).

Kimball's review of carbon dioxide effects suggests that the consumptive use of water may be reduced up to 10 percent by doubled carbon dioxide. Because corn responds to carbon dioxide by reducing transpiration more than by increasing photosynthesis, it may reduce water use the most. Doubled carbon dioxide may just compensate for mild water stress (Kimball 1985). This may be an important factor if soil moisture in the Midwest does decline as climate warms.

On the other hand, as carbon dioxide enrichment causes plants' leaf area and root systems to grow larger, total transpiration from the plants may decrease or it may remain the same or increase (Acock 1990). So even reduced transpiration per unit of leaf area doesn't necessarily mean less water will be used at the crop level (Acock and Allen 1985). Total demand for water may actually increase. This could mean that crops use up a limited supply of soil moisture earlier in the season (Acock and Allen 1985).

There are other factors that may alter the rate of water use by crops: changes in temperature, solar radiation, wind speed or humidity as well as the rate of evaporation from the soil. Direct evaporation from soil may offset the benefits of reduced transpiration under high carbon dioxide conditions (Acock and Allen 1985).

How might these factors interact to affect total evapotranspiration and consequently, soil moisture? One study estimated that with a 5.4°F increase in temperature, evapotranspiration in a Nebraska wheat field is likely to increase between 1 and 24 percent when accounting for temperature, net radiation, humidity, reduced transpiration from leaves and increased leaf area. Evapotranspiration was estimated either to increase by as much as 17 percent or to decrease by as much as 4 percent from Kansas grassland (Schneider and Rosenberg 1989). The extent of this increase or decrease in evapotranspiration depended on degree of cloudiness and humidity. According to Parry (1990), a 10% increase in evapotranspiration could produce a considerably larger mid-summer soil moisture deficit than occurs today.

Carbon Dioxide and Other Stresses

In addition to water stress, it has been demonstrated that carbon dioxide enrichment can help to counteract other adverse conditions such as nutrient limitation, soil salinity, cool temperatures and air pollution (IPCC 1990b). For example, in preliminary studies Hunt et al. (1990) found that doubled carbon dioxide caused increased growth in temperate grasslands despite nitrogen limitations. However, they also found that the growth response declines (though it is not eliminated) when the nitrogen limitation is made more severe (Hunt 1992).

Growing plants in high carbon dioxide environments can make them more tolerant of saline conditions and other pollutants. But even here, there must be qualifications. Sulfur dioxide--a significant pollutant and a component of acid rain--reduces the growth of C4 plants under high carbon dioxide conditions (Acock and Allen 1985).

Carbon Dioxide and Temperature Effects

The interaction of increased carbon dioxide and temperature has not received much attention, and those studies that have been done differ in their conclusions. The outcome seems to depend on the crop and the extremity of the temperature, but available studies suggest that most plants grow best at high carbon dioxide levels and lower-than-average temperatures (Acock and Allen 1985; Rose 1989). This might benefit crop production in the most northerly parts of the Midwest but would not help the current major corn-growing regions.

In studies reported by Rose (1989) where plants were exposed to both high carbon dioxide concentrations and high temperatures, the negative effects of the high temperature overpowered the beneficial effects of increased carbon dioxide. Idso (1990), however, has found in his research that the benefit of increased carbon dioxide actually increases with increased temperature. And Kimball reports that cotton yields under doubled carbon dioxide respond very positively to hot temperatures, and the hotter the temperature the bigger the response (Kimball 1992).

The difference in these conclusions may be due to the extent of the temperature increase. The range of tolerable temperatures is more limited under higher carbon dioxide levels. A temperature too high or too low, can wipe out any yield response to carbon dioxide, increasing starch accumulation and stunting photosynthesis (Acock and Allen 1985). And the greater the concentration of carbon dioxide, the narrower the temperature range over which the plant can take advantage of it. Thus, more frequent periods of extreme temperatures and increased temperature variability could both counteract any potential benefit from higher carbon dioxide levels.

For most crops, increased carbon dioxide may not help and in fact could conceivably worsen the effects of the higher temperatures we can expect with global warming. However, the interactive effects of higher carbon dioxide and temperatures on the life cycles of plants simply cannot currently be predicted with certainty (Rose 1989).

There may be other temperature effects as well. Even if higher temperatures don't counteract the effects of higher carbon dioxide on photosynthesis and growth, higher temperatures over the growing season could shorten the period when plants fill out with grain. For "determinant" plants like wheat, which stop growing when they begin to produce reproductive organs, this may cancel out the carbon-dioxide enriched photosynthesis, leaving yield the same or even lower. This could encourage a shift to "indeterminate" species such as alfalfa or some soybean varieties, that continue to grow and produce yield over a longer season (Rose 1989).

Carbon Dioxide and Nitrogen Use

Current levels of nitrogen fertilization could limit the ability of a crop to respond to higher carbon dioxide (Acock and Allen 1985). Plants will require one third more fertilizer than they currently do (Kimball 1985) to take full advantage of increased carbon dioxide.

This has implications for water quality if farmers continue the trend of over-applying nitrogen as security. Moreover it could significantly increase emissions of nitrous oxide from nitrogen fertilizer and increase its contribution to the greenhouse effect.

On the other hand, nitrogen fixation by legumes could be enhanced by higher carbon dioxide, though this may be limited by rising temperatures. Existing strains of Rhizobium (nitrogen fixing bacteria that live in symbiosis with plant roots) adapted to those specific soil temperatures may need to be replaced (something researchers have not found an easy proposition) to take full advantage of the increased carbon dioxide (IPCC 1990b). However, the world wide bank of Rhizobium adapted to other conditions does provide a major genetic resource (Evans 1992).

Will Carbon Dioxide Bring Long-Term Productivity Gains?

Can the short-term gains in productivity from increased carbon dioxide concentrations be sustained over the long-term? There is some evidence that plants will acclimate themselves to the higher levels of carbon dioxide and return to their previous rates of photosynthesis, lowering yields back to earlier levels. This occurs apparently because the accumulation of carbohydrates in the plant from increased photosynthesis inhibits the rate of photosynthesis. Wheat response to carbon dioxide may be limited in this way. Soybeans, by contrast, may not be. This suggests that crop varieties may need to be selected for their greater ability to store newly synthesized carbohydrates, for example in their root systems (Rose 1989).

An interesting aside: Some argue that the yield increases we have experienced in the past may be partly, even substantially, due to the effects of increased carbon dioxide

(Easterling 1992).

Other Effects of Higher Carbon Dioxide Levels

Carbon dioxide will affect more than crop yield. For example, it will affect the quality of the food material produced. This will influence feeding by pests. Rising carbon dioxide will also affect competition from weeds. In addition, carbon dioxide increases will impact carbon storage and decomposition rates, and overall ecosystem productivity.

Carbon dioxide may affect the quality of both human food crops and animal feed by increasing the carbohydrate content of grains, fruits and vegetables, and especially foliage (Kimball 1992). For example, a higher carbon-to-nitrogen ratio means reduced protein, and it may affect palatability and storage qualities. Feed grains and especially forage may have lower crude protein, more starch and higher fiber, affecting the growth of livestock (IPCC 1990b). Higher carbohydrate levels may also affect the storage and palatability of animal feeds. If the animals are able to select only the higher quality forage they may be able to make up for some of the quality reduction (Owensby 1991).

Plant pests may become more voracious as well, because the increased carbon levels in a plant may lower its nutritional value to the pest. The effects of this on the life cycle and population growth of pests will vary. Experimental studies have shown that the pests ate more leaves, but the individuals were smaller and population growth was probably reduced (IPCC 1990b). Still, some studies have shown that the impact of insects may increase, depending on the plant and the insect (Kimball 1985). The increased feeding by pests could offset the growth enhancement brought by higher carbon dioxide (Lincoln 1990).

Weeds, like crop plants, will respond to carbon dioxide fertilization and all the other factors discussed here. It is likely that C3 type weeds will become more of a problem for C4 crops such as corn and sorghum. On the other hand, C3 crops may benefit from reduced competition from C4 weeds. Fourteen of the world's 17 most troublesome weeds are C4 plants in C3 crops (Parry 1990).

Finally, the increased carbon content of plants due to carbon dioxide fertilization will likely affect the carbon cycle. With increased growth under doubled carbon dioxide, there is likely to be about 30 percent more plant residue left after harvesting. This should help both reduce soil erosion and increase organic matter in the soil (Kimball 1985). Though this means that more carbon will be stored in plants and the soil, it probably won't be enough to keep pace with the present rate of carbon dioxide emissions (Hunt et al. 1990).

This higher carbon content compared to nitrogen and phosphorous will also slow down the rate at which the plant matter decomposes, which could deprive the next cycle of growth of needed nutrients (IPCC 1990b). On the other hand, increased temperatures are expected to increase the rate of decomposition and tend to reduce soil organic matter. Higher temperatures could thus accelerate nutrient cycling (Parry 1990).

The extent to which these offsetting effects will counteract each other is not known. Ecosystem studies such as those described in the USDA Global Change Strategic Plan are badly needed to address these interactive effects.

Altered Climate Effects on Agricultural Conditions

Summary: Climate change will affect pests, diseases, weeds, and the availability of water for crops. Warmer temperatures will move pest and disease ranges northward, and seasonal infestation periods will lengthen, exposing crops and livestock to pests and diseases longer. Demand for irrigation to offset soil moisture losses will increase, but increased evaporation rates and decreased precipitation levels might reduce available supplies of water for irrigation, and lower groundwater levels would increase pumping costs. If farmers shift to crops that will tolerate higher temperatures, they will also require more moisture, increasing water demand even more.

We have seen that increased carbon dioxide is likely to act directly to improve crop productivity and reduce competition from some weeds, though pest problems may increase. The higher carbon content in plants could also slow down the process of decomposition, making nutrients less available to a new generation of plants. In relation to possible climate changes, we have seen that carbon dioxide may help crops survive in a drier climate, while potentially making higher temperatures more limiting. But what about the possible effects of a changed climate on pests and diseases, and water availability? We will examine the evidence on these questions here, and in the next section consider projections of crop yields and viable cropping ranges.

Potential Effects of Climate Change on Pests and Diseases

Insect pests, weeds and plant diseases will all be encouraged as the global climate becomes warmer and wetter (Easterling, Parry and Crosson 1989). Warmer temperatures will likely result in the northward extension of the ranges of pests and diseases affecting both plants and animals. Tropical diseases may spread to the Southern U.S., though not likely to the Midwest. Most agricultural diseases will have a greater potential to reach severe levels under warmer conditions (IPCC 1990b), making it more difficult to control their spread.

Vector borne diseases (diseases that are spread by intermediate organisms rather than directly from individual to individual) such as Lyme disease, which is spread by ticks, may become more important as larger areas provide suitable habitats for infected organisms. As more vector generations are born, control of vector borne disease will become more difficult and resistance to controls may evolve more rapidly.

Zoonotic diseases (those transmitted between animals and people, such as rabies) will also become more threatening as their seasons are extended or their animal or environmental habitat grows (Stem et al. 1989).

Macroparasites (e.g. parasitic worms or insects) that infect domestic animals are likely to increase as the environmental conditions in which they flourish are prolonged by a combination of temperature and humidity. The season for Trichostrongylus and Ostertagia (round stomach worms of cattle and sheep) in the Midwest is likely to lengthen, as is the transmission season for Barber's pole worm (another round stomach worm) in all parts of its U.S. range (Dobson 1989). All of these, though particularly the former, are significant in the Midwest (White 1991).

Horn flies, an important cattle pest, would likely increase everywhere in the U.S. except in the extreme southern states where they would be suppressed in summer. A warmer climate will not only expose cattle to the horn fly earlier in the spring and later in the fall, but it will increase the density of horn flies. Populations may increase from the current average of 100-300 per head of cattle to over 500 (Schmidtmann and Miller 1989).

This could reduce weight gain. For example, an increase in Nebraska of 225-250 flies/head could reduce weight gain 22.5 lbs per head for calves and 11.24 lbs/head for feeder/stocker cattle. Increased fly populations may affect milk production as well, and could encourage total confinement housing of dairy cattle. These increased populations would either intensify the use of insecticidal controls (to which horn flies have rapidly developed resistance in recent years) or intensify the need for effective alternative methods of control (Schmidtmann and Miller 1989).

Crop pests could also become more significant in a warmer climate. The over-wintering range and population density of a number of important pests (e.g. potato leafhopper -- a serious pest of soybeans and other crops) could be increased. In general, if planting dates remained the same, pest invasions would occur earlier in the season on younger, more susceptible plants (Parry 1990). Moreover, higher temperatures may allow more pests to survive control treatments in each generation and allow additional generations in a season (IPCC 1990b; Gage 1990; Stinner et al. 1989).

Overall, scientists are not sure about the potential effect of changes in temperature, precipitation, and humidity on pests and their predators, parasites and diseases. But besides effects on individual pests or diseases, climate change may well alter the interactions among pests, predators and parasites (IPCC 1990b).

Economic losses due to only one pest (among the many that could be affected by climate change) could be enough to remove the profit margin in farming. For example, corn earworm, currently a serious pest of soybeans in the southern states could become a serious problem in the Corn Belt as well, and one study suggests the damage from this insect will result in serious economic losses for Midwestern grain farmers (Stinner et al. 1989).

Irrigation Potential

How will climate change affect the opportunity for irrigation? Can the impacts of climate change be mitigated by increasing irrigation?

A number of studies have attempted to evaluate how the climate changes described above will affect the demand for and availability of water for irrigation. Clearly, with reduced soil moisture and increased variability in precipitation, demand for irrigation will grow. The actual increase in irrigation will depend on the availability and cost of the water (including energy costs). Most experts agree that with rising temperatures we will see increased competition among diverse users for water supplies that are likely to decline (see for example Adams et al. 1990). It is likely that we will see increases in both demand for, and cost of water for irrigation (IPCC 1990b).

Several factors need to be considered. First, will the climate changes alter the amount of water available to meet growing demand? We expect that increased evaporation and/or decreased precipitation would reduce both streamflow and groundwater recharge, shrinking irrigation water supplies. Dudek notes that a 10 percent reduction in precipitation can reduce streamflow by 50 percent (1991). Higher rates of precipitation in winter could help provide water for irrigation if it collects as snowpack, but if winter temperatures are too warm and precipitation just runs off, the water won't be in the rivers when it's needed. Early melting of heavy snows also could overload storage capacity, again making extra precipitation unavailable for irrigation. Surface waters in the Middle Border region are often already overcommitted and the distribution of available water is highly contentious. Surface water supplies flowing into Missouri, Iowa, Nebraska and Kansas are already declining as a result of increased upstream use (Crosson 1990).

The Ogallala aquifer under the Great Plains is already being depleted as withdrawals for irrigation and other uses exceed the rate of recharge. At 1980s rates of withdrawal, the continued depletion of the Ogallala would force major reductions in groundwater use before 2030 (Crosson 1990). Crosson argues that not only will the water table decline, but the economic costs will increase due to both greater depth of pumping and rising energy prices. Thus especially in western Kansas and Nebraska, even while demand for irrigation water increases, its availability will decline. Crosson suggests that if economic conditions are favorable, irrigation in eastern Nebraska and Kansas, Iowa and Missouri might increase, but not as much as it decreases to the west. Since currently 77 percent of corn produced in Nebraska and Kansas is under irrigation this has significant implications for the relative share of national corn production by farmers in the Middle Border.

However, as with everything else, because of the uncertainties and differences among the models, the likely increased demand for irrigation is not altogether clear cut. With the beneficial effects of increased carbon dioxide considered, Rosenzweig (1990) found the required irrigation water for wheat would decline somewhat and for corn it could either decrease (under the GISS model[4]) or still increase significantly (under the GFDL scenario) depending on the extent and direction of temperature and precipitation changes. McKenney, Easterling and Rosenberg (1992) also found that required irrigation for wheat could decline, though corn and sorghum would need more water.

On the other hand, if farmers shift to crops or varieties that offset the effects of global warming, they could require more irrigation water. Allen and Gichuki (1989), for example, concluded that if farmers shifted to varieties that could benefit from increased temperature and solar radiation, wheat in Nebraska and Kansas would require a 10 percent increase in irrigation.

Alfalfa with its longer growing season would require the greatest increase in irrigation. For a mix of alfalfa, corn and winter wheat, even without any shifts in varieties to adjust to temperature increases, Allen and Gichuki (1989) estimate that 15 percent more water will be needed during the irrigation season. The water required during peak periods especially would increase, which may require a larger capacity in irrigation systems and increase peak energy demand. But peak and seasonal requirements could be offset somewhat by higher carbon dioxide concentrations.

All this points to the need for the development and shift to more conserving irrigation management systems. It also implies that water allocation politics will become much more important and a reasonable water allocation policy will need to be developed if the goals of resource conservation and equity in water use are to be served.

Midwestern Crop Yields and Crop Ranges Under a Changed Climate

***Summary:* Estimates of crop yield changes are extremely speculative and vary widely. We summarize nine studies of crop yield changes in the Middle Border and find mostly predicted declines for soybeans and especially corn, with more optimism regarding possibility of yield increases for wheat. Corn production will become far more tenuous in much of the present Corn Belt, with wheat and sorghum replacing corn. Declining or more variable rainfall will likely make yields more variable as well. Cost of producing livestock is likely to increase due to more disease and pest problems, higher energy costs, and death losses. Farming in sandy soils may become especially difficult as drought conditions cause the sands to shift**

If the climate changes projected for the Midwest come to pass, what will be the effect on crop yields, viable crop ranges, and livestock? We will consider each of these possible impacts in turn.

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4. See Table 1 in the Appendix for a description of the climate conditions projected by these models.

Potential Changes in Crop Yields

In evaluating the impact of climate changes on crop yields we are once again more in the realm of speculation than prediction. Though a number of studies have been conducted that estimate changes in yields or crop ranges under specific temperature and moisture scenarios, much of what has been discussed above (climate variability and effects on pests, for example) has not been accounted for in the models. Moreover, they generally do not attempt to account for adaptive responses such as different crop varieties, new yield enhancing technologies, shifts in planting dates, and so on. Some modeling studies have incorporated estimates of the direct effect of increased carbon dioxide levels on crop growth, but most of these probably overestimate the benefit of carbon dioxide during the time frame studied because much of the warming that occurs during this time frame is due to other greenhouse gases, and only partly to carbon dioxide.

The most comprehensive study that has been conducted to date (sponsored by Resources for the Future) considered the effect the warmer, drier climate that occurred in the 1930s (see Easterling et al. in Tables 1b and 1c in the Appendix) would have on the agriculture of today, and on the agriculture that may exist 40 years from now. The study considered only the region of Missouri-Iowa-Nebraska-Kansas (MINK) and went beyond projections of agricultural yields to consider the net economic effects of such a climate change on the region. In projecting impacts on crop agriculture, the study made a systematic attempt to account not only for carbon dioxide increases (at a moderate, more realistic level) but also new technologies, farming practices and crop varieties (Easterling et al. 1992a and 1992b; and McKenney, Easterling and Rosenberg 1992). The findings (described below) are in one sense encouraging, but they also highlight the need for a strong and practical agricultural research system and the need for farmers to be able to make a smooth transition in farming practices. The study is also limited in that it still does not account for climate variability or unpredictability, potentially worsened pest problems, a potentially more adverse climate, or negative interactions between carbon dioxide and high temperatures.

Under current agricultural and CO_2 conditions, with no adjustments by farmers to the changed climate, the climate of the 1930s reduced yields of dryland and irrigated corn, soybeans, sorghum, alfalfa and wheatgrass, especially under marginal climatic conditions. Irrigated wheat yields increased. Higher carbon dioxide increased both dryland and irrigated wheat yields but did not fully compensate for yield declines in the other crops except alfalfa (see Tables 1, 2 and 3 in the Appendix for details on corn, wheat and soybeans). In addition, the animal-carrying capacity of rangeland under current carbon dioxide levels was reduced by the 1930s climate. The study calculated that a 500 lb steer would require almost 2.5 additional acres of rangeland (Easterling et al. 1992b).

Under the agricultural conditions of 2030 (that is, assuming a substantial 72% improvement in crop productivity), the study examined how technological adaptations (increased drought resistance of cultivars and increased irrigation efficiency) and farmer adjustments (planting date, change in variety to accommodate longer growing season, and furrow diking for moisture conservation), as well as increased carbon dioxide would affect yield declines. Without these adaptations and adjustments, the percentage yield declines under a 1930s climate were comparable to the yield declines described in the first scenario, except that wheat yields also decline slightly. Yields for alfalfa, wheat and irrigated crops are actually increased by the adjustments. Dryland, warm season crops still decline, though not as much. Added carbon dioxide boosts yields of wheat, alfalfa, wheatgrass and sorghum, but corn yields still decline and soybean yields equal what they would have been under an unchanged climate (see Tables 1, 2 and 3 in the Appendix for details). With the caveats discussed above, these are fairly encouraging results, though the authors note that a more severe climate change could result in serious and irredeemable losses (McKenney, Easterling and Rosenberg 1992).

It is difficult to directly compare the results of all the studies of climate change impacts on Midwestern crop yields that have been conducted, since the precise region studied varies, as does the climate scenario used. Tables 1, 2 and 3 in the Appendix show a comparison of studies that have projected the impact of climate change on the yields of corn, wheat and soybeans. In some cases, these studies considered temperature and precipitation changes derived from two major global warming models, while others, such as the Resources for the Future study just described, simply made plausible guesses at these changes. Some of the studies added in the direct effect of increased carbon dioxide on crop growth, and a few projected the effects of changed planting dates or crop varieties.

The wide range of projected change in yield is striking. One study estimates a 153 percent increase in dryland wheat production at a site in Texas (incorporating a change in planting date and variety), while another model projected a 55 percent decrease at the same site. Considered all together the studies conclude that, without carbon dioxide or changes in planting date or variety, dryland wheat yields will decline, possibly quite substantially. The inclusion of irrigation, doubled carbon dioxide levels, or changed technology improves the situation, but yields still could decline.

There is about as much uncertainty over projected changes in soybean yields, ranging from an increase by more than 40 percent with doubled carbon dioxide, to a decline of 25 percent without it. Even with added or even doubled carbon dioxide levels, and/or farming adjustments, however, most scenarios project a decline or a very small increase in dryland soybean yields.

Corn yield projections also range from a 100 percent decline to more than a 40 percent increase. However, the overall trend of corn yields is down, even accounting in some cases for carbon dioxide increases, irrigation and a changed planting date. The projected declines in yield tend to be much more substantial for corn than for the other two crops.

A 1986 summary of the studies then available on the impacts of warming on crop yields suggested that with no change in precipitation, a warming of 1.8°F could decrease average yields by 1 to 9 percent, while a 3.6°F increase might reduce them from 3 to 17 percent (Warrick, Gifford and Parry 1986). A more recent review found that a 3.6°F temperature increase combined with reduced precipitation could lower average yields over 20 percent (Parry 1990). It is worth noting that the 1988 drought, which was accompanied by mean temperatures about 3.6°F above normal, decreased the corn crop almost 40 percent (Rosenzweig 1989).

In general, global warming will also make the growing season longer. But unless new varieties are developed that can take advantage of the higher temperatures, grain yield potential and the actual growing season may be reduced because higher temperatures will encourage plants to mature more rapidly, shortening the period of grain filling (IPCC 1990b).

Another way of thinking about the impact of climate change on yield and crop viability is to consider how the change will affect the risk of crop damage. Any changes in average warmth or dryness, or their variability, would have a marked effect on the level of risk in agricultural production, particularly in a marginal area for a given crop (Parry 1990; Easterling et al. 1992).

For example, severe temperature stress during the 10 day period when corn is silking will result in crop failure (Mearns, Katz and Schneider 1984). As we have seen, an increase in average temperature will significantly increase the frequency of a stressful period (e.g. several days in succession) of severe temperatures.

A study by Waggoner on the wheat yields in North Dakota under a slightly warmer and drier climate change found that the chance of extremely low yields (24 percent or more below expected median yield) jumped from 1 in 8 years to 1 in 2.3 years--a 300 percent increase in risk. On the other side, there was much less chance of unusually high yields (Warrick, Gifford and Parry 1986).

In addition, Neild et al. (1979) studied the potential effects of a climatic warming on the likelihood of spring freeze damage to corn. Ironically, they found that a longer series of days with ***above-normal*** temperatures in the northern U.S. corn belt would actually increase the risk of freeze damage to early-planted corn, because the warmer temperatures would promote earlier emergence, exposing the plant to a longer period of potential freezing conditions. And farmers might be even more tempted to plant early, not only because of warmer temperatures, but also to take advantage of more winter and early spring moisture and to avoid late season stress due to reduced summer moisture.

Mearns, Rosenzweig and Goldberg (1991) have conducted the only computer simulation study to date of the possible effects of increased temperatures *and* increased temperature and precipitation variability on the variability of yields and the risk of crop failure. Their findings for the most part spell bad news for farmers in the Middle Border. They found that in western Kansas (Goodland) under both a fallow system and an irrigated system, wheat yields became more variable both with an increase in mean temperature, and with an increase in temperature variability. On the good side, a decrease in temperature variability mitigated the impact of a very large increase in mean temperature (8.1°F). Unfortunately, a decline in temperature variability actually slightly increased the yield variability under a smaller temperature increase of 2.7°F.

The likelihood of crop failure under fallow conditions rose considerably (up to a 17% chance of failure) as both temperature variability and mean temperature were increased.

Under dryland wheat conditions in eastern Kansas (Topeka), yields varied significantly with an increase in temperature variability, but the good news is that increases in mean temperature did not significantly affect yield variability.

However, increasing the variability of precipitation increased yield variability in both Topeka and Goodland, but more so in Topeka. Increased mean precipitation decreased yield variability at both locations, but a decrease in mean precipitation increased variability in yields. In Goodland, the probability of (fallow) crop failure increased three fold (3 to

10%) as precipitation became more variable, regardless of whether mean precipitation increased.

These findings cast a bit of a damper on the relatively benign results from the study by McKenney, Easterling and Rosenberg reported earlier.

Potential Shifts in Cropping Ranges

Will changes in yield potentials (and risk) result in shifts in regional agronomic patterns? Using models of current crop/climate zones, scientists have estimated how crop ranges will change due to potential changes in yields and risks. The dilemma here, once again, is that the geographic range assumed to be appropriate for a crop is based on today's varieties and technologies. It is reasonable to assume that plant breeders can at least partially adjust crop varieties to new climatic conditions. The question is, to what extent can we count on this, will it be timely, and what will be the costs in making adjustments?

Rosenberg (1982) found that due to farmer interest and responsive plant breeding efforts, the growing region for hard red winter wheat expanded between 1920 to 1980, accommodating differences in mean annual temperature and precipitation at least as great as those projected for a doubled carbon dioxide climate. In 1920, central Nebraska formed the northern border of the hard red winter wheat zone. By 1980 the zone reached beyond the Canadian border in central Montana. The southern border also moved, from the panhandle of Texas down to central Texas.

Kimball also cites a study by Wittwer that found that agriculture had been able to accommodate an interannual variation of 11.8 in. of rain in eastern Kansas, a two week change in the Minnesota growing season, a +0.18°F per year trend in temperature in Indiana between 1915 and 1945, and a total 3.6°F increase in temperature in Indiana over the whole of the past century (Kimball 1985). These findings affirm the optimistic view that as plant breeders continue to test new varieties over a wide climatic range, their traditional selection process will result in varieties appropriate to changing conditions (Kimball 1985). However, this assumes that the rate of climate change will be manageable, and that increased variability and a greater frequency of extreme weather won't compromise such efforts. It also underlines the importance of continuous plant breeding efforts under field conditions.

What happens if these breeding adjustments are not made? Studies that assume today's crop varieties, planting dates and carbon dioxide levels indicate the potential for some pretty dramatic shifts in growing regions. Parry (1990) describes a transient climate scenario which suggests that crop zones may shift to the north by as much as 93 miles per decade from 1990 to 2030, and by 149 miles per decade from 2030 to 2060. This prediction is based on a continuation of the emission growth rates of the 1970s and 1980s. If emissions are reduced so that the rate of warming is cut by one third, the northward shift could be reduced to 31 to 62 miles per decade, still no small stress for farmers.

In another study Flores-Mendoza et al. (1989) projected the effect of several different climate change scenarios on major cropping areas. A 5.4 degree (F) increase in temperature accompanied by a 20 percent increase in precipitation resulted in a general reduction of corn acreage, and a "strongly marked" reduction in the major production areas of Illinois and Iowa. Though a few areas might respond well to the increased precipitation, the high temperatures would have a strongly negative effect. To maintain current production levels of corn, yields would need to increase by 10 percent to make up the difference in cropped acreage.

For winter wheat, the same climate change would reduce plantings in northeast Kansas and southeast Nebraska, but overall the pattern of production would not be greatly changed. However, if precipitation went down by 20 percent instead of up, wheat planting would increase in areas where corn is now the main crop. Soybean planting would increase with the increased precipitation and temperature in most states where the crop is now grown. If the precipitation decreased, there would be a slight decrease in plantings compared to the present. Sorghum planting would increase in either climate scenario. 1989).

Blasing and Solomon (1983) found that every degree Centigrade (1.8°F) rise in temperature could move the corn belt by about 109 miles to the north and northeast. In a second study (Blasing and Solomon 1984), they estimated how the current corn belt might shift if temperature were increased 5.4°F, annual precipitation increased 3.2 inches, and July/August precipitation were down about two tenths of an inch. Their projections were based on the current heat and moisture characteristics of the corn belt. They found that even taking into account earlier planting dates, the corn belt would shift entirely out of Nebraska, Kansas, Missouri, southwest Iowa, southern Illinois and most of South Dakota, and would require irrigation in most of Iowa, northern Illinois, southwest Minnesota and eastern North Dakota, where water for irrigation is less available than in Kansas or Nebraska.

On the other hand Newman (1980) concluded that a rise in precipitation rates could counteract a displacement due to

Table 3

CHANGES IN FARMING PRACTICES THAT MAY BE ENCOURAGED OR NECESSITATED BY GLOBAL WARMING:

Change in planting dates (earlier in the spring or later in the fall).
Change in crop varieties (e.g. more drought or heat tolerant).
Shift in crop mixture (e.g. corn to sorghum) or adoption of new crops.
Replace cool season with warm season crops in northern areas.
Increase use of irrigation water.
Invest in irrigation to compensate for reduced or more variable rainfall.
Shift to high value crops that can make more economic use of irrigation.
Adoption of more efficient irrigation systems as competition for water increases.
Higher rates of fertilizer applications to take advantage of higher CO_2.
More vigilant or intensive pest control activities.
Increased fall tillage to offset a wetter spring.
Less nitrogen application in the fall to avoid leaching and denitrification during warmer, wetter winter.
Reduced planting densities to respond to drier soils.
Earlier harvest especially if using short season varieties.
Double-cropping.
Longer period of field drying of corn.
More diverse crop mixes.
Increase in acreage planted in response to lower yields.
New investments in capital equipment (e.g. livestock buildings, new farm machinery to accommodate new crops).
Removal of marginal lands from production if production costs increase.
Farm abandonment.

Sources: Rosenzweig 1989; Easterling 1989; IPCC 1990b; Smith and Tirpak 1989

prepare for a wet spring would have the same effect (Easterling 1989).

If fall tillage is accompanied by fall fertilizer applications, and if fertilizer applications increase to take advantage of higher carbon dioxide, the risk of nitrate contamination of the water supply will increase, especially with the increased leaching potential caused by winter thaws and heavier rains. Moreover, nitrous oxide emissions from fertilizer will increase, exacerbating the greenhouse effect. On the other hand, drier conditions could reduce fertilizer application rates and decrease leaching.

Greater use of pesticides to respond to intensified pest problems will also pose greater risks to the environment. With the potential for both increased irrigation and depleted ground and surface water, the risks to water quality will increase as more pollutants are washed through the soil and there is less water to dilute its effects (Easterling 1989). On the other hand, pesticide and nitrate leaching may tend to be less, due to changes in seasonal precipitation and increased evaporation (Smith and Tirpak 1989).

Expansion of irrigation and shifts in production patterns in the Midwest would both increase competition for (and depletion of) water resources, and reduce wildlife habitat. If the increased demand for water requires more and larger reservoirs, there will be increasing pressure to develop remaining undisturbed stretches of river, and to sacrifice wildlife to economic values (Adams et al. 1990). Increasing irrigation will likely mean more energy will be consumed, and most likely, yet more carbon dioxide emitted. There may also be greater pressure to bring more marginal, highly erodible, land into production and to convert areas that currently are protected, such as wetlands.

An increase in irrigated acreage could also lead to greater soil salinity problems if leaching requirements are not met (Allen and Gichuki 1989). Higher evapotranspiration rates could also contribute to salinity (Dudek 1991).

No one to our knowledge has assessed comprehensively how energy use in agriculture may be affected by climate change. However, several authors expect that energy required for crop drying in the Midwest will decline because there will be a longer and warmer period for the crop to dry in the field. However, peak and potentially seasonal energy demands are likely to increase with an increase in either peak or seasonal irrigation requirements (Allen and Gichuki 1989). As in other sectors of the economy, energy use for air conditioning in the summer will likely increase while heating requirements in the winter decline.

Another environmental consequence of climate change that could be detrimental to agriculture is the potential decline in biological diversity (that is, at a faster rate than at present). EPA argues that if biological diversity shrinks, agriculture will have an even more difficult time adapting to climate change because doing so depends, in part, on a broad base of germplasm from which to change or produce new crops (Smith and Tirpak 1989). The EPA studies of biological diversity found that while the effects of climate change on species and ecosystems will vary, it will affect ecological interactions, alter the outcome of species competition, and destabilize ecosystems in unpredictable ways (Smith and Tirpak 1989).

Taking a Position

Summary: The optimistic view that increased carbon dioxide will enhance plant growth relies too much on too few certainties and ignores too many problematic uncertainties. Climate change is a significant problem with serious consequences for agriculture, especially in the Middle Border. Neither social nor technological developments such as those affecting greenhouse gas emissions are inevitable, but depend on choices made by real people.

From the evidence reviewed here, we conclude that the picture painted by some in agriculture -- higher yields, farmer adaptability, and technological change -- is misleading and counterproductive. It derives too much from a tendency to emphasize only the uncertainties about climate change while applauding the certainties about the direct effects of carbon dioxide (which are limited).

This optimism also comes from focusing on the entire agricultural sector rather than on the people and farms that are part of it. But it is individual people, not the "agriculture sector" as a whole, who will suffer the disruption and dislocation as the sector adjusts to climate change.

And that optimism also seems to ignore the negative environmental effects of the adjustments farmers may make to climate change.

The optimistic view focuses on the benefits of carbon dioxide and the ability of farmers and scientists to adapt. The assumption seems to be that people and nature can continuously adapt to one another, and that neither nature nor human society may be irrevocably damaged by the effects of an industrialized world.

From a more critical perspective, climate change appears to be a significant problem with serious consequences. This view rests on the assumption that real damage can be done, and technology may not always be able to make up for insults to nature's balance between the climate and the terrestrial ecosystem.

These differing world views also separate on another issue. Is climate change preventable or inevitable? Those who believe in a technological fix usually also assume that the character of our industrial system was an inevitable development. Industrialization and technological change are seen as having their own internal momentum, to which society, and nature, adapt. The forces which have created the conditions for climate change could hardly have been otherwise, and to try to change them now in the absence of certain disaster is not worth the tremendous cost.

But industrialization is a long series of choices made by people, choices that could have been made differently. Climate change (beyond that to which we are already inevitably committed by greenhouse gas emissions to date) is clearly preventable if we begin to make different choices now about our technological life. Since we're always making choices to begin with, it is not such a monumental task to consider making them differently in order to avoid significant though uncertain risk. Making different technological choices today to try to ward off that risk need not entail great social costs, especially when so many actions that we could take would be beneficial for other reasons as well.

There are other values at stake in these differing views of the world. How willing are we to accept risks, in particular to put succeeding generations at risk in order to avoid potentially difficult changes in our own lives? Faith in the technological fix suggests that we needn't worry about the effects tomorrow of relatively speculative risks today. A more cautious approach looks at the magnitude of damage that *could* be done and asks what needs to happen today to prevent that damage.

People must judge for themselves whether they prefer to err on the side of caution or blithe optimism.

Our choice in developing this report has been to become as informed as possible about various scenarios, simulations and predictions, focus on their implications for farms and farmers, and take seriously the potential for disruption and hardship. We do not see social and technological trends and their impacts on nature as inevitable. A technological fix may or may not serve society as a whole. But the changes in technology, and the problems they're intended to fix, always involve social (and environmental) disruption and dislocation in the process.

For example, what kind of technology gets developed and when it is applied depends on people's <u>perception</u> of the need. It will not be a simple matter to decide when and how climate has changed, what to expect in each new growing season and when to try something new (e.g. a new crop variety). Because climate changes will likely continue well into the future, farmers will face this dilemma every year for many years to come.

Our preference is to highlight the social choices that can and should be made, and to involve the average person in making those choices.

In the next part, we'll analyze how agriculture, particularly in the Midwest, contributes to the global warming problem, and what farmers and farm policy makers can do to reduce greenhouse gas accumulations in the atmosphere.

III. AGRICULTURE'S CONTRIBUTION TO GREENHOUSE GAS EMISSIONS

How much does agriculture contribute to greenhouse gas emissions and, ultimately, to global warming? Globally, that is an extraordinarily complex question. Clearing and burning rain forests in the tropics is certainly a major contributor to carbon dioxide, as is rice production to methane.

But our concern is more regional -- the American grain and beef belt, where modern agricultural technologies are fully deployed. So in this part, we examine what science knows about the agriculturally related emissions of greenhouse gases with special attention to the sources of emissions which, though national (or global) in nature, are especially important in our region. We look in turn at each of the three major agricultural greenhouse gases -- carbon dioxide, methane, and nitrous oxide. For each gas, we review emissions data and factors and consider strategies for reducing agriculture's contributions to the problem.

Finally, in this part we comment on the importance of considering the whole farming system when analyzing agricultural contributions to global warming. Focussing on disaggregated parts of the whole and on emissions of a single gas can lead to mistaken conclusions about appropriate management strategies to reduce greenhouse gas emissions from agriculture.

Carbon Dioxide: A Pivotal Role for Agriculture

Summary: Only a small fraction of the earth's carbon in stored in living plants and animals, the soil, and the atmosphere, but it is the interaction of these pools of carbon that form the basis for life. Agriculture plays a big role as both a "source" of carbon emissions to the atmosphere and a "sink" for its removal from the atmosphere to the living matter and soil. Agriculture emits about 121.7 million tons of carbon dioxide annually from energy consumption, of which over one-third is from fertilizer and pesticide manufacture. Nearly another 24 million tons is emitted from eroded soils.

A five part strategy for reducing these emissions and removing carbon from the atmosphere is outlined, including (1) planting trees as field windbreaks and shelterbelts, (2) planting grass on previously cultivated lands, (3) reducing soil erosion on cultivated land, (4) reducing fossil fuel consumption, and (5) rebuilding organic matter in cultivated land. These strategies have the potential to reduce net emissions (total emissions minus carbon removed from the atmosphere) by the equivalent of nearly 104 million tons of carbon dioxide per year, an amount equal to about 85 percent of the emissions from American agriculture's fossil fuel consumption.

Carbon dioxide is the most prevalent of the greenhouse gases. At a current atmospheric concentration level of about 350 parts per million (ppm), it is 200 times as concentrated as methane and 1,000 times as concentrated as nitrous oxide. It has increased about 20 percent in the past 100 years and is now increasing at a rate of about 0.5 percent per year. Burning fossil fuels and cutting down (and burning) forests are the most commonly cited sources of carbon dioxide emissions.

Although it is the most voluminous of the greenhouse gases, carbon dioxide is not the most potent. Pound for pound, it has less than 2 percent of the warming effect of methane, and less than 0.5 percent the warming effect of nitrous oxide. Nonetheless, due to its sheer volume in the atmosphere, scientists estimate that it accounts for over half of the warming effect. Moreover, it persists in the atmosphere for 100 years or more, ten times as long as methane and perhaps as long as the far less prevalent nitrous oxide (IPCC 1990a).

There are, however, many opportunities to reduce carbon dioxide emissions. Improving the energy efficiency of fuel-burning machinery is high on the list. Conserving forests is, too.

Moreover, once it is emitted to the atmosphere, carbon dioxide is also the easiest of the greenhouse gases to remove. In part, that's because carbon dioxide is a crucial medium of exchange between plants and animals, a key ingredient in both photosynthesis and respiration. In respiration, animals breath in oxygen and exhale carbon dioxide. Plants, in turn, take in carbon dioxide, photosynthesize the carbon into plant tissue, and release oxygen. Photosynthesis thus removes carbon from the atmosphere and stores it in plant tissue. When plants die, some of that carbon is released into the atmosphere, but some may be stored for longer periods in lumber or other wood products. Some is also stored more permanently in the soil.

There are therefore many opportunities to use plants and soil to remove carbon dioxide from the atmosphere. That gives agriculture a pivotal role in addressing the global warming issue.

The Carbon Budget

Carbon dioxide is a gas composed of carbon and oxygen. Since oxygen is always amply present in the atmosphere, the only way to prevent excessive accumulation of carbon dioxide is to regulate the amount of carbon available to mix with oxygen (or "oxidize") to form carbon dioxide.

Carbon is one of the most common elements, but most of it is not readily oxidized into carbon dioxide. Well over 99 percent of the earth's carbon is stored in rock. In that form, it is very stable -- little of it oxidizes as carbon dioxide. Still, there are about 49,280,000 million tons of carbon that circulate more readily through chemical and biological processes between various global reservoirs. Of this, the vast majority -- about 41,800,000 million tons -- is stored in the deep ocean and circulates very slowly into the atmosphere as carbon dioxide (or to a lesser extent, as carbon monoxide).

Another 4,400,000 million tons of carbon is stored in fossil fuels. It wouldn't form much carbon dioxide either, except that people burn it or convert it to other products which are oxidized in one way or another. About 5,500 million tons of carbon is released each year from fossil fuel burning (producing about 20,166 million tons of carbon dioxide).

The remaining 3,080,000 million tons of carbon -- only about 6 percent of the carbon not stored in rock -- is stored in living plants and animals (605,000 million tons), the atmosphere (825,000 million tons), and the soil (1,650,000 million tons). Nonetheless, the interaction of these relatively small pools of carbon through photosynthesis, respiration, and the decomposition of organic matter in soil, is the foundation for life.

While carbon stored in rock, in the ocean, and in fossil fuels is relatively stable, carbon moves somewhat more readily between the atmosphere, the land, and vegetation in the process of sustaining life. But even among these more volatile, life-sustaining pools of carbon, the rate of flux varies. The biomass of living plants and animals yields carbon readily through both respiration and decomposition after death. The atmosphere also yields carbon readily into plant life through photosynthesis.

Notice that the largest of these most active pools is the soil, with three times as much carbon storage as in plants, and twice the level in the atmosphere. On average, there are 47.6 tons of soil carbon beneath each acre of land, but that figure doesn't mean a great deal because carbon levels vary dramatically with soil type and climate. Generally, the wetter and colder the soil, the more carbon is stored. Thus, wetlands may achieve over 311 tons per acre, and the northern tundra 89. Tropical forests, which store much more carbon in living vegetation above ground, still achieve soil carbon levels of about 53 tons per acre. Deserts, by contrast, have as little as 9 tons per acre. In temperate zones, where agriculture thrives, grassland soils store about 49 tons per acre and forests soils about 40 (Post 1982).

But carbon stored in the soil is more stable than it is stored in plant tissue, especially once stabilized in the soil as organic matter (Table 6). Once it reaches that state, it remains there on average about 72 years before being emitted to the atmosphere as carbon dioxide. That average includes all soils, including those that lose soil carbon much more quickly, especially those that are tilled. Carbon stored in undisturbed grass or forested soils have much longer retention times, some for thousands of years (Johnson and Kern 1991)

By contrast, surface litter composed of decomposing plants retains carbon only about 1.2 years before emitting it to the atmosphere (Post 1990 quoted in Johnson and Kern 1991).[1] Managing soil organic matter is therefore an important strategy for removing carbon dioxide from the atmosphere, placing it in long term storage and reducing atmospheric emissions.

Agriculture and the Carbon Budget

Agriculture therefore can play a significant role -- both positive and negative -- in determining how much carbon is in the atmosphere at a given time. Agriculture is both a source of atmospheric emissions and a way to store carbon in plants and the soil.

Agriculture is almost unavoidably a source of emissions. Carbon is oxidized and released into the atmosphere as carbon dioxide when land is cleared for farming, when trees and crop residues are burned, when fossil fuels are consumed to make fertilizer and pesticides or to operate field equipment or crop drying facilities, and even when

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1. The figures for average retention time attributed to Post here are not as reported in Johnson and Kern 1991. They have been modified by Post in a personal communication with the authors. The framework for this analysis was reported in Johnson and Kern 1991.

Table 6 Retention of Carbon in Soils

Type of Soil Carbon	Total Stored	Annual Input	Annual Emissions	Avg. Retention Time
	------ (million tons)		---------	(Years)
Surface Litter	79,200	66,000	46,200	1.2
Organic Matter	1,430,000	19,800	19,800	72.2
Total	1,509,200	66,000	66,000	22.9

Source: Post 1990 quoted in Johnson and Kern 1991.

soils are merely exposed to air through tillage and erosion.

And commercial agriculture, with its emphasis on high yields, tends to induce ever greater carbon dioxide emissions. That's because most crops have been bred to produce more of their plant material above the ground where it can be harvested as fruit, seed, fiber, or fodder. Generally, the more biomass produced above ground, the less is produced in root systems. The more produced above ground, the more carbon is released into the atmosphere when the plant dies and decomposes, and the less is stored in the soil. Moreover, the portion of the crop that is removed for consumption by people or animals is not returned to the soil.

To get a handle on the extent of U.S. agricultural emissions, let's consider two general categories of emissions: energy consumption and land use practices.

Carbon Dioxide Emissions From Energy Use in U.S. Agriculture

American agriculture consumed about 1,667,505 billion BTU's of energy in 1987, the last year for which detailed data are available. That's a decline of about 16 percent from the nearly 2,000,000 billion BTU consumed in 1974.

The change in the mix of energy sources consumed reveals a great deal about the reason for the decline (Table 7).

First, the shift from gasoline to higher fuel efficiency diesel tractors and the adoption of conservation tillage systems reduced liquid fuel consumption significantly, with gasoline falling by 59 percent while diesel increased by only a little over 11 percent. LP gas also fell by 57 percent. Offsetting these reductions somewhat were increases in fertilizer energy use (5 percent) and pesticide energy use (38 percent). Electricity use, reflecting increased use of confinement livestock facilities, irrigation, and crop drying, also increased 11 percent.

This general decline in energy consumption occurred despite an overall increase of about 20 percent in output.

But as a result of these shifts, pesticides and fertilizers now constitute about 43 percent of the energy consumption in U.S. agriculture, up from 37 percent in 1974. With electricity, these "invested" forms of energy now constitute over half of all energy use in American agriculture. This striking reliance on fossil fuel derivatives that have significant other environmental impacts (including other global warming effects), will be discussed later.

Carbon dioxide emissions from U.S. agriculture's energy use can be estimated by multiplying the BTU consumption for each energy source by carbon dioxide emission coefficients developed by Edmonds and Reilly (1985). In 1987, U.S. agriculture's use of fossil fuels contributed an estimated 33.2 million tons of carbon (121.8 million tons of carbon dioxide) into the atmosphere, about 0.6 percent of the global total carbon emissions. That is about 15 percent less than the estimated emissions for 1974, about the same rate of decline as energy consumption (Table 8).

The largest absolute increase in emissions is from diesel fuel (0.9 million tons), although this is clearly a substitute for gasoline which declined by 6.2 million tons (60 percent). The largest rate of emissions increase is from pesticides (38

Table 7 Energy Consumption in U.S. Agriculture, 1974 and 1987.

Energy Source	Consumption 1974	Consumption 1987	Unit	Bil. BTU 1974	Bil. BTU 1987
Direct Energy					
Gasoline	3.7	1.5	Bil gal.	462,763	187,607
Diesel	2.6	2.9	Bil gal.	360,594	402,201
LP Gas	1.4	0.6	Bil gal.	127,866	54,800
Natural Gas	137	54	Bil Cu Ft.	139,877	55,134
Total Direct				1,091,100	699,742
Invested Energy (1)					
Electricity	31.8	35.2	Bil kwh	216,696	239,952
Fertilizer	18.1	19.1	Mil Ton	591,610	620,393
Pesticide	0.6	0.8	Bil lbs.	80,563	107,418
Total Invested				888,869	967,763
Total Energy (Bil BTU)				1,979,969	1,667,505

Source: USDA, Roger Conway, Office of Energy, personal communication.

Note:

(1) Invested energy includes the energy value of fuel stocks used to produce electricity, fertilizer and pesticide. For electricity, kwhs were multiplied by a weighted average efficiency coefficient based on the number of fossil fuel (carbon dioxide emitting) BTUs consumed in the generation of the nation's electrical supply in 1990 (Annual Outlook for U.S. Electric Power in 1991, Energy Information Administration, DOE, July, 1991). Although most fossil fuel plants consume from 2.5 to 4 BTUs of fuel to generate one BTU of electricity, the average number of fossil fuel BTUs used to produce a BTU of electricity is only 2 because some electricity is produced by nuclear or renewable energy sources. This calculation assumes that the electricity consumed by agricultural operations is produced using the same mix of fuel stocks as the nation as a whole. None of these invested energy calculations include energy consumed in mining, transporting or processing fuel stocks, or transporting and handling the end-use products.

Table 8 Carbon Emissions From U.S. Agriculture's Energy Consumption, 1974 and 1987

Energy Source	--- Bil. BTU --- 1974	1987	Tons C per Bil BTU (1)	Emissions (Mil Tons C) 1974	1987
Direct Energy					
Gasoline	462,763	187,607	22.282	10.3	4.2
Diesel	360,594	402,201	22.282	8.0	8.9
LP Gas	127,866	54,800	15.8989	2.0	0.9
Natural Gas	139,877	55,134	15.8989	2.2	0.9
Total Direct	1,091,100	699,742		22.5	14.9
Invested Energy					
Electricity	216,696	239,952	25.288(2)	5.5	6.1
Fertilizer	591,610	620,393	15.8989	9.5	9.9
Pesticide	80,563	107,418	22.282	1.8	2.4
Total Invested	888,869	967,763		16.8	18.4
TOTAL	1,979,969	1,667,505		39.3	33.2

Note:

(1) From Edmonds, J.A. and J.M. Reilly, 1985. **Global Energy: Assessing the Future**, New York: Oxford U. Press.

(2) For electricity, we again estimated a carbon dioxide coefficient based on the weighted average coefficients for each fossil fuel stock used to generate electricity.

percent). And while gasoline had been the largest contributor to emissions in 1971, fertilizer now is.

Carbon Dioxide Emissions From Land Use Practices in U.S. Agriculture

Some scientists have estimated that land use changes associated primarily with agriculture in the past two centuries have released more carbon into the atmosphere than all fossil fuel burning (Houghton et al. 1983). The level of carbon in the temperate soils where agriculture is most widespread has fallen markedly since the advent of commercial farming. Most soil scientists estimate that 40-50 percent or more of the carbon stored in the upper eight inches of these soils prior to cultivated agriculture has been lost to the atmosphere (Parton 1991b; Schlesinger 1985; Balesdent et al. 1988).

Moreover, if global warming increases soil temperature, more carbon will be lost. An increase in soil temperature of 3 degrees centigrade in the temperate zone would release to the atmosphere another 11 percent of the carbon stored in those soils, resulting in an 8 percent increase in atmospheric carbon dioxide (Buol 1991 in Johnson and Kern 1991).

Generally, the loss of soil carbon is rapid in the early stages of cultivation, and is more gradual the longer the land is tilled. But scientists are not sure if cultivated land ever reaches a new "equilibrium" where the amount of carbon lost each year does not exceed the amount added from decomposing plant material. For some time, they believed that after 50-60 years, further carbon loss was unlikely. But recent studies have sufficiently challenged this view (Tiessen et al. 1982). Now, scientists are inclined to believe that there is no absolute minimum level of carbon, but that management practices that add carbon to cultivated lands, such as fertilizing which increases the plant material, some of which subsequently releases carbon into the soil, can offset continuing carbon depletion and produce a new equilibrium in carbon levels (Rasmussen and Collins 1991).

Nonetheless, research in the Canadian prairie provinces indicates that one percent of the remaining carbon continues to be lost each year from cultivated soils that have already lost 20-30 percent of their organic matter (Benzing-Purdie 1990). If all of that carbon is oxidized as carbon dioxide, the emission levels would be significant. For example, it is estimated that the carbon content of the mineral soils in twelve Midwestern farm states is 22,880 million tons (Franzmeier et al. 1985). If one percent of that oxidized each year, the annual emission would total 229 million tons of carbon from 12 Midwestern states, an amount equal to about 4 percent of the annual net increase in atmospheric carbon.

Another way to look at the problem of soil carbon loss to the atmosphere is to examine only that part of the loss which can be attributed to erosion.

According to one study, erosion at the relatively low rate of about 5.0 tons per acre per year removes about 121 lbs. of carbon per acre per year from soil that has about 1.2 percent organic carbon (Rasmussen 1991). While this figure would undoubtedly vary considerably with soil type and climate, a panel of soil scientists convened by the U.S. Environmental Protection Agency (Johnson and Kern 1991) estimates that as much as half of the soil carbon eroded globally may be oxidized. It's probably more than that in the tropics and less than that in the temperate zones.

Some scientists we talked to doubted that anywhere near as much as half the eroded carbon oxidizes as carbon dioxide, arguing that much eroded soil is ultimately deposited in lowlands or in bodies of water, where carbon would be *less* susceptible to oxidation than if it remained uneroded in cultivated fields. However, offsetting this is the indirect effect of erosion on carbon emissions. Eroded soils are less productive, increasing demand for cultivated land. This both increases carbon dioxide emissions from soil carbon and reduces the efficiency with which plants remove carbon from the atmosphere (because less productive soils produce less plant growth). In short, it is inescapable that erosion means more carbon in the atmosphere and less in the soil.

It is possible to make a crude estimate of the total contribution of U.S. cropland erosion to carbon dioxide emissions. The USDA (1989) estimated that in 1982, total soil lost to erosion from U.S. cropland was 3,088 million tons (1,840 million tons to water erosion and 1,248 million tons to wind erosion).[2] If this soil averaged only 0.9 percent organic carbon (less than the level in the Rasmussen study cited above, but closer to the probable level of organic carbon in the major soils of the Midwest, as reported in Franzmeier et al. 1985), carbon loss to erosion from U.S. cropland would be 27.8 million tons per year. If half (13.9 million tons) of that carbon is oxidized, it would contribute 50.9 million tons of carbon dioxide to the atmosphere each year. Assuming that the oxidation rate from erosion of U.S. soils is much lower than the estimated global average of 50 percent, however, this figure might be considerably lower, perhaps as low as 6 or 7 million tons of carbon per year.

It should be noted, moreover, that some eroded carbon is likely to be emitted to the atmosphere not as carbon dioxide, but as methane, a much more potent greenhouse gas.

A Five-Part Strategy to Reduce Carbon Emission from Agriculture and Store Carbon in Agricultural Soils

U.S. agriculture can both reduce its contribution of carbon dioxide emissions and manage productive land in a manner that actually removes carbon from the atmosphere and stores it in the soil and in living plants. For American agriculture, there are five promising strategies for doing so, which we describe below. Each of these strategies is consistent with current farm policy objectives and all can be accomplished by adjustments made within the framework of current farm policy legislation. The strategies are:

(1) Plant trees to serve as field windbreaks and shelterbelts for farmsteads and rural residences.

(2) Plant grass on land previously cultivated.

(3) Reduce soil erosion to levels that are naturally offset by soil formation.

(4) Reduce fossil fuel use.

(5) Rebuild organic matter (carbon) in cultivated soils.

These strategies are overlapping and, to some extent,

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[2] This includes cropland erosion only. Erosion from all U.S. land totals 5,390 million tons, 3,394 millions tons from water and 1,996 from wind.

competitive. That is, success in one area may be partially at the expense of success in another area. However, each is compatible with good farm management and long term improvements in productivity. By emphasizing the interactions among these strategies, it is possible to achieve multiple benefits.

But it is important to recognize that each of these strategies has its relative strengths and weaknesses. Strategies that remove a lot of carbon quickly may not remove it for long. Strategies that remove a lot of carbon for a long time may require decades to achieve their objective.

Consider, for example, the relative merits of planting trees or grass as a means of cleansing the atmosphere of carbon dioxide and storing carbon in either plant tissue or the soil. Trees store carbon in above-ground biomass more slowly than grass in the short run, because they grow more slowly. However, trees produce more biomass per acre over the long term than grass, because grass reaches its full growth potential much sooner with less carbon storage. Moreover, the carbon in trees may be stored as lumber or other wood products long after the trees die.

On the other hand, because grass produces a relatively larger portion of its biomass below ground as roots, it contributes a larger portion of its carbon to organic matter. Once the carbon is in the soil as organic matter, it may stay there for centuries. Grass also grows in some locations where it is very difficult to establish trees, and it is generally cheaper to plant grass than trees. Both trees and grass have a place in a diversified agriculture, and clearly, both have important virtues in an agriculturally based carbon storage strategy.

But it is even more important to remember this: It is both easier and more effective over the long term to reduce emissions of carbon dioxide than it is to remove it from the atmosphere. Strategies that reduce emissions are better than those that remove excess emissions from the atmosphere.

Strategy 1. Plant trees as field windbreaks and shelterbelts.[3]

Brandle et al. (in press) have estimated that a ''minimum'' program of establishing farmstead and livestock shelterbelts and field windbreaks to protect farmsteads, livestock, and cropland, (currently, only about 2 percent are protected) would require 1.3 billion trees and shrubs on 4.9 million acres and could store as much as 24.4 million tons of carbon in the biomass alone within the 50-year lifespan of the shelterbelt and windbreak planting.

Over 50 years, that works out to an average of 0.1 tons of carbon per acre per year. On 4.9 million acres, the total reduction in carbon emissions would be 0.49 million tons per year for the 50 years, for a total of 24.3 million tons.

These estimates are based on extremely conservative assumptions about the carbon storage potential of trees in shelterbelts. Most analysts place the annual accumulation rate for trees at between 1 and 2 or 2.5 tons per acre per year (Trexler 1991 and Ward et al. 1991), at least ten times the rate assumed by Brandle et al. But Brandle et al.'s estimate of 0.1 tons per acre per year is for trees placed in agricultural shelterbelts and field windbreaks, while the higher estimates of others are an average for carbon storage rates in forests conditions. The agricultural tree plantings can be expected to store carbon less rapidly because:

** they are planted linearly rather than in blocks, and are therefore more susceptible to wind and moisture stress,

** they are planted disproportionately in semi-arid and subhumid, high wind areas (the Great Plains and Western Corn Belt),

** they are stressed by adjacent agricultural practices, including tillage and herbicide use,

** they are planted closer together to protect land, animals, and buildings from the wind,

** they are composed of species selected for adaptability to the above conditions, not for their rapid carbon storage potential.

For these reasons, we accept the Brandle et al. estimate of carbon storage potential of field windbreaks and shelterbelts, recognizing that if the carbon storage rate is actually closer to those more commonly accepted for forest plantings, the benefits of this strategy would be significantly greater than we now assume. They could easily be ten times greater if even the lower estimate by Trexler (1991) and Ward et al. (1991) is accepted for carbon accumulation rates in trees.

Moreover, in addition to the "direct" benefits identified, Brandle et al. point out that there would be indirect benefits in the form of reduced diesel fuel and fertilizer consumption due to conversion of cropland to trees, reduced fuel consumption for home heating due to the insulating effects of shelterbelts, and reduced fuel consumption for snow

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[3] All carbon storage strategies report data in terms of carbon rather than carbon dioxide. To convert this data to carbon dioxide equivalents, multiply by 3.667.

removal due to living snow fences along roadways. They calculate these benefits to be equivalent to 63.7 million tons of carbon over the 50 year life of the planting. Such indirect benefits are significant and apply to most of the strategies under discussion here, but are not included in this analysis.

Strategy 2. Plant and maintain grass on 45 million acres of land previously farmed.

Planting warm season native grasses on previously cultivated soils that have been farmed for 100 years or more and depleted of roughly 40-50 percent of their original soil carbon will store carbon in both the biomass of the grass and in the soil. Much of it will be stored in the deep soil profile where it will be retained for a very long time.

When fully established, a warm season tall prairie grass typical of that planted under the Conservation Reserve Program (CRP) in Eastern Nebraska, would have about 4,095 lbs. of carbon per acre in its biomass above and below ground, and another 2,137 lbs. per acre of carbon in dead but not yet decomposed biomass below ground. Together, this means that an established acre of tall, warm season prairie grass stores about 3.1 tons of carbon in living and undecomposed biomass (Parton 1991a).

Carbon storage in the soil is more difficult to estimate. The native prairie grasses used so often in the Conservation Reserve Program are particularly potent soil carbon producers, yielding six times more biomass below ground than corn and wheat, and twice as much as alfalfa or the introduced cool season grass, brome (Kramer and Weaver 1936, as cited in Granatstein 1991). The native grasses also produce relatively more of their biomass below ground than do trees. Sixty percent of native grass biomass is below ground, compared to about 20 percent for trees. The grass also has a much higher rate of root mortality than trees, adding more carbon. Accordingly, native grass stores more of its carbon in the soil than do row crops, small grains, introduced grasses, or trees. Grassland soils, in temperate climates at least, therefore have higher carbon content than even forested soils (Jenny 1941 quoted in Rasmussen and Collins 1991; and Johnson and Kern 1991).

It isn't surprising then that grass planted in cultivated soils that have diminished soil carbon levels increases those levels, and fairly quickly. Research at Iowa's Leopold Center for Sustainable Agriculture indicates that within about 15 years of planting grass on previously cultivated soils, carbon levels had increased to between 2.09 to 2.6 percent, about 60 percent higher than the levels in cultivated soils. Within the same time frame, root biomass had already reached the level of virgin prairie (Christiansen and Thompson 1990).

How much carbon does grass build in soil then? That's hard to say, and the answer would vary greatly by soil type and climate. Climate is an especially critical issue. Generally, the wetter and warmer the climate, the more carbon will be stored in soil from grass. Research in eastern Colorado indicates that unfertilized grass will add about 3.1 tons of soil carbon per acre in 100 years, or about 0.03 tons per acre per year. But the scientist who conducted that research estimates that in the subhumid soils of the western corn belt, the rate of carbon accumulation under grass would more likely be closer to five times that rate, or about 0.15 tons per acre per year (Parton 1991a).

That would be very close to results from research in Great Britain indicating soil carbon accumulation rates of 0.11 to 0.22 tons per acre per year over 80 years from converted farmland (Jenkinson 1991, cited in Johnson and Kern 1991). It is also more conservative than the preliminary results from more relevant studies in Iowa (Christiansen and Thompson 1990).

At those rates of accumulation, an acre of native grass would add 3.1 tons of soil carbon in only 20 years -- roughly the same amount of carbon as in the biomass of the grass itself. In fifty years it could have added a total of as much as 7.7 tons. At some point, an equilibrium is reached in which decomposition and release of carbon equals the amount of soil carbon produced by the grass. But this would not likely occur until the soil carbon levels reached near virgin soil levels, which would probably take more than 50 years.

Considering both the carbon in the biomass of the grass and the carbon stored in the soil, an acre of native grass could store 10.8 tons of carbon within 50 years, an average of over 0.2 tons per acre per year. Over the shorter 20 year timeframe, its total carbon storage would be lower (6.2 tons), but its annual rate higher (0.31 tons/ac/yr).

This strategy has already been partially implemented under the Conservation Reserve Program, although erosion control, not carbon storage, is the objective of the program. So far, about 34 million acres of highly erodible farmland has been removed from production and planted to grass. If another 11 million acres authorized for the program were planted to grass the total 45 million acres of CRP land could reduce carbon emissions by an average of about 13.8 million tons each year over 20 years. Over a fifty year period, the per-year average would drop (to about 9.7 million tons per year) because no more carbon would be added to the biomass and the rate of soil carbon buildup might slow, although it would not stop completely.

Strategy 3. Reduce soil erosion to levels that are naturally offset by soil formation.

USDA officials estimate that erosion has been reduced on the 34 million acres already planted to grass under the CRP by an average of 19 tons per acre (USDA 1990).

If so, atmospheric carbon emissions from erosion on these lands may have already been reduced by about .044 tons per acre per year, or about 1.5 million tons per year. If the full 45 million acres authorized for CRP planting is achieved, the annual carbon emissions to the atmosphere could be reduced by about 2.0 million tons.

But what about the excessive erosion on all farmland still in cultivation? USDA estimates that excessive erosion -- that above the rate of natural soil rebuilding -- on all U.S. cropland totals 1,624 million tons per year (USDA 1989). If that were eliminated, the carbon emissions would be reduced by an estimated 3.6 million tons per year.

That goal is not likely to be achieved under current policy, but some important strides forward are being made. Farmers who till erodible land are now required to adopt and implement approved conservation plans by the year 1995 if they are to continue to participate in federal farm programs. So far, conservation compliance plans have been approved for over 135 million acres, and USDA scientists estimate that if fully implemented, these conservation compliance plans will reduce erosion on these lands by 50 percent (USDA 1990).

Assuming these lands are now eroding at the average rate for all cropland in the U.S. eroding in excess of tolerable levels, (13.6 tons/ac), and that their organic carbon level is about 0.9 percent, and that about 25 percent of eroded carbon oxidizes as carbon dioxide into the atmosphere, conservation compliance could reduce carbon emissions by about .015 tons/ac/yr on this land. If 11 million more acres are entered into the CRP, they would come from this 135 million acres, however, so the land benefited by conservation compliance would be reduced to 124 million acres. Total annual reduction in carbon emissions on this 124 million acres would be 1.9 million tons.

Taken together, these soil erosion mitigation strategies offer the opportunity to reduce carbon emissions by over 194 million tons over 50 years, or about 3.9 million tons per year. The benefits are, of course, immediate and continuous, as with all emission reduction strategies.

Strategy 4. Reduce Fossil Fuel Use

U.S. agriculture has done very well reducing its energy consumption by about 16 percent between 1971 and 1987 while increasing production by about one-fifth.

Nonetheless, there remain opportunities for further strategic reductions in energy use. Importantly, in each of these areas, energy conservation is cost-effective, will improve net farm income and produce a net economic benefit to society as well.

(1) Reduce Commercial Fertilizer Use

One area where energy use can be reduced is in fertilizer use, which now constitutes over one-third of total U.S. agriculture energy consumption.

Fertilizer, especially nitrogen, is now uneconomically overapplied in the United States, at least on some farms (see section on nitrous oxide). By a combination of better nitrogen management, adjustment in yield goals, field testing of available soil nitrogen, better use of manures, and changes in cropping patterns, U.S. agriculture could reduce nitrogen fertilizer consumption by 40 percent without sacrificing yield and thereby improving net farm income. A more immediate goal involving only improved nitrogen fertilizer management would seek reductions of 25 percent, or 2.8 million tons (using a 1990 base of 11.1 million tons of nitrogen fertilizer consumed in the U.S.).

If nitrogen fertilizer applications were reduced that much, fuel consumption would be reduced by about 144,558 billion BTUs. That would reduce carbon dioxide emissions by 5.3 million tons per year, or carbon emissions by 1.4 million tons.

Substituting manure for nitrogen fertilizer would reduce emissions more and have other benefits, as well. Manure adds carbon to soils, raising soil organic carbon rates by about 0.1 percent per year (or about 2 lbs per ton of soil per year, Rasmussen and Collins 1991). That further reduces carbon dioxide emissions and places carbon in the relatively stable form of soil organic matter. Studies in England found that long term manuring resulted in large increases in soil organic matter that persisted long after annual manuring ceased (Jenkinson 1991). Nonetheless, the strategy we outlined above involves only judicious reductions in nitrogen fertilizer use, not the further reductions possible by improved manure management.

(2) Extend Conservation Tillage in Combination With Crop Rotations

Energy efficiency has improved in American agriculture in large part due to a continuing shift toward conservation tillage which minimizes soil disturbance and reduces the number of trips across a field. Conservation tillage is conventionally defined as any tillage system leaving 30 percent or more of the soil surface covered with previous crop residue after the new crop is planted. Corn produced with conservation tillage may reduce tractor fuel consumption per acre by one-third (Hull and Hirning 1974).

Conservation tillage is now used on about 72 million acres in the U.S. (22.7 percent of all planted acres) and is likely to continue to increase as farmers meet conservation compliance requirements on over 135 million acres of highly erodible cropland (USDA 1990).

Conservation tillage coupled with crop rotations can have further benefits. The use of small grains in rotation with row crops would further reduce energy use and carbon dioxide emissions by reducing both fertilizer and pesticide requirements. Energy used on an acre of small grains with conservation tillage is about one-third less than energy use on corn under conservation tillage (Hull and Hirning 1974). Moreover, the small grain rotation will reduce weed and insect infestation in the field, reducing the need for pesticide use in the years when row crops are planted.

If, for example, use of conservation tillage were doubled to include an additional 72 million acres and small grains were planted on just 10 million more of those acres (conservation tillage is used mostly on row crops), energy consumption from field operations could be reduced by about 30,000 bil BTUs (between 27,266 and 33,706 bil BTUs, depending on whether diesel or gasoline fuel is conserved). This would reduce carbon emissions by 0.65 million tons per year.

(3) Reduce Fossil Energy Use in Crop Drying

U.S. agriculture consumed about 68,100 bil. BTUs of energy in crop drying in 1981, the most recent year for which data are available (Torgerson et al. 1987). If crop drying efficiency increased as much as efficiency in all areas of farm energy consumption between 1981 and 1987, energy use in crop drying in 1987 would have been about 53,900 bil. BTUs, and carbon emissions from this source would have been about 857,010 tons, or about 3.1 million tons of carbon dioxide.

This figure can be reduced considerably. Crop drying is concentrated in states that produce corn and (to a lesser extent), tobacco. In 1981, four states (North Carolina, Iowa, Illinois, and Minnesota) consumed over 57 percent of the energy used in crop drying. About two-thirds of that energy was from propane (Torgerson et al. 1987). A gallon of propane will dry from 5 to 7 bushels of corn depending on drying conditions and the moisture level of the corn when harvested.

In at least two of these states, Iowa and Minnesota, climatic conditions are ideal for the use of solar and low temperature drying systems that eliminate or sharply reduce the use of energy.

Research dating to the 1970s in eastern Nebraska indicates the potential for solar applications to crop drying. Three cooperators in an experimental energy conservation project constructed several types of customized but simple low-temperature solar grain dryers mounted on the southern two-thirds of their standard grain drying bins. The collectors were built by the farmers with materials costing about $500 (Center for Rural Affairs, 1980). All three collectors have been in regular service, except one that was damaged by a storm and required repair. Only one of the three farmers reports using supplemental heat to dry grain, and in only one of the last 14 years (Center for Rural Affairs 1992).

The solar grain dryers are particularly effective on smaller bins (about 6,000 bushels) because the ratio of bin surface to volume of storage is greater, providing more collector surface per bushel of corn. They are also more effective when only about 800 bushels of new corn at 21 percent moisture are added per day, as is the case with farm on which the size and number of harvesting machines limits the daily addition to such amounts. Drying corn in several batches allows these solar grain dryers to dry as much as 11,000 bushels per year (Center for Rural Affairs 1980).

At an average rate of 6 bushels per gallon of propane for conventional corn drying systems, propane consumption would have been reduced by 79 million gallons (nearly 7,215 bil. BTUs) in Iowa and Minnesota alone in 1987 if just 25 percent of those states' 1.9-billion bushel corn crop had been dried with solar equipment that year. That would represent a national equivalent of 13.4 percent less energy use in crop drying, and would have reduced annual carbon emissions by over 0.1 million tons.

Such a carbon emissions reduction is modest -- only about 0.3 percent of the total carbon emissions from U.S. agriculture that year. But if each state found equivalent cost-effective ways to reduce energy consumption and carbon emissions, U.S. agriculture's contribution to carbon emissions would have been about 2.9 million tons (8.6 percent) less than it was in 1987.

These energy conservation strategies could reduce carbon emissions from U.S. agriculture's energy use by about 2.2 million tons per year, or about 6.6 percent of 1987's estimated emissions. They would also reduce other greenhouse gas emissions, erosion, and water pollution while lowering farm expenses.

Strategy 5. Rebuild carbon levels in cultivated soils

It is widely accepted that about 40-50 percent of the soil carbon in the top 8 inches of cultivated soils has been lost since cultivation began. These depleted soils can be rebuilt by specific management measures. Indeed, some agronomists and soil scientists believe that the higher yields and attendant increase in residues which are returned to the soil have already stabilized and may actually be increasing soil carbon levels in some cultivated soils that have been substantially depleted of carbon. In other words, at this stage of soil carbon depletion, it is possible to deliberately transform cultivated farming from being a source of carbon dioxide emissions to the atmosphere, to being a sink for carbon dioxide removal from the atmosphere.

The management factors involved in stabilizing carbon in cultivated soils are:

(1) Returning crop residues to the soil; the more crop that is produced, the more residue is available to return, so fertilizing some crops or improving yield can contribute to carbon levels if the residue is returned to the soil. Several studies (summarized in Rasmussen and Collins 1991) support the conclusion that the addition of crop residues in sufficient quantity can increase soil carbon. This strategy is limited by the fact that 60-75 percent of the carbon in the residue is emitted as carbon dioxide after only one year in the soil (Martin and Stott 1983, cited in Rasmussen and Collins 1991).

(2) Reducing tillage intensity -- the deeper and more frequently the land is disturbed, the more carbon dioxide emissions and the more erosion.

(3) Minimizing fallowing -- the more the land lies bare, the less crop residue is available to return to the soil, the greater the wind and water erosion, and the higher the ground temperature (increasing oxidation to carbon dioxide).

(4) Rotating row crops with grasses and deep-rooted legumes that increase moisture holding capacity and reduce ground temperature, discouraging carbon dioxide formation, reducing erosion, and adding soil carbon through extensive root systems.

(5) Returning manure to the land, especially if the carbon and nitrogen nutrients in the manure have been stabilized by composting. Research in Oregon indicates that while carbon levels fell by an estimated 31 percent between 1881 and 1931, an annual application of 10 tons of manure per acre increased soil carbon levels about 10 percent over the next 50 years (Rasmussen et al. 1989). Only about half of the manure is deposited on pasture and rangeland and about half of the nutrients in the rest is lost before it is returned to the land (much of it as methane as well as carbon dioxide). The loss of the nitrogen is particularly important to carbon conservation because without the nitrogen, the carbon in the manure is more likely to convert to carbon dioxide (Benzing- Purdie and Mathur 1990).

The potential for this strategy is significant. Soil carbon in the top eight inches of cultivated soils in the North Central United States averages about 20.9 tons per acre (Franzmeier et al. 1985). If management practices such as those described above were implemented on such land, it would be reasonable to expect soil carbon to increase by between one-half and one percent per year, or from 0.1 to 0.2 tons/ac/yr on most cultivated soils in North America.

How long this rate of increase can be sustained is problematic. Likely, the rate of buildup would be rapid at first, then taper off significantly. Eventually, a saturation point would be reached at which additional carbon accumulation would not exceed losses. But scientists cannot predict whether the rate would begin to decline significantly in twenty or forty or one hundred years, or how soon the equilibrium would be reached.

Nonetheless, we conservatively estimate for the sake of this general analysis that with 20 years of the kind of management noted, it would be easily possible to increase carbon in cultivated lands by over 3 tons per acre (an average of 0.16 tons/ac/yr). This would, for example, amount to a 20-year carbon increase in the top eight inches of various Corn Belt soils of between 7 and 17 percent (Franzmeier et al. 1985).

If the average annual rate of carbon accumulation fell to 0.1 tons/ac/yr over a fifty year period, the total carbon increase per acre would be 5 tons, still a modest 12-28 percent increase for typical Corn Belt soils. In many of the more depleted soils, the buildup rate might well be faster. Some soil scientists are much more optimistic (Parton 1991).

The outside limits of the potential for this strategy would involve over 440 million cultivated acres in the U.S. At the

Table 9 Direct Benefits of Selected U.S. Agriculture Strategies for Reducing Atmospheric Carbon (1)

Strategy	20-Year Time Span				50-Year Time Span			
	Tons Per AC/YR	Mil Tons/Yr	Total Tons/Yr	Total Mil Tons	Tons Per AC/YR	Mil Tons/Yr	Total Tons/Ac	Total Mil Tons
1. Plant 4.9 mil ac trees								
A. Biomass	0.1	0.49	2.0	9.8	0.1	0.49	5.0	24.3 (2)
B. Soil Carbon		Negligible				Negligible		
C. Total	0.1	0.49	2.0	9.8	0.1	0.49	5.0	24.3 (2)
2. Plant 45 mil ac grass								
A. Biomass	0.15	6.9	3.1	138.6	0.06	2.8	3.1 (3)	138.6
B. Soil Carbon	0.15	6.9	3.1	138.6	0.15 (4)	6.9	7.7	346.5
C. Total	0.31	13.8	6.2	277.2	0.22	9.7	10.8	485.1
3. Reduce Soil Erosion								
A. Current CRP (34 mil ac)	0.044	1.5	0.9	29.9	0.044	1.5	2.2	74.8
B. New CRP (11 mil ac)	0.044	0.5	0.9	9.7	0.044	0.5	2.2	24.2
C. Reduce Erosion to T on 124 Mil Highly Erodible Acres	0.015	1.9	0.31	37.2	0.015	1.9	0.8	95.4
D. Total	0.023	3.9	0.44	76.8	0.23	3.9	1.1	194.4
4. Reduce Fossil Fuel Use								
A. Reduce Fertilizer Use by 25% (5).	NA	1.4	NA	28.0	NA	1.4	NA	70.0
B. Extend Conservation Tillage and Crop Rotations on 72 mil ac.	0.009	0.65	0.18	13.0	0.009	0.65	0.45	32.5
C. Reduce Energy Use in Crop Drying by 13%	NA	0.11	NA	2.2	NA	0.11	NA	5.5
D. Total	NA	2.16	NA	43.2	NA	2.16	NA	110.0
5. Increase Carbon in 50 Mil Ac. Cultivated Soils By 25% over 20 Yrs. and By Another 10% Over the Next 30 Yrs.	0.16	8.0	3.2	160.0	0.1	5.0	5.0	250.0
TOTAL		28.35		567.0		21.35		1,063.8

NOTES:

(1) To estimate carbon dioxide emissions, multiply the given figures for carbon by 3.667.

(2) Brandle et al., in press

(3) Achieves potential within 20 years and reaches equilibrium

(4) Parton 1991a; and Jenkinson 1991.

(6) on all fertilized acres.

rates of soil accumulation noted above, this strategy could store as much as 70 million tons of carbon per year, an amount equal to over 1 percent of global fossil fuel emissions.

The 1990 Farm Bill provides the framework for such a policy on a more modest scale. Farmers who participate in commodity programs may now elect to also participate in an Integrated Farm Management Program. In return for contracting to hold erosion to tolerable levels and increasing use of soil conserving crops, these farmers are granted protection from the loss of certain farm program benefits they would suffer if they made these cropping changes under traditional farm program rules.

Since many of the practices called for in this innovative program will also result in soil carbon buildup, it would be possible to specify soil carbon management as an objective of the program. This would be the first time that soil policy was specifically integrated into the farm commodity programs.

The farm bill currently authorizes up to 25 million acres to be entered into the program over the next five years. At the accumulation rates noted above, those acres could remove about 80 million tons of carbon (4 million tons per year) over twenty years and 125 million tons (2.5 million tons per year) over 50 years.

We recommend doubling the program to permit 50 million acres to be enrolled. At that level, the program would remove 160 million tons of carbon over 20 years (8 tons per year), and 250 million tons over 50 years (5 tons per year).

Importantly, the cost of this program is negligible and it may actually save the federal government money. Under the Integrated Farm Management Option, farmers receive no more support from the government than they would have received if they had continued to produce program crops. The reduced output of those crops might raise their market prices, reducing the government's obligation to make deficiency payments on those program crops.

Strategies Reviewed

The strategies for reducing U.S. agricultural carbon emissions or storing carbon in agriculturally managed reservoirs (grass, trees and soil) are summarized in Table 9. Over the short term (20 years), these strategies reduce the atmospheric presence of carbon by about 567 million tons, or an average of nearly 28.4 million tons per year. Over 50 years, the total atmospheric carbon reduction increases to about 1,064 million tons, lowering the average annual carbon emissions reduction to 21.4 million tons.

These figures may not seem significant in the face of total annual net carbon emissions. They represent only about 0.5 percent of global net carbon emissions. Indeed, they represent only about 1.4 to 1.9 percent of U.S.-derived carbon emissions from fossil fuel consumption (Trexler 1991).

Nonetheless, if U.S. agriculture reduced its contribution to net carbon emissions by 28.4 million tons per year, it would have eliminated the equivalent of 85 percent of its own current fossil fuel emissions. That would be a remarkable achievement for any sector of the economy in the industrialized world. Moreover, all of these carbon-related strategies have other environmental benefits, such as soil conservation and reduced toxic waste pollution.

Methane: The Most "Agricultural" Gas

Summary: Animals produce about 15 percent of all methane emissions, most of it from the unique digestive process by which ruminants break down carbohydrates and proteins in grass. Generally, the higher the digestible energy in cattle feed, the lower the rate of methane emissions, especially when the animal is eating well above the amount needed to maintain its weight. All told, methane emissions from the U.S. beef herd are about 3.6 million tons, far less per pound of meat produced than in developing nations where feed quality is lower.

Methane is also produced by manure, primarily when it decomposes anaerobically (in the absence of oxygen, primarily when in water). Water-based waste management systems, especially anaerobic lagoons such as those used in large-scale livestock facilities, are particularly potent methane producers. Overall, beef and dairy cattle and hogs in the U.S. produce about 3.7 million tons of manure methane, nearly half of it from the small percentage of animals raised in large facilities with lagoon waste management systems. We recommend that such facilities be required to reduce methane emissions to levels typical of animals raised on dry waste management systems.

Although atmospheric methane concentration is only now about 1.7 ppm, it has about 58 times the warming effect of carbon dioxide (IPCC 1990a) and it has increased at a rate of about 1 percent per year over the period 1978-89 (Blake and Rowland 1988), currently contributing about 18 percent of the warming effect. Methane concentration doubled in the past 300 years, but with annual emissions now totaling about 605 million tons, or about 44 million tons more than is removed out of the atmosphere naturally (Khalil and Rasmussen 1989), it will double again in the next 60 years (Craig et al. 1988). The concentration has never been more than half the present level (Khalil and Rasmussen 1989).

Methane is, however, relatively shortlived (8-12 years), so measures to reduce emissions can quickly affect concentration levels.

Methane is produced naturally whenever organic matter decomposes in the absence of oxygen (anaerobically), so wetlands, oceans, lakes, tundra and tropical forests are substantial natural producers of methane. Estimates vary widely on the volume of these natural emissions, but 9 of 11 studies summarized by Khalil and Rasmussen (1989) conclude that natural emissions account for less than half of total emissions, and the most recent studies reviewed seem to place natural emissions at closer to one-third of the total. Methane is therefore largely released by human activity.

It is also the most ''agricultural'' of the greenhouse gases. Over one fifth of total global emissions is from rice paddies, (by comparison, about one fourth is produced from natural wetlands), one sixth is from digestive and waste elimination processes of domesticated farm animals, and one-tenth is from biomass burning (Donald Johnson et al. 1991). Nearly half of all methane emissions is from agriculture.

Because our interest centers on Midwestern agriculture, this section addresses primarily the role of livestock, especially ruminants (cattle, sheep, goats, and most other animals that graze on grass) in methane emissions.

Ruminants

Scientists estimate that all animals produce about 88 million tons of methane per year, or about 15 percent of all global methane emissions (Table 10). Of this amount, nearly 81.4 million tons is produced by ruminants (cattle, sheep, goats, buffaloes, and camels), and of that, over 62.7 million tons comes from cattle. Cattle in the developed world produce relatively less methane than those in the developing world because their diet is higher in digestible energy.

Ruminants produce methane naturally as a byproduct of their unique digestive process. Within their ''fore-stomach,'' or rumen, diverse microorganisms break down carbohydrates and proteins in undigested grass which is subsequently regurgitated into the animal's mouth to be chewed and re-swallowed for processing by the rest of its digestive system. This unique feature of the ruminant's digestive system makes it a very special part of the food system. It is uniquely qualified to convert grass into food suitable for human consumption. In the process, however, some of the organic matter in the food ferments. This enteric (intestinal) fermentation produces methane which is released into the atmosphere.

How Much of the Food Energy Fed to a Ruminant is Emitted as Methane?

Overall, about 6 percent of the energy value in feed eaten by a ruminant ends up emitted as methane, although rates can be as low as two percent and as high as 12 percent, depending primarily on the amount and the quality of the feed it eats (Donald Johnson et al. 1991). Generally, if the energy content of the feed is high and the animal is eating more than the amount needed simply to maintain its weight (i.e., it is gaining weight), the percentage of food energy converted to methane is lower than if the animal is eating low-energy feed and only eating enough to maintain its current weight.

In fact, at lower levels of intake[4] -- up to about 2.25 times the level of feed energy necessary to maintain current weight -- the percentage of energy emitted as methane increases as the quality of the feed increases. On the other hand, if the feed intake is more than 2.25 times that needed to maintain weight, the percentage of energy emitted as methane declines as the energy content of the feed increases.

All that means that the rate of methane emissions varies significantly as the animal's diet changes with its age and growth characteristics.

Consider a beef steer raised as a calf on grass until it weighs 500 pounds; then as a stocker calf, it is fed a roughage ration of hay and silage until it weighs about 750 pounds; then it is finished in a feedlot on corn and silage until it weighs 1100 pounds.

As a calf, the animal can only eat enough grass (at roughly 50-60 percent digestible energy) to double its

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[4] Feed intake is measured as the percentage of the feed energy consumed relative to the amount of feed energy required to just maintain the animal's body weight. Since the purpose of domestic livestock production is to produce meat by feeding animals enough to grow and gain weight, most animals are fed twice (200 percent) the amount needed to maintain weight.

Table 10 Global Methane Emission By Animals

Species	Number (1984) (millions)	Daily Methane Output (liters/hd/day)	Global Methane Amount (mil tons)	Global Methane Percent
Cattle in Developed World	603	151	36.4	41
Cattle in Developing World	688	96	26.5	30
Water Buffalo	126	138	6.9	8
Sheep	1,150	14	7.6	9
Goats	460	14	2.5	3
Camels	17	161	1.1	1
Pigs	800	4	1.1	1
Horses/Mules	117	53	1.9	2
Wild Animals	237	?	4.4	5
Total			88.4	100

Source: Adapted from Crutzen et al. (1986) and Lerner et al. (1988) by Donald Johnson et al. (1991).

maintenance level of energy intake per day. It will grow slowly, yielding about 6.5 percent of that energy as methane. As a stocker, the animal's higher quality feed (from 60 to 80 percent digestible energy) will allow it to reach 250 percent of its maintenance level, adding weight faster and emitting 6.3 percent of its feed energy as methane. Then as a feedlot steer, it is fed a rich corn ration at three times the energy intake required to maintain body weight. Its rate of weight gain increases and its methane emission rate drops to about 5.2 percent. Recent analysis suggests that with very high energy diets, cattle on feed in feedlots may yield even less -- only about 3.5 percent -- of the energy they consume as methane (Donald Johnson et al. 1991).

This example is typical of agriculture in the developed world where feed rations are of high quality and plentiful. In the developing world where feed grain is rare and even grass may be scarce, animals consume diets with less digestible energy and may not consume much more than enough to maintain weight. Their methane emission rates may be much higher, and they may require much longer to grow.

Feeding Systems and Methane Emissions

But the total amount of methane actually emitted per animal depends not only on how much of the feed energy it consumes is emitted as methane, but also on the amount of feed it consumes. An animal that merely maintains weight on low energy feed may emit a higher percentage of that feed energy as methane than one that eats three times as much as necessary to maintain weight on the high energy feed, but the first animal may emit less total methane simply because it is eating only one-third as much feed energy. It requires less of a higher quality feed to produce the same level of energy intake as it does to produce that level of intake with a lower quality feed.

Table 11 explores the relationship between level of feed intake and quality of feed as factors in annual methane emissions for an 1100 pound steer.

Notice first that at each level of feed intake, an increase in feed quality means a drop in daily methane emissions. The increase in percent of energy intake emitted as methane is more than offset by a reduction in the amount of the higher quality feed needed to achieve the same level of weight gain. More energy in the diet, less methane emitted per pound of meat produced.

On the other hand, as the level of intake of a particular feed increases, methane emissions increase. For lower quality feeds, the overall emission levels increase rapidly as intake increases, although the intake level never goes above 200 percent because the animals simply cannot eat enough

Table 11 Daily Methane Emissions For Various Feed Regimes

	Level of Energy Intake (1)				
Digestibility	100	150	200	250	300
	(pounds of methane per day per 1100 pound steer)				
50%	.343	.585	*	*	*
60%	.312	.513	.706	*	*
70%	#	.464	.614	.741	*
80%	#	#	.548	.634	.686
90%	#	#	.495^	.554^	.567^

(1) 100 equals the amount of intake necessary to maintain weight; 150 means the animal is consuming 50 percent more energy than necessary to simply maintain weight.

* An animal could not eat enough of this quality feed on a given day to achieve energy intake equal to this percentage of maintenance requirement.

\# As a practical matter, feeds of this quality are not usually fed at such low levels of feed intake.

^ It is very difficult to achieve a diet composed of 90% digestible energy.

Source: EPA 1989

volume of grass or low quality forage to reach such a high level of energy intake. For higher quality feeds, the total methane emissions increase much more slowly as intake increases because the animals convert more of the feed increase into meat.

So, for example, if the steer consumes twice as much of a moderate quality feed (70 percent digestibility, typical of a good quality forage or corn silage) as necessary to maintain its body weight, it will emit 0.614 pounds of methane per day. But if it is fed two-and-a-half times maintenance level with the same feed, it will emit 0.741 pounds of methane per day. With higher quality feed (80 percent digestible, with more corn), the animal will emit only 0.634 pounds of methane in a day at 2.5 times maintenance level of feed intake. Bump the intake up to 3 times maintenance level, and the daily emission jumps to 0.686 pounds.

Of course, as feed intake increases, the animal is gaining more weight per day, that is, producing more pounds of meat in less time. In this case, efficiency is generally on the side of environment. For the energy that is converted to methane in a ruminant's digestive system would otherwise be available to convert into meat or milk (or draft power in the Developing World). The bottom line is, therefore, how much meat will the animal produce per pound of methane it emits to the atmosphere over its lifetime under various feeding and management schemes?

How Much Digestive Methane is Produced in a Pound of Beef?

Table 12 estimates the lifetime digestive methane emissions of a steer raised and fed for beef production, assuming it is raised on grass as a calf for 210 days until it weighs 500 pounds, fed harvested forage and silage as a stocker-feeder another 150 days and then finished on a high-corn ration to either select (95 days) or choice (130 days) grade.

Most of the estimated emissions occur at the stocker stage of production because the animal is being fed for 150 days at high energy intake levels (at least 2.5 times maintenance) with a ration that is only moderately high in digestible energy (60-80 percent). This ration helps the animal build up its bone and body structure, preparing it for the rapid meat production made possible by an energy-rich diet of corn in the feedlot. At the feedlot stage, which lasts only about 95-130 days (depending on the grade level the producer is trying to attain), the animal's intake level is very high (about triple maintenance) and its diet very high in digestible energy (85 percent). Total methane emission for

Table 12 Lifetime Methane Emissions From Slaughter Steer

Stage	No. Days	Methane Yield (1)	Pounds Methane Emitted/Day	Total Emissions (pounds)
Calf	210	6.0	.08	17.6
Stocker	150	6.5	.32	48.0
Feeder				
Select	95	3.5	.24	23.1
Choice	130	3.5	.24	31.5
Total				
Select			.64	88.7
Choice			.64	97.0

(1) Percentage of dietary energy intake emitted as methane.

Source: Compiled from data in Donald Johnson et al., 1991.

the animal is between 88.7 and 97.0 pounds, depending on grade.

The difference in methane emissions between animals that grade "select" and those that grade "choice" is significant. Cattle that grade choice are fed the same as those that grade select at all stages of production, but are left in the feedlot for about 35 days longer than those that grade select. That generates about 8.4 more pounds of methane, or about 9.4 percent more than emitted by the select grade cattle. However, they yield about 8 percent more retail meat, so on a per unit of production basis, the difference in methane yield is not large.[5]

That is not the whole story, however. To determine the total methane emissions per pound of retail beef, we must factor in the methane emissions embodied in the breeding stock that produced the calf (Table 13). Assuming a cow is bred for the first time at 15 months of age, bears her first calf at two years of age, and produces five more calves over the next five and a half years, she will embody about 170.7 pounds of atmospheric methane emissions in each of her calves. If the bull sires his first calf at one year and sires 85 calves over the next five years, he will embody about 13.6 pounds of methane emissions in each calf.

The cow and bull together emit about 184.4 pounds for each calf they produce. This is about double the methane emissions derived directly from the animal itself.

The embodied and direct emissions together total 281.4 pounds (184.4 embodied plus 97.0 direct) for a choice grade steer. If that choice steer weighs 1,125 pounds and yields 473 pounds of beef to the consumer, the total methane emissions is estimated at 0.59 pounds per pound of retail beef (Table 14). For the select grade steer weighing 1,040 lbs, the total emissions is 273.0 pounds (184.4 embodied, 88.7 direct) and the emissions per retail pound is 0.62 pounds. Per-pound emissions for the select grade steer are actually a little higher than for the choice because the embodied emissions are the same for both animals, but the choice steer produces more meat.

There were 25.9 million cattle slaughtered for human consumption in the U.S. in 1989 (excluding cows and bulls which have already been accounted for in the methane emissions embodied in their calves). Methane emissions from the entire beef herd then is estimated at 3.6 million tons.[6] That is well under one percent of annual global methane emissions (605 million tons), but about 8 percent of the net annual increase in global atmospheric methane (44 million tons).

Americans also eat imported beef. This beef probably has higher emission rates because imported beef comes from cattle generally fed less corn. But, if the emissions rates for these cattle are the same as they are for cattle produced domestically, the average American who eats 64 pounds of retail boneless beef per year (from both foreign and domestic sources) contributes 38.7 pounds of atmospheric methane. Collectively, U.S. consumers contribute over 4.4 million tons of methane from beef consumption.

Methane From Manure[7]

The foregoing analysis considers only methane produced in the digestive tract of animals through enteric fermentation. It does not take into consideration methane emissions from the decomposition of manure. Scientists have given this issue relatively little attention.

But the potential magnitude of the problem is serious. Both ruminants and non-ruminants such as swine contribute to manure methane emissions. It has been estimated that theoretically, as much as 183.7 million tons of methane could be emitted per year from animal waste globally (Safley 1989). That is double the amount emitted from the digestive tract of ruminants.

The key variables in determining the amount of methane emitted from manure are (1) the waste characteristics of the animal species, (2) the animal's diet, and (3) the manner in which the manure is disposed of by the farm operator. The species and the animal's diet are the leading factors in determining the **potential** methane emissions from manure; the way the manure is handled is the key factor in determining how much of the potential methane is actually emitted.

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5. The two products are not identical, of course, nutritionally or environmentally. Because select grade involves less corn feeding, it is leaner and emboddies less fossil fuel energy consumption and fewer CO2 and N2O emissions.

6. This slightly overstates methane emission related to beef consumption because some of these emissions should be attributed to milk production from cows whose calves were raised and slaughtered for meat. In this analysis, we attribute it to the beef produced by their calves by considering the cow's emissions to be "embodied" in her calves.

7. This section depends heavily on the comprehensive treatment of this issue by Casada and Safley (draft 1990).

Table 13 Emissions Embodied in Slaughter Steer From Breeding Stock

Stage	No. Days	Methane Yield(1)(2)	Pounds Methane Emitted/Day(2)	Total Emissions (Pounds)
A. Cow				
1. Calf	210	6.0	.08	17.6
2. Stocker	150	6.5	.32	48.0
3. Replacement	365	6.5	.35	126.9
4. Reproductive	2,000	6.2	.42	831.6
Total Emissions, Cow				1,024.1
Emission Per Calf (6 calves)				170.7
B. Bull				
1. Calf	210	6.0	38	17.6
2. Stocker	150	6.5	145	48.0
3. Reproductive	1,825	6.0	274	1,100.2
Total Emission, Bull				1,165.8
Emission Per Calf (85 calves)				13.6

Total Embodied Methane Emission Per Calf

	Pounds Methane
From Cow	170.7
From Bull	13.6
Total	184.4

(1) Percentage of dietary energy intake emitted as methane.
(2) Source: Donald Johnson et al., 1991.

Table 14 Methane Emission Per Pound Retail Beef

	Pounds Methane
1. Breeding Stock Emission Embodied in Calf	184.6
2. Slaughter Steer Lifetime Emissions (Choice grade)	97.0
3. Total	281.4

Pounds of Retail Beef in 1,125 lb. Choice Grade Steer: 473 lbs.
(1,125 live weight x .63 = 709 lbs. carcass weight x .667 = 473 lbs. retail boneless weight)

Total Emissions Per Pound Retail Beef: .59 pounds (281.4 lb per 473 lbs.)

Potential Manure Methane Emission

The potential for methane emissions from manure depends on how much of the manure constitutes "volatile solids," or organic matter (Table 15). Dairy cattle, swine, and broilers all produce more manure per unit of body weight than other farm animals, but there is proportionally more organic matter in the manure from broilers and sheep than from other species, and broilers produce significantly more waste organic matter per unit of body weight than other species. The amount of potential methane emitted from this organic matter varies by species as well, from a low for young cattle (.37 cubic meters per pound organic matter) to a high for fat hogs (1.0 cubic meeter per pound of organic matter).

Beyond these basic genetic characteristics of species, potential manure emissions also depend on diet. Here, there is somewhat of a trade-off between the digestive methane yield and the manure methane yield. That is, as we saw in the previous section, at high feed intake levels, increases in the digestible energy in feed produce decreases in methane emission rates in the digestive process. But the opposite is generally true of methane emissions from manure: As the digestible energy in the diet increases, methane emissions from manure increase.

For example, in ten experiments, steers fed a high-energy ration of flaked corn (85 percent), chopped alfalfa (11 percent) and mineral supplement (4 percent) produced manure which emitted four to 17 times as much methane as steers fed a straight forage of chopped grass (Lodman et al. 1990a).

Likewise, Hashimoto et al. (1981) found that a corn silage feed ration would potentially produce one-half as much methane per pound of beef manure as a high energy corn ration. Blending as little as 7 percent corn silage with a corn ration would reduce the methane emissions from manure by 12 percent.

For dairy animals, potential manure methane appears to decline as digestible energy declines. Animals fed 58-68 percent silage would potentially produce .173 pounds of methane per pound of manure (Morris 1976). Feeding 72 percent roughage instead (lowering digestible energy) would lower potential methane production to .122 pounds of methane per pound of manure (Bryant et al. 1976). And feeding poor quality roughage (even lower digestible energy) would lower potential methane to .072 pounds per pound of manure (Chen 1988).

Managing Waste Makes A Difference

Whether the manure's potential for methane emissions is actually realized depends largely on management decisions about how the waste is handled and the extent to which it is allowed to decompose in the absence of oxygen. If it decomposes under water or in moist conditions, it will be exposed to little or no oxygen (anaerobic decomposition) and it will produce much more methane. The estimate that livestock and poultry manures could potentially produce up

Table 15 Methane Potential in the Manures of Farm Animals

Species	Lb Manure/Day Per 1000 lb Animal Mass	Percent of Manure as Organic Matter	Lb Org. Matter Per 1000 lb Animal Mass	Cubic Meter Methane/lb Org. Matter
Beef Cattle	58	12.4	7.2	.08-.15
Dairy Cattle	86	11.6	10.0	.11
Swine	84	10.1	8.5	.16-.21
Layer Hen	64	18.8	12.0	.15
Broiler	85	20.0	17.0	.14
Sheep	40	23.0	9.2	.09-.16

Source: Taiganides and Stroshine, 1971, Hashimoto 1981, Morris 1976, Summers and Bousfield 1980, Chen 1983, Hill 1982 and 1984, all as reported in Casada and Safley, 1990 draft.

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8. These studies were summarized by Casada and Safley, draft 1990.

to 183.7 million tons of methane per year assumes that all the manures decomposed anaerobically (Safley 1989).

But most manure, both in the United States and globally, is left to dry and decompose in the open air, either in the pasture where it falls or on fields where it is spread after being gathered from drylots or livestock housing facilities. Generally, if manure decomposes in the open air, the proportion of potential manure that is actually produced and emitted to the atmosphere falls to about 10 percent or less. One estimate is that actual manure methane emissions worldwide are less than 15 million tons per year (Verma et al. 1988).

However, in the United States and other developed nations there is a trend toward mechanized handling of manure from large-scale confinement livestock facilities. These mechanized systems frequently depend on diluting the manure with water for easier movement, and on anaerobic decomposition in pits or lagoons. These systems produce significantly more of the potential methane production than the more traditional dry systems.

In fact, a lagoon system typical of large-scale hog confinement systems that increasingly dominate U.S. hog production will cover the manure in a lagoon with at least six feet of water. Such systems will produce up to 90 percent of the potential methane in the organic matter of this manure.[9] Other slurry or pit systems in which the manure is only temporarily stored in less water until taken to the field for spreading might yield from 10 to 20 percent of the potential methane.

Climate can also affect the potential methane emissions. Generally, colder, drier conditions will reduce potential emissions, provided such factors are not overcome by management practices that introduce moisture to the decomposition process.

Estimates of U.S. Manure Methane Emissions

Casada and Safley (1990) have estimated global and U.S. manure methane emissions by species, type of waste management system, and state. They conclude that worldwide, about 31.1 million tons per year is emitted, of which 4.3 million tons comes from U.S. livestock and another 12.9 million tons from Canada and Europe. In other words, over half comes from the developed world.

Among species, beef cattle lead manure methane emissions with 10.3 million tons per year, followed by dairy cattle (6.5 million tons/yr) and swine (6.4 million tons/yr). Together, these three types of animals emit about three fourths of the manure methane globally. Within the U.S., 1.5 million tons of methane is emitted by beef cattle, 1.1 by dairy, and 1.2 by swine, and together, these three leading farm animals emit about 90 percent (3.8 of the 4.3 million tons) of U.S. manure methane emissions.

These estimates from Casada and Safley (1990) are not undisputed. Assuming lower emissions yields from beef cattle manure in pasture and drylots, Lodman et al. (1990b) estimated that U.S. methane emissions from cattle is only 0.68 million tons per year, about one-half of the estimate by Casada and Safley. These estimates are all very rough and preliminary.

But of these emissions, we can be confident that a disproportional amount comes from liquid waste management systems. Overall, Casada and Safley (1990) estimate that 11.1 million tons (35 percent) of the 31.1 million tons of global manure methane emissions comes from either anaerobic lagoons or liquid/slurry storage systems, and 9.0 million tons of that is produced in Europe and North America. Thus, while Europe and North America have about 35 percent of the world's livestock, they produce over half the manure methane emissions.

In the U.S., for example, only 28 percent of the hogs and pigs are kept in facilities in which waste is handled by anaerobic lagoons, but those lagoons emit 73 percent of the swine manure methane. Only 11 percent of the dairy cattle and a scant 1 percent of the beef cattle are on lagoon systems, but they emit 60 and 6 percent of the manure methane from those species respectively (Table 16). Overall, nearly half (about 1.7 of 3.7 mil tons) of the manure methane emissions from cattle and hogs in the U.S. come from anaerobic lagoon waste management systems.

Geographic Variation and Waste Management Technology

Because the livestock confinement systems that employ mechanized liquid manure handling systems have also helped redefine traditional production zones for livestock, especially dairy and swine, methane emissions vary considerably by geographic region even within the same species.

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[9] Some portion of the methane emissions may be reoxidized at or near the surface of these lagoons as the methane releases into the air.

Table 16 U.S. Waste Management System

	Anaerobic Lagoon			Liquid/Slurry/Pits			Dry Systems (1)			Total	
		Methane			Methane			Methane		Methane	
Species	% Pop	Mil Tons	%	% Pop	Mil Tons	%	% Pop	Mil Tons	%	Mil Tons	%
Beef Cattle	1	0.08	6	0	0.00	0	99	1.28	94	1.36	100
Dairy Cattle	11	0.34	60	21	0.13	23	65	0.10	17	0.57	100
Swine	28	1.28	73	43	0.34	20	29	0.12	7	1.74	100
Total		1.70			0.47			1.50		3.67	100

(1) Includes pasture, range, drylots, solid storage, daily spread, and other non-water based systems.

Table 17 Leading States, Livestock Methane Emissions

		Methane Emissions (tons)	Methane (tons) Anaerobic Lagoon	Percent Anaerobic Lagoon	Leading Species	Emission(tons) from Leading Species	Methane (tons) Per 1,000 Head		
							Beef	Dairy	Swine
1	TX	351,912	65,541	19	Beef	230,868	17.3	141.4	25.6
2	CA	333,947	223,738	67	Dairy	248,686	14.9	164.7	51.2
3	MO	282,717	203,288	72	Swine	133,718	16.9	222.2	47.0
4	IA	250,542	28,386	11	Swine	150,763	15.8	55.7	10.9
5	NE	206,525	81,495	39	Swine	92,622	19.9	40.3	22.9
6	IL	171,217	87,963	51	Swine	119,442	19.0	52.3	21.3
7	KS	153,528	38,770	25	Beef	110,910	19.1	43.7	22.2
8	NC	151,670	112,025	74	Swine	107,100	16.4	60.1	39.7
9	IN	145,220	70,627	49	Swine	95,841	17.8	90.6	22.3
10	MN	135,312	0	0	Dairy	51,027	14.5	43.3	9.2

The ten states that emit the most manure methane are identified in Table 17. Of the ten, only two -- No 1. Texas and No. 7 Kansas -- produce more methane from beef than any other species. In each case, this reflects the large number of cattle in these states, not waste management practices.

Swine produce most of the manure methane in six of the other leading states, but the methane produced varies from a low of 10.9 tons per 1000 head of hogs in Iowa, where anaerobic lagoons are rare, to 39.7 tons per 1000 head in North Carolina where they are common among that state's rapidly growing large-scale hog confinement units. In the two states where dairy cattle are the principle contributors to manure methane emissions, the variation is also great. In Minnesota, a traditional dairy state with smaller herds and more labor intensive waste management systems, methane yield is 43.3 tons per 1000 head, while in California, where herds are larger and waste management is more capital-intensive and water-based, manure methane emissions are 164.7 tons per 1000 head.

The impact of waste management technology is also evident among the leading states in production of each species. Among the ten leading hog producing states, the percentage of waste treatment by anaerobic lagoon varies from a low of 3 percent in Iowa to 70 percent in North Carolina, and the methane emissions vary from 320 pounds of methane per ton of live animal mass in Iowa to 1,195 pounds of methane per ton of live animal in North Carolina (Table 18). In other words, Iowa produces only 27 percent as much atmospheric manure methane per pound of pork it produces as does North Carolina.

A similar situation exists with respect to milk production. In four leading traditional states (Wisconsin, Minnesota, New York, and Pennsylvania), lagoon systems are for all practical purposes absent, and manure methane emissions run from one eighth to one fourth as high per unit of animal mass as they do in California, where 40 percent of the dairy herd is kept in facilities that use lagoons. California alone emits more manure methane from its dairy herd than the other four leading dairy states combined (Table 19).

Strategies to Reduce Methane Emissions from Livestock

The U.S. Environmental Protection Agency convened a group of scientists to examine the issue of methane emissions from livestock and to suggest ways of reducing those emissions (Gibbs et al. 1989). Here are some of their major recommendations:

1. Adopt feeding practices that minimize methane emissions without sacrificing animal productivity.
2. Increase rate of gain and feed conversion efficiency with hormones.
3. Increase the feed efficiency of male meat animals by foregoing castration.
4. Modify the meat grading system to encourage less fat, reducing slaughter weights and feeding time.
5. Develop methane digesters to capture emissions from anaerobic lagoons, using the methane to generate electricity.
6. Develop genetically engineered bacteria to pre-treat feed, modifying the bacterial activity in the rumen and reducing methane yield.

Table 18 Impact of Waste Technology on Annual Methane Emissions, Swine

State	Animal Mass (tons)	Percent of Animal Mass on Ana. Lagoon	Methane Tons/yr	Methane Pounds/Ton Mass
IA	941,897	3	150,763	320
IL	391,600	25	119,442	610
MN	324,858	0	45,873	282
IN	300,850	25	95,841	637
NE	272,426	35	92,622	680
MO	206,228	80*	133,718*	1,297*
NC	179,218	70	107,100	1,195
OH	154,457	37	60,059	778
SD	123,054	20	30,776	500
KS	101,223	30	33,253	657
U.S.	3,818,153	28	1,237,588	648

* not reliable

Table 19 Impact of Waste Technology on Annual Methane Emissions, Dairy

	Animal Mass (tons)	% of Animal Mass on Ana. Lagoon	MCF	Methane ton/yr.	Methane Pounds/ton Mass
Dairy					
WI	1,717,782	0	.08	79,724	93
CA	1,020,646	40	.48	248,686	487
MN	799,612	0	.11	51,027	128
NY	761,614	0	.09	37,556	99
PA	689,656	0	.06	21,805	63
U.S.	9,840,980	11		1,114,771	227

7. Develop methane inhibitors as feed additives.
8. Improve reproductive efficiency of breeding stock to reduce the size of the herd needed to produce animals for slaughter.
9. Breed animals that are low methane producers.

These options build primarily on the possibility of improving animal productivity at the same time as reducing methane emissions. They relate only to reductions in methane emissions, however, and do not consider any net effect such changes would have on emissions of other greenhouse gases or on other environmental aspects of agriculture.

Moreover, these recommendations primarily address ruminant feeding practices rather than changes in livestock manure management. They seem to assume that the trend toward housing livestock in intensive facilities is irreversible. This reflects an unjustified preoccupation with ruminant emission levels to the near exclusion of concern over manure emissions.

This is unfortunate because both management trends and economic factors should place greater emphasis on manure. Increasing feed efficiency in ruminants is compatible with attempts to reduce emissions. Farmers therefore have an incentive to reduce emission levels. However, there is a conflict between attempts to mechanize waste management by using water based systems, especially anaerobic lagoons, and efforts to reduce methane emissions. Industry trends in ruminant nutrition therefore generally reduce emissions, while industry trends in waste management clearly exacerbate the problem.

This situation varies considerably by species. All cattle are high emitters digestively, but dairy cattle are far more likely to be kept in facilities involving water-based management systems, and swine are even more likely to be kept in such facilities. Swine is also the species undergoing the fastest change in waste management practice. And while improved breeding and feed efficiency and reduced beef consumption have shrunk the cattle herd in the U.S. by over 25 percent since 1975, the number of hogs in confined buildings with water based waste management systems has grown dramatically.

As a result of these trends, livestock manure is now a bigger source of methane emissions than ruminant digestion in U.S. agriculture, and if current trends continue, the gap between these two sources of emissions will widen. We therefore place a higher priority on methane emission from manure waste management systems. Methane from lagoon systems can be captured and used for beneficial uses, especially as a source of energy. The technology for doing so is available, though not necessarily at competitive costs.

This is the clearest instance we are aware of, in which the steps required to mitigate agriculture's contribution to greenhouse gas emissions may be adverse to the economic interests of producers. However, in this instance, the producers involved are deliberately selecting a management technology that will significantly increase emissions. It is still early in this trend, a minority of animals has been placed in facilities using anaerobic lagoons, and an even smaller minority of producers has such facilities. Generally, these are larger scale producers making new, capital-intensive investments in modern swine and dairy facilities.

We therefore recommend that producers using anaerobic lagoons be required to reduce methane emissions from those facilities to levels that approximate those for animals in dry systems. Under ordinary management, water-based facilities emit about 90 percent of their potential manure methane. Under the proposed policy, they would emit no more than 10 percent of their potential. The management options include capturing the methane and using it to generate electricity, aerating the lagoons to reduce anaerobic digestion and methane production, and replacing water based management systems with dry systems.

If this level of emission control is achieved, emissions would drop by about 1.4 mil tons per year, or by about 3 percent of the global net annual increase in atmospheric levels.

Nitrous Oxide: Wasted Fertilizer

Summary: Nitrogen fertilizer is a major source of nitrous oxide emissions and North American (principally U.S.) agriculture contributes from about one-third to one-half of the global fertilizer-derived emissions of nitrous oxide. The U.S. share is so high not only because we use more nitrogen on more acres, but also because we use a disproportionate amount of anhydrous ammonia, which has a high emission rate (about 2.7 percent compared with other types which run from 0.07 to .44 percent). As a result, the U.S. emissions are about three to four times our share of total nitrogen fertilizer use.

U.S. emissions could be reduced by roughly one-fourth through improved nitrogen fertilizer management (without loss of yield), by another 10 percent through better manure management, and by another 8 percent through improved cropping rotations. These steps would reduce nitrogen fertilizer-derived emissions by a total of 40-45 percent below current levels in the short term. These goals can be accomplished by expansion of the Integrated Farm Management Program and a tax on nitrogen fertilizer (particularly anhydrous ammonia) which would fund a nitrogen management program to help farmers achieve management objectives.

Nitrous oxide is a particularly potent greenhouse gas which has over 200 times the warming effect of carbon dioxide and lasts 150 years in the atmosphere. Over the past century, nitrous oxide has increased by only about .02 parts per million (ppm) to .310 ppm. During that period, it has contributed only about three percent of the global warming. Nonetheless, it is now increasing at a rate of about .00075 ppm per year, and it is projected to reach .340 ppm by the year 2030. (U.S. Congress 1991).

Nitrous oxide is one of the least well understood of the greenhouse gases. When the Intergovernmental Panel on Climate Change analyzed the global warming problem, it concluded that given the known increases in nitrous oxide in the atmosphere, emission must equal from 11 to 19.3 million tons of nitrogen per year. But the IPCC could only account for from 4.8 to 11.6 tons from estimates of known sources (U.S. Congress 1991). This "emission gap" is considered to be caused by human activity and underscores the uncertainty associated with this particular trace gas.

The principal source of nitrous oxide is probably natural processes in the soil, accounting for perhaps as much as one-half of total emissions (U.S. EPA 1990). Another 15 percent or so is naturally produced from bodies of water. The rest is a result of human activity, principally fossil fuel burning, biomass burning, land clearing which increases emission from soil, and fertilizers. While fertilizer emissions might be a relatively small portion of the total, it is the portion that American agriculture might best reduce.

Nitrous Oxide Emissions From Soil and Natural Fertilizers

Unfertilized soil will emit nitrous oxide naturally. Studies to determine fertilizer-derived emissions have attempted to measure this baseline of "natural" emissions as a means of determining how much of the total emissions from fertilized fields can be attributed to the fertilizer. These studies (summarized by Eichner 1990) indicate that natural emissions range from 0.125 to 3.5 lbs per acre per year, and average about 1.09. A survey of Iowa soils never fertilized found that nitrous oxide emissions did not exceed 0.45 lbs per acre.

There have been very few studies of nitrous oxide emissions from legumes (which naturally remove nitrogen from the atmosphere and deposit it in the soil) and manure, a common fertilizer. One study (Bremner et al. 1980) found that soybean fields emit from 0.47 to 2.76 lbs per acre. Another (Duxbury 1984) found that samples from an alfalfa field yielded from 2.76 to 6.43 lbs of nitrous oxide per acre, while samples from a pasture of timothy grass (heavily weeded) emitted from 0.98 to 2.66 lbs per acre. Neither of these studies measured the baseline of natural emissions from the same fields without legumes. The natural emissions might reduce the legume-derived emissions in each of these instances by about 0.7 to 1.1 lbs per acre.

There has been even less effort to measure emissions from manure. Potentially, manure will increase nitrous oxide emissions because unlike commercial fertilizer, manure has high levels of soluble carbon which provides a source of energy for the microorganisms that produce nitrous oxides.

Duxbury and Bouldin (1982) found more nitrous oxide emitted from manured fields than from corn fields fertilized with urea and ammonium nitrate (4.1 versus 3.1 lbs per acre in one trial, and 5.3 versus 4.1 lbs per acre in another). But the rates of application in this study seem inappropriate. The fertilizer was applied at a modest rate of 117.5 lbs per acre while the manure was applied at an impracticably high rate of 20 tons per acre. Cates and Keeney (1987) found emission rates of 4.6 and 6.8 lbs per acre (after subtracting the natural emission rates from unfertilized fields) from the application of manure in combination with ammonium nitrate and with ammonium nitrate and urea.

This scant evidence indicates that any effort to enhance yields by adding nitrogen to the soil -- whether by rotating legumes, spreading manure, or applying fertilizer -- will require management to avoid nitrous oxide emissions.

Fertilizer Emissions

In the United States, commercial fertilizer is so widely used that any effort to address nitrous oxide emissions must begin with an analysis of fertilizer emission rates.

Soils emit nitrous oxide naturally at widely varying rates, but fertilizing land with nitrogen adds significantly to emissions. One Iowa study found emissions from unfertilized farmland averaged 0.71 lbs per acre, but similar land fertilized had emissions averaging 3.96 lbs per acre, five and a half times as much (Breitenbeck and Bremner 1986a).

Estimates vary widely on the total amount of nitrous oxide derived from fertilizer in the world, from as low as .01 to as high as 2.4 million tons per year, or from 10 to 80 percent of all emissions from human sources (IPCC 1990a).

There are several factors affecting the rate of nitrous oxide emissions from fertilizer, including the amount of nitrogen fertilizer applied, the moisture level of the soil, the depth at which the fertilizer is applied in the soil, and the kind of nitrogen fertilizer used.

Nitrous oxide emissions are strongest when soils are wet. That's because some nitrous oxide is produced by bacteria that function anaerobically, in the absence of oxygen (Anderson and Levine 1987). Under a hotter and drier climate, nitrous oxide emissions produced anaerobically might be reduced.

But nitrous oxide is also produced by aerobic digestion, and generally, the more nitrogen applied, the greater the nitrous oxide emissions produced by this method (see Figure 4). Total emissions increased from 1.71 to 5.73 lbs per acre of nitrous oxide[10] as application of anhydrous ammonia (at 20 centimeters) increased from 67 to 400 lbs of nitrogen per acre, although the rate of emission ***per pound of nitrogen applied*** fell from 1.6 to .9 percent. For other fertilizers that were broadcast and subsequently incorporated into the soil, however, both the rate of emission per pound of nitrogen applied and the total emissions increased as the rate of application increased (Breitenbeck and Bremner 1986b).

Also, when 246 lbs of nitrogen per acre (applied as anhydrous ammonia) was injected at a depth of 12 inches (roughly 50 percent deeper than most farmers inject anhydrous, except on light soils), emission rates were 21 percent higher than when the same amount of anhydrous was injected at the more standard depth of 8 inches, and 107 percent higher than when injected at 4 inches.

The timing of the application is important. Emissions may be as much as three times greater when fertilizer is applied in the fall than when applied in the spring. Because of such nutrient losses, fall fertilizing has long been frowned upon by agronomists. It became more popular when fertilizer additives inhibiting nitrification losses were introduced. With such inhibitors, nitrous oxide emissions were reduced 63 percent (Bremner et al. 1981). However, although these improvements made fall fertilizing relatively more attractive, nitrous oxide emissions were still 19 percent higher from fall applications with inhibitors than from spring application without inhibitors (Bremner et al. 1981).

But importantly, not all fertilizers are equal in emission of nitrous oxide. Table 20 shows emission rates (above the natural emission rates of the soil itself) for various groupings of nitrogen fertilizers commonly used throughout the world. The figures in Table 20 are based on a summation by Eichner (1990) of 24 scientific studies involving 104 experiments at nine locations in five countries (all, like the U.S., in the temperate zone), and some were excluded from the summary analysis because they involved application rates considered well in excess of commercial standards, or involved mixed fertilizers, manures, or green manures. The 24 studies vary widely in their emission findings, but the summary findings in Table 20 nonetheless suggest a significant difference by type of fertilizer.

According to these results, anhydrous ammonia delivers 2.7% of its nitrogen to the atmosphere in nitrous oxide, from

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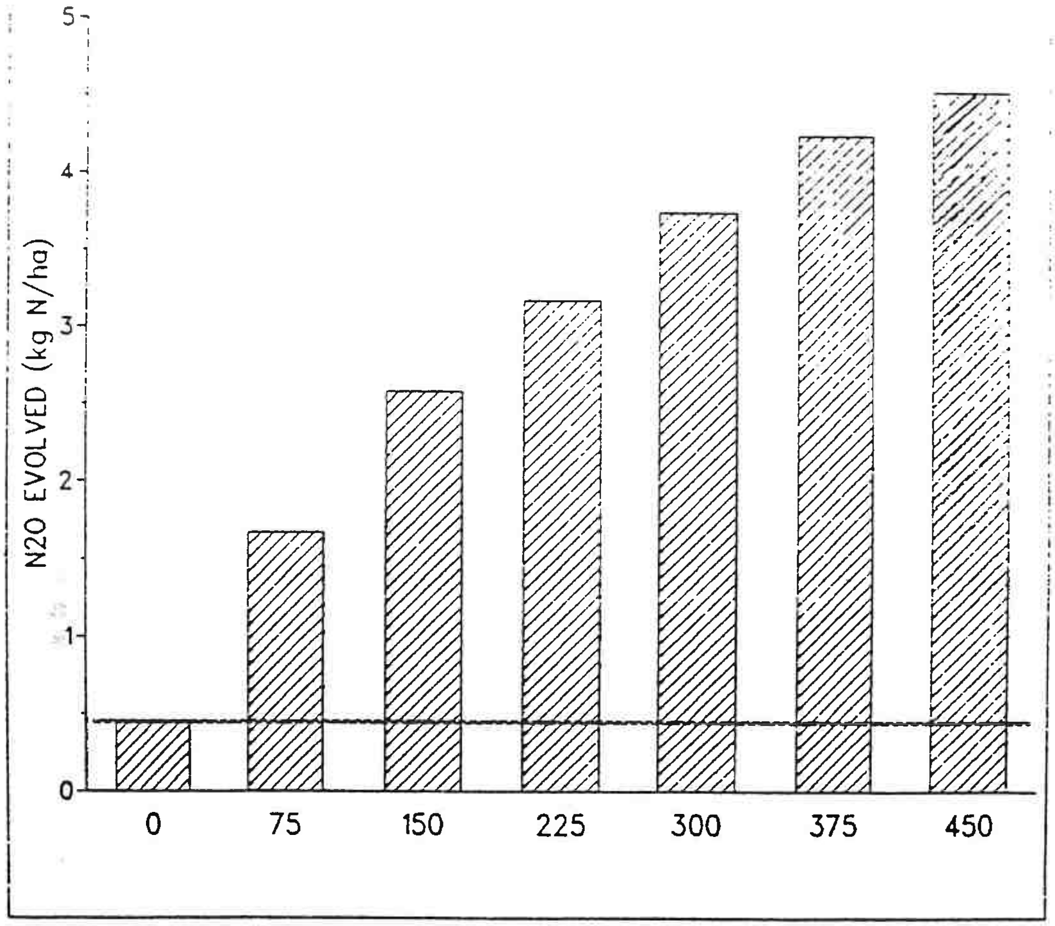
[10] Or, 1.92 to 6.43 kg/ha of N_2O. Nitrogen constitutes 36 percent of the total weight of N_2O.

Figure 4. Effects of Various Rates of Anhydrous Ammonia Fertilization on Nitrous Oxide Emissions



Source: USEPA 1990

Table 20 Nitrous Oxide Emission by Type of Nitrogen Fertilizer

Fertilizer Type	Average Percent of N Fertilizer Emitted as N_2O	Daily Average N_2O Emissions Per Acre (grams)	Daily Avg. N_2O Emissions per lb N Applied/Acre (milligrams)	Ratio of Total Emissions to Natural Emissions
AA	2.70	0.98	58.0	6.1
AN	0.44	0.10	11.6	2.5
A	0.25	0.10	12.8	1.4
U	0.11	0.04	3.1	1.5
N	0.07	0.03	4.4	1.1

Note: AA = anhydrous ammonia; AN = ammonium nitrate; A = ammonium type, ammonium chloride, ammonium sulfate; U = urea; N = calcium nitrate, potassium nitrate, sodium nitrate.

Source: Eichner 1990.

6 to 38 times as high as the rate of the other nitrogen fertilizers. Its daily emission rates range from 10 to 30 times that of others, regardless of the amount applied, and its daily emissions per pound of nitrogen applied range from 5 to 13 times that of the others. Ammonium nitrate and other ammonium based fertilizers are the next worse emitters.

The anhydrous and urea emissions in Table 20 may be high because those studies primarily involved application of fertilizer to bare soil prior to planting, a condition which invites emissions. Studies of the other fertilizers frequently involved application on grass, small grains, or growing crops. Nonetheless, in real farming situations, most anhydrous and urea are, in fact, applied to bare soil or to row crops in early stages before the plants cover the ground, and most emissions occur prior to significant crop growth. Moreover, anhydrous at least is applied in a "band" (it is injected into the ground under pressure in narrow strips,), a method which may contribute to increased nitrous oxide emissions. In fact, the ultimate emission levels of anhydrous and urea are determined by these farm management and agronomic realities, and they are best evaluated on those terms.

Fertilizer Use and Emissions by Region

Globally, about 88.8 million tons of nitrogen was projected by USDA to have been applied as fertilizer in 1990. The U.S. was projected to consume about 11 million tons of nitrogen, or about 12.5 percent of the global total. Of this, USDA estimates that nearly 40 percent (or five percent of the global total) was consumed in seven states in the western Corn Belt and eastern Great Plains (Illinois, Iowa. Kansas, Minnesota, Missouri, Nebraska, and South Dakota). the main grain producing region (USDA 1991).

Since anhydrous ammonia is the most demanded source of nitrogen fertilizer in the U.S., these data suggest that U.S. agriculture contributes a substantial share of nitrous oxide emissions. Data from the Food and Agriculture Organization was assembled by the U.S. Environmental Protection Agency (EPA) to describe fertilizer use in the regions of the world by type of fertilizer for 1984 (U.S. EPA 1990). By assigning emission rates (from Eichner 1990) for each type of fertilizer according to each region's level of use, we can estimate each region's contribution to global nitrous oxide emissions.

These results are presented in Table 21. Under this

Table 21 Global Consumption and Emissions of Fertilizer-Derived Nitrous Oxide (Eichner Coefficients)

Type Fertilizer	Emission Rate	Africa	Latin America	North America	Asia	Western Europe	CPE	Oceana	Total Use	N_2O Emissions
				--- million tons ---						
Anhydrous Ammonia	0.027	0	0.22	9.79	0.22	0.33	0.22	0	10.78	0.457
Urea	0.0011	0.55	1.65	1.76	20.24	0.88	2.97	0.11	28.16	0.049
Ammonia Nitrate	0.0044	0.44	0.22	0.88	1.10	5.17	12.10	0	19.91	0.138
Other Ammonias	0.0025	0.11	0.88	0.44	5.06	0.55	0.88	0.22	8.14	0.032
Other Nitrates	0.0007	0	0	0	0.11	0.22	0	0	0.33	*
Other Complex	0.027	0.77	0.33	0	3.96	3.74	0.77	0	9.57	0.406
Total Consumption		1.87	3.3	12.87	30.69	10.89	16.94	0.33	76.89	
Total N_2O Emissions		0.024	0.020	0.271	0.153	0.135	0.085	0.001		1.082
Percent of Total Emissions		3.4	2.9	39.4	22.2	19.6	12.4	0.1		100.0

* less than .0005

analysis, global fertilizer-derived emissions of nitrous oxide totaled 1.08 million tons in 1984, and North America contributed 0.43 million tons, or 39 percent (of which most -- about 33 percent -- is from the U.S.). That is about two-and-a-half times the region's proportionate share of nitrogen fertilizer use. The disproportion is due to the heavy reliance in North America on the most polluting fertilizer, anhydrous ammonia.

This analysis is crude because of the considerable uncertainty regarding actual emission rates. It is especially unclear what emission coefficient should be assigned to a fertilizer category that EPA terms "other complex." Since this category accounts for 12.5 percent of global usage, its emission coefficient is important to this analysis. EPA assumed that the "other complex" category would have emission rates equal to the highest emission category, that for anhydrous ammonia.

Since the fertilizers in the "other complex" category are used primarily in Asia, Western Europe, and Africa, the assignment of a high emission rate tends to lower the share of total emissions attributable to the U.S. If, for example, the "other complex" fertilizers had emission rates equal to the weighted average of all other fertilizers used (.0064) instead of the highest emission rate (.027), global emissions for 1984 would be estimated at 0.77 million tons of nitrous oxide, and North American's 0.43 million tons would have represented 56 percent of the total global emissions (Table 22).

We also considered these emission rates using preliminary estimated emission coefficients developed by EPA for each type of fertilizer (U.S. EPA 1990). These estimates are more conservative, particularly for ammonia products (1% instead of 2.7% of nitrogen emitted as nitrous oxide). Again using a weighted average, total global emissions were estimated at just under 0.50 million tons, of which 0.17 (or 34 percent) originated in North America (Table 23).

Since 1984, the volume of nitrogen fertilizer use in the United States has been largely stagnant, while it has increased substantially in the rest of the world, especially in Asia. Overall consumption is up 13.6 percent. Using USDA estimated consumption of nitrogen fertilizer by region for 1990, the global nitrous oxide emissions range from 0.56 (using EPA emission coefficients) to 0.81 million tons (using coefficients from Eichner 1990). The North American share of emissions ranges from 30 percent in the former case to 52 percent in the latter.

Based on these composite findings, we conclude that global fertilizer-derived emissions of nitrous oxide total between 0.50 and 1.09 million tons, and that North American (predominately U.S.) fertilizer consumption results in no less than 30 percent and perhaps as much as 56 percent of that total. This is from two to over three times its

Table 22 Global Consumption and Emissions of Fertilizer-Derived Nitrous Oxide
(Weighted Average Coefficients)

Type Fertilizer	Emission Rate	Africa	Latin America	North America	Asia	Western Europe	CPE	Oceana	Total Use	N_2O Emissions
					--- million tons ---					
Anhydrous Ammonia	0.027	0	0.22	9.79	0.22	0.33	0.22	0	10.78	0.457
Urea	0.0011	0.55	1.65	1.76	20.24	0.88	2.97	0.11	28.16	0.049
Ammonia Nitrate	0.0044	0.44	0.22	0.88	1.10	5.17	12.10	0	19.91	0.138
Other Ammonias	0.0025	0.11	0.88	0.44	5.06	0.55	0.88	0.22	8.14	0.032
Other Nitrates	0.0007	0	0	0	0.11	0.22	0	0	0.33	*
Other Complex	0.0064	0.77	0.33	0	3.96	3.74	0.77	0	9.57	0.096
Total Consumption		1.87	3.3	12.87	30.69	10.89	16.94	0.33	76.89	
Total N_2O Emissions		0.008	0.013	0.271	0.071	0.058	0.070	0.001		0.772
Percent of Total Emissions		1.6	2.7	55.2	14.5	11.8	14.2	0.1		

Table 23 Global Consumption and Emissions of Fertilizer-Derived Nitrous Oxide
(EPA Coefficients)

Type Fertilizer	Emission Rate	Africa	Latin America	North America	Asia	Western Europe	CPE	Oceana	Total Use	N_2O Emissions
					--- million tons ---					
Anhydrous Ammonia	0.027	0	0.22	9.79	0.22	0.33	0.22	0	10.78	0.169
Urea	0.0011	0.55	1.65	1.76	20.24	0.88	2.97	0.11	28.16	0.221
Ammonia Nitrate	0.0044	0.44	0.22	0.88	1.10	5.17	12.10	0	19.91	0.031
Other Ammonias	0.0025	0.11	0.88	0.44	5.06	0.55	0.88	0.22	8.14	0.013
Other Nitrates	0.0007	0	0	0	0.11	0.22	0	0	0.33	*
Other Complex	0.0041	0.77	0.33	0	3.96	3.74	0.77	0	9.57	0.062
Total Consumption		1.87	3.3	12.87	30.69	10.89	16.94	0.33	76.89	
Total N_2O Emissions		0.006	0.013	0.108	0.126	0.029	0.033	0.001		0.496
Percent of Total Emissions		2.0	4.1	34.2	39.8	9.1	10.5	0.2		

proportional use of nitrogen fertilizer.

Is Fertilizer Wasted?

There is substantial evidence that fertilizer use in the U.S. (and much of the developed world) is excessive from agronomic, environmental, and economic perspectives.

Farmers tend to apply fertilizer generously, especially nitrogen, because it is inexpensive relative to the increased yield it produces. Although the rate of yield increase falls as application rates increase, the low unit cost of nitrogen (about $.12 per pound for anhydrous ammonia in the spring on 1991) encourages high levels of application. Because nitrogen fertilizer leaches into the groundwater or oxidizes as nitrous oxide especially during heavy rainfalls, there is a further tendency to make heavy applications to protect against lower yields due to such losses.

But there is evidence of excessive use. A recent survey (Schepers et al. undated) of farmers in an area in Nebraska where nitrate pollution levels are sufficiently high to trigger some regulatory controls over fertilizer application, found that:

** 14 percent of the land in the survey area received more than 89 lbs of nitrogen per acre in excess of recommended fertilizer levels.

** Some farmers who were advised not to apply any nitrogen fertilizer because nitrogen levels in the soil were already more than 312 lbs per acre still applied an average 200 lbs per acre.

** Farmers who applied less than the recommended nitrogen fertilizer rates attained the same yield as those who applied excessive amounts of nitrogen fertilizer.

Excessive fertilizer rates may burden the environment. The most frequently observed problem occurs when nitrogen leaches into the groundwater as nitrate, especially in the western Corn Belt. A 1987 study of domestic drinking water wells in Nebraska estimated that 23 percent of the drinking water wells in cropped areas have nitrate levels in excess of the safe level (Jacobs 1988). In Iowa, an estimated 18.3 percent of rural, private drinking water wells are contaminated with nitrate in excess of safe standards (Iowa Department of Natural Resources 1989).

One cause of excessive fertilizer application is failure of farmers who apply manure to the fields to reduce commercial fertilizer accordingly. A survey of Iowa farmers found that 47 percent of those who spread manure made no adjustment in fertilizer application rates, and among those who did adjust, only 51 percent reduced nitrogen fertilizer (the others reduced phosphorous or potassium). Moreover, among those who spread liquid manure from swine operations, the average rate of application per acre would supply sufficient crop nutrients for continuous production of corn for six years (Duffy and Thompson 1991).

Are these excessive application rates cost-effective? Not necessarily. A study by the University of Illinois used actual business records for 161 farms in that state. Data for eleven years (1976-1986) were analyzed. The farms were grouped into three categories: the 25 percent which spent the least on cash inputs, including fertilizer and pesticides; the 25 percent which spent the most; and the 50 percent in the middle. In eight of the eleven years, net income per acre was highest for the group that spent the least on inputs. In two years, the middle group's net income per acre was highest. In the other year, the low- and middle-use groups tied for most profitable. In none of the eleven years did the high-use group perform best. Over the eleven years, the low-use group was most profitable, averaging $165 per acre profit versus $136 for the high-use group, despite lower yields (Hornbaker 1989).

Better Fertilizer Management Is Possible

Recent evidence from Iowa indicates that better nitrogen fertilizer management is both possible and profitable for farmers.

A project involving state and federal agricultural agencies[11] used a network of on-farm demonstration projects coupled with an "aggressive marketing and information delivery plan" to encourage adoption of management techniques designed to reduce nitrogen fertilizer application rates without reducing yield. The most intensive part of the project has been in place since 1981, but the effort was expanded more generally after 1986.

Three management strategies were emphasized:

(1) Giving more consideration to the nitrogen value of manure spread on fields and reducing nitrogen fertili-

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[11] The Iowa Department of Natural Resources, Iowa State University (ISU) Cooperative Extension, ISU Department of Economics, ISU Department of Agronomy, ISU Department of Sociology, the Iowa Department of Agriculture and Land Stewardship, the USDA Soil Conservation Service, the Leopold Center for Sustainable Agriculture at the University of Iowa (IU), and UI's Public Policy Center.

zer accordingly;

(2) Making more realistic yield goals and better matching nitrogen fertilizer use to those goals;

(3) Using a new soil test designed specifically to manage soil nitrogen.

Between 1985 and 1990, Iowa farmers have reduced nitrogen fertilizer application rates on corn by about 800 million pounds, with no decline in yields. Average nitrogen fertilizer application rate on corn in Iowa declined 12 percent between 1985 and 1990. That has saved Iowa farmers about $120 million, or about $40 million per year. Officials calculate that every dollar spent on the project saved Iowa farmers $8.00 in fertilizer cost. Indications are that with continued effort, Iowa farmers could reduce nitrogen application rates much further -- to perhaps one-third lower than the 1985 rate (Hallberg et al. 1991).

Significantly, the management strategies used in this project involved only judicious reductions in use. They did not involve either a significant change in cropping patterns or an increased substitution of manure for fertilizer. Increased crop rotations and better manure management might further reduce fertilizer application rates. It is possible that in Iowa, nitrogen fertilizer use could be one half of its 1985 level with no loss of yield.

Strategies to Reduce Fertilizer-Derived Nitrous Oxide Emissions

American agriculture can significantly reduce its contribution to nitrous oxide emissions by the following strategies:

(1) Adopt a National Nitrogen Management Program Modeled on the Successful Iowa Program.

The results in Iowa are so encouraging that it seems negligent not to adopt it nationally. A program that operates as intensively as the Iowa program would be expensive nationally, but results indicate that farmers could afford to self-finance the program with a tax on nitrogen fertilizer. A tax of 1.5 percent on nitrogen fertilizer would raise about $33 million, enough for a substantial national program. If that program had results similar to Iowa's, national nitrogen fertilizer consumption might fall in three to four years by about 1.3 million tons. That would reduce nitrous oxide emissions by .027 million tons, or about 12 percent.

Over the longer term, reductions from current use could conservatively reach 25 percent. That would reduce nitrous oxides emissions proportionally, or by about .058 million tons.

(2) Discourage Anhydrous Ammonia Use by Weighting a Nitrogen Tax Against It.

To gain greater emission reduction benefits from the fertilizer management program, the nitrogen tax could be weighted against the fertilizer source with the highest emission rates, anhydrous ammonia. This would encourage a shift from anhydrous to other forms of nitrogen with lower emission rates. Since anhydrous ammonia constitutes about three-fourths of U.S. nitrogen fertilizer use, more funds could be raised to support nitrogen management programs by doubling the tax to 3 percent and applying it only to anhydrous ammonia.

(3) Manage Manure More Efficiently.

Manure probably emits nitrous oxide as freely as commercial fertilizers, but improving its management could lower commercial fertilizer requirements and reduce overall emission levels.

About 15 percent of the total commercial nitrogen fertilizer applied on U.S. farms could be replaced by nutrient that is economically recoverable from manure (National Research Council 1989). Much less than that is recovered, however, because it is lost during handling and storage, especially in the use of lagoon storage pits and large drylot feedlots. More is lost as a result of application methods that fail to incorporate the manure in soil.

Moreover, according to the Iowa survey noted above, much of the manure that is applied to the land is applied at application rates far in excess of recommended levels. Worse, only about one-fourth of the farmers who apply manure reduce nitrogen fertilizer applications as a consequence.

If manure were properly managed and commercial fertilizer applications reduced accordingly, nitrous oxide emissions could be reduced by another 10 percent, conservatively estimated.

(4) Change Cropping Patterns.

Nitrogen is used principally on corn, cotton, wheat, and rice, all crops chronically in surplus and supported by federal farm commodity programs. Benefits under these programs are pegged to continuous production of these crops and to yield levels which encourage excessive nitrogen use. Farmers who adopt cropping rotations and reduce fertilizer use are penalized by loss of program benefits.

Under the Food, Agriculture, Conservation, and Trade Act or 1990, farmers now have an option. Those who agree to plant at least 20 percent of their program acres in resource conserving crops (generally, not nitrogen fertilizer users and frequently nitrogen builders), are protected from loss of program benefits. Enrollment in this Integrated Farm Management Program is limited to 25 million acres.

If 20 percent of those acres (5 million acres) are removed from nitrogen using crops, and nitrogen fertilizer is reduced 12.5 percent on remaining acres due to rotations that include nitrogen fixing crops, total nitrogen fertilizer use could be reduced by at least 500,000 tons. That would reduce nitrous oxide emissions by about .01 million tons, or over 4 percent of the U.S. total emissions. Doubling the IFM program could reduce annual emissions by at least 8 percent.

The Importance of Integrated Analysis

Summary: In designing strategies to reduce agriculture's contribution to global warming, it is important to take into account the multiple environmental impacts of agriculture as a system over the long term. Unfortunately, too much of the analysis of greenhouse gas emissions considers only the immediate effects of each gas separately.

For example, when considering only methane emissions, it is easy to conclude that systems that place calves on high-corn feeding systems quickly produce far less emissions than those using high- forage systems. Both the feed quality and the faster rate of weight gain of the animal on the high-corn system makes methane emissions about 75 percent greater for the animal on the high- forage system. However, when the carbon dioxide and nitrous oxide emissions from corn production and the carbon dioxide storage in forages are factored into the analysis, and the long term relative global warming potential of the gases are also considered, the high-forage system contributes less to global warming in the long run.

The high-forage system compares more favorably as the complexity of the analysis increases and the time frame lengthens because it is fashioned on the biologically determined advantage of the ruminant as an animal that can convert grass directly into protein, and that therefore fits within a highly integrated farming system that makes diverse and integrated uses of land.

Agriculture is a human intervention into natural systems for the purpose of food production. As such, it helps distinguish humans from other animals, and hunter/gatherer societies from more complex societies.

But the more extreme the intervention, the greater the environmental impact. Gathering, selecting, and sowing seed, controlling competitive plants and predator insects and animals, and enhancing nutrient availability all have environmental implications.

Conversely, the more closely agriculture imitates nature, the less will be its environmental impact.

These principles are nowhere more manifest than in the problem of global warming, a long term environmental disruption toward which agriculture is a major contributor. Agriculture's contribution to global warming is largely a function of the elimination of diverse ecosystems in favor of single-species (crop) land use systems involving tillage, artificial fertilizer, and chemical pest control. This process produces the following general effects, among others:

(1) land clearing releases carbon from vegetation as carbon dioxide and methane;

(2) tillage releases carbon from the soil as carbon dioxide;

(3) nitrogen fertilizer releases nitrous oxide;

(4) removal of livestock from free or nearly free range to confined space enhances methane emissions from waste, especially when the waste is handled with a water-based management system;

(5) intensified use of fossil fuel energy to fuel mechanical power, to control weeds and supply nutrient, to move waste products, to pump water, and to dry crops, increases carbon dioxide emissions.

It is essential that efforts to address agriculture's contribution to global warming consider the inter-related nature of these problems. Modern agriculture is an integrated system of technologies, not a series of isolated activities. Likewise, greenhouse gas emissions are a product of interacting bio-chemical processes that are products of such technical systems.

In designing strategies to reduce agriculture's contribution to global warming, it is important to take into account the multiple environmental impacts of agriculture as a system -- to consider the whole picture in the long term. Unfortunately, much of the analysis about greenhouse gas emissions is directed at the immediate effects only of each gas separately, depending on the field of interest of the specialist doing the analysis.

For example, from reading the literature about methane emissions, one might conclude that wetlands should be drained and farmed, since they are a major source of methane emissions. However, wetlands are also among the best storage basins for carbon, and they provide other environmental benefits not directly related to global warming.

To consider the necessity of integrated analysis of these issues, let's return to the question of methane emissions from beef. The research presented indicates that methane emissions are increased with lower quality feeds (that is, those with lower digestible energy content). Based on this information alone, we might conclude that a shift to a high-corn diet for beef cattle would mitigate American agriculture's contribution to global warming. And that, indeed, is the direction the U.S. beef industry has moved over the past 30 years (in the interest of feed efficiency, of course, not in the interest of mitigating global warming).

But that conclusion is not justified, as a more thorough analysis indicates, for it fails to take into account the energy consumption, fertilizer use, manure management, and land uses associated with beef produced on high corn rations.

Increasingly, beef cattle are moved as quickly as possible from the range to the feedlot, nearly eliminating the ''stocker'' period during which the animal traditionally would have been fed roughage and silage. Instead, soon after weaning, a calf is placed on a transition diet that includes corn for about 40 days, then placed on full feed (70-80 percent corn) for about 210 days until it is ready for slaughter at about 1,100 pounds. These animals gain weight rapidly on relatively less feed and are alive only about 15 months, minimizing the interest paid on borrowed capital to purchase the animals and pay for their feed. For very large commercial feedlots, these are crucial costs. This system is characteristic of such feedlots.

On its face, this ''***high corn***'' system of production emits less methane than the traditional system described in Table 12. During the 40-day transition stage, it is estimated that methane yield is high (6.5 percent of feed energy intake) and total daily methane emission is high (0.264 lbs). During the finishing stage, emission rates are estimated to be very low (3.5 percent of digestible energy). Overall, total emissions over the life of the animal is about 79.0 pounds of methane, about 18.6 percent less than for the traditional system.

Another alternative exists. This involves a more land-based system of beef production in which, during a prolonged stocker stage, the cattle are allowed to graze cornstalks after harvest and are fed hay, silage, or straw during the late winter when snow cover is too deep or when grazing stalks do not provide enough feed. As soon as early season grasses begin to grow, the cattle can be moved to summer pasture where they graze on early and late season grasses. These winter and summer grazing periods combined last about 10 months, after which the animal is placed on a high corn finishing ration for about 110 days. This is a ''***high-forage***'' production system.[12]

These cattle enter the feeding stage at about 800-900 pounds, have larger frames and more muscular development than the calves on the high-corn system. Because they have grown heavier frames more slowly than the corn-fed calves, they gain weight faster once they are placed on corn feed during the finishing stage. They also finish out at a heavier weight, about 1,200 pounds. Because this system is more land-based and involves integrated crop and livestock systems, it is suited only to diversified farms. These farms are typically family farm operations.

This system clearly emits more methane (Table 25) than either the high-corn system (Table 24) or the traditional system (Table 12). The longer grazing period on lower quality feeds during the winter and summer grazing periods boosts emissions to 151.0 pounds. On a per-retail-pound basis, this is about 75 percent more methane.

But to achieve this apparently superior performance, the high-corn fed calves had to consume over 50 percent more corn than the high-forage fed cattle (75 compared to 49 bushels per animal). The high-corn system therefore consumes more fuel and fertilizer and produces more erosion. By contrast, the high-forage feeding system relies more on grass and hay, which absorb carbon from the atmosphere and store it in soil. All these factors have important global warming implications.

First, the nitrogen fertilizer applications needed to produce the extra 26 bushels of corn each animal consumes in the high-corn system increase nitrous oxide emissions by nearly 1.2 pounds.[13]

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[12] This high-forage system has been analyzed and described by animal scientists at the University of Nebraska-Lincoln; see Stock, et al. 1990.

[13] If anhydrous ammonia is applied at a rate of 250 lbs per acre for a yeild of 150 bu and has an emission rate of 2.7 percent (Eichner 1988), the nitrous oxide emission will be .045 pounds per bushel. The high corn system requires 75 bushels of corn per animal, producing 3,375 pounds of nitrous oxide. The high forage system requires 49 bushels corn per animal, producing 2.205 pounds of nitrous oxide.

Table 24 Direct Methane Emissions for Cattle on High-Corn Feeding Systems

Stage	No. Days	Methane Yield (%)	Grams Per Day	Total Emission (pounds)
Calf	210	6.0	.084	17.6
Transition	40	6.5	.264	10.6
Finishing	210	3.5	.242	50.8
Total	460			79.0

Corn consumed (bu):	75
Market weight (lb):	1,100
Lbs. methane per lb. retail meat (based on 462 lb. retail):	.171

Table 25 Direct Methane Emissions for Cattle on High-Forage Feeding System

Stage	No. Days	Methane Yield (%)	Grams Per Day	Total Emission (pounds)
Calf	210	6.0	.084	17.6
Stocker				
Winter Grow	180	6.5	.308	55.4
Summer Grow	120	6.0	.374	44.9
Finishing	110	3.5	.308	33.4
Total	720			151.0

Corn consumed (bu):	49
Market weight (lb):	1,200
Lbs. methane per lb. retail meat (based on 504 lb. retail):	.300

Second, the energy consumed in the fuel and fertilizer needed to produce the additional 26 bushels of corn increases carbon dioxide emissions by about 109 pounds.[14] This considers only the direct energy value of the fuel and the fertilizer, not the energy used in their production or distribution.

In addition, a comparison of the two systems must consider the fact that the high-forage system includes land uses that will tend to withdraw carbon from the atmosphere and store it in soil. Each stocker in the high-forage system will require one acre of grass for summer grazing, a little over half of which should be warm season grasses with especially high carbon storing potential. This is beyond the grass required to support the animal and its parent stock during the breeding and calving stages.

An acre of unfertilized grass will store about 308 pounds of carbon per year in the soil (this does not include the carbon stored in the biomass of the grass itself, since a good deal of it will be recycled into the atmosphere by the grazing animals). This is the equivalent of about 1,128.6 pounds of carbon dioxide.

Moreover, Mosier et al. (1991) found that unfertilized grass will withdraw methane directly from the atmosphere at a rate of about .0042 pounds per day for the period March through December. This represents a withdrawal of about 1.0 pounds of methane per acre per year.

The removal of carbon dioxide and methane from the atmosphere by grass partially offsets the methane emissions of the stocker animals in the high-forage system. Coupled with the additional emissions of greenhouse gases from the additional fertilizer and fuel consumed in corn produced for the high-corn fed animal, the ***net*** emissions for the high-corn animal are only about 11 percent less than the net emissions of the high-forage animal on a per-retail-pound basis (Table 26).

When other long term factors are considered, such as the different levels of persistence of the various greenhouse gases, the relative level of concentration of each gas, and the indirect effect each has on the formation of other gases once in the atmosphere, the difference between these feeding systems becomes even smaller. These factors have been integrated into an analysis of the Global Warming Potential (GWP) of emissions for each gas over various time periods (IPCC 1990a).

For example, over a 20 year period, a pound of methane emitted to the atmosphere today has 61 times as much global warming potential as a pound of carbon dioxide emitted. But over longer time periods, its relative global warming potential declines because it is a shorter-lived compound, among other reasons. Over a 100 year period, a pound of methane emitted today will have only 21 times the global warming potential of pound of carbon dioxide; over 500 years, it has only nine times the effect. Nitrous oxide, by contrast, has 270 times the warming potential of carbon dioxide over 20 years, 290 times over 100 years, and then drops off to 190 times the effect over 500 years. Methane constitutes a far larger portion of the greenhouse gas emission of the high-forage feeding system, while nitrous oxide constitutes a much larger portion of the high-corn system. The longer the time period of analysis, then, the better the high-forage system looks in comparison to the high-corn system.

In fact, over a 500 year period, the global warming effect of the emissions from the high-forage animal is actually smaller per pound of retail meat produced than that from the high-corn animal (Table 26).

This analysis does not consider the possibility that cattle on high-corn rations will increasingly be fed in confinement facilities in which the waste is managed in water-based systems, primarily lagoons. This will substantially increase the methane emissions from anaerobic digestion of the waste.

The analysis also does not consider the fact that grazing cornstalks under the high-forage system will tend to deplete soil carbon. But this is offset by another variable not incorporated into the analysis: the fact that additional acreage sewn to hay crops for the supplemental winter feeding of animals on the high-forage system will build up soil carbon levels.

Other positive aspects of the high forage system need to be considered, as well, such as:

* less soil erosion due to reduced corn acreage and more crop rotation;

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[14] With 250 lbs of nitrogen and 6.9 gallons of diesel fuel per acre and 150 bu yield, carbon dioxide emissions will total about 4.2 lbs per bu. The additional 26 bushels used in the high corn system will therefore generate about 109 more pounds of carbon dioxide. Assumptions: Diesel fuel has 138.690 BTUs per gallon and emits 22.282 tons of carbon per Bil. BTUs (81.7 tons of carbon dioxide); fertilizer has 32,558,000 BTUs per nutrient ton and emits 15.8989 tons of carbon per Bil BTUs (58.3 tons of carbon dioxide). Source: USDA/ERS.

Table 26 Net Greenhouse Gas Emissions From Cattle on High Corn Versus High Forage Feeding Systems

Source	High Corn		High Forage	
	Current Emissions	Global Warming Potential (1)	Current Emissions	Global Warming Potential (1)
	------Carbon Dioxide-Equivalents in Pounds------			
I. Gas Emissions				
Direct emissions	4,582	711	8,758	1,359
Embodied in breeding stock (see Table 13)	10,695	1,660	10,695	1,660
Nitrous Oxide from fertilizer on corn	695	641	454	419
Carbon Dioxide from fuel and fertilizer on corn	315	315	206	206
	=====	=====	=====	=====
Total Emissions	16,287	3,327	20,113	3,644
II. Removal of Gases From Atmosphere				
Methane uptake on pasture	0	0	58	9
Carbon storage in pasture soils	0	0	45	45
Total Removal	0	0	103	54
	=====	=====	=====	=====
III. Net Emissions	16,287	3,327	20,010	3,590
IV. Net Emissions Per Pound Retail Beef (462 lbs for high corn animal, 504 lbs for high forage animal)	35.25	7.2	39.7	7.1

(1) Global Warming Potential over 500 years, assuming that methane has 9 times the global warming impact as carbon dioxide over that time period, and nitrous oxide has 190 times the impact of carbon dioxide over that period (IPCC 1990a).

** Insects, weeds, and plant diseases will all be encouraged by warmer, and possibly wetter, climates in late spring and early summer, and the range of pests may move northward affecting both crop and livestock production.

** Changing climatic conditions and shifts in cropping patterns will increase demand for groundwater, but supplies will shrink and costs of pumping will increase as groundwater levels decline.

** The net effect of these changes on crop yields is extremely difficult to estimate, but they are probably negative overall, and corn yields will probably decline most.

** No matter how much yields decline on average, variability in yield will likely increase, and the probability of significant crop failure with current varieties will increase sharply.

** If crop varieties, planting dates, and carbon dioxide levels don't change, the agronomic zone of crops will move northward and eastward, perhaps by as much as 100 miles per decade, requiring irrigation in parts of the Corn Belt where groundwater for irrigation is scarce and encouraging a shift from corn to sorghum and wheat. There will be less change in the Wheat Belt unless precipitation declines, in which case the Wheat Belt would invade and displace the Corn Belt.

These sobering projections are not firm predictions, but all are based on accumulating scientific evidence and the judgments of many leading climatologists. We are not qualified to evaluate the studies that reach these conclusions, but we are impressed by the extent to which they concur on or do not contest these points with respect to our region.

U.S. Agriculture's Contribution to Greenhouse Gas Emissions

U.S. agriculture is a major contributor to greenhouse gas emissions, and the advance of industrial farming methods increases its contribution.

U.S. agriculture, with its heavy dependence on fossil fuels for mechanical power, fertilizer, pest control, crop drying, and water heating, emitted about 33.2 million tons of carbon (121.8 million tons of carbon dioxide) in 1987. Almost one-third of the carbon dioxide emissions (36.3 million tons) are from the fuel stock used to produce fertilizer, and another 8.8 million tons were emitted from pesticide manufacture. The use of these petrochemicals and fertilizers on cultivated lands, especially those highly susceptible to erosion, also releases carbon from the soil to the atmosphere. We estimate that as much as six to seven tons of carbon per year is emitted as carbon dioxide (23.8 million tons) from eroded soils in the U.S. Tillage of all soils also causes carbon dioxide emissions.

Nitrogen fertilizer is a major source of nitrous oxide emissions, especially in the U.S. where anhydrous ammonia, which has exceptionally high nitrous oxide emission rates, is heavily used. We estimate that annual global fertilizer-derived nitrous oxide emissions are between 0.5 and 1.08 million tons, and that because of its heavy use of anhydrous ammonia, U.S. agriculture accounts for between 30 and 56 percent of that total (from two to three times its share of total fertilizer use). We also estimate that U.S. emissions total about 0.25 million tons (equivalent to about 51.5 million tons of carbon dioxide). This is an especially grievous situation because nitrous oxide is both a potent warming agent (over 200 times the warming power of carbon dioxide) and a persistent gas (lasting 150 years in the atmosphere), and because the evidence is that American agriculture uses substantially more than optimum amounts of nitrogen fertilizer.

Methane is the most ''agricultural'' of the greenhouse gases because the human activities that contribute most to emissions are rice and livestock production. Livestock is a very important part of Midwestern agriculture.

Both the special digestive processes of ruminant livestock and the decomposition of manure from all livestock contribute to methane emissions. Generally, for ruminants, there are three factors in methane emissions: the lower the quality of the feed, the more the animal eats, and the longer it is fed, the more total methane emissions. A USDA grade choice steer weighing 1,125 pounds at slaughter will represent 281.4 pounds of methane emission (97 pounds directly and 184.6 pounds indirectly from the breeding stock that produced the animal), or about 0.59 pounds of methane per pound of retail meat. Beef production in the U.S. represents about 3.6 million tons of methane emission (equivalent to about 208.8 million tons of carbon dioxide).

More than that, about 3.7 million tons, is emitted from cattle and hog manure (with about another 0.4 million tons from other livestock manure). Manure management is the key in determining methane emissions from that source. If manure decomposes in dry conditions, as it is in pasture conditions or when spread regularly on fields, only about 10 percent of the potential methane is actually emitted into the atmosphere. However, if it decomposes in water, as it does in many large-scale livestock systems that use anaerobic lagoons to manage waste removal, emissions rates are as high as 90 percent. Overall, about 1.7 million tons of methane emissions (about one-fifth of all methane from all U.S. livestock sources) derive from the manure of animals kept in facilities with anaerobic lagoons in the U.S.

Major U.S. agricultural sources of greenhouse gas emissions are summarized in Table 27. This analysis includes only national agricultural factors that are present in the Midwest. So, for example, it does not include methane emissions from U.S. rice production (which we estimate at about 1.1 million tons of methane). Nor does it include what may be the largest single source of greenhouse gas emissions from U.S. agriculture: carbon dioxide from soil cultivation caused by factors other than erosion. There simply are no reliable estimates of annual emission rates from this source, although they are expected to be very large.

Table 27 shows that major U.S. agricultural sources are responsible for annual emissions of greenhouse gases equal in warming capacity to about 644 million tons of carbon dioxide. Over two-thirds comes from methane from ruminant digestion and all livestock manure (in roughly equal proportion). More than another fourth comes from nitrous oxide emissions from fertilizer and carbon dioxide emissions from both fertilizer manufacture and other fossil fuel use. The remainder is carbon dioxide loss from soil erosion. Our confidence in this latter estimate, however, is not very high.

Some positive notes should be added to this evidence that American agriculture is a major contributor to greenhouse gas emissions. First, energy use in American agriculture has improved dramatically. Between 1974 and 1987, farm energy consumption declined about 16 percent while output increased 20 percent. Second, while methane emissions from ruminant livestock remain very high, the high feed qualities and the efficient rate of gain achieved in animal livestock production in the U.S. mean that methane emissions per pound of retail meat produced are low compared to that of many other nations.

Lifetime Global Warming Potential of These Emissions

The total warming potential embodied in these emissions can be estimated by adjusting the emissions for each gas by a factor which accounts not only for its relative potency as a warming agent (the carbon dioxide equivalent) but also its relative longevity in the atmosphere, its current level of concentration, and the nature of its interaction with other greenhouse gases. This is an extremely complex issue which scientists are only beginning to address. Nonetheless, the IPCC (1990a) has made a preliminary assessment of the global warming potential of each of the greenhouse gases under consideration over three time periods -- 20 years, 100 years, and 500 years.

Table 28 presents estimates of the total global warming potential of major sources of U.S. agricultural greenhouse gas emissions over these three time horizons, measured in carbon dioxide equivalents. Because methane is much shorter lived than the other gases, its relative importance as a warming agent shrinks over time. By contrast, because nitrous oxide is so long lived, its relative importance grows.

Accordingly, over the 20-year time period, the sheer volume of agricultural methane emissions makes it the leading cause of warming. In that period, methane emissions will contribute 70 percent of the warming potential of emissions from U.S. agricultural sources. However, its total contribution drops sharply over the longer horizons, to 43 percent over 100 years and 26 percent over 500 years. By contrast, nitrous oxide grows from 10 percent of the warming contribution over 20 years to 19 percent in 100 years, and maintains approximately that share through the 500 year horizon.

Although not as potent as nitrous oxide, the carbon dioxide emissions are even more persistent in the atmosphere. Their share of the total contribution to warming from all agricultural sources grows from 20 percent over the 20-year period to 39 percent over the 100-year period and 56 percent over the 500 year period.

This means that the combined nitrous oxide and carbon dioxide emissions from nitrogen fertilizer manufacture and use contributes more to global warming in the 100 year time horizon than either ruminant methane or manure methane, and more than both combined over the 500 year horizon. While livestock based emissions fall in share of warming contribution from 70 percent over 20 years to 26 percent over 500 years, land-use based emissions (erosion and fertilizer) increase from 18 percent to 41 percent. These relative shifts do not consider energy use emissions, which would increase the relative importance of land use decisions.

In short, the longer the planning horizon, the more important cultural practices on the land become and the less important livestock sources of emissions become.

Table 27 Major Sources of Greenhouse Gas Emissions From U.S. Agriculture

Source	Gas	Million Tons	Carbon Dioxide Equivalent (Mil Tons)	Percent
Ruminant Livestock (1)	Methane	3.60	208.8	32
Livestock Manure	Methane	4.10	237.8	37
Fertilizer	Nitrous Oxide	0.25	51.5	8
	Carbon Dioxide	36.30	36.3	6
Energy Use	Carbon Dioxide	85.40	85.4	13
Erosion	Carbon Dioxide	23.80	23.8	4
Total			643.6	100

(1) Beef only. Does not include sheep, goats, or other ruminants.

Table 28 Lifetime Global Warming Potential of Major Sources of Greenhouse Gas Emissions From U.S. Agriculture

		Annual Emissions (Carbon Dioxide Equivalent Million Tons)	Global Warming Potential (Carbon Dioxide Equivalent - mil tons)					
Source	Gas		20 Yrs	%	100 Yrs.	%	500 Yrs	%
Ruminant Livestock	Methane	208.8	226.8	32	75.6	20	32.4	12
Livestock Manure	Methane	237.8	258.3	37	86.1	23	36.9	14
Fertilizer	Nitrous Oxide	51.5	67.5	10	72.5	19	47.5	18
Fertilizer	Carbon Dioxide	36.3	36.3	5	36.3	10	36.3	14
Energy Use	Carbon Dioxide	85.4	85.4	12	85.4	23	85.4	33
Erosion	Carbon Dioxide	23.8	23.8	3	23.8	6	23.8	9
Total		643.6	698.1	100	379.7	101	262.3	100

Strategies to Help Agriculture in the Middle Border Cope With Global Warming

Four principles should guide farmers interested in strategies designed to cope with the climate change. Each of these principles respond to this central premise:

> **Although we cannot be certain exactly how climate will change, we know that it will change, and farming during a changing climate (especially one that is less predictable and more variable) will be more difficult than farming under a new, stable climate, even one that is more hostile than the current climate.**

The four principles that guide farming in this condition are:

** *Flexibility*: Farmers should adopt investment and management strategies that allow them to change their operation quickly and easily. Also, avoiding high levels of debt and high cost farming strategies will help make a farming operation more resilient to adverse conditions.

** *Diversity*: Farmers should aim for a diverse operation in which the failure of one crop or enterprise due to unfavorable weather will be cushioned by other parts of the operation. This principle of diversity should also apply to selection of breeds or varieties. Long term commitments to specialized crop or livestock production will make farmers particularly vulnerable to climate change.

** *Conservation*: In a more hostile and changing climate, critical non- climate resources must be conserved. Soil fertility, soil structure, and soil moisture holding capacity will be especially important in combating changes in seasonal precipitation and temperature. Conservation of groundwater is also important to ensuring future water quality and availability.

** *Renewable Energy Use*: The cost of farming in a more hostile or more unpredictable environment will be particularly hard on farmers who rely on energy intensive farming systems because it will require more inputs (fertilizers, pesticides, energy for irrigation etc.) to assure the same level of production. Farmers who use renewable strategies will maintain lower costs and reduce their vulnerability to interruptions or restrictions in supply.

In considering strategies farmers might use to cope with global warming, we deliberately reject those that, though they might help cope with the problem, would also contribute to further accumulations of greenhouse gases. Energy intensive irrigation and confinement livestock production are good examples. These strategies might help farmers cope in the short run, but they worsen the problem in the long run. They might give agriculture just enough rope to help hang itself.

Instead, we recommend the fundamentals of a diversified farming system:

** **Combinations of crops and livestock systems** that make full use of land resources while minimizing erosion, recycling soil nutrients, and maximizing resource conserving crops.

** **Crop rotations, including moisture conserving and fertility building crops,** will help to conserve and build soil, reduce energy and costs in the form of fertilizers and pesticides, and help diversify a farm operation.

** **Use of green manures** will also improve the soil's moisture holding capacity and reduce the need for fertilizer applications which are costly and may pose a greater threat to future water quality.

** **Interseeding with cover crops** will help to hold the soil, build soil structure and retain soil moisture.

** **Manure management (e.g. composting) aimed at maximizing the conservation of organic matter and crop nutrients** will help to build soil, provide a renewable source of fertilizer, and reduce the cost of external inputs.

** **Soil conservation practices, including field windbreaks, strip cropping, grass waterways, terraces, and conservation tillage,** will particularly help to hold the soil in place and reduce water runoff.

** **Integrated pest management to minimize the use of petro-chemicals** will reduce costs and reliance on external sources and help to ensure future water quality.

** **Increased water use efficiency in irrigation, including soil moisture testing and proper timing** will help to protect future water resources and reduce energy requirements.

** **Better timing of field work** (for example eliminating fall tillage) will reduce soil and moisture loss.

** **Energy conservation, including especially tractor maintenance, weatherization, solar crop drying, and off-peak irrigation** will help to reduce farm costs.

** **Plant tree or tall grass windbreaks** to help conserve soil and soil moisture.

Not all of these practices are as well established as others, and there is more research needed on each. However, in principle, a diversified farm that conserves soil, moisture, and energy, integrates crops and livestock production, recycles nutrients, and reduces liabilities will cope best under a more hostile climate. All of the above practices have the added advantage of making a significant contribution to the reduction of greenhouse gases in the atmosphere.

Planting grass is important because it is an economically viable long term sink for substantial amounts of carbon, and because the strategy fits so well with efforts to reduce erosion, conserve fertilizer, and rotate crops. Pasture livestock systems also lower methane emissions from manure.

Reducing manure methane emissions from anaerobic lagoons is important primarily because it has very high immediate impact. While the mitigation technologies necessary to accomplish this goal are not particularly cost effective from the producer's standpoint, they are technically available and have been adopted by some producers. There are, however, significant economics of scale in methane conversion to electricity. Smaller producers using anaerobic lagoons will be particularly disadvantaged.

Implementing Policies

The public policies needed to implement or to encourage adoption of these strategies by farmers are varied and complex. Moreover, nearly all of these policies are already being considered in the context of other issues, such as water quality, energy conservation, and commodity policy. In most of the instances where these policy measures are already under consideration, the public interest in their adoption is more immediate and keener for reasons other than to mitigate or cope with global warming. Nonetheless, taken together, these disparate policies constitute a national agricultural global warming policy. We summarize the salient elements of such a policy below.

1. Farm Programs

In general, policies that encourage diversification, integrated use of resources, purchased input reduction, and reduced cultivation of soils are desirable. Policies that encourage monoculture, intensive use of fossil-fuel inputs, and increased cultivation, are undesirable.

Currently, farm program benefits are pegged to the yield of a small range of crops on a specified number of acres. This formulation encourages repeated prduction of a limited number of crops using the most intensive inputs. A broader range of crops should be benefited under the programs, especially soil conserving crops, and reduced emphasis should be placed on yield per acre of all crops.

Specifically, we urge **improvement and expansion of the Integrated Farm Management (IFM) Program.** Barriers to participation in the program should be identified and eliminated. At a minimum, year-long haying and grazing on resource conserving crops that may be harvested (both set-aside acres and payment acres) should be permitted. The program should also embrace more resource-conserving cropping systems, and should be supported by agricultural research that support development of such systems, such as those involving new small grains (e.g., triticale) and the underseeding of legumes.

Moreover, inasmuch as the systems involved in the IFM program are very complex and require substantial multi-year planning, USDA should do a much better job of getting program rules and regulations published well in advance of the date farmers are required to enroll in the program. In 1992, the regulations were issued only a few weeks before the enrollment period.

Our strategy calls for enlarging the program from its current 25 million acre authorization to 50 million acres. Congress should authorize this expansion at the earliest opportunity.

Congress should also help farmers deal with the growing climatic uncertainty by developing an actuarially and environmentally sound crop insurance program in which farmers pay into the cost of the program in years when crop yields and farm income are high and draw from the program in years when yield and income are low. The cropping practices actually in use on a farm should be among the actuarial factors considered in determining the participant's premiums. Those who rotate crops and practice good soil and water conservation should pay lower premiums than those who do not.

2. Soil Policy

We believe that the United States should explicitly embrace soil policy objectives and integrate them into farm programs. The strategy we recommend of increasing soil carbon on fifty million cultivated acres over a fifty year period is a good starting point. But we are sure that a more comprehensive national soils policy is needed to address erosion, tilth, nutrients, and microbiology. We urge the President and the Congress to establish a National Commission on Soils to develop such a policy and to recommend implementing actions for the private sector and for all levels of government.

Congress and the Administration should also work to accomplish the goal of enrolling 45 million acres in the Conservation Reserve Program (CRP). To extend the benefits of this enrollment to as many more acres as possible, enrollment should be targeted to the portions of

Table 31 Priority Strategies for Reducing Greenhouse Gas Emissions

Strategy	Practical	Immediate Impact	Lifetime Warming	Mitigation Rate	Farm/Consumer Impact	Enviro Impact	Complementary
Reduce nitrogen fertilizer use by 25%	VH	VH	VH	VH	H	H	M
Reduce soil erosion on 169 mil. acres	M	M	M	M	L	H	M
Extend conservation tillage and crop rotations on 72 mil. acres	H	L	L	L	L	H	VH
Reduce energy use in crop drying by 7%	L	L	L	M	M	M	M
Reduce methane emissions from livestock manure in lagoon systems by 80%	L	VH	H	L	M	L	L
Plant 4.9 mil. acres of trees	M	L	M	M	L	H	M
Plant 45 mil. acres of grass	M	H	H	M	L	H	M
Increase carbon in cultivated soils by 25% over 20 yrs and by another 10% over the next 30 yrs.	L	M	L	M	L	L	H

VH = Very High H = High M = Medium L = Low

cropped fields that are in grass waterways, filter strips and field windbreaks (partial field enrollment).

Congress should solidify the gains made in the 1985 Farm Bill by taking steps to keep as much as possible of the land in the CRP in grass after the 10-year contracts with landowners expire. To do this, Congress should recognize that economic use of this grassland is essential. Long term paid agreements in which the owner agrees to keep the land in grass but is allowed to hay and graze it would greatly reduce the cost of accomplishing this goal. Funds now used to pay annual contract rents should be used for these agreements. However, easements now required for partial field enrollments that do not involve tree planting should either be limited to the length of the current contract or not extended beyond the contract period unless they are paid. The current practice of requiring unpaid easements that last longer than the paid contract simply discourage enrollment in the program.

Congress and the Administration should also stop the backsliding that has weakened the conservation compliance provision of the 1985 Farm Bill. Under this provision, farmers who want to continue to receive farm program benefits must implement conservation plans on their entire farm by 1995. By various means of redefining the terms of this compliance, the policy has been seriously weakened. Conservation compliance should be reinforced and effectively implemented on schedule in 1995.

3. Nitrogen Management

Congress should adopt a national nitrogen fertilizer management program aimed at making better use of manure, reducing commercial fertilizer waste, and improving fertilizer application technologies. The program should consist of research and education initiatives and should be financed by an excise tax on commercial nitrogen fertilizer. A tax of 1.5 percent would raise about $33 million, enough for a substantial national program.

4. Livestock Waste Management

Livestock producers who deliberately choose to employ water-based waste management systems that pollute the atmosphere with methane should be required to reduce the methane emissions to 10 percent of the total potential emissions. The federal Clean Water Act should specify that anaerobic lagoons are an unacceptable remedy to point source livestock waste pollution unless these emissions are reduced to the acceptable level. Otherwise, the Act will have merely succeeded in forcing the environmental impact of an onerous practice from one medium (water) to another (air).

In this context, it seems appropriate to discontinue the practice of encouraging the adoption of anaerobic lagoon management systems. USDA should therefore not provide cost-sharing under the Agricultural Conservation Program for construction of any livestock waste management system that employs anaerobic digestion, unless the methane emission levels are reduced to the acceptable level. Funds now allocated for livestock waste management total about $13.5 million. The portion going to anaerobic digestion systems without methane digesters should be diverted into field windbreaks, strip crops, and other land use practices designed to reduce erosion and conserve moisture.

5. Climate Research

There are clearly innumerable uncertainties yet about how the climate will change and how the changes will affect agriculture. In addition to improving the ability of the climate models to predict regional effects, we particularly need greater study of how the variability and predictability of weather may change as greenhouse gases exert their influence on the atmosphere. Much of the research conducted to date on the possible impacts of greenhouse gases and climate change on agriculture is limited by considering only one piece of the puzzle at a time. There is a need for more research on interactive effects of climate change, and especially effects not just on individual plants and animals, but on whole fields, farming systems and whole farm operations.

In addition to studies of the impacts of climate change on agriculture, there is a great need for further study of how agricultural practices contribute to greenhouse gas emissions or sequestration. Far too little is known yet about the role of soil disturbance in contributing to carbon emissions, or the sources of methane, or the potential for carbon sequestration through farm management practices.

6. Agricultural Research

Generally, research to help farmers reduce their use of purchased inputs by relying on greater use of renewable resources will help reduce costs, vulnerabilities, and emissions simultaneously. Similarly, research supporting integrated crop/livestock farming systems and diversified farming operations will provide greater farm flexibility and encourage dispersion of livestock populations across the landscape.

To address the particular problems presented by global warming, agricultural research should pay special attention to the following goals:

* Identify opportunities and develop farming practices that ameliorate greenhouse gas emissions (such as carbon storage strategies);

* Improve nutrient testing methods to help prevent over-fertilization;

* Develop improved high-forage feeding systems to reduce methane emissions from high forage rations;

* Develop methane digesters and other renewable energy strategies feasible for use at a small scale;

* Improve composting methods;

* Improve efficiency of water and energy use in irrigation;

* Design and improve farming practices that conserve soil and water resources, and especially those that improve interseasonal soil moisture management;

* Develop the potential of alternative crops that will enable greater farming diversity;

* Develop and improve both laboratory and on-farm conservation of plant and animal germplasm diversity;

* Study and develop the potential for agroforestry on temperate zone farms;

* Maintain a vigorous plant breeding program and identify varieties that withstand high temperatures, drought, intense rainfall, and variable weather as well as pests and diseases;

* Study the carbon cycle to better understand how higher carbon content and greater volume of plant matter, combined with higher temperatures, will affect decomposition and soil organic matter.

* Assess the unviersal soil loss equation to determine if practices that build organic matter or otherwise improve soil are adequately credited.

To further this research agenda, the federal government should take two steps:

Congress should substantially increase funding for the Sustainable Agriculture Research and Education program.

The United States Department of Agriculture should invite climate and agricultural research such as that identified above in its request for proposals under the competitive grants program of the National Research Initiative.

7. Water Quality

The Water Quality Incentive Program providing per-acre payments to farmers who adopt management practices reducing the source of agricultural chemical pollutants should be strengthened with larger appropriations. Despite late implementation of the program, far more farmers signed up for it than could be served by limited funds in 1992. With more funds, the program should also be opened up to farmers in counties not part of a USDA water quality demonstration project, and could be targeted to assist farmers in implementing their conservation compliance plans. Once fully implemented by these means, the program should be evaluated for effectiveness.

8. Agricultural Tree Planting

Agricultural conservation programs should encourage the planting of field windbreaks and shelterbelts. These not only reduce atmospheric carbon, but also conserve soil, moisture, and energy. Greater priority should be placed on providing cost-sharing for establishing these practices. Tall grass windbreaks should also be considered for cost-sharing in all arid and semi-arid areas where tree planting is less practical. Tall grass windbreaks are already eligible for cost-sharing in some counties under the Great Plains Program, and have now been made eligible for the Conservation Reserve.

9. Beef Grading Standards

Although better than in the past, current USDA beef grading standards still place too much emphasis on marbling and other factors that encourage high corn rations. Standards should encourage production of lean, high-forage fed beef. This will reduce fertilizer-derived emissions of nitrous oxide and carbon dioxide emissions from fertilizer and fuel use in corn production, while increasing demand for grass and forage and thereby increasing carbon storage in soil.

10. Energy Conservation

Many low-cost applications of solar technology for heating livestock buildings and drying crops are available and should be more widely adopted. Research and education programs designed to encourage the further development and use of these technologies by farmers should be offered by the federal government through state universities or appropriate non-profit organizations. We do not, however, generally support the use of tax incentives in this area. These tend to subsidize high-cost, capital-intensive investments in new buildings and equipment when many of the best investments are low-cost and labor-intensive investments in retrofit technologies.

Conclusion

American agriculture's contribution to global warming is significant (about 644 million tons of carbon-dioxide equivalent per year). The impact on agriculture of the climate change produced by greenhouse gases is difficult to predict, but it will be substantial, particularly in the farm belt region we call the "Middle Border."

We have identified and assigned tentative priorities to farm management strategies that will reduce emissions by 116.6 million tons and store 60.4 million tons of carbon dioxide equivalent in soil. Overall, these strategies will reduce net emissions from agriculture by 177 million tons, or 28 percent.

The policy recommendations we make are intended to be general guides rather than detailed proposals. They are offered as examples of concrete steps that can be taken to encourage the adoption of the strategies we outline for making serious reductions in the net greenhouse gas emissions of American agriculture. Significantly, nearly all of these policies can be supported for other good reasons as well, and most of them are well within the framework of existing national agricultural policies.

In Perspective

To place U.S. agriculture's role in global warming into some perspective, it is useful to note that if the average on-road fuel efficiency of all cars and light trucks in the U.S. were increased just one mile per gallon (from 20 to 21 mpg), annual carbon dioxide emissions would be reduced by 50 million tons. That would lower the greenhouse gas emissions by half again as much as farmers could if they reduced fertilizer use by 40 percent, or about the same amount they could if they planted 45 million acres of grass. If the car/truck fuel efficiency were increased to 25 miles per gallon, carbon dioxide emissions would be reduced by far more than all the changes we are recommending here for agriculture.

Finally, we cannot stress enough that most of the steps that commercial agriculture can take to reduce its contributions to global warming require no sacrifice at all, and most will help make farms more resilient to coming climate changes.

Table 1a
CORN YIELDS
Studies/Scenarios

	Study Authors	Geographic Region	Model	Irrigated or Dryland (Rainfed)	CO_2 Effect Included (ppm)	Other Conditions
1	Adams et al. 1990	ND, SD, NE, KS, MN, WI, MI	CERES/GISS	Rainfed	630	
2	Adams et al. 1990	IA, MO, IL, IN, OH	CERES/GISS	Rainfed	630	
3	Adams et al. 1990	SD,ND,NE,KS,MN,IA,MO,WI,IL	CERES/GFDL	Rainfed	600	
4	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GISS	Dryland		
5	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GISS	Dryland	660	
6	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GISS	Irrigated		
7	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GISS	Irrigated	660	
8	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GFDL	Dryland		
9	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GFDL	Dryland	660	
10	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GFDL	Irrigated		
11	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GISS	Irrigated	660	
12	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GISS	Dryland		Chng Planting Date
13	Waggoner 1983	IA, IL, IN		Rainfed		
14	Liverman et al. 1986	Kansas City, Bismark	YIELD	Irrigated		Normal cloudiness
15	Liverman et al. 1986	Kansas City, Bismark	YIELD	Rainfed		Normal cloudiness
16	Liverman et al. 1986	Kansas City, Bismark	YIELD	Irrigated		Normal cloudiness
17	Liverman et al. 1986	Kansas City, Bismark	YIELD	Rainfed		Normal cloudiness
18	Bach 1979 (cited in Easterling et al. 1989)					
19	Benci et al. 1975 (cited in Smit et al. 1988)	Midwest				
20	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland[36]		
21	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland[36]	450	
22	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated[36]		
23	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated[36]	450	
24	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland		2030 Base[37]
25	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland		2030 Base[37]
26	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland		2030 Base[37] + Adjust[38]
27	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland	450	2030 Base[37] + Adjust[38]
28	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated		2030 Base[37]
29	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated	450	2030 Base[37]
30	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated		2030 Base[37] + Adjust[38]
31	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated	450	2030 Base[37] + Adjust[38]

Table 1b
CORN YIELDS
Temperatures

Study Authors	Increase in Winter Temp (in °C)	Increase in Spring Temp (in °C)	Increase in Summer Temp (in °C)	Increase in Fall Temp (in °C)	Increase in Annual Temp (in °C)
1 Adams et al. 1990					4.7[40]
2 Adams et al. 1990					4.9[39]
3 Adams et al. 1990					5.95[1]
4 Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
5 Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
6 Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
7 Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
8 Rosenzweig (EPA study)	4.78[11]	4.9[12]	5.05[13]	4.88[14]	4.93
9 Rosenzweig (EPA study)	4.78[11]	4.9[12]	5.05[13]	4.88[14]	4.93
10 Rosenzweig (EPA study)	4.78[11]	4.9[12]	5.05[13]	4.88[14]	4.93
11 Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
12 Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
13 Waggoner 1983					1.0
14 Liverman et al. 1986					2.5-5.0
15 Liverman et al. 1986					2.5-5.0
16 Liverman et al. 1986					2.5-5.0
17 Liverman et al. 1986					2.5-5.0
18 Bach 1979 (cited in Easterling et al. 1989)			1.0		
19 Benci et al. 1975 (cited in Smit et al. 1988)					1.0-2.0
20 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
21 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
22 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
23 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
24 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
25 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
26 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
27 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
28 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
29 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
30 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
31 Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85

To convert Celsius
to Fahrenheit
multiply by 1.8.

Table 1c
CORN YIELDS
Precipitation

Study Authors	Change in Winter Precip (mm/mo)	Change in Spring Precip (mm/mo)	Change in Summer Precip (mm/mo)	Change in Fall Precip (mm/mo)	Change in Annual Precip (mm/mo)
1 Adams et al. 1990					+5.85%(40)
2 Adams et al. 1990					+2.7%(39)
3 Adams et al. 1990					+1.9%^{1}
4 Rosenzweig (EPA study)	-5.6^{7}	+3.6^{8}	-5.4^{9}	-3.0^{10}	-3.33
5 Rosenzweig (EPA study)	-5.6^{7}	+3.6^{8}	-5.4^{9}	-3.0^{10}	-3.33
6 Rosenzweig (EPA study)	-5.6^{7}	+3.6^{8}	-5.4^{9}	-3.0^{10}	-3.33
7 Rosenzweig (EPA study)	-5.6^{7}	+3.6^{8}	-5.4^{9}	-3.0^{10}	-3.33
8 Rosenzweig (EPA study)	+1.08^{15}	+0.25^{16}	+5.0^{17}	-1.0^{18}	+1.53
9 Rosenzweig (EPA study)	+1.08^{15}	+0.25^{16}	+5.0^{17}	-1.0^{18}	+1.53
10 Rosenzweig (EPA study)	+1.08^{15}	+0.25^{16}	+5.0^{17}	-1.0^{18}	+1.53
11 Rosenzweig (EPA study)	-5.6^{7}	+3.6^{8}	-5.4^{9}	-3.0^{10}	-3.33
12 Rosenzweig (EPA study)	-5.6^{7}	+3.6^{8}	-5.4^{9}	-3.0^{10}	-3.33
13 Waggoner 1983					-10%
14 Liverman et al. 1986					-25%
15 Liverman et al. 1986					-25%
16 Liverman et al. 1986					+25%
17 Liverman et al. 1986					+25%
18 Bach 1979 (cited in Easterling et al. 1989)					-10%
19 Benci et al. 1975 (cited in Smit et al. 1988)					+10-20%
20 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
21 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
22 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
23 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
24 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
25 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
26 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
27 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
28 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
29 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
30 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}
31 Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr^{35}

To convert millimeters to inches, multiply by .03937

Table 1d

CORN YIELDS

Study Authors	Change in Yield Worst or Decline	Change in Yield Best or Increase	Change in Yield Average	
1 Adams et al. 1990	+40%	+49%		
2 Adams et al. 1990	10%	+19%		
3 Adams et al. 1990	-20%	-11%		
4 Rosenzweig (EPA study)	-43%	-4%		26
5 Rosenzweig (EPA study)		+31%		31
6 Rosenzweig (EPA study)	-23%	-9%		27
7 Rosenzweig (EPA study)	-11%			31
8 Rosenzweig (EPA study)	-90%	+9%		28
9 Rosenzweig (EPA study)	-44%			31
10 Rosenzweig (EPA study)	-37%	-11%		29
11 Rosenzweig (EPA study)	-25%			31
12 Rosenzweig (EPA study)	-32%	+.1%		30
13 Waggoner 1983	-4%	-3%	-3.3%	
14 Liverman et al. 1986	-30%	-5%		32
15 Liverman et al. 1986	-100%	-65%		32
16 Liverman et al. 1986	-30%	0%		32
17 Liverman et al. 1986	-55%	-20%		32
18 Bach 1979 (cited in Easterling et al. 1989)	-11% -1.5%			
19 Benci et al. 1975 (cited in Smit et al. 1988)	-20%	-10%		
20 Easterling et al. 1992	-25%			
21 Easterling et al. 1992	-17%			
22 Easterling et al. 1992	-7%			
23 Easterling et al. 1992	-1%			
24 Easterling et al. 1992	-28%			
25 Easterling et al. 1992	-19%			
26 Easterling et al. 1992	-17%			
27 Easterling et al. 1992	-7%			
28 Easterling et al. 1992	-9%			
29 Easterling et al. 1992	-4%			
30 Easterling et al. 1992		+3%		
31 Easterling et al. 1992		+10%		

Table 2a

SOYBEAN YIELDS

Studies/Scenarios

	Study Authors	Geographic Region	Model	Irrigated or Dryland (Rainfed)	CO2 Effect Added (ppm)	Other Conditions
1	Adams et al. 1990	IA,MO,IL,IN,OH	SOYGRO/GISS	Rainfed	630	
2	Adams et al. 1990	SD,ND,NE,KS,MN,WI,MI	SOYGRO/GISS	Rainfed	630	
3	Adams et al. 1990	IA, MO, IL, IN, OH, KY	SOYGRO/GFDL	Rainfed	600	
4	Adams et al. 1990	ND, SD, NE, KS, MN, WI, MI	SOYGRO/GFDL	Rainfed	600	
5	Waggoner 1983	IA, IL, IN		Rainfed		
6	Schuhardt et al. 1989	1978 area w/ 56.9-299.3 kg/GISS		Rainfed		
7	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland[36]		
8	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland[36]	450	
9	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland		2030 Base[37]
10	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland	450	2030 Base[37]
11	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland		2030 Base[37] + Adjust[38]
12	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland	450	2030 Base[37] + Adjust[38]

Table 2b

SOYBEAN YIELDS

Temperatures

	Study Authors	Increase in Winter Temp (in °C)	Increase in Spring Temp (in °C)	Increase in Summer Temp (in °C)	Increase in Fall Temp (in °C)	Increase in Annual Temp (in °C)
1	Adams et al. 1990					4.9[39]
2	Adams et al. 1990					4.7[40]
3	Adams et al. 1990					5.5[39]
4	Adams et al. 1990					6.15[40]
5	Waggoner 1983					1.0
6	Schuhardt et al. 1989					
7	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
8	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
9	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
10	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
11	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
12	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85

To convert Celsius
to Fahrenheit,
multiply by 1.8.

Table 2c

SOYBEAN YIELDS

Precipitation

	Study Authors	Change in Winter Precip (mm/mo)	Change in Spring Precip (mm/mo)	Change in Summer Precip (mm/mo)	Change in Fall Precip (mm/mo)	Change in Annual Precip (mm/mo)
1	Adams et al. 1990					+2.7%[39]
2	Adams et al. 1990					+5.85%[40]
3	Adams et al. 1990					+8.9%[39]
4	Adams et al. 1990					-1.6%[40]
5	Waggoner 1983					-10%
6	Schuhardt et al. 1989					
7	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
8	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
9	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
10	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
11	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
12	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]

To convert millimeters
to inches, multiply
by .03937

Table 2d

SOYBEAN YIELDS

Study Authors	Change in Yield Worst or Decline	Change in Yield Best or Increase	Change in Yield Average
1 Adams et al. 1990	+30%	+39%	
2 Adams et al. 1990	+40%	+49%	
3 Adams et al. 1990	-10%	-1%	
4 Adams et al. 1990	0%	+9%	
5 Waggoner 1983	-7%	-4%	-5.7%
6 Schuhardt et al. 1989	-15%	-2%	
7 Easterling et al. 1992	-25%		
8 Easterling et al. 1992	-13%		
9 Easterling et al. 1992	-25%		
10 Easterling et al. 1992	-14%		
11 Easterling et al. 1992	-12%		
12 Easterling et al. 1992		+1%	

Table 3a

WHEAT YIELDS

Studies/Scenarios

	Study Authors	Geographic Region	Model	Irrigated or Dryland (Rainfed)	CO_2 Effect Included (ppm)	Other Conditions
1	Adams et al. 1990	SD,ND,NE,KS,MN,IA,MO,WI,IL	CERES/GFDL	Rainfed	600	
2	Adams et al. 1990	SD,ND,NE,KS,MN,IA,MO,WI,IL	CERES/GISS	Rainfed	630	
3	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GISS	Dryland		
4	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GISS	Dryland	660	
5	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GISS	Irrigated		
6	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GISS	Irrigated	660	
7	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GFDL	Dryland		
8	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GFDL	Dryland	660	
9	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GFDL	Irrigated		
10	Rosenzweig (EPA study)	NE, KS, northern OK	CERES/GFDL	Irrigated	660	
11	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GISS	Dryland		Chg PD + Cult[23]
12	Rosenzweig (EPA study)	NE, KS, OK, TX	CERES/GISS	Irrigated		Chg PD + Cult[23]
13	Waggoner 1983	ND, SD, NE, KS, OK		Rainfed		
14	Warrick 1984	Great Plains	IES	Rainfed		1975 technology
15	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland[36]		
16	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland[36]	450	
17	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated[36]		
18	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated[36]	450	
19	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland		2030 Base[37]
20	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland	450	2030 Base[37]
21	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland		2030 Base[37] + Adjust[38]
22	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Dryland	450	2030 Base[37] + Adjust[38]
23	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated		2030 Base[37]
24	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated	450	2030 Base[37]
25	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated		2030 Base[37] + Adjust[38]
26	Easterling et al. 1992	MO,IA,NE,KS	EPIC/Drought[34]	Irrigated	450	2030 Base[37] + Adjust[38]

Table 3b

WHEAT YIELDS

Temperatures

	Study Authors	Increase in Winter Temp (in °C)	Increase in Spring Temp (in °C)	Increase in Summer Temp (in °C)	Increase in Fall Temp (in °C)	Increase in Annual Temp (in °C)
1	Adams et al. 1990					5.95[1]
2	Adams et al. 1990					4.8[2]
3	Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
4	Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
5	Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
6	Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
7	Rosenzweig (EPA study)	4.78[11]	4.9[12]	5.05[13]	4.88[14]	4.93
8	Rosenzweig (EPA study)	4.78[11]	4.9[12]	5.05[13]	4.88[14]	4.93
9	Rosenzweig (EPA study)	4.78[11]	4.9[12]	5.05[13]	4.88[14]	4.93
10	Rosenzweig (EPA study)	4.78[11]	4.9[12]	5.05[13]	4.88[14]	4.93
11	Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
12	Rosenzweig (EPA study)	5.13[3]	4.27[4]	4.13[5]	4.77[6]	4.6
13	Waggoner 1983					1.0
14	Warrick 1984					1932-40 drought
15	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
16	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
17	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
18	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
19	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
20	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
21	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
22	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
23	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
24	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
25	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85
26	Easterling et al. 1992	0.9	0.4	1.3	0.8	0.85

To convert Celsius to Fahrenheit multiply by 1.8.

Table 3c

WHEAT YIELDS

Precipitation

	Study Authors	Change in Winter Precip (mm/mo)	Change in Spring Precip (mm/mo)	Change in Summer Precip (mm/mo)	Change in Fall Precip (mm/mo)	Change in Annual Precip (mm/mo)
1	Adams et al. 1990					+1.9%[1]
2	Adams et al. 1990					+4.8%[2]
3	Rosenzweig (EPA study)	-5.6[7]	+3.6[8]	-5.4[9]	-3.0[10]	-3.33
4	Rosenzweig (EPA study)	-5.6[7]	+3.6[8]	-5.4[9]	-3.0[10]	-3.33
5	Rosenzweig (EPA study)	-5.6[7]	+3.6[8]	-5.4[9]	-3.0[10]	-3.33
6	Rosenzweig (EPA study)	-5.6[7]	+3.6[8]	-5.4[9]	-3.0[10]	-3.33
7	Rosenzweig (EPA study)	+1.08[15]	+0.25[16]	+5.0[17]	-1.0[18]	+1.53
8	Rosenzweig (EPA study)	+1.08[15]	+0.25[16]	+5.0[17]	-1.0[18]	+1.53
9	Rosenzweig (EPA study)	+1.08[15]	+0.25[16]	+5.0[17]	-1.0[18]	+1.53
10	Rosenzweig (EPA study)	+1.08[15]	+0.25[16]	+5.0[17]	-1.0[18]	+1.53
11	Rosenzweig (EPA study)	-5.6[7]	+3.6[8]	-5.4[9]	-3.0[10]	-3.33
12	Rosenzweig (EPA study)	-5.6[7]	+3.6[8]	-5.4[9]	-3.0[10]	-3.33
13	Waggoner 1983					-10%
14	Warrick 1984					1930s drought
15	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
16	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
17	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
18	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
19	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
20	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
21	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
22	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
23	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
24	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
25	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]
26	Easterling et al. 1992	+6.5	-29.5	-40.5	-7.5	-70.75mm/yr[35]

To convert millimeters
to inches, multiply
by .03937

Table 3d

WHEAT YIELDS

	Study Authors	Change in Yield Worst or Decline	Change in Yield Best or Increase	Change in Yield Average	
1	Adams et al. 1990	-30%	-21%		
2	Adams et al. 1990	0%	+9%		
3	Rosenzweig (EPA study)	-55%	-10%		19
4	Rosenzweig (EPA study)		+11.3%		31
5	Rosenzweig (EPA study)	-48%	+7%		20
6	Rosenzweig (EPA study)		+26.7%		31
7	Rosenzweig (EPA study)	-55%	-12%		21
8	Rosenzweig (EPA study)	-16%			31
9	Rosenzweig (EPA study)	-43%	+.2%		22
10	Rosenzweig (EPA study)		+14%		31
11	Rosenzweig (EPA study)	-30%	+153%		24
12	Rosenzweig (EPA study)	-257%	-33%		25
13	Waggoner 1983	-12%	-2%	-7%	
14	Warrick 1984	-13.5%	-9.3%		33
15	Easterling et al. 1992		0%		
16	Easterling et al. 1992		+10%		
17	Easterling et al. 1992		+9%		
18	Easterling et al. 1992		+11%		
19	Easterling et al. 1992	-7%			
20	Easterling et al. 1992		+8%		
21	Easterling et al. 1992		+5%		
22	Easterling et al. 1992		+20%		
23	Easterling et al. 1992	-1%			
24	Easterling et al. 1992		+9%		
25	Easterling et al. 1992		+6%		
26	Easterling et al. 1992		+18%		

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