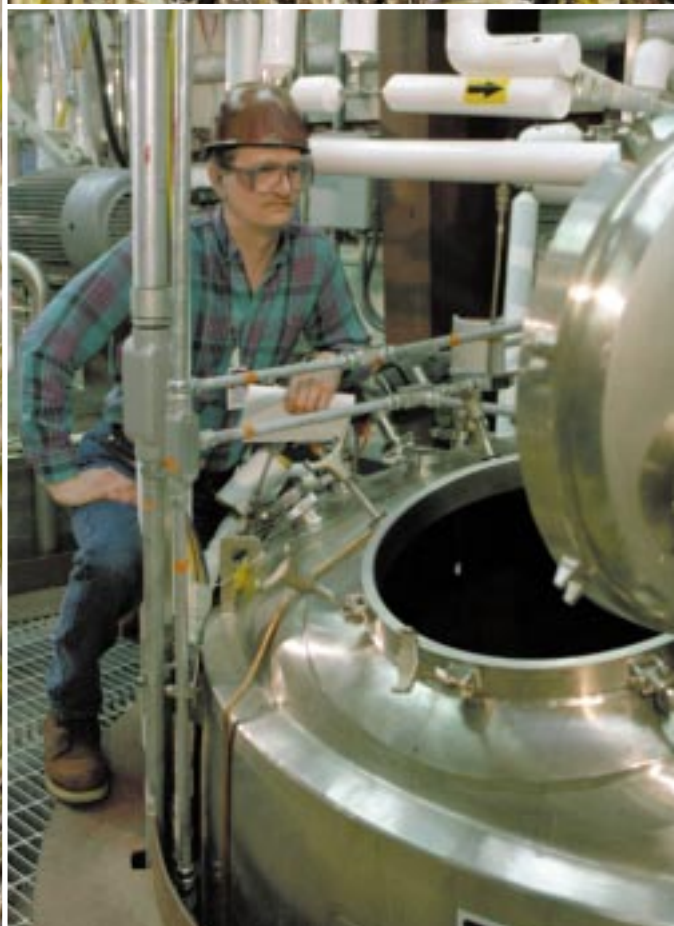# Emission and Reduction of Greenhouse Gases from Agriculture and Food Manufacturing

A SUMMARY WHITE PAPER
DECEMBER 1999

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Office of Industrial Technologies

Department of Energy
Washington, DC 20585

LETTER TO THE READER

One of the least understood links affecting global climate change is the one between the broad agricultural and energy sectors. America's farmers use many different forms and amounts of energy to grow our food and fibers. Those bountiful harvests can also be used in bioenergy applications: transportation fuels, electricity, and industrial chemicals and materials. All of these processes have some kind of impact on the production of greenhouse gases.

This white paper—Emission and Reduction of Greenhouse Gases from Agriculture and Food Manufacturing—summarizes the current scientific and technological knowledge about greenhouse gas emissions from various agricultural practices and the manufacturing of food. In addition, the study, which was commissioned from SC Johnston Associates, Inc., also provides estimates that compare agriculture-related alternatives for reducing greenhouse gas emissions.

Dan W. Reicher,
Assistant Secretary for
Energy Efficiency and
Renewable Energy

Although the paper is only a first step in understanding the complex issues regarding greenhouse gases and agriculture, a few conclusions emerged that may have significant implications for future public policy. First, while agriculture, broadly defined for all energy inputs, contributes about 10% of the total U.S. greenhouse gas emissions, technologies and practices exist today that could significantly reduce these emissions both in the United States and worldwide. Second, emerging technologies in this industry hold the promise of even greater emissions reductions nationally and globally. The level of carbon dioxide emissions from the food manufacturing industry, broadly defined for all energy inputs, is similar to agriculture; and this industry too possesses opportunities for technology-driven emissions reductions. Finally, further analyses must be conducted in order to fill in the many gaps in knowledge regarding these issues.

This paper complements another study issued this year by the Pew Center on Global Climate Change. "Agriculture and Global Climate Change" looked primarily at how greenhouse gas buildup in the atmosphere could affect the U.S. agriculture industry. The report noted that a shift to plants as an alternative source of energy could offer new economic opportunities for farmers and also help ameliorate the overall greenhouse gas buildup.

We at the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy are now working to advance the integration and development of the emerging bioenergy industry. Our Bioenergy Initiative links industry, national laboratories, universities, states, and non-governmental organizations in a focused national effort to accelerate the development of biobased technologies. Together with our public and private sector partners we are also working to implement the President's National Biobased Products and Bioenergy Executive Order issued on August 12, 1999 which will contribute to reducing U.S. greenhouse gas emissions and strengthening the American economy.

So, we view this white paper as presenting both an opportunity and a challenge. Tremendous potential exists to reduce our growing reliance on imported oil and thus to transform the economies of the next century. But, we also know that much remains to be done before the country will see the full benefits of this transformation to biobased industries. We look forward to working with our industry, university, and laboratory partners in order to meet this goal.

AUTHOR'S NOTES

As we developed this paper, we encountered many challenges in gathering data. The paucity of data in some areas and inconsistencies in the way data were collected and reported in other areas led us to consider the following in the preparation of this paper.

In some cases, we have extended published data by calculating new quantities from those data to reveal trends of current interest. An example is the estimate of carbon dioxide emission from knowledge of the energy consumed by a particular process or technology, such as food manufacturing. Estimates of potential future emissions reductions were based either on previous studies or on estimates of potential future energy reductions that were converted to emissions reduction. Also considered were the effects of fuel shift on carbon emissions for the food manufacturing and agriculture industries. Only human-caused emissions are considered—the impacts on atmospheric greenhouse gas inventories caused by natural processes are excluded.

We did not, however, address scientific, technological, or policy issues of global climate change. These topics have been extensively covered in the literature and are the subject of worldwide debate.

The inconsistency of greenhouse gas emissions data reported in the literature did, however, present some difficulty in the preparation of this white paper. We made no attempt here to resolve those differences—rather, we merely noted them in our data tables. Also, no attempt was made to normalize data to a single year. After comparing data from different years within the past decade we observed that, for the most part, for the purpose of this study, there were no significant differences among data separated by a span of 10 years. This was not the case for nitrous oxide, however; the inclusion of new anthropogenic sources of soil nitrogen, as noted in a recent U.S. Environmental Protection Agency (EPA) study, resulted in a large increase in estimates of nitrous oxide emissions by U.S. agriculture. Further, we used mid-range values of data estimates of past and future greenhouse gas emissions and reductions only up to the year 2010.

We obtained most of our data from the following sources: *Preparing U.S. Agriculture for Global Climate Change*, published in 1992 by the Council for Agricultural Science and Technology (CAST), supported by a grant from the U.S. Department of Agriculture; various publications of the Intergovernmental Panel on Climate Change; *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, Lal et al. 1998; publications of the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE); EPA publications; and, in the private sector, an energy consumption study of the food industry prepared by Energetics, Inc., for DOE. Data formatting followed the CAST report (which was updated using EIA 1998, EPA 1999, and Lal, et al. 1998) because it was the only publication that reported carbon dioxide emissions for the agriculture industry. This database served as the basis for further calculations, from which trends were identified and conclusions drawn.

Sheridan Johnston
SC Johnston Associates, Inc., Danville, California

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Cover photo credits: Warren Gretz, NREL.
Left—PIX02665, top right—PIX02277, bottom right—PIX03454

EXECUTIVE SUMMARY

Agriculture is unique among the world's industries in that its own carbon dioxide emissions are low, and it has the potential for removing and sequestering large amounts of carbon dioxide from the atmosphere. We include forestry in our meaning of the word agriculture.

On a global scale, all of the world's agriculture accounts for about one-fifth of the annual human-caused increase in greenhouse gas emissions, and most of this is due to methane and nitrous oxide. World agriculture contributes about 4% to global carbon dioxide emissions (See Summary Graphic A). However, agriculture plays an important role as a carbon sink by sequestering large amounts of carbon in vegetation, soil, and long-lived commercial goods produced from plants.

Globally, agriculture in the United States contributes about 2% of the gases that lead to the greenhouse effect (Summary Graphic B). In the United States, agriculture contributes about 10% of the total amount of gases emitted that could lead to greenhouse gas warming (Summary Table 1). The largest fraction of that 10% is attributable to methane and nitrous oxide emissions rather than carbon dioxide emissions. Moreover, U.S. agriculture has the capacity for making significant reductions in U.S. atmospheric carbon emissions.

In the United States, the amount of forest land has remained fairly constant over the past several decades, with an annual average fluctuation of about 0.1% per year. Improved forest management practices, reforestation, and timber harvesting and use have resulted in a net annual uptake of carbon.

In recent years, domestic manufacturing of food and kindred products generated about two-thirds as much carbon dioxide as all U.S. agricultural sources, and does not generate significant levels of methane or nitrous oxide.

Summary Graphic C gives estimates of potential reductions in global and U.S. carbon emissions using a variety of mitigation options available to U.S. agriculture. This chart uses essentially all of the information contained in this white paper that relates to reduction, or estimates of reduction, in greenhouse gas emissions. In producing Summary Graphic C, all greenhouse gas emissions were reduced to a common denominator— their carbon equivalent, which is a standardized measure of carbon emission to the atmosphere for all greenhouse gases. The resulting carbon-equivalent reductions are presented in this graph, which shows food manufacturing's and agriculture's options for reducing greenhouse gas emissions. Since the values are not absolute and in some cases are not additive, they can only provide indications as to technically possible (but not necessarily economically feasible) areas where potential impacts could be made in the near term (i.e., by 2010). An understanding of the real impact, now and in the future, awaits further research and development.

The information displayed in Summary Graphic C highlights two facets of agricultural and food manufacturing technologies. First, there are technologies

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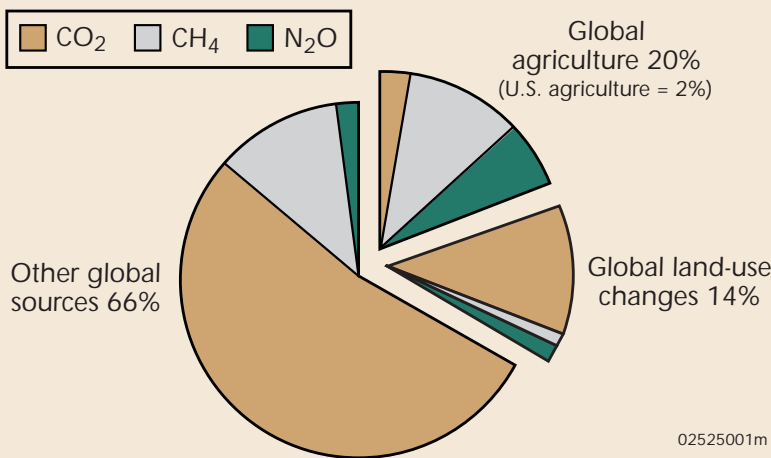
Summary Graphic A: Percent contributions to the annual increase in the greenhouse gases carbon dioxide, methane, and nitrous oxide, based on global warming potential. U.S. agriculture emissions are 2% of the carbon equivalent emissions of the three greenhouse gases shown. Global land-use changes are agriculture related. Source: IPCC 1996.


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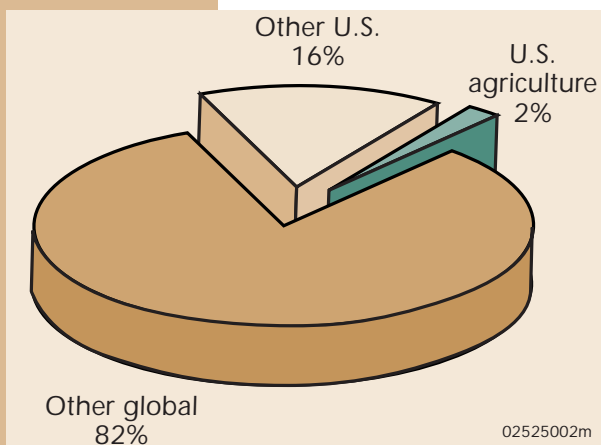
Summary Graphic B: U.S. contributions to the greenhouse gas emissions of carbon dioxide, methane, and nitrous oxide, based on global warming potential. Source: Table 2.

Summary Table 1. Greenhouse gas emissions attributable to U.S. farming, based on global warming potential[1]

	Carbon dioxide (%)	Methane (%)	Nitrous oxide (%)	All three gases (%)
As % of Global	1	3	15	2
(From all other sources)	99	97	85	98
As % of U.S.	3	30	71	10
(From all other sources)	97	70	29	90

[1] Values were rounded.
Source: This information was obtained from Table 2 by taking vertical ratios.

and practices that are being used to differing degrees today that could quickly impact greenhouse gas emissions—improved cropping systems, improved irrigation and water management, and conservation tillage. There are other technologies and practices—biobased products, biofuels/biopower, and afforestation—that could potentially have a major impact once the needed research and development to implement them has been fully undertaken. Second, there are advanced technologies and practices, which in aggregate could provide a 1%-2% reduction in U.S. carbon-equivalent emissions. These include emerging and advanced practices in technologies such as food manufacturing, nitrous oxide management, agricultural systems, and livestock management.
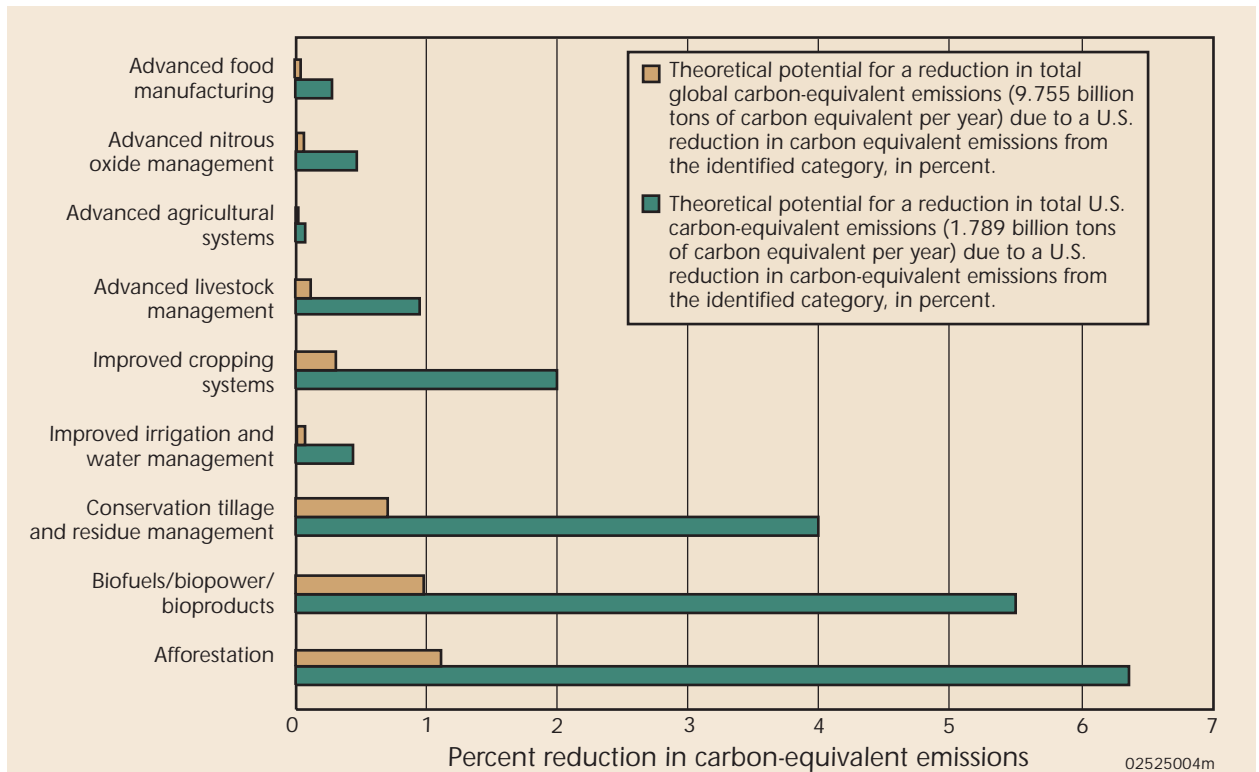
Summary Graphic C: Theoretical potential for annual reduction or sequestration of human-caused greenhouse gas emissions from agriculture and food manufacturing, expressed in percent reduction in total carbon or carbon equivalent emitted to the atmosphere from three greenhouse gases (carbon dioxide, methane, and nitrous oxide). It is not possible to simultaneously achieve both sequestration using afforestation and biofuels/ biopower/bioproducts reductions because each has been estimated assuming exclusive use of the same available land. The biofuels/biopower/bioproducts reduction and the sequestration using afforestation may be altered by climatological and ecological factors, as well as by economic efficiencies and competitiveness, actual available cropland, crop yield, and new technologies. In the future, there will be a competition for land for the production of food, feed, fiber, and industrial-agricultural products, as well as for social uses. Source: Appendix C.

1. THE GREENHOUSE EFFECT

GREENHOUSE GASES

The Earth absorbs energy from the sun in the form of solar radiation. About one-third is reflected, and the rest is absorbed by different components of the climate system, including the atmosphere, the oceans, the land surface, and the biota. The incoming energy is balanced over the long term by outgoing radiation from the Earth-atmosphere system, with outgoing radiation taking the form of long-wavelength, invisible infrared energy. The magnitude of this outgoing radiation is affected in part by the average temperature of the Earth-atmosphere system (Climate Action Report 1997).

Several human and natural activities can change the balance between the energy absorbed by the Earth and that emitted in the form of long-wavelength infrared radiation. On the natural side, these include changes in solar radiation (the sun's energy varies by small amounts— approximately 0.1 percent over an eleven-year cycle—and variations over longer periods also occur). They also include volcanic eruptions, injecting huge clouds of sulfur-containing gases, which tend to cool the Earth's surface and atmosphere over a few years. On the human-induced side, the balance can be changed by emissions from land-use changes and industrial practices that add or remove "heat-trapping" or "greenhouse" gases, thus changing atmospheric absorption of radiation (Climate Action Report 1997).

Greenhouse gases of significance include carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); the chlorofluorocarbons (CFCs) and their substitutes, including hydrofluorocarbons (HFCs); the long-lived fully fluorinated hydrocarbons, such as perfluorocarbons (PFCs); and ozone (O_3). Although most of these gases occur naturally (the exceptions are the CFCs, their substitutes, and the long-lived PFCs), the concentrations of all of these gases are changing as a result of human activities (Climate Action Report 1997).

Three greenhouse gases are associated with agriculture: carbon dioxide from the burning of fossil fuels and decaying organic matter; methane from wetlands and ruminant animals; and nitrous oxide from fertilizer. Table 1 summarizes information about these gases.

Table 1. Selected greenhouse gases that have been affected by human activity

	Carbon dioxide	Methane	Nitrous oxide
Preindustrial concentration*	278 ppmv	700 ppbv	275 ppbv
Concentration in 1994	358 ppmv	1720 ppbv	312 ppbv
Percent change from Preindustrial times to 1994	**29%**	**146%**	**13%**
Rate of concentration change**	1.6 ppmv/yr 0.4%/yr	8 ppbv/yr 0.6%/yr	0.8 ppbv/yr 0.25%/yr
Global emissions to the atmosphere by human activity, 1992	26,033 MMT	375 MMT	6 MMT

Sources: Intergovernmental Panel on Climate Change (IPCC 1996a), U.S. Department of Energy/Energy Information Administration (DOE/EIA 1998), and Lal et al. 1998.

1 ppmv = 1 part per million by volume of gas
1 ppbv = 1 part per billion by volume of gas
1 MMT = one million metric tons of gas (10^{12} grams of gas)
* Prior to 1850
** Averaged over the decade 1984–1994

Aerosols

In addition to the gases listed in Table 1, aerosols can alter the radiation received by the sun. Aerosols are a suspension of ultramicroscopic solid or liquid particles in the troposphere that are derived naturally from sources such as the oceans (dimethyl sulfide) or terrestrial vegetation (non-methane hydrocarbons). These particles are then oxidized in the troposphere. Aerosols are derived anthropogenically from the emission of sulfur dioxide from burning fossil fuels or biomass. Aerosols can both absorb and reflect solar radiation, and they can alter cloud properties by increasing cloud droplet concentration in the lower atmosphere; they can also increase ice formation in the upper atmosphere (Baker 1997). However, in most cases, aerosols tend to act in an opposite manner than greenhouse gases and cool the atmosphere. They also disappear far faster than greenhouse gases through sedimentation and atmospheric precipitation. Recent studies (Haywood 1999) have been aimed at determining how tropospheric aerosols affect the radiative forcing of Earth's climate, but the variable concentrations of the aerosols complicate an understanding of their global influence (Kiehl 1999).

Radiative Forcing and Global Warming Potential

Anything that alters the radiation received from the sun or lost to space, or which alters the redistribution of energy within the atmosphere—or between the atmosphere, land, and ocean—can affect climate. A change in the energy available to the global Earth/atmosphere system is called radiative forcing. (It is important to consider radiative forcing here in order to compare the relative warming effects of the greenhouse gases.)

One characteristic of greenhouse gases is that an increase in their concentrations in the atmosphere reduces the efficiency with which the Earth cools to space. This results in a positive radiative forcing, which tends to warm the lower atmosphere and surface of the Earth. On a per-unit-mass basis, methane is 58 times as effective in warming the atmosphere as is carbon dioxide, and nitrous oxide is 206 times as effective in warming the atmosphere as is carbon dioxide. In other words, it takes a smaller amount of methane or nitrous oxide to have the same warming effect as carbon dioxide. This is why methane and nitrous oxide are important, even though their absolute emissions to the atmosphere (in tons of gas) are considerably less than those for carbon dioxide.

Another important characteristic of a greenhouse gas is its lifetime in the atmosphere; that is, how long the radiative forcing by the gas will go on. Methane remains in the air for a much shorter time than either carbon dioxide or nitrous oxide, and a unit of methane will cause radiative forcing about one-tenth as long as carbon dioxide.

The characteristics of radiative forcing and lifetime combine into a single index that shows the potential of a unit of each gas for warming the Earth. This global warming potential (GWP) is the cumulative radiative forcing over a specified time horizon resulting from the emission of a unit mass of gas relative to some reference gas (IPCC 1995). Although GWPs are quoted as single values, the typical uncertainty is ±35%. (See Appendix D for a more complete discussion of GWP.) The GWPs of the three agricultural greenhouse gases are given in the third line of Table 2. At the current rate of emission of methane and nitrous oxide into the atmosphere, these gases would not be important if it were not for their considerable global warming potentials.

Global Carbon Inventories and Transport

The Earth's atmosphere holds an inventory of about 775 gigatons of carbon (GTC) (Climate Change Technology Strategy [CCTS] 1997), and each year the inventory increases about 3.5 GTC (See Figure 1). Natural processes dominate the carbon dioxide budget, accounting for 97% or more of all sources and sinks. Biota on the Earth holds an inventory of about 610 GTC, and soil and detritus hold about 1580 GTC. Thus, there is more carbon in the atmosphere than there is in the entire world's plant life and 2–3 times as much carbon in the surface soils of the world than in its plants.

Approximately 61.7 GTC pass into plants annually on the land via photosynthesis. Respiration, which occurs in living things and the organisms responsible for plant-matter decay, emits about 60 GTC back to the atmosphere. About 6 GTC are released to the atmosphere from burning fossil fuel, and about 1.4 GTC stream into the atmosphere from changes in land use (primarily deforestation). A new study gives an upper estimate of 0.35 GTC for terrestrial carbon sequestration for the entire U.S. during the 1980s, including forestry and land-use changes (Houghton et al. 1999).

About 50% of the initial uptake of carbon through photosynthesis is used by plants for growth and maintenance (gross primary production). The remaining carbon is called net primary production. Part of this is shed as litter and enters the soil, where it decomposes, releasing nutrients to the soil and CO_2 to the atmosphere. The carbon remaining after these emissions is net ecosystem production.

Table 2. Human-caused greenhouse gas emissions from global, U.S., and U.S. agricultural sources for three greenhouse gases, 1997

	Carbon dioxide	Methane	Nitrous oxide	All three gases
Radiative forcing, per unit mass relative to CO_2	1	58	206	
Mean atmospheric lifetime (years)	125	12	120	
GWP[1], 100 years relative to CO_2	1	21	310	
Emissions of gas in gigatons[2] (GT)				
All global sources	26.03[A]	0.375[B]	0.006[C]	
All U.S. sources	5.503[D]	0.0314[E]	0.00129[F]	
All U.S. agricultural sources	0.163[G]	0.00945[H]	0.000913[I]	
Emissions of carbon dioxide equivalent[3], in GTCO$_2$E				
All global sources	26.03	7.88	1.86	35.8
All U.S. sources	5.503	0.659	0.40	6.56
All U.S. agricultural sources	0.163	0.198	0.283	0.644
Emissions of carbon equivalent[3], in GTCE				
All global sources	7.10	2.15	0.507	9.76
All U.S. sources	1.50	0.180	0.109	1.79
All U.S. agricultural sources	0.044	0.054	0.077	0.175
Emissions, percent of total global carbon equivalent[4]				
All global sources	72.8	22.0	5.20	100
All U.S. sources	15.4	1.84	1.12	18.4
All U.S. agricultural sources	0.45	0.55	0.79	1.79

Sources: Adapted from DOE/EIA 1998; Lal et al. 1998; and EPA 1999. Data in Table 2 refer to only three (of several) greenhouse gases emitted from anthropogenic terrestrial sources, and thus do not represent the climatic carbon cycle, which is shown in simplified form in Figure 1.

[1] Global Warming Potential (GWP) is the radiative forcing of a unit of gas emitted, multiplied by its concentration in the air integrated for 100 years, where radiative forcing is a change in the energy available to the global Earth/atmosphere system. IPCC reported these results to be preliminary because of the uncertainties regarding the lifetime of methane, the single lifetime specified for CO_2 (despite greatly different rates of its transfer amongst different reservoirs), and the assumption that lifetimes of trace gases remain constant during the integration period (CAST 1992).

[2] 1 gigaton = 10^9 metric tons = 10^{15} grams = 10^3 teragrams (Tg)

[3] Carbon dioxide equivalent is the concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases. Carbon dioxide equivalents are computed by multiplying the amount of the gas of interest by its estimated global warming potential. From the carbon dioxide equivalent it is possible to define a "carbon equivalent," which is the carbon dioxide equivalent multiplied by the molecular weight ratio of carbon to carbon dioxide (i.e., 12/44).

[4] Total global carbon equivalent of all three greenhouse gases (carbon dioxide, methane, and nitrous oxide) is 9.755 GTCE.

[A] Total global carbon emissions from carbon dioxide emissions = 26,033 MMTCO$_2$ x 12/44 = 7100 MMTC, from DOE/EIA 1998, Table 2, p. 2, Data for 1992.

[B] DOE/EIA 1998, Table 2, p. 2, Data for 1992.

[C] DOE/EIA 1998, Table 2, p. 2, Data for 1992.

[D] Total carbon emissions from U.S. carbon dioxide emissions = 5503 MMTCO$_2$ x 12/44 = 1501 MMTC, from DOE/EIA 1998, Table ES1, p. ix. There is a slight discrepancy between the DOE/EIA value of 5503 MMTCO$_2$ and the EPA 1999 value of 5456 MMTCO$_2$, which are both for 1997.

[E] EPA 1999, Table ES-1, p. ES2. There is a slight discrepancy between the DOE/EIA 1998 value of 29.1 MMTCH$_4$ and the EPA 1999 value of 31.4 MMTCH$_4$, which are both for 1997.

[F] EPA 1999, Table ES-1, p. ES2. There is a discrepancy between the EPA 1999 value of 1.29 MMTN$_2$O and the DOE/EIA 1998 result of 1.0 MMTN$_2$O, which are both for 1997. The EPA 1999 result was used because it was felt that the EPA nitrous oxide study was the more comprehensive.

[G] This value was obtained by taking the Lal et al. 1998 value, which was based on DOE/EIA 1996 data, and scaling it to DOE/EIA 1998 data = (157 MMTCO$_2$) x (5503/5287) = 163 MMTCO$_2$. Lal et al. 1998 was used because neither DOE/EIA 1998 nor EPA 1999 separately identified carbon dioxide emissions for agriculture. This omission of CO_2 contributions by agriculture leads to lower estimates of the total percent contribution of agriculture to the emission of the three greenhouse gases considered here. For example, our estimate for agriculture's contribution is (0.175)/(1.79) x 100 = 9.8% whereas the EPA would calculate (0.131)/(1.79) x 100 = 7.3%, since they omit agriculture's 0.044 GTCE contribution to CO_2. When the contributions of CFCs, HCFCs, and PFCs are included (from EPA 1999), agriculture's contribution to total U.S. emissions of all greenhouse gases is (0.175)/(1.827) x 100 = 9.6%. Agriculture's share of greenhouse gas emissions is shown in Summary Table 1 and Table 3, rounded to 10%. Total carbon dioxide from agriculture is the sum of contributions from soil erosion (15 MMTC) and contributions from fuel use (15 MMTC) and fertilizers and pesticides (12.9 MMTCE), which totals to 42.9 MMTC.

[H] EPA 1999, Table 5.1, p. 99; or it can be approximated by taking the Lal, et al. 1998 value, which was based on DOE/EIA 1996 data, and scaling to DOE/EIA 1998 data = (9 MMTCH$_4$) x (29.1/30.93) = 8.47 MMTCH$_4$. There is a discrepancy between the DOE/EIA 1998 value of 8.6 MMTCH$_4$ and the EPA 1999 value of 9.45 MMTCH$_4$, which are both for 1997. The EPA 1999 value was used because it was felt the EPA methane study was the more comprehensive.

[I] EPA 1999, Table 5.1, p. 99. There is a discrepancy between the DOE/EIA 1998 value of 0.642 MMTN$_2$O and the EPA 1999 value of 0.913 MMTN$_2$O. The EPA 1999 value was used because it was felt the EPA nitrous oxide study was the more comprehensive.
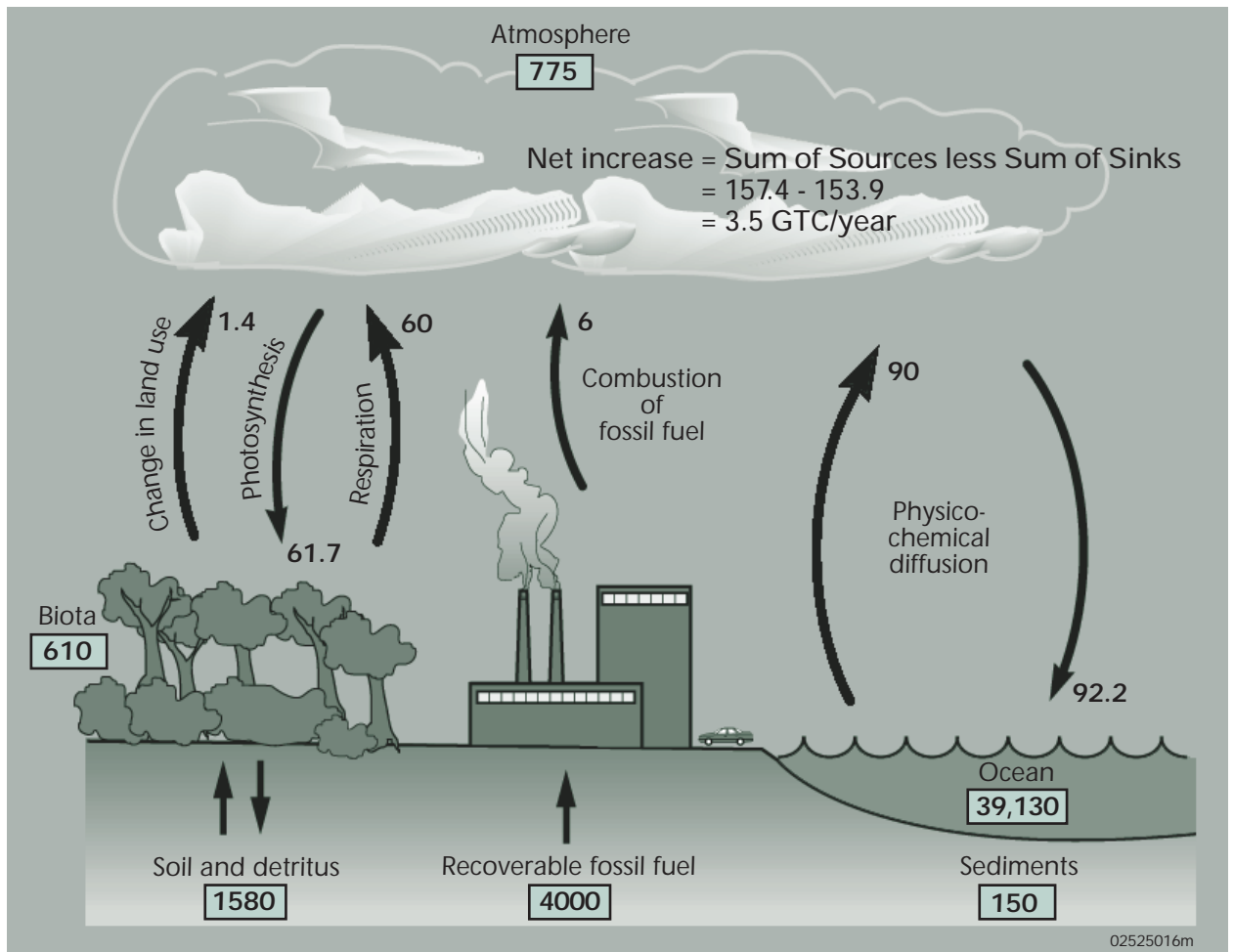
Figure 1. Simplified Global Carbon Cycle with major reservoirs in gigatons of carbon (GTC) and fluxes in GTC/year.
The net annual increase in atmospheric carbon is about 3.5 GTC.
Biota is the total flora and fauna; detritus are small pieces of dead and decomposing plants and animals.
Source: Adapted from IPCC 1996a, CCTS 1997, and Moore and Bolin 1986.

Much of this is lost by nonrespiratory processes such as fire, insect damage, and harvest. The remaining carbon (1–2 GT/yr) is called net biome production and is a small fraction of the initial uptake of CO_2 from the atmosphere. Net biome production can be positive or negative; at equilibrium it would be zero. Net biome production is the critical factor to consider in long-term terrestrial carbon storage (IGBP Terrestrial Carbon Working Group 1998).

Because the inventory of carbon in living and dead things on the land plus the soil is about 2190 GTC, this inventory would only have to be increased by 0.16% (3.5/2190) per year to arrest the annual 3.5 GTC rise in the atmospheric inventory. Or, the net flux of carbon from the atmosphere to living things would only have to be increased 6% (3.5/61.7) to arrest the annual rise in atmospheric carbon.

Although there is a high degree of uncertainty in estimates concerning both flux rates and carbon storage capacity, these simple reckonings show that moderate changes in total photosynthesis, less respiration and decay on land, could dramatically slow, or accelerate, CO_2 enrichment of the atmosphere (Follett 1993).

However, for the United States, where deforestation is not a critical issue, two significant agriculture-related actions that could reduce atmospheric greenhouse gas inventories are possible. One involves sequestering carbon in soils and trees or in highly durable products made from trees. The second involves displacing fossil fuel utilization with biomass that can be used for energy supply and industrial products.

2. Agricultural Emissions

Greenhouse Gas Emissions: Introduction

Based on the combined carbon equivalent of carbon dioxide, methane, and nitrous oxide, the United States emits about 18% of the global emissions of these three gases (See Figure 2), whereas U.S. agriculture emits about 2% of these greenhouse gases.

On a global scale, agriculture accounts for one-fifth of the annual increase in the radiative forcing due to greenhouse gas emissions (See Figure 3). Most of this is due to CH_4 and N_2O; agriculture produces about 50% and 70%, respectively, of their human-activity-related emissions. World agriculture contributes about 4% to global emission of carbon dioxide (See Figure 3). All of the activity in the United States taken together emits 21% of the global CO_2, but smaller percentages of the global methane (8.4%) and of the global nitrous oxide (21.5%). Greenhouse gas emissions from U.S. farming, based on global warming potential, are given in Table 3. The last column of Table 3 reveals that when the three greenhouse gases are taken together, U.S. farming emits about 2% of the global and about 10% of the U.S. emissions of the three gases combined. When the contributions of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and perfluorocarbons (PFCs) are included in total greenhouse gas emissions, these latter percentages remain about the same.

Potential for Reduction

Carbon Dioxide

Carbon dioxide mitigation options in agriculture include reducing agricultural emissions, sequestering carbon in soils and trees, and utilizing biomass for the production of fuels and products.

Since the late 1970s production agriculture in the United States has undergone a significant decline in emission of carbon dioxide from fossil fuels. This is the result of decreases in gasoline use, shifts from gasoline-powered engines to more fuel-efficient diesel-powered engines, and technology (See Figure 4). Examples where fossil fuel use by agriculture can be further reduced are conservation tillage, irrigation scheduling, solar drying of crops, and improved fertilizer management.

Carbon dioxide emissions associated with soil erosion, the manufacture of agricultural equipment and agrochemicals, and with fuel use on farms is about 3% of all other U.S. emissions of carbon dioxide (See Table 2; Duxbury and Mosier 1993; Stiles 1998).

Finally, it should be noted that there is a high degree of uncertainty in estimates concerning both flux rates and carbon storage capacity, as well as in the level at which various mitigation options could be implemented.

Forestation

Forests are comprised of four interrelated carbon storage pools that include trees, understory, the forest floor, and soil, which act together to form a complex ecosystem. Biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, and replanting) cause carbon to be continuously cycled through the forest ecosystem, as well as between the forest ecosystem and the atmosphere.

As trees age, they continue to accumulate carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and increase soil organic carbon. The net change in forest carbon is the sum of the net changes in the total amount of carbon stored in each of the four carbon pools over time (EPA 1999).

Recent evidence suggests that forests store much more carbon than had been previously thought. Previous estimates indicated that they take up about as much carbon dioxide during photosynthesis as they give off during respiration-—resulting in little net carbon flow into or out of forests. But new results, some from reanalyses of old data and others from field studies, indicate that forests, and the carbon they sequester, have been undervalued (Moffat 1997).
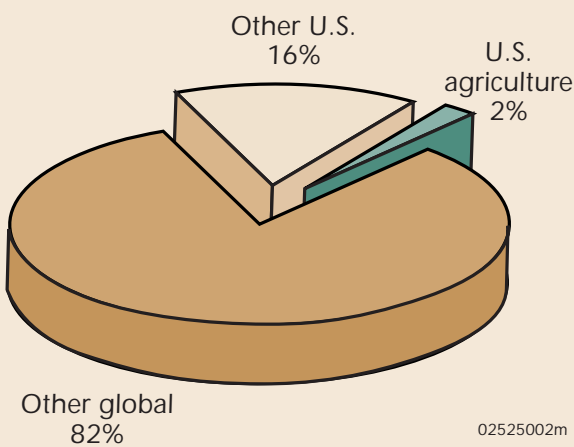
Figure 2. Percent contribution of U.S. agriculture to global greenhouse gas emissions of carbon dioxide, methane, and nitrous oxide, based on global warming potential. Source: Table 2.
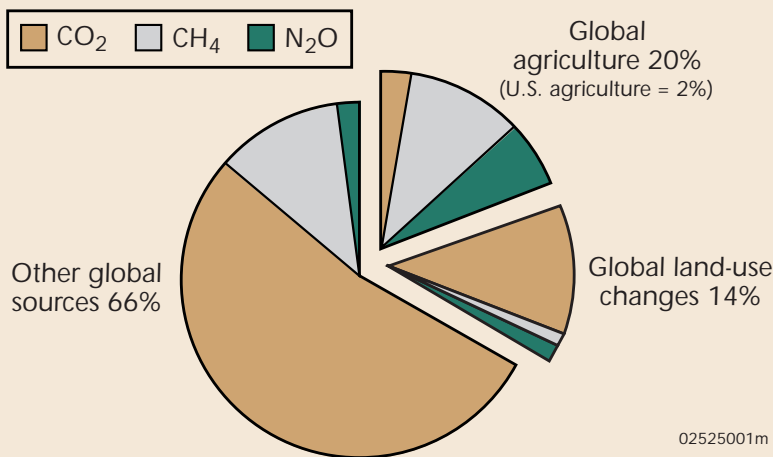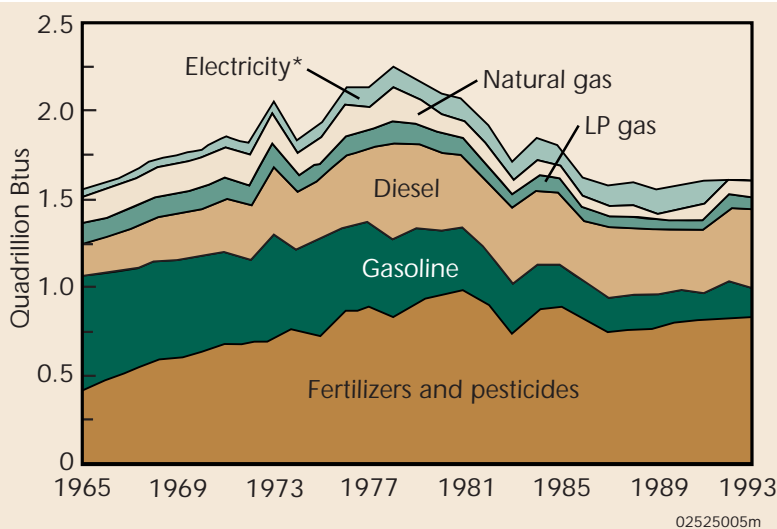

Figure 3. Percent contributions to the annual increase in the greenhouse gases carbon dioxide, methane, and nitrous oxide, based on global warming potential. U.S. agriculture emissions are 2% of the carbon equivalent emissions of the three greenhouse gases shown (see Table 3). Global land-use changes are agriculture related. Source: IPCC 1996.

Table 3. Greenhouse gas emissions attributable to U.S. farming, based on global warming potential[1]

	Carbon dioxide (%)	Methane (%)	Nitrous oxide (%)	All three gases (%)
As % of Global	1	3	15	2
(From all other sources)	99	97	85	98
As % of U.S.	3	30	71	10
(From all other sources)	97	70	29	90

[1] Values were rounded.
Source: This information was obtained from Table 2 by taking vertical ratios.

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Figure 4. Energy use in production agriculture, 1965-93. *No data on electricity use since 1991. Source: Gill 1997 (Redrawn with permission of the USDA).

ecosystems, including forests and their soils and agriculture, can account for some of the missing carbon (Moffat 1997).

However, the idea of a large, missing carbon sink over North America has sparked controversy (Kaiser 1998). In support, one modeling study found that CO_2 levels dropped off slightly from west to east across North America, even though fossil fuel emissions should boost levels in the east (Fan et al. 1998). That meant that there must be a big carbon sink in North America, one large enough to absorb the continent's fossil fuel carbon emissions. The suggestion has been made that terrestrial carbon inventories may have missed a lot of forest regrowth on abandoned farmland and formerly logged forests in the east, fertilized by CO_2 or nitrogen pollution, and that they fail to account for carbon stored in soils and wetlands (Fan et al. 1998). Others argue that the carbon sink is not as large as previously suggested, and that past alterations in land management—including changes in timber harvesting, abandonment of agricultural land, and wildfire supression—are emerging as possible explanations for the terrestrial U.S. carbon sink (Field and Fung 1999).

One author offers several possible explanations, for the missing carbon sink, ranging from the role of deep-ocean transport-and-release of CO_2 to forest dynamics in the northern regions (Schindler 1999). Several authors argue that the model results described above are filled with uncertainties that make them unreliable, further suggesting that more and better data are needed, including direct measurements of carbon storage and flux over land (Kaiser 1998). Finally, Houghton et al. 1999 reconstruct the rates at which lands in the U.S. were cleared for agriculture, harvested for wood, and burned during the period 1700-1990. They then used a terrestrial carbon model to calculate annual changes in the amount of carbon stored in terrestrial ecosystems, including wood products. The study found that during the 1980s, the net flux of carbon attributable to land management offset 10% to 30% of U.S. fossil fuel emissions, which are considerably lower than the estimates of Fan et al.1998.

The Intergovernmental Panel on Climate Change suggests that improved use of forests worldwide could store enough carbon in soils, trees, and other vegetation between 1995 and 2050 to offset 12% to 15% of fossil fuel emissions during that period.

In the United States, the amount of forestland (737 million acres) has remained fairly constant over the past several decades, with an annual average fluctuation of about 0.1% per year. Improved forest management practices, reforestation, and timber harvesting and use have resulted in a net annual uptake of carbon (EPA 1999).

Forest harvesting for wood products or energy alters the natural cycle of carbon between forest ecosystems and the atmosphere. Most of the timber that is harvested from U.S. forests is used in wood products that are eventually disposed of by landfilling, rather than by incineration. Thus, significant quantities of harvested carbon are transferred to long-term storage pools (e.g., the timber used to construct a house) rather than immediately being released to the atmosphere (e.g., combustion as a fuel). As global human population has increased, the size of these long-term

Earlier, widely cited studies focused on old-growth forests, in which carbon flux is typically in equilibrium (Bowyer 1993). Several earlier studies had neglected to include the huge amounts of carbon stored in peat and other organic matter in soils—now estimated to account for about two-thirds of the total carbon sequestered, primarily in high-latitude forests (Moffat 1997). In the United States, revised estimates indicate that the net CO_2 uptake from forests was projected at 171 MMTC for 1997 when all four carbon storage pools identified above are considered (EPA 1999). This is about 11% (171/1501) of the total CO_2 emitted by the United States in 1997.

In addition, it is now recognized that young, relatively fast-growing forests sequester carbon much more rapidly than they release it (Bowyer 1993).

The new picture of forest dynamics may help solve a long-standing enigma: When researchers estimate annual carbon dioxide releases and compare those figures to actual carbon dioxide concentrations in the atmosphere and known sinks, such as the oceans, they typically come up short by about 1 billion to 2 billion metric tons. In other words, roughly 20% of the total CO_2 released each year is apparently missing. But the forest studies suggest where at least part of this carbon dioxide could be going. Terrestrial

storage pools has steadily increased as well. Estimates of the net-annual harvested carbon that has been transferred to the long-term storage pools of wood products and landfilled wood are 18 and 20 MMTC, respectively, for 1997, giving a total carbon sequestration of 209 MMTC (765 $MMTCO_2$), including forest carbon pools (EPA 1999).

A computer-modeling effort at Oak Ridge National Laboratory (Moffat 1997) suggests that planting and harvesting fast-growing forests can tie up even more carbon than mature, protected forests that are left alone. Studies in New Zealand involving *Pinus radiata* found that a radiata pine plantation that is replanted each time it is harvested sequesters 45.3 metric tons of carbon per acre over the 26 years it takes a tree to mature, or 1.7 TC/acre/yr (Marland 1998).

Recent research results from an 8-year-old stand of loblolly pine (*Pinus taeda* L.) growing on an infertile, excessively drained sandy site in Scotland County, North Carolina, indicate that total biomass production efficiency increased 91% with fertilization, 29% with irrigation, and 120% with both fertilization and irrigation. It was hypothesized that the change in total biomass production efficiency may have been a result of greater allocation to foliage (photosynthesizing tissue) and less allocation to fine roots (high-maintenance respiration tissue) under fertilization and irrigation treatments (Albaugh et al. 1998).

In the United States, carbon emissions to the atmosphere from forest harvest and the use of wood products were about 140 MMTC in 1990, the year of the most recent wood product survey. Regrowth of forests offsets a large proportion of the emissions from harvested wood and thus reduces overall emissions from the forest products sector, making most developed countries a net carbon (C) sink (Winjum et al. 1998).

Idle cropland in the United States totaled about 56 million acres in 1995 (Daugherty 1997). (It is projected in IPCC 1996, page 604, that this number will more than double to 128 million acres by 2030, largely because of expected increases in crop yield.) If an area this size were planted in trees (afforestation), and if an average weight of about 2.0 TC/acre, including increases in soil and litter carbon (Lal et al. 1998; Follett 1998; Birdsey 1998; Sampson 1998,— representative of a fertile soil site in the Southeastern U.S.) were stored each year, the total carbon uptake would be about 112 MMTC/yr, or about 8% of total U.S. carbon dioxide emissions in 1992 (Follett 1993). Thus, afforestation in the United States could theoretically increase by about two-thirds (i.e., 112/171) the carbon that is now sequestered in U.S. forests.

It is anticipated that even if all the idle cropland in the United States were available for afforestation, climate and economic, social, and ecological factors would reduce the actual number of acres that could be converted to forest. For example, many of the idle acres of U.S. cropland are in regions with insufficient rainfall to grow trees. (Western Kansas is a good example.) However, it might be feasible to grow perennial grasses (e.g., switchgrass) on such semi-arid land, which would enhance carbon sequestration (Kuch 1998).

Some fraction of the 591 million acres of pastureland and rangeland in the United States could be used for afforestation (Kuch 1998). A discussion of the potential for carbon sequestration on revegetated or set-aside land, degraded land, pastureland, and rangeland is given by Bruce et al. 1998.

In balance, the estimates given in this section are possibly high for this carbon removal and sequestration option.

Biomass-Derived Fuels, Power, and Products

Another way to reduce carbon dioxide emissions is to displace some of the carbon that is now emitted to the atmosphere from the combustion of fossil fuels with carbon derived from renewable resources. Reports indicate that only a very small net atmospheric buildup occurs in biomass combustion (for example, power generation) when the biomass is grown sustainably because released carbon dioxide is largely compensated for by that withdrawn from the atmosphere during photosynthesis (Mann and Spath 1998; Hart 1997; Gill 1997, and Magretta 1997). Displacing a unit of energy from gasoline with a unit of energy from ethanol (derived from lignocellulosics, not corn) in light-duty vehicles results in a 90% reduction in carbon emissions (Tyson 1993). Similar reductions can be expected from other biofuels, such as methanol and biodiesel (CCTS 1997).

Plant matter is associated with three basic crops: cellulosic crops (wood, cotton); starch crops (corn); or oil crops (soybeans). Large-scale displacement of petroleum will rely primarily on low-cost cellulosic feedstocks: starch crops such as corn will play an important transitional role (CCTS 1997). Potential cellulosic biomass sources include municipal solid waste, industrial and agricultural residues, forests, and energy plantations for crops such as switchgrass and hybrid poplar.

Such biomass sources have a distinct potential for renewable energy and bioproduct production even using just a fraction of available land. For example, on a global scale, biofuel production on 10%–15% of the land area currently in agricultural use or in agricultural set-asides could substitute for about 784 MMTC/yr of fossil fuel carbon (IPCC 1996). Substitution estimates are based on assumptions for energy conversion and degree of substitution (energy substitution factor of 0.7 used) for fossil C (IPCC 1996). This estimate does not include the indirect CO_2 offsets of biofuel production through increasing C storage in standing woody biomass, and possibly by increased soil C sequestration. (See Table 5 for an estimate.) Recovery conversion of crop residues could substitute for an additional 150 MMTC/yr of fossil fuel carbon (IPCC 1996). These mid-range values sum to 934 MMTC/yr of fossil fuel carbon that could be displaced by biofuels for the entire globe (Sampson 1999). This value is about 28% lower than the equivalent value given in Paustian et al. 1998, so we underestimate the fossil fuel offset compared to that work. Based on the U.S./global cropland ratio, this roughly translates to 121 MMTC/yr of fossil fuel carbon that could be displaced from U.S. sources. Using the global fossil fuel displacement numbers given in Paustian et al. 1998, this number would be 169 MMTC/yr.

Another way to determine the dedicated energy crop potential for the United States is as follows: For the United States, dedicated energy crop yields of about 2 TC/acre/yr currently are achievable from good cropland (IPCC 1996). In National Research Council 1999 it is estimated that biomass yield per acre could increase four-fold from 2.5 tons/acre currently

to 10 tons/acre with some crops (e.g., switchgrass). If the approximately 56 million acres of idle cropland in the United States in 1995 (12% of total U.S. cropland) were used to plant energy crops, this would yield 113 MMTC/yr fossil fuel carbon offset. Assuming the same ratio of crop residue availability as for global production, the residue is 21 MMTC/yr, yielding a total of 134 MMTC/yr. Applying an energy substitution factor of 0.7, this is about 94 MMTC /yr, or 94/7100, or about 1.3% of the global carbon-offset potential and 94/1501, or about 6.3% of total 1997 U.S. carbon emissions (from carbon dioxide).

Paustian et al. 1998 offer a discussion about increasing agricultural production of biofuels, and we quote an excerpt: "First, the area for biofuel production can be increased by substituting for other agricultural crops (particularly those in surplus) or by intermixing biofuel crops with food or forage crops in an agro-forestry approach. Biofuel crops can also be incorporated into land conservation systems such as windbreaks and shelterbelts within agroecosystems. Unused or abandoned agricultural land can be converted to biofuel production. In addition, there is potential to increase the use of crop residues for biofuels provided this is consistent with the maintenance of adequate levels of soil organic matter and erosion control."

As important as irrigation is to crop growth, that practice inevitably leads to salinization of soil and water, which, in turn, limits or reduces crop yield. As irrigation water evaporates or is taken up by plants, dissolved salts and minerals are left behind, causing deleterious effects. In the U.S., the problem affects some 30% of irrigated lands. In response to this problem, researchers at the University of Toronto have produced genetically modified plants that manage to flourish even when watered with concentrated salt solutions. This recent development could lead to an increase in the available cropland in the U.S. (Apse et al. 1999; Frommer et al. 1999).

Since it is obvious that an accurate number for the total cropland available (from all potential sources) for biomass-derived fuels, power, and products is not available, our use of an approximate number above of 56 million acres seems reasonable to us. (For a discussion about biomass production and carbon offset potential, see Appendix E.)

The above estimates are made without specification as to how the energy crops are to be utilized: whether they would be used to generate electricity by substituting biomass for coal in existing power plants; used alone in power plants that displace new fossil fuel-fired plants; used in gasified form to produce power from advanced gas turbines; used to produce liquid transportation fuels; or used to produce bio-based products. Thus, the estimates for carbon-offset potential given here will be reduced further by thermodynamic constraints and by real-world constraints such as market forces (that are influenced greatly by the prevailing price of a barrel of oil), public policy decisions, and the economics of production, including the cropland quality.

In the appendices of CCTS 1997, carbon reduction estimates were made only on ethanol, using switchgrass as a feedstock at 10% and 95% blends, compared with reformulated gasoline, and with market penetration for these blends of 4 billion gallons in 2010 and other projections for future years. Using these parameters and the low projected price of gasoline, CCTS 1997 concluded that neat ethanol is not cost effective enough to use as a transportation fuel during the next 30-year period. (However, it is estimated in Wooley et al. 1999 that in the near term, using "Best of Industry" technology, the cost of ethanol will be reduced from $1.16/gal currently to $0.76/gal in 2015, a reduction of 34 percent.). For the year 2010, carbon reductions were estimated at 10 MMTC/yr for ethanol, which included biomass-generated electricity returned to the grid from ethanol plants, and 15 MMTC/yr for biopower applications. The sum of these estimates of carbon offset (25 MMTC/yr) is about one-quarter of the estimate based on technical potential as reported in IPCC 1996 and adapted to the United States in this work (94 MMTC/yr).

Yet another way to reduce atmospheric carbon is to produce materials that are made from biomass, which has the effect of directly displacing fossil fuel-derived products and the carbon release that is associated with their production. An associated benefit is that biomass-derived products (e.g., wood products) can typically be produced using much lower energy inputs than traditional alternatives such as those made from metals, cements, or petrochemicals (Bowyer 1993). A further benefit is that the carbon is sequestered for long periods of time in the bio-products themselves, before it is released back into the atmosphere through biological decay or other oxidative processes. Substitution of bio-based products for fossil fuel-based products has the potential to reduce greenhouse gas emissions by 3.5 MMTC by 2010 (CCTS 1997), which translates to 0.2% of total carbon emissions by the United States and 0.04% total global carbon emissions, based on 1997 carbon emission data.

Another consideration in the economic use of biomass for fuels, power, and products in the United States is that only a fraction of the idle cropland would be available since such cropland is typically found in small parcels that are physically scattered from one another (Follett 1998).

Conservation Tillage and Residue Management

Losses of soil carbon as a consequence of cultivation are ubiquitous and well documented (IPCC 1996). Historical losses of carbon observed in many soils were due, in part, to low production levels, erosion, inadequate fertilization, removal of crop residues and other biomass, and intensive tillage. In general, high residue production, perennial forage crops, elimination of bare fallow, and reduced tillage will promote sequestration of soil organic carbon.

Maintaining and increasing soil organic matter (SOM) adds to soil fertility, water retention, and crop production. Recently, many soil scientists have suggested that the sequestration of atmospheric carbon dioxide in SOM could also contribute significantly to attempts to adhere to the Kyoto Protocol. Conversion of large areas of cropland to conservation tillage, including no-till practices, during the next 30 years could sequester all the CO_2 emitted from agricultural activities and up to 1% of today's fossil fuel emissions in the United States (Schlesinger 1999). From Table 2 of this document, this amount of carbon is 44 MMTC from U.S. agriculture and 11 MMTC

Table 4. World and U.S. land area and cropland area

	Land area (millions of acres)	Cropland (millions of acres)
World	32,213	3560
United States	2264	464
U.S. fraction of world (%)	7	13

Source: United Nations 1994.

Table 5. Enhanced carbon sequestration using improved cropping practices

Practice	MMTC/yr
Fertilizer management	12
Organic manures and by-products	6
Rotation and winter cover crops	10
Summer fallow elimination	2
Management of rice straw	1
Idle land conversion to biofuels: increased soil organic carbon	4
Total	**35**

Source: Lal et al. 1998. Technical and economic feasibility are not always well differentiated.

Assuming a recovery of one-half to two-thirds of historic carbon losses as a reasonable upper limit, the global potential for carbon sequestration in cultivated soils over the next 50 years would be approximately 20 GTC (IPCC 1996). Paustian et al. 1997 estimate this value to be 20-30 GTC over the next 50-100 years. Because U.S. cropland area is 13% of the world value (See Table 4), total carbon sequestration over 50 years in the United States would be 2600 MMTC, or an average annual rate of 52 MMTC/yr. A recent estimate focused on U.S. cropland reports this number to be about 71 MMTC/yr, or about 4% of the total U.S. carbon emission in 1997 if conservaton tillage were to be widely adopted on U.S. cropland for 25 years (Lal, et al. 1998).

Improved Cropping Systems

These systems represent current technologies that can be applied more effectively using existing techniques. Adoption of improved cropping systems has vast potential for increased carbon sequestration in agricultural lands already in use. An important component of best management practices (BMPs) is increasing the efficiency of fertilizer use. Improved cropping systems and more efficient fertilizer use are integral components of increased productivity of agricultural lands. Components of improved cropping systems are shown in Table 5 and discussed at length in Lal et.al. 1998, to which the reader is referred for a more in-depth treatment than was possible in this white paper. Estimates of the potential for enhanced carbon sequestration achievable using these techniques are given in Table 5.

Improved Irrigation and Water Management

The basic idea of this approach to enhancing soil organic carbon is to convert less-productive soils to economic cropland using irrigation. This practice can result in large increases in biomass production both above and below ground. A good example of this is the irrigated farming practiced in California, Texas, and other arid and semiarid regions. There are a variety of irrigation techniques that are employed, including drip, sprinkler, flood, and others. In flood irrigation, residue-free level land is required. No-till technology for such irrigated systems is of questionable applicability using current technology. It is estimated that the total potential of irrigated cropland in carbon sequestration is about 4 MMTC/yr in soil carbon sequestration (Lal et al. 1998).

Opposite to irrigation is the drainage of seasonally wet agricultural land, which leads to a net loss in soil organic carbon. Drained soil has a lower soil organic content than undrained soil for all tillage methods, but is best managed with conservation tillage. Lal et al. 1998 estimated that improved management of drained cropland would lead to about a 4 MMTC/yr increase in soil carbon sequestration.

Advanced Agricultural Systems

Agricultural managers have for decades taken advantage of new technologies, including information technologies, that enabled better management decision making and improved economic efficiency of operations. The extent and rate of change now occurring in the development of information technologies have opened the way for significant change in crop production management and agricultural decision making (National Research Council 1997). These technologies represent advanced,

from fossil fuel emissions, summing to 55 MMTC. Although our own estimate of 52 MMTC/yr agrees closely with Schlesinger's estimate, the value we use in Appendix C, 71 MMTC (see below), exceeds this value since it is the Lal et al.1998 estimate, which is based upon widespread adoption of conservation tillage. Beyond conservation tillage, however, many of the techniques recommended to increase carbon sequestration in soils contain hidden carbon "costs" in terms of greater emissions of CO_2 to the atmosphere (Schlesinger 1999).

For the first time, U.S. farmers are planting more acres to crops using conservation tillage methods than traditional methods. In 1997, 37.3 percent of U.S. cropland was planted in no-till, ridge-till, and mulch-till systems compared to 36.5 percent conventionally tilled or plowed. The achievement represents a gain of 5- to 6-million acres (*The Kiplinger Agricultural Letter* 1998; Purdue 1998). Conservation tillage leaves at least 30 percent of the field covered with residue from previous crops after planting. Although no-till systems are setting the pace, reduced till is also on the rise. This method leaves 15%–30% residue on the land (See Appendix A for a more complete description). Increases in the soil organic carbon pool are nonlinear with time, increasing very slowly for several years and then displaying rapid growth over the next several years, increasing over a period of 25 to 50 years (Lal et al. 1998).

site-specific technologies that could be used to improve cropping and other agricultural systems.

One of today's major goals is to optimize nutrient, water, and pesticide inputs to crops. Some components of advanced agricultural systems such as use of global-positioning systems to map yields are in or close to commercial use, whereas others such as real-time monitoring of water and nutrient status are not. Fertilizer delivery and the fate of applied chemicals have been significantly improved over the last 10 years, but advances in areas such as biologically released fertilizers and control of microbial processes still require significant efforts. Detailed real-time and small-area geographic matching of fertilizers and other agricultural chemicals to plant requirements are in the early stages of development. Technologies involving biocontrol of pests are evolving and some are to the point of commercial development.

Estimates derived in the Climate Change Technology Strategy report to the U.S. Department of Energy (CCTS 1997) indicate that by the year 2010 a reduction of about 1.5 MMTC/yr could be achieved through the use of advanced, site-specific information technologies. This translates into about a 0.1% decrease in total carbon emission for the United States and about a 0.02% decrease in global carbon emissions to the atmosphere.

Because agricultural information is so ubiquitous, it is not possible to state with certainty the impact of new information-based technologies on greenhouse gas emissions. Indeed, enhanced information can be used to manage other production systems, such as livestock and forestry, in addition to crop production. Thus, the overall impact of information technologies could be enhanced by their use beyond crop production.

A summary comparing all of the major carbon dioxide mitigation options for agriculture in the United States is given in Table C1 of Appendix C.
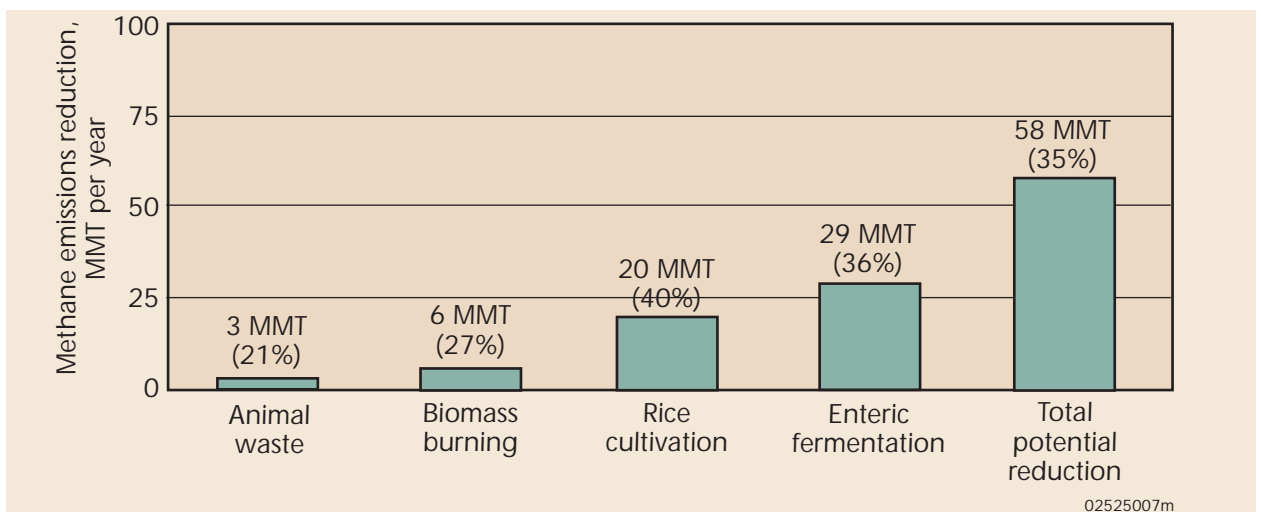
Methane

The current global average atmospheric concentration of methane is 1720 ppbv, more than double its pre-industrial value of 700 ppbv. About 70% of global methane production arises from anthropogenic sources and about 30% from natural sources. Agriculture is considered to be responsible for about two-thirds of the global anthropogenic sources of methane (Duxbury and Mosier 1993). In the United States, agriculture contributes about 30% of anthropogenic methane gas emissions. U.S. anthropogenic sources of methane gas emission are shown in Figure 5. The primary sink for methane is oxidation with hydroxyl radicals (OH) in the troposphere; in addition, soil provides an aerobic sink for about 10%–20% of methane emissions.

Global methane emissions could be reduced by improved nutrition of ruminant animals, which reduces enteric fermentation, and better management of rice-paddy fields. Additional methane decreases are possible by altered treatment and management of animal wastes and by reduction of biomass burning. These combined practices could reduce methane emissions from agriculture by 15%–56% (IPCC 1996). The potential for reducing global
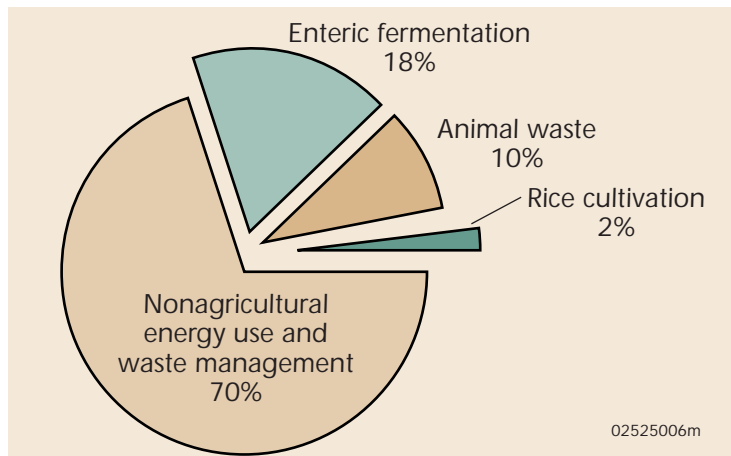
Figure 5. U.S. methane gas emissions from anthropogenic sources. Source: Table 6 (Adapted from DOE/EIA 1998).

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Figure 6. Global comparative estimates of the effect of mitigation options on reducing anthropogenic methane gas emissions (in millions of metric tons of methane gas per year) and their equivalent percentage decrease from global emission levels for each category. Source: Adapted from IPCC 1996.

Table 6. U.S. methane emission from agricultural sources

| Source | Methane emitted (1997) | | Carbon dioxide equivalent[1] | Carbon equivalent[2] |
	Millions of metric tons	% of U.S. total	Millions of metric tons	Millions of metric tons
Enteric fermentation	5.36	18.41	112.56	30.70 {34.1}
Animal waste	2.77	9.52	58.17	15.86 {17.0}
Rice cultivation	0.43	1.48	9.03	2.46 {2.7}
Biomass burning	0.04	0.14	0.84	0.23 {0.2}
Total agricultural sources	8.6	29.55	180.6	49.25 {54.0}
Total from all U.S. sources[3]	29.11		611.31	166.72 {179.6}

Source: Adapted from DOE/EIA 1998. Numbers in parentheses { } are from EPA 1999.

[1] Carbon dioxide equivalent is calculated by multiplying the source concentration by the global warming potential for 100 years, which, for methane, is 21.

[2] Carbon equivalent is calculated by multiplying the carbon dioxide equivalent by 12/44.

[3] Other U.S. sources of methane emission include energy use and waste management, which contribute approximately equal amounts to the atmospheric methane inventory.

methane emission from anthropogenic sources is shown in Figure 6.

Enteric Fermentation

Major sources of U.S. methane emissions are shown in Table 6. The most significant methane reduction opportunities for U.S. agriculture are in emissions from livestock. Technically feasible and cost-effective strategies exist to reduce methane emissions per unit of milk and meat produced in the United States. About one-third of the emissions reduction per unit of product are estimated to be from the dairy industry, whereas two-thirds are from the beef industry (EPA 1993).

Methane is produced when carbohydrates are broken down in the digestive tract of animals. The volume of methane produced from this process, called enteric fermentation, is largest in those animals that possess a rumen, or forestomach, such as cattle, sheep, and goats. The forestomach allows these animals to digest large quantities of cellulose found in plant material. Microorganisms in the rumen, some of which are methanogenic bacteria, accomplish this digestion. These bacteria produce methane while removing hydrogen from the rumen. About 90% of the methane produced by the methanogenic bacteria is released through normal animal respiration and eructation. The remainder is released as flatus (DOE/EIA 1996). In the U.S., cattle are the source of 95% of enteric fermentation emissions and 44% of emissions from animal waste (DOE/EIA 1998).

Biomass burning associated with agriculture also contributes to the global methane budget.

Dairy Industry

Significant improvements in milk production per cow are anticipated in the dairy industry as the result of continued improvements in management and genetics.

By increasing milk production per cow, methane emissions per unit of milk produced declines (EPA 1993).

Beef Industry

The main options for reducing methane emissions from the beef industry are the refinements to the marketing system and improved cow-calf sector performance. The refinements to the marketing system are needed to promote efficiency (which will reduce methane emissions by eliminating unnecessary feeding) and shift production toward less methane-emissions-intensive methods. To be successful, the refinements to the marketing system require that the information flow within the beef industry be improved (EPA 1993).

Improvement in the quality of pastureland and grazing lands would yield reductions in methane emission through better digestion, and it would increase the rate of carbon sequestration (Kuch 1998).

Methane emissions from U.S. livestock and profitable emissions reductions are shown in Table 7.

Animal Waste

Methane is produced during the anaerobic decomposition of the organic material in livestock and poultry manure. (Anaerobic decomposition is a microbiological process that occurs in an oxygen-free environment.) Liquid-based livestock manure systems such as anaerobic lagoons produce about 80% of the total. Methane recovery systems can collect the methane produced by liquid manure management systems so that the methane can be used as a fuel. With methane recovery systems it is technically feasible to reduce total methane emissions from livestock manure by 80% to about 0.6 MMT. Although it is technically feasible for virtually all farms using liquid-based manure management systems, methane recovery systems are only profitable for large farms in warm climates. At these farms, it is profitable to

Table 7. Methane emission from U.S. livestock and profitable emissions reduction

Year	Baseline emissions (MMT)		Profitable emissions reduction (MMT)		Profitable emissions reduction (%)	
	Low	High	Low	High	Low	High
2000						
Dairy Industry	1.4	2.0	0.3	0.5	21	25
Beef Industry	3.4	5.5	0.8	1.2	24	22
Other	0.2	0.4	0.0	0.0	0	0
Total	5.0	7.9	1.1	1.7	22	22
2010						
Dairy Industry	1.4	2.4	0.4	0.7	30	30
Beef Industry	3.1	5.4	0.7	1.2	23	22
Other	0.2	0.4	0.0	0.0	0	0
Total	4.7	8.2	1.1	1.9	25	23

Source: EPA 1993, Exhibit 5-1, p. 5-3. This EPA report evaluates options for reducing methane emissions from anthropogenic sources in the U.S. and presents estimates for the portion of current and future emissions that could be reduced through the use of such options. The report was written in partial fulfillment of Section 603 of the Clean Air Act Amendments of 1990, which requires that the EPA prepare and submit to Congress a series of reports on domestic and international issues concerning methane. See Appendix A for definitions of terms used in this table.

Table 8. Methane emission from U.S. livestock waste and profitable emissions reduction

Year	Emissions without recovery (MMT)			Profitable emissions reductions (MMT)		
	Dairy	Swine	Total	Dairy	Swine	Total
2000	1.7	2.6	5.6	0.4 (24%)[1]	0.4 (15%)	0.8 (14%)
2010	2.0	2.6	6.0	0.5 (25%)	0.5 (19%)	1.0 (17%)

Source: Adapted from EPA 1993, Exhibit 6-1, p. 6-4.

[1] Numbers in parentheses are the percent reduction based on the corresponding "Emissions Without Recovery" values displayed in the left side of the table.

collect the methane and use it to meet a portion of the farm's energy requirements.

Estimates of potential methane emission reduction achievable through application of methane-capture technology are given in Table 8.

Methane emissions reduction from advanced livestock management, which includes methane emissions from livestock and livestock waste, can be calculated in terms of the carbon equivalent of methane. The total methane emission reduction in 2010 is estimated to be 2.9 million metric tons, obtained from the best-case scenarios of Tables 7 and 8. This value was converted to carbon equivalent (2.9 x 21x12/44 = 16.6 MMTCE) and is shown in percentage form in Table C1 of Appendix C.

Nitrous Oxide

Soil Nitrogen

On a global scale, agricultural practices contribute approximately 70% of anthropogenic nitrous oxide emissions (DOE/EIA 1998). These emissions occur primarily through decomposing organic matter in soil as it undergoes a series of oxidative and reductive processes, called nitrification and denitrification, respectively (Smith et al. 1997). However, it is the reductive process, denitrification, that is responsible for the primary loss of gaseous nitrogen (N) compounds to the atmosphere (CAST 1992). In denitrification, nitrate ion (NO_3-) is reduced first to nitrite (NO_2-), then to nitric oxide (NO), then to nitrous oxide(N_2O), and finally to nitrogen (N_2). In addition to requiring an oxygen-poor environment, denitrification most often also requires effective microbes, reducing agents such as organic carbon, and oxides of nitrogen to proceed (CAST 1992). It is the loss of N as N_2O (and not as N_2) that is of concern, because of the large global warming potential of nitrous oxide. Nitrous oxide is destroyed primarily by photochemical decomposition in the stratosphere (IPCC 1996a).

Anthropogenic activities account for both direct and indirect nitrogen additions to soils. Direct additions occur through cropping practices such as the application of synthetic nitrogen and organic fertilizers, production of nitrogen-fixing crops, and cultivation of high organic soils, called histols, and through livestock waste management. Previous estimates of N_2O emissions from U.S. soils included only those that result from the application of synthetic and organic nitrogen fertilizer on the soil. More recent estimates (EPA 1999) also include direct soil emissions from animal production (livestock wastes that are spread on cropland and pasture or that are deposited by

grazing livestock in pastures and paddocks) and emissions from soils indirectly induced by agricultural activities.

Indirect sources include volatilization and subsequent atmospheric deposition of NH_3 and NO_x that originate from the application of fertilizers and the production of livestock wastes, both of which result in further soil additions through surface runoff and leaching of nitrogen. As a result of these newly considered sources of N, the new estimates of N_2O are more than twice as large as previous estimates (EPA 1999).

Estimates of the effects of irrigation, tillage practices, and fallowing of land were not included in EPA 1999 because of the significant uncertainties in N_2O fluxes associated with these practices.

Important variables that control the rates of production of N_2O are soil water content, which regulates oxygen supply; temperature, which controls rates of microbial activity; nitrate or ammonium concentration, which regulate reaction rates; available organic carbon, which is required for microbial activity; and soil pH, which is a controller of both nitrification and denitrification rates and the ratios of N_2O/N_2 (EPA 1999). Because interactions among the physical, chemical, and biological variables are complex, N_2O fluxes from agricultural systems are highly variable in both time and space. Consequently, the prediction of nitrous oxide emissions associated with a unit of N applied to a specific field or fixed by legumes is not yet reliable.

Animal Waste

Another category included in EPA 1999 is N_2O produced as part of the agricultural nitrogen cycle through the denitrification of the organic nitrogen contained in animal manures. This nitrous oxide differs from that discussed in the previous section because it consists of livestock manures that are managed using liquid and slurry systems, as well as manures that are collected and stored, whereas the previous section addressed only unmanaged livestock manures on pastures, ranges, and paddocks.

Biomass Burning

Nitrous oxide is also directly evolved during biomass burning, and is produced in soil after burning. However, in the United States, field burning is not a common method of agricultural residue disposal and N_2O emissions from this source are not significant (<0.1%). (More typically, agricultural residues are plowed back into the field, composted, landfilled, or collected and used as fuel or as feedstock for the production of chemicals and materials.)

Discussion

In the United States, most anthropogenic nitrous oxide emissions can be attributed to energy-related and agricultural sources. Agricultural sources account for 71% of the total U.S. emission of nitrous oxide, with energy use and industrial emissions accounting for the remaining 29% (See Figure 7).

Table 9 gives U.S. nitrous oxide emission from agricultural sources and Figure 8 shows the estimated decrease in global N_2O emissions for various mitigation options followed on a worldwide scale.

The underlying concept of limiting N_2O emissions is that if fertilizer N (all N applied to improve crop growth) is utilized better by the crop, the amount of N needed to meet the increasing demand for food will be less. Therefore, less N_2O will be produced and less N will leak from the system (IPCC 1996). Thus, the key to decreasing nitrous oxide emissions is improving the efficiency of utilization of nitrogen fertilizer by plants.

The author did not find estimates of potential reductions in U.S. nitrous oxide emissions while preparing this white paper. However, an estimate of U.S. nitrous oxide reduction potential can be obtained from Table 2 and Figure 8 by taking the ratio of the U.S. agriculture-to-global carbon equivalent emissions shown in Table 2 (0.077/0.507 = 0.15), and then multiplying that ratio by the estimated carbon equivalent of total global emission reduction for nitrous oxide (0.71 x 310 x 12/44 = 60.03 million metric tons) shown in Figure 8. This calculation yields an estimated reduction (admittedly overestimated) of 9.1 million metric tons of carbon equivalent for the United States alone, which is (9.1)/1789 x 100 = 0.51% of the total U.S. carbon equivalent emissions for the three greenhouse gases.

In summary, we found that nitrous oxide emissions were the most troublesome ones for which to obtain information. In addition, the information that was obtained is of questionable accuracy. However, inclusion of nitrous oxide in the Kyoto Protocol and revised emissions factors that doubled its share of U.S. emissions have increased the attention given to nitrous oxide. As a result the uncertainty of future estimates is likely to be reduced (DOE/EIA 1998).

RESEARCH NEEDS

The IPCC 1996 notes that there are deficiencies in our collective scientific understanding of greenhouse gas processes, as well as inadequacies in the information base needed to apply the knowledge that we do have. They conclude that the most pressing problem, however, is not a lack of adequate scientific understanding, but rather a lack of baseline data in an organized and useable format. With that in mind, they propose the following three major focus areas for compiling and analyzing baseline information.

Bioenergy and Biomaterials Production from Agricultural Land

Research needed to improve assessments of CO_2 mitigation potential through increased use of
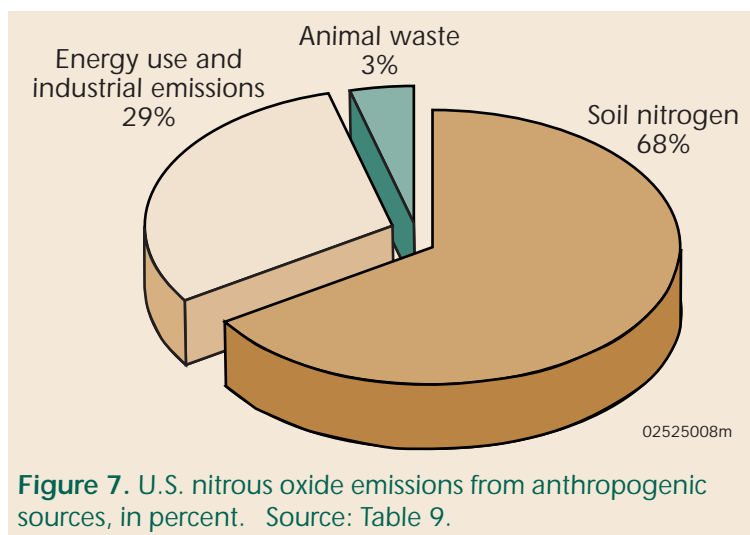
Figure 7. U.S. nitrous oxide emissions from anthropogenic sources, in percent. Source: Table 9.

Pie chart labels:
- Energy use and industrial emissions 29%
- Animal waste 3%
- Soil nitrogen 68%
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Table 9. U.S. nitrous oxide emission from agricultural sources in 1997 (MMTCE)

| Source | Nitrous oxide emitted (1997) | | Carbon dioxide equivalent | Carbon equivalent |
	Thousands of metric tons	Percent of U.S. total	Millions of metric tons	Millions of metric tons
Soil nitrogen	876.2	67.98	271.6	74.1
Animal waste	35.8	2.78	11.1	3.0
Crop residue burning	1.6	0.12	0.5	0.1
Total U.S. agricultural sources[1]	914	70.91	283.3	77.3
Total from all U.S. sources[2]	1,289		399.6	108.9

Source: Adapted from EPA 1999.

biomass includes: (1) improved information on the actual carbon feedstock value of forest, agroforestry, and agricultural management systems; (2) better data on energy inputs for the production of plant-derived goods and chemicals; (3) better data on land availability for bioenergy and biomaterials production, including cultural, social, and political factors that may preclude some lands from use for C offset projects; and (4) better data, including economic analyses, for the use and efficiency of biofuels.

Carbon Sequestration in Agricultural Systems

The assessment of potentials to increase carbon stocks in agricultural systems could be improved by using a structured, model-based analysis with global coverage. Suitable models for such a task currently exist and have been used for regional-level analysis. The elements that are lacking are (1) spatial databases linking climate, soils, and land use and management, which are needed as model inputs; and (2) reliable experimental data to calibrate and/or verify model predictions. A compilation of agricultural land-use

information to develop a classification and mapping of agroecological/management zones for the world is much needed. Existing long-term agricultural experiments can provide information to evaluate model predictions for different management systems and soil and climate conditions. Efforts are underway to establish networks of long-term experiment sites and data, but they are still at an early stage.

CH$_4$ and N$_2$O Emissions from Agricultural Lands

Existing data need to be applied to validate and calibrate process-based models. Model estimates of gas fluxes should incorporate soil, cropping system, climate, and fertilizer management influences. Field data on gas fluxes are still woefully inadequate. Research needs include year-round field flux measurements in a variety of soils, climates, and cropping systems to compare the impact of management on gas fluxes and to determine the tradeoffs between CH$_4$ and N$_2$O flux when management options are exercised.
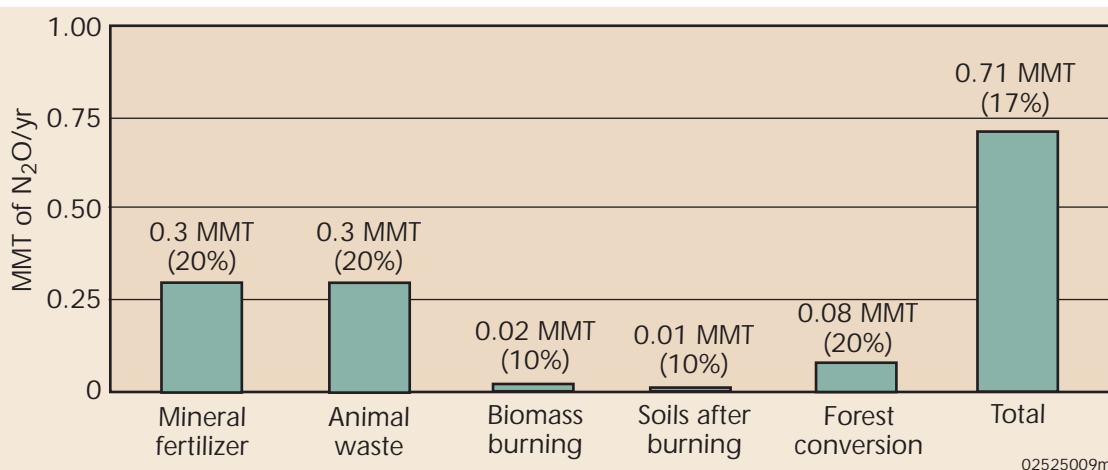
Figure 8. Estimated global mitigation potentials for reducing N$_2$O emission (in millions of metric tons of N$_2$O per year) and their equivalent percentage decrease from global N$_2$O emission levels in each category. Source: Adapted from IPCC 1996.

3. FOOD-MANUFACTURING EMISSIONS

CARBON DIOXIDE

Over the past few years, food and kindred products generated annually about two-thirds as much carbon dioxide as did all us agricultural sources (Figure 9). In this section, we examine carbon emissions of the food and kindred products sector in more detail.

In our literature search, we did not find specific data on greenhouse gas emissions in the food-manufacturing sector. Extensive data do exist, however, on energy consumed by the food and kindred products sector, through data published by the U.S. Departments of Energy and Commerce. Thus, it was necessary to calculate greenhouse gas emissions from energy consumption data.

Although other greenhouse gases might be emitted to the atmosphere during the manufacturing of food and kindred products, we assumed that the primary greenhouse emission is carbon dioxide. This greenhouse gas is created through the combustion of fossil fuels directly, for example, in pasteurization, heat treatment, evaporation, concentration, or indirectly for the production of electricity used for refrigeration and freezing.

We followed the approach taken by Marland and Pippin 1990, in which the amount of CO_2 emitted to the atmosphere during food manufacturing is estimated by converting fuel consumption data to joules and using "carbon coefficients" in units of $kgC/10^9$ joules to estimate carbon dioxide emissions. This requires knowledge of the quantity of fuel burned, the carbon content of that fuel, and the efficiency of combustion. A complete energy balance is required, as are summary data on fuel chemistry, and an estimate of the efficiency of fuel oxidation, and the fate of unoxidized materials and non-fuel products of fossil fuels. We calculated carbon dioxide emissions for the U.S. manufacturing sector using this procedure. (See Figure 10 for a breakdown of the sources of these emissions.)

Energy sources for the food and kindred products industry include electricity, residual fuel oil, distillate fuel oil, natural gas, liquid petroleum gas (LPG), and coal. We used energy consumption data from the Energetics, Inc., 1990 report for this white paper. Although the historical data contained in that report are now dated, only the projections for the year 2010 were used to estimate carbon emission reduction (Table C1 of Appendix C.)

In Table 10, historical and projected domestic energy consumption data for the U.S. food and kindred products sector were converted to carbon emissions using the carbon coefficient

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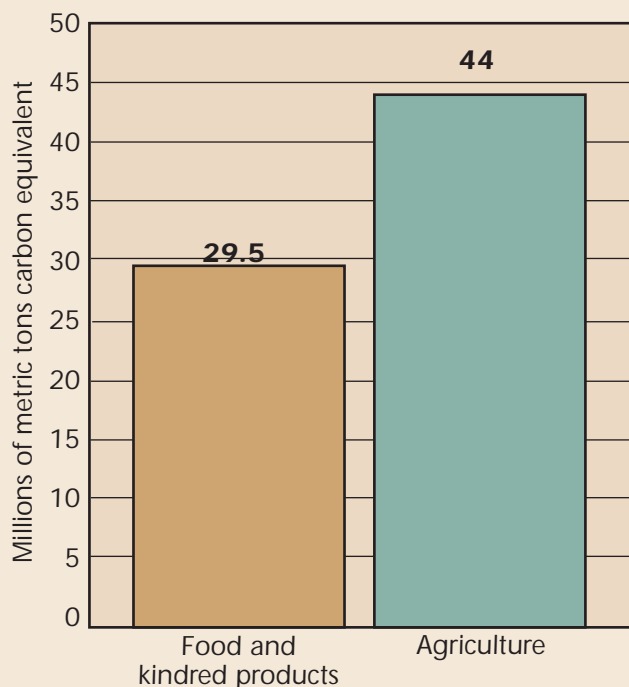
Figure 9. Comparison of carbon dioxide emissions in millions of tons of carbon equivalent emitted into the atmosphere. The food and kindred products data was from Table 10 using the 1994 data. The agriculture data was from Table 2 for all U.S. agricultural sources for 1997.

method outlined above and translated, for our purposes, into MMTC/quad.

Because the baseline data for Table 10 were developed in 1990, years shown in parentheses were projections made at that time. Actual 1994 data are shown for comparison purposes.

A graphical representation of the carbon emissions data in Table 10 is presented in Figure 11 for the years 1985 and 2010.

We obtained data on future carbon emission reductions for the 13 main food-processing sub-industries by converting the energy use estimates in Energetics 1990 to carbon emission estimates. Only the technology scenario represented as "100% advanced" was used to estimate carbon emission reductions in the year 2010, because that scenario represents the maximum reduction found possible by Energetics 1990. Table 11, which represents 13 food-processing sub-industries and is a subset of Table 10, gives the numerical carbon emission reductions, and Figure 12 is a graphical representation of the carbon emission reduction. The total carbon emission reduction (6.688 MMTC) is shown in a percentage representation in Summary Graphic C in the Executive Summary of this white paper.

The three technology scenarios described in Energetics 1990 are:
1. Current practices: Continuation of the technology used today.
2. Business as usual: Uses 30% current technology, 45% state-of-the-art technology, and 25% advanced technology. This is supposedly the "most likely" mix of current, state-of-the art, and advanced technology and forecasted production level and mix in 2010.
3. Advanced: Use of 100% advanced technologies. These technologies are conceptual or under development and have not yet reached pilot-plant scale, but have potential for industry acceptance.

The projections given for future reduction of carbon emissions in food manufacturing should be viewed as the best that can be done, not necessarily what will be done, because they are based on the use of "100% advanced technology" in the year 2010. In some sectors of food manufacturing (especially canning, freezing, baking, and drying), new technologies tend to be implemented slowly due to capital cost requirements. Even the 30%/45%/25% "Business as Usual" technology mix identified above and quantified in Table 11 may not be accurate for
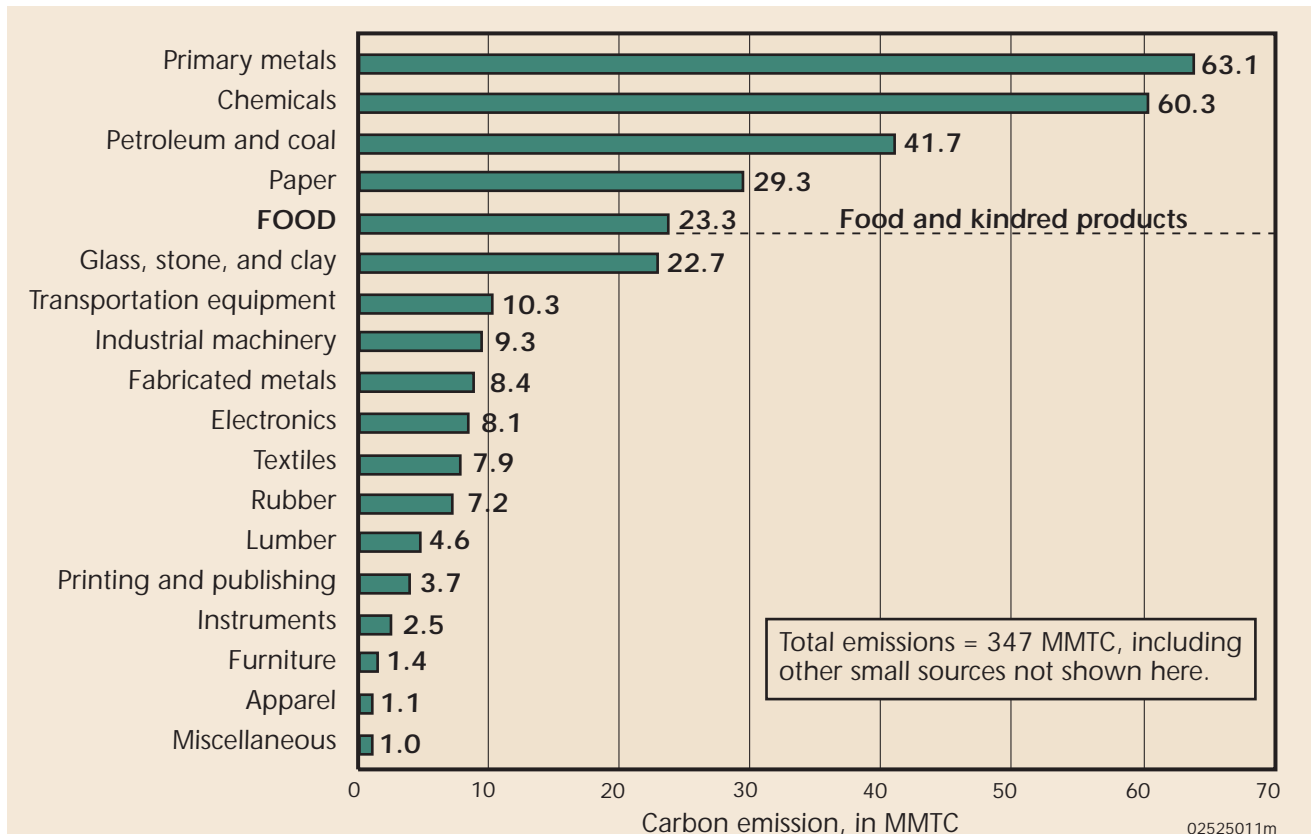
Figure 10. Carbon dioxide emissions from the U.S. manufacturing sector in 1987, given in MMTC
Source: Marland and Pippin 1990.

Table 10. Historical and projected carbon emissions for the U.S. food industry, in MMTC

Year	Electricity[1]	Natural gas	Oil	Coal	LPG	Other	Total
1975	6.4	10.0	3.5	1.9	0.1	0.0	21.9
1980	6.9	10.5	2.4	2.5	0.1	0.7	23.1
1985	7.6	9.6	1.4	2.4	0.2	2.3	23.5
(1990)[2]	8.2	9.7	0.3	2.8	0.2	3.3	24.5
1994 Actual[3]	9.8[A]	12.6	1.0[B]	3.3	N/A	2.8[C]	29.5
(1995)	8.8	9.5	0.0	3.1	0.2	3.7	25.3
(2000)	9.4	9.2	0.0	3.4	0.2	3.8	26.0
(2005)	10.0	9.0	0.0	3.6	0.3	3.9	26.8
(2010)	10.6	8.8	0.0	3.9	0.3	4.0	27.6

Source: Carbon emissions were calculated using the carbon coefficient method applied to energy use (first use). Energetics 1990 was used for the Historical and Projected Energy Use for the U.S. Food Industry (Table 10 in that reference) and Marland and Pippin 1990 for the derived average carbon coefficient of 20 MMTC/quad at 99% combustion efficiency for hydrocarbon fuels. (This carbon coefficient differs slightly from the value of 21 at full combustion derived from EIA 1996.) A different average carbon coefficient was used for those processes that use predominantly electrical energy: 16 MMTC/quad, derived from Marland and Pippin 1990.

[1] Gross electricity use, which includes all the energy that was used to produce the electricity less transmission losses. Gross electricity is associated with the conversion factor (10,500 Btu/kWh) and net electricity is associated with the conversion factor (3412 Btu/kWh). Net electricity use is obtained by summing purchases, transfers in, and generation from noncombustible renewable resources, minus quantities sold and transferred out. It does not include electricity inputs from outside cogeneration or generation from combustible fuels because that energy has already been included as generating fuel (for example, coal) (Pellegrino 1998).

[2] Data for years in parentheses are projections from Energetics 1990 report.
  1 quad = 1 quadrillion Btus = 10^{15} Btus

[3] MECS 1994.

[A] The MECS 1994 net electricity value was converted to gross electricity by applying the scaling (net electricity) x (10,500/3412) = Gross electricity.

[B] "Distillate Fuel Oil" includes Nos. 1, 2, and 4 fuel oils and Nos. 1, 2, and 4 diesel fuels.

[C] "Other" includes net steam (the sum of purchases, generation from renewables, and net transfers), and other energy that respondents indicated was used to produce heat and power or as feedstock/raw material inputs.
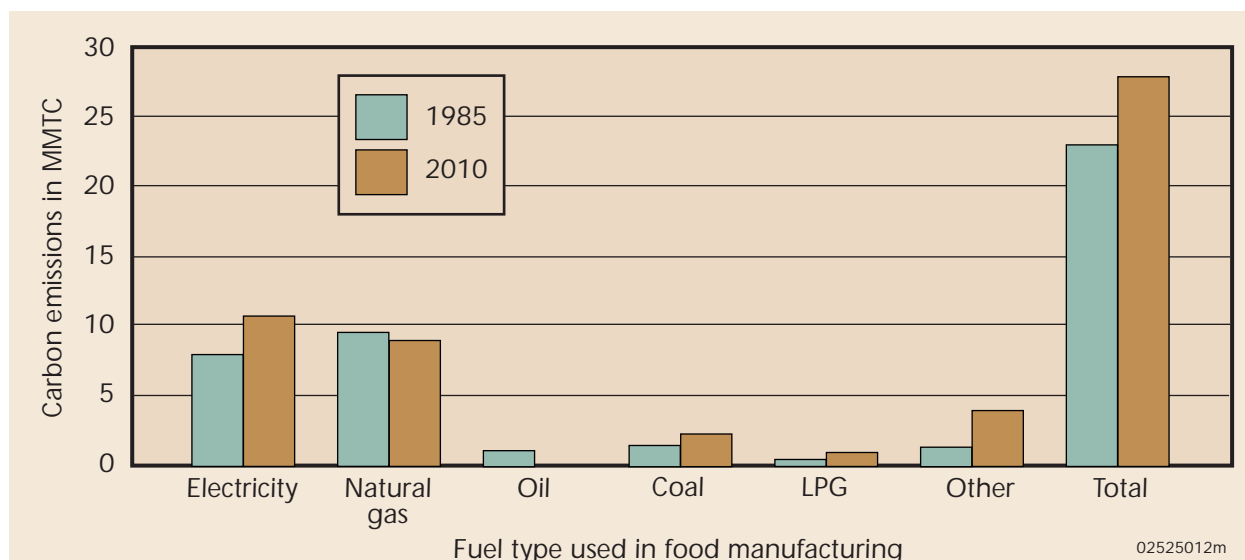
Figure 11. Carbon emissions to the atmosphere by fuel type in the manufacturing of food and kindred products, in millions of metric tons. 2010 estimates are based on a linear regression projection of historical data and a total energy use of 1.5 quads for SIC-20 (Standard Industrial Classification) in that year. Source: Adapted from Energetics 1990 and Table 10.

Table 11. Summary of energy use and potential savings in the year 2010 for three technology-use scenarios; and carbon emission reduction for 100% advanced technology use in the year 2010

Process	Energy use (10^{12} Btu) in 2010					Carbon emissions reduction in 2010	
	Current practices	Business as usual		100% advanced		Carbon coefficient (MMTC/quad)	Carbon emission[1] reduction (MMTC)
	Use	Use	Savings	Use	Savings		
Evisceration	21.3	13.8	7.5	4.2	17.1	20	0.342
Rendering	17.7	11.3	6.4	1.8	15.9	20	0.318
Cooking	37.4	26.6	10.8	5.0	32.4	20	0.648
Baking	16.7	13.2	3.5	7.1	9.6	20	0.192
Exhausting	6.6	3.6	3.0	0.2	6.4	20	0.128
Heat treatment/ pasteurization	40.7	24.7	16.0	3.7	37.0	20	0.740
Evaporation/ concentration	103.7	73.8	29.9	29.1	74.6	20	1.492
Conditioning	11.7	8.4	3.3	1.0	10.7	20	0.214
Drying	90.5	60.3	30.2	4.7	85.8	20	1.716
Chilling/cooling/ refrigerating	44.6	28.7	15.9	3.0	41.6	16	0.666
Freezing	16.2	10.9	5.3	1.7	14.5	16	0.232
TOTAL	**407.1**	**275.3**	**131.8**	**61.5**	**345.6**		**6.688**

Carbon Emissions Reduction in % of 1997 Total U.S. CO_2 Emissions (1501 MMTC) =   0.45%

Carbon Emissions Reduction in % of 1992 Total Global CO_2 Emissions (7100 MMTC) =   0.09%

Source: Adapted from Energetics 1990 and Marland and Pippin 1990.

1 Uses an average carbon coefficient of 20 MMTC/quad at 99% combustion efficiency for hydrocarbon fuels derived from Marland and Pippin 1990. This carbon coefficient differs slightly from the value of 21 at full combustion derived from EIA 1996. In producing Table 11, a different average carbon coefficient was used for those processes that use predominantly electrical energy. The carbon coefficient used for electrical energy (gross electricity) is 16 MMTC/quad, derived from Marland and Pippin 1990.
1 quad = 1 quadrillion Btus = 10^{15} Btus

these segments. Adaptation of new technology is especially slow in the seasonal, commodity-based portion of the food industry because it is difficult to justify significant expenditures for costly new technology when equipment may be utilized only a few months a year.

The principal factor driving reductions in carbon and other greenhouse gas emissions in the food industry is cost savings through more efficient use of energy, as is probably the case in most other industries. It is also difficult to determine the impact that advances in biotechnology will have on the industry, or on agriculture in general. By 2010, new crops and cropping systems may be available. Also, a greater variety of nontraditional foods (e.g., nutraceuticals) may constitute a significant portion of the diet. The impact of these new materials on energy requirements is difficult to predict.

RESEARCH NEEDS

We obtained information in this section from the Food Manufacturing Coalition (FMC), an ongoing, industry-driven technology transfer program sponsored by the EPA and the USDA. It is hosted by the University of Nebraska's Lincoln Food Processing Center (Taylor 1998).

Through extensive surveys and focused prioritiza-tion of generic technology needs, industry experts
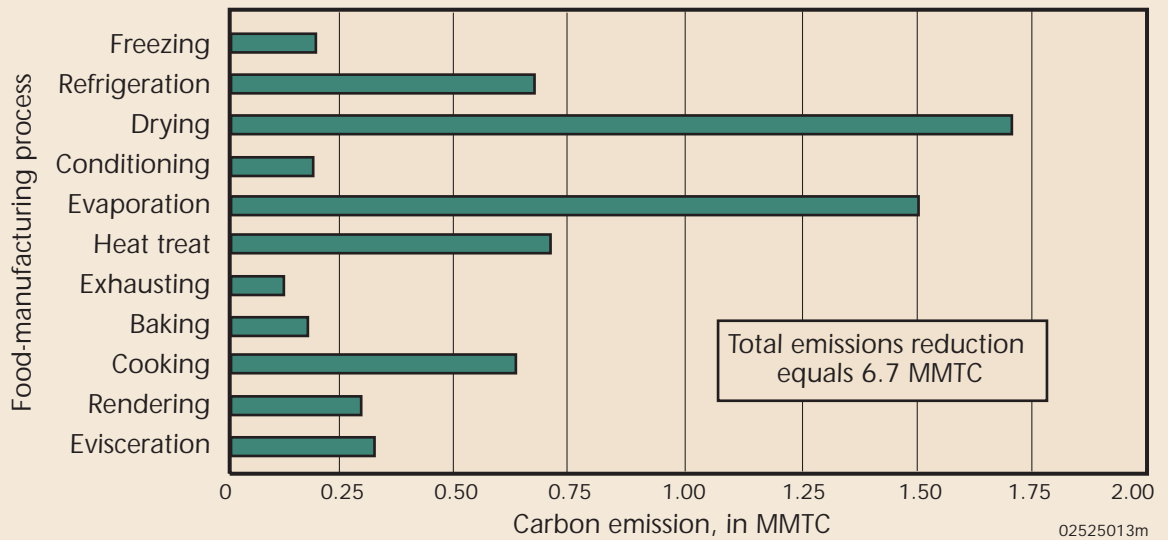
Figure 12. Potential reduction in carbon emissions to the atmosphere by process type used in food manufacturing using 100% advanced technologies in the year 2010. These projected reductions should be viewed as an upper limit that will likely be reduced by economic factors related to decisions necessary for profitable business operation.
Source: Adapted from Energetics 1990 and Marland and Pippin 1990.

developed a number of needs statements. To address these needs, FMC searched for technology from a wide variety of researchers, technology developers, and laboratories, including, for example, aerospace, medical, military, environmental, and process-engineering sources. A total of 20 potential projects directed toward maximizing air and water quality, minimizing solid waste, and increasing control and processing efficiencies were designated for further analysis and effort. These are listed below.

- Recycling processes for plastic food containers
- Detection, monitoring, and management of allergenic foods in manufacturing operations
- Real-time microbiological analysis of foodborne pathogens
- Alternative methods for the use of solvent-based coatings, ink, and glues
- Eggshells (by-products/disposal)
- Reduction of food-processing waste stream volume through membrane filtration
- Biochemical oxygen demand and nutrient removal from food-processing wastewater
- Odor control of food-processing operations by applications of air-cleaning technologies
- Management and removal of fats, oils, and greases
- Volatile organic compound reduction control in the food-processing industry
- Management training for integration of process systems
- Efficient peeling technology

- Efficient use of steam (reduction and alternatives)
- Management of chlorine compounds in production processes
- Blanching and dehydration technology
- Life-cycle cost analysis
- Extraction, separation, and/or reuse of solid wastes from food processing
- Raw material inspections and sorting technologies
- Sensors (humidity, temperature, and critical parameters) for process monitoring
- Thawing (bulk products).

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APPENDIX A: ABBREVIATIONS, ACRONYMS, AND DEFINITIONS

C	Carbon
CAST	Council for Agricultural Science and Technology
CCTS	Climate Change Technology Strategy
CE	Carbon equivalent
CH_4	Methane
CO_2	Carbon dioxide
DOE/EIA	U.S. Department of Energy/Energy Information Administration
EPA	U.S. Environmental Protection Agency
Gg	Gigagram, 10^9 grams (one thousand metric tons)
GTC	Gigatons of carbon, 10^9 metric tons (10^{15} grams)
GTCE	Gigatons of carbon equivalent
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change (United Nations Environment Program)
kg	Kilogram, 10^3 grams
M	Million (metric)
MECS	Manufacturing Energy Consumption Survey
MMTC	Million metric tons of carbon (10^6 metric tons), 10^{12} grams
MMTCE	Million metric tons of carbon equivalent ("carbon" from gases other than carbon dioxide)
MT	Metric ton, 10^6 grams
MTC	Metric tons of carbon (carbon from carbon dioxide)
N	Nitrogen
N_2O	Nitrous oxide
OH	Hydroxyl radical
ppbv	part per billion by volume
ppmv	part per million by volume
SIC	Standard Industrial Classification (Manual)
Tg	Teragram, 10^{12} grams (one million metric tons)
TMTC	Thousand metric tons of carbon, 10^9 grams
USDA	U.S. Department of Agriculture

Advanced agricultural systems: Information-based agricultural systems comprised of three components: (1) capture of data at an appropriate scale and frequency; (2) interpretation and analysis of that data; and (3) implementation of an agricultural-management response at an appropriate scale and time.

Aerosols: A suspension of ultramicroscopic solid or liquid particles in the troposphere that are derived naturally from biogenic sources such as the oceans or terrestrial vegetation, followed by oxidation in the troposphere; distinguished from the propellant used in spray cans.

Afforestation: The process of converting to forest land that has not previously been forested.

Anaerobic: A microbiological process that occurs in an oxygen-free environment.

Anthropogenic: Caused or produced by humans.

Biofuels: Fuels obtained as a product of biomass conversion (e.g., ethanol).

Biogas: A gas composed principally of a mixture of methane and carbon dioxide produced by anaerobic digestion of biomass.

Biomass: The total quantity of living matter in a particular habitat; plant and organic waste materials used as fuel and feedstock in place of fossil fuels.

Bioproducts: As distinguished from biofuels, these are chemicals and products produced from plant/crop-based materials, such as paints, adhesives, lubricants, textile fibers, surfactants, plasticizers, carbon black, detergents, and plastics.

Biota: The total flora and fauna.

British Thermal Unit (Btu): The quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit.

Carbon cycle: All carbon reservoirs and exchanges of carbon from reservoir to reservoir by various chemical, physical, geological, and biological processes. Usually thought of as a series of the four main reservoirs of carbon interconnected by pathways of exchange. The four reservoirs (regions of the Earth) in which carbon behaves in a systematic manner are the (1) atmosphere, (2) terrestrial biosphere (usually includes freshwater systems), (3) oceans, and (4) sediments (includes fossil fuels). Each of these global reservoirs may be subdivided into smaller pools, ranging in size from individual communities or ecosystems to the total of all living organisms (biota).

Carbon dioxide equivalent: The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases. Carbon dioxide equivalents are generally computed by multiplying the amount of the gas of interest by its estimated global warming potential. From the carbon dioxide equivalent it is possible to define a carbon equivalent, which is the carbon dioxide equivalent multiplied by the molecular weight ratio of carbon to carbon dioxide (i.e., 12/44).

Carbon sequestration: The biochemical process through which carbon in the atmosphere is absorbed by biomass such as trees, soils, and crops.

Cellulose: A linear polysaccharide made up of glucose residues joined by β,1,4 linkages: the most abundant
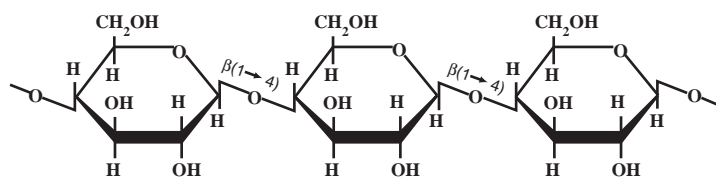
organic compound in the biosphere, comprising the bulk of plant and algal cell walls, where it occurs as cellulose microfibrils.

Conservation tillage: Any tillage and planting system that covers 30 percent or more of the soil surface with crop residue, after planting, to reduce soil erosion by water or 1,000 pounds per acre of flat, small grain residue equivalent on the surface during the critical wind erosion period. Conservation tillage includes no-till, ridge-till, and mulch-till. Reduced tillage refers to any tillage and planting system that covers 15-30 percent or more of the soil surface or 500-1,000 pounds per acre during the critical wind erosion period. Conventional tillage refers to any tillage and planting system that covers less than 15 percent or more of the soil surface with crop residue or less than 500 pounds per acre on the surface during the critical wind erosion period.

D-linked; L-linked: Prefixes denoting particular molecular configurations, defined according to convention, of certain optically active compounds, especially monosaccharides and amino acids. The L configuration is a mirror image of the D configuration. In living cells such molecules usually occur in one or the other of these configurations, but not in both (e.g., glucose as D-glucose, amino acids always in the L form in proteins).

Enteric fermentation: A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Evisceration: The process of removing the entrails of an animal.

Flatus: Gas generated in the intestines or the stomach of an animal.

Fuel-grade ethanol: Starch has the same chemical formula as cellulose ($C_6H_{10}O_5$), and both are polymers of glucose, a simple sugar. The difference between starch and cellulose is the way the glucose units are joined; 1,4-α-D-linked in the case of starch and 1,4-β-D-linked in the case of cellulose (Shoemaker 1998). This difference makes cellulose a much more compact structure and much more difficult to break down, compared to starch (Morris and Ahmed 1992). This is also why fuel-grade ethanol produced from cellulosic biomass is not yet commercial, whereas fuel-grade ethanol produced from corn is a 1.5-billion-gal/yr industry.

Global warming potential (GWP): A numerical index created and used to provide a means of estimating the relative radiative effects of the various greenhouse gases. GWP is the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that of 1 kg of a reference gas.

Greenhouse gas: Any gas that absorbs infrared radiation in the atmosphere.

Hydroxyl radical (OH): An important chemical scavenger of greenhouse gases.

Liquefied petroleum gas (LPG): Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate new natural gas plant liquids.

Nitrification: The oxidation of ammonium to nitrites and the further oxidation to nitrates.

Nutraceutical: Any substance that can be considered to be a food or part of a food, and which provides medical or health benefits, including the prevention and treatment of disease.

Photosynthesis: Light-driven oxidation of water resulting in the production of O_2. This oxidation is coupled to the reduction of CO_2 or other physiological electron acceptors (e.g., NO_2^-, SO_4^-, and O_2).

Primary energy: The energy that is embodied in resources as they exist in nature (e.g., coal, crude oil, natural gas, uranium, or sunlight).

Profitable Methane Reduction (Refers to Tables 7 and 8):Profitability is defined with respect to an owner, operator, or investor in a methane recovery project. Profitability is assessed by comparing the net present value (NPV) of the costs and benefits of the mitigation opportunities. Projects with a positive NPV are considered profitable. Discount rates for the NPV analysis were selected on the estimated uncertainty and riskiness of the methane mitigation projects for each of the methane sources. High estimates assume substantial increases in milk production for export and a small increase in beef production associated with beef maintaining its domestic market share of red meat consumption. Low estimates assume that beef production declines by 2010 and that dairy production increases at the rate of domestic consumption only. These emissions estimates include an uncertainty of about +/-20%, based on the uncertainty of the factors that form the basis of the 1990 emissions estimate.

Quad: One quadrillion British Thermal Units (10^{15} Btus).

Radiative forcing: A simple measure of the importance of a potential climate change mechanism. Radiative forcing is the perturbation to the energy balance of the Earth-atmosphere system (in watts per square meter) following, for example, a change in the concentration of carbon dioxide or a change in the output of the sun; the climate system responds to the radiative forcing so as to reestablish the energy balance. A positive radiative forcing tends to warm the surface and a negative radiative forcing tends to cool the surface. The radiative forcing is normally quoted as a global and annual mean value. (A more precise definition of radiative forcing, as used in Intergovernmental Panel on Climate Change reports, is the perturbation of the energy balance of the surface-troposphere system, after allowing for the stratosphere to readjust to a state of global-mean radiative equilibrium.)

**Reforestation**: The process of renewing forest cover on land previously forested.

Rendering: The conversion of wastes from meat-packing operations into industrial fats and oils.

Respiration: The metabolic process by which organisms meet their internal energy needs and release CO_2. In plants it is the oxidation of reduced carbon compounds with the production of CO_2 and the transfer of electrons to O_2, resulting in its chemical reduction to H_2O.

Rumen: The large first compartment of the stomach of certain animals in which cellulose is broken down by the action of bacteria.

Soil organic carbon pool: The aggregate of carbon present in crop residues, plant roots, and other organic material returned to the soil by various agricultural practices. Organic materials of high importance to enhancing organic soil carbon content and carbon sequestration are the below-ground or root biomass and the total biomass produced by weeds.

Starch: Polysaccharide made up of a long chain of glucose units joined by α,1,4 linkages, either unbranched or branched at an α,1,6 linkage, and which is the storage carbohydrate in plants.
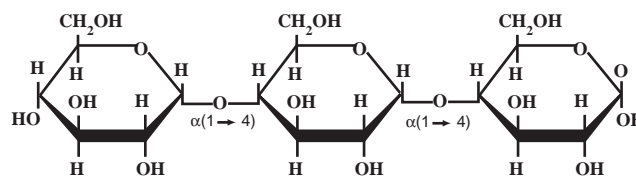
Sustainable: A term used to characterize human action that can be undertaken in such a manner as to not adversely affect environmental conditions (e.g., soil, water quality, or climate) that are necessary to support those same activities in the future.

Troposphere: The inner layer of the atmosphere below about 15 kilometers, within which there is normally a steady decrease of temperature with increasing altitude. Nearly all clouds are formed, and weather conditions manifest themselves, within this region. Its thermal structure is caused primarily by the heating of the Earth's surface by solar radiation, followed by heat transfer through turbulent mixing and convection.

Understory: A foliage layer lying beneath and shaded by the main canopy of a forest. The plants that form the foliage understory of a forest sometimes distinguished from ground cover.

APPENDIX B: ENERGY USE IN FOOD MANUFACTURING

The largest energy consumers in the U.S. manufacturing sector are shown in Figure B1. Energy use by fuel type for the main thermal and chemical processes used to manufacture food is given in Table B1 for 1987 and in Table B2 for estimates in the year 2010.

Figure B1. Largest energy consumers in U.S. manufacturing sector, 1994. Source: MECS 1994.
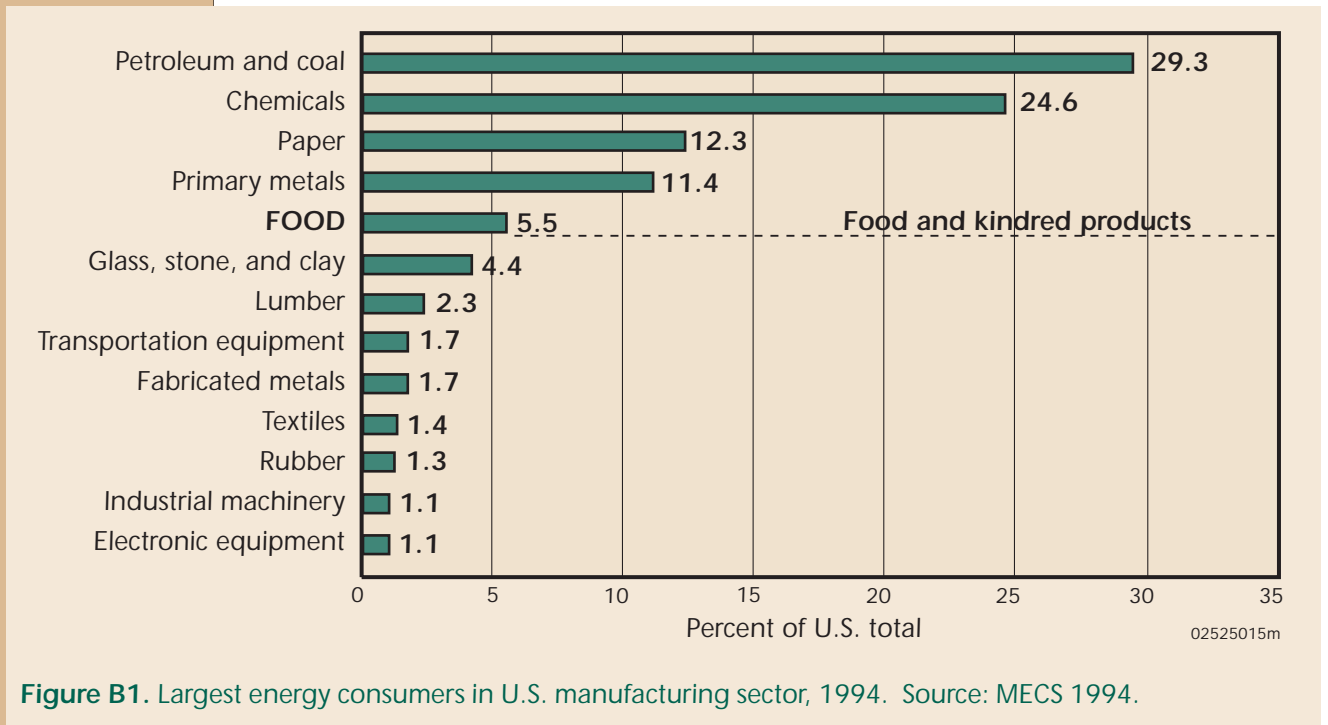
Table B1. Energy use by fuel type for major processes used in food manufacturing, 1987

Energy use (10^{12} Btu) in 1987

Process	Electricity	Gas	Oil	Coal	Propane	Other	Total
Evisceration	0.3	8.7	1.2	1.9	0.1	1.3	13.5
Rendering	1.9	5.7	1.0	1.5	0.1	1.0	11.2
Cooking	-	14.6	2.4	3.8	0.3	2.6	23.7
Baking	0.7	7.8	0.5	0.9	0.1	0.6	10.6
Exhausting	-	2.6	0.4	0.7	0.1	0.4	4.2
Heat treatment/ pasteurization	-	15.9	2.6	4.2	0.3	2.8	25.8
Evaporation/ concentration	-	40.6	6.6	10.7	0.8	7.1	65.8
Conditioning	-	4.6	0.7	1.2	0.1	0.8	7.4
Drying	4.0	42.2	2.9	4.7	0.4	3.2	57.4
Chilling/cooling /refrigerating	26.9	1.4	-	-	-	-	28.3
Freezing	10.3	-	-	-	-	-	10.3
TOTAL	**44.1**	**144.1**	**18.3**	**29.6**	**2.3**	**19.8**	**258.2**

Source: Energetics 1990.

Table B2. Estimated energy use by fuel type for major processes used in food manufacturing, 2010

Energy use (10^{12} Btu) Business-As-Usual case, 2010

Process	Electricity	Gas	Oil	Coal	Other	Total
Evisceration	0.3	9.0	1.2	1.9	1.4	13.8
Rendering	1.9	5.8	1.0	1.5	1.1	11.3
Cooking	-	16.4	2.7	4.3	3.2	26.6
Baking	0.9	9.7	0.7	1.1	0.8	13.2
Exhausting	-	2.2	0.4	0.6	0.4	3.6
Heat Treatment/ Pasteurization	-	15.2	2.5	4.0	3.0	24.7
Evaporation/ Concentration	-	45.5	7.5	12.0	8.8	73.8
Conditioning	-	5.2	0.8	1.4	1.0	8.4
Drying	4.2	44.3	3.1	5.0	3.7	60.3
Chilling/cooling/ refrigerating	27.3	1.4	-	-	-	28.7
Freezing	10.9	-	-	-	-	10.9
TOTAL	**45.5**	**154.7**	**19.9**	**31.8**	**23.4**	**275.3**

Source: Energetics 1990.

APPENDIX C: THEORETICAL POTENTIAL FOR REDUCTION OF GREENHOUSE GAS EMISSIONS*

Table C1. Source data and calculations of the theoretical potential for reducing carbon and carbon equivalent emissions of carbon dioxide, methane, and nitrous oxide by U.S. agriculture and food manufacturing

Category	Theoretical potential for reduction in U.S. emissions (MMTCE/yr)	U.S. carbon-equivalent emissions reduction due to a reduction in carbon equivalent emission from the indicated category (%)	Global carbon-equivalent emissions reduction due to a U.S. reduction in carbon equivalent emission from the indicated category (%)
Advanced food manufacturing	6.7[A]	0.38	0.069
Advanced nitrous oxide management	9.1[B]	0.51	0.093
Advanced agricultural systems	1.5[C]	0.085	0.015
Advanced livestock management	17[D]	0.94	0.17
Improved cropping systems	35[E]	2.0	0.36
Improved Irrigation and water management	8[F]	0.45	0.082
Conservation tillage and residue management	71[G]	4.0	0.73
Bioproducts	3.5[H]	0.20	0.036
Biofuels/biopower	94[I]	5.3	0.96
Afforestation	112[J]	6.3	1.1

* Shown in graphical form in Summary Graphic C in the Executive Summary of this document.

Sources:

A From Table 11 of this document. The annual rate is a projection for the year 2010.

B Estimated from the global mitigation potential for reducing N_2O shown in Figure 8 of this document, and from Table 2. (0.71) x (310) x (12/44) = 60.03 MMTCE global reduction potential = (60.03) x (0.077)/(0.507) = 9.1 MMTCE. U.S. agriculture reduction potential = (9.1/9755 x 100 = 0.093% reduction in global C equvalent emission due to a U.S. emission reduction in this category = (9.1)/1789 x 100 = 0.51% reduction in U.S. C equivalent emissions due to an emission reduction in this category.

C From CCTS 1997, Appendix B4.2, p. B-35, for the year 2010.

D Obtained by adding 1.9 MMTCH4 from Table 7 (year 2010) to 1.0 MMTCH4 from Table 8 (year 2010) = (2.9) x (21) x (12/44) = 16.609 MMTCE U.S. agriculture reduction potential = (16.609)/9755 x 100 = 0.17% reduction in global C equivalent emission due to a U.S. emissions reduction in this category = (16.609)/1789 x 100 = 0.928% reduction in U.S. C equivalent emission due to a reduction in this category.

E From Table 5 of this document, following Lal et al. 1998, based on their mid-range values.

F From Page 12 of this document, following Lal et al. 1998, based on their mid-range values.

G From Page 11 of this document, following Lal et al. 1998, based on their mid-range values. Most of the options dealing with land use and soil C sequestration are limited in duration in that vegetation and soils, under a given set of environmental and management conditions, have a finite capacity to sequester carbon. An exception is carbon accumulation in wetlands, where carbon increases can be sustained for much longer periods.

H From CCTS 1997, Appendix B4.1, p. B-33, for the year 2010.

I From page 11 of this document. An energy substitution factor of 0.7 was used to obtain the 94 MMTC/yr number. The above estimate of 94 MMTC/yr is made without specifying how the biofuels will be used (i.e., they can be used to generate electricity by substituting for coal in existing power plants, or used alone in plants that displace new fossil fuel-fired plants, or they can be used in gasified form to produce power in advanced gas turbines or to produce transportation fuels for automobiles and trucks). Thus, the estimate of 94 MMTC/yr given here should be viewed as an upper limit that will likely be reduced further by thermodynamic constraints and by real-world constraints such as market forces (that are influenced greatly by the prevailing price of a barrel of oil) and public policy decisions. In the appendices of CCTS 1997, carbon reduction estimates were made only on ethanol, using switchgrass as a feedstock at 10% and 95% blends, compared with reformulated gasoline, and with market penetration for these blends of 4 billion gallons in 2010 and other projections for future years. Using these parameters, CCTS 1997 concluded that neat ethanol was not cost effective enough to use as a transportation fuel during the next 30-year period. Carbon reductions were estimated at 10 MMTC/yr in 2010 for ethanol, which included biomass-generated electricity returned to the grid from ethanol plants, and 15 MMTC/yr for biopower applications in the year 2010. The sum of these estimates of carbon offset (25 MMTC/yr) is about one-quarter of the estimate based on technical potential alone as reported in IPCC 1996, and adjusted to the United States in this white paper (94 MMTC/yr). Lal et al. 1998 estimated the carbon offset to be 45 MMTC/yr (including residues) by assuming energy and short-rotation woody crops would be grown on approximately one-half of the available U.S. idle cropland (24.7 million acres by their estimate) and further assuming an energy substitution factor of 0.7 for the biofuels. In Table C above, the Biofuels/ biopower entry was obtained using the full 55.8 million acres of idle U.S. cropland discussed earlier in this white paper, along with a 0.7 energy substitution factor, to obtain 94 MMTC/yr. We acknowledge that it may not be economical to utilize all of the available idle U.S. cropland using fixed processing facilities because of geographic separation and quality of some of the parcels that comprise that cropland.

J From page 10 of this document. The average net weight of 2.0 tons of carbon per acre per year was obtained from three independent sources: Birdsey 1998; Lal et al. 1998; and Sampson 1998.

Appendix D: Global Warming Potentials for CH_4 and N_2O

Global warming potential (GWP) is a numerical index created and used to provide a means of estimating the relative radiative effects of the various greenhouse gases. The index is defined as the cumulative radiative forcing between the present and some later time "horizon" caused by a unit mass of gas emitted in the present, expressed relative to some reference gas. (CO_2 is used in this white paper.)

In general, such indices are used to estimate the relative impact of emission of a fixed amount of one greenhouse gas compared to another for globally averaged radiative forcing of the climate system over the chosen time horizon. These gases can exert a radiative forcing of the climate system both directly and indirectly. Direct forcing occurs when the emitted gas is itself a greenhouse gas. Indirect forcing occurs when a chemical transformation of the original gas produces or destroys a gas or gases that themselves are greenhouse gases. The future global warming impact of a greenhouse gas over the reference time horizon is the appropriate GWP multiplied by the amount of gas emitted. Although GWPs are quoted as single values, the typical uncertainty is +/-35%. GWPs have a number of important limitations and underlying assumptions. For example, the GWP concept is currently inapplicable to gases and aerosols that are very unevenly distributed, as is the case for tropospheric ozone and aerosols and their chemical precursors. Further, the indices and the estimated uncertainties are intended to reflect global averages only, and do not account for regional effects.

There are three main technical factors that affect the index (IPCC 1994). These are:

1. The strength with which a given chemical species absorbs long-wavelength radiation and the spectral location of its absorbing wavelength. Although the absorption of infrared radiation by many greenhouse gases varies linearly with their concentrations, a few important ones display nonlinear behavior (e.g., CO_2, CH_4, and N_2O). For these gases, the relative radiative forcing will depend on concentration, and hence on the scenario adopted for the future trace-gas atmospheric concentrations. A key factor in the greenhouse role of a given chemical species is the location of its own absorption spectrum relative to the holes in the absorption spectrum of water vapor, through which most outgoing planetary thermal radiation escapes to space.

2. The lifetime or response time of the given chemical species in the atmosphere. Greenhouse gases differ greatly in how long they reside in the atmosphere once emitted. Generally speaking, greenhouse gases that persist in the atmosphere for a long time are more important in radiative forcing than those that are shorter lived. An initial dominance of molecular absorption strength for one gas (e.g., most hydrochlorofluorocarbons) in determining the instantaneous radiative forcing at early times can be overwhelmed by the longer lifetime of another gas (e.g., nitrous oxide) having a lower molecular absorption of infrared radiation.

3. The time period over which the radiative effects of the species are to be considered. It is the cumulative forcing of a greenhouse gas, rather than its instantaneous value, that is of primary importance to the construct of a relevant radiative forcing index. As a consequence, such indices involve an integral over time. Figure D-1 shows the integrals for nitrous oxide and methane, relative to carbon dioxide, over a period ranging from 1 to 500 years. The integral of carbon dioxide relative to itself is unity for all integration time periods.
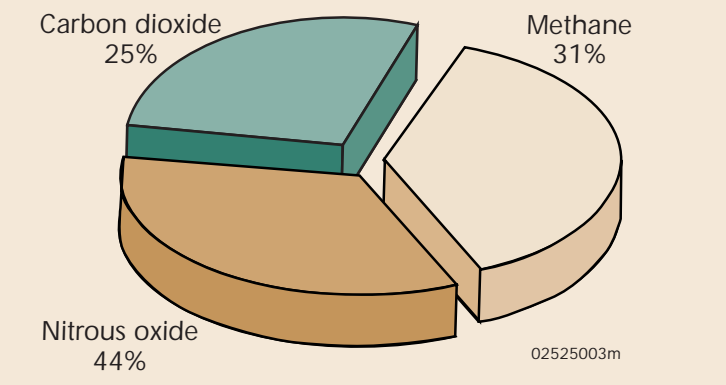
An illustration of how these indices are reflected in emissions of greenhouse gases from agriculture is shown in Figure D2. The relative carbon equivalent emissions for nitrous oxide and methane are revealed to be slightly greater than carbon dioxide alone.

N₂O → labels on graph, axis "Global warming potential", "Time horizon (yrs)"

Figure D2. Relative carbon equivalent emissions of the three greenhouse gases attributable to U.S. agriculture. Total annual emission by U.S. agriculture of the carbon equivalent of these three gases is about 175 million metric tons, or about 10% of all U.S. emissions of these three greenhouse gases. Source: Table 2 by taking horizontal ratios.

Figure D1. Global warming potential (GWP) for nitrous oxide, methane, and carbon dioxide, for differing lifetimes of as many as 500 years, using CO_2 as the reference gas. GWP is the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that of 1 kg of a reference gas. The global warming potential of gas i is defined mathematically as

$$GWP_i = \int_0^{TH} a_i[c_i(t)]dt \, / \int_0^{TH} a_r[c_r(t)]dt,$$

where TH is the time horizon over which the integration is performed; a_i is the instantaneous radiative forcing due to a unit increase in the concentration of gas i; and $[c_i(t)]$ is the time-decaying concentration of gas i at time t after its release. The corresponding quantities for the reference gas r are in the denominator. Source: IPCC 1994.

Appendix E: Topological Relationship Among Carbon Offset Potential, Cropland Acres, and Crop Yield

Estimations have been given in this summary white paper of the theoretical technical potential for increased use of biofuels/biopower/bioproducts to reduce anthropogenic carbon dioxide emissions from agriculture. Also given has been the theoretical technical potential of carbon sequestration using afforestation on agricultural lands.

There are many parameters involved in making such estimates, and we have restricted ourselves in this white paper to only the simplest of reckonings to make comparisons among different alternatives. Parameters involved in making estimates of carbon offset potential that are possible from agricultural management practices include:

- available cropland
- percent of cropland used
- cropland quality
- crop yield
- plant species
- collection and transport

- conversion efficiencies
- fuel substitution factors
- economics of production
- public policy decisions
- price of a barrel of oil
- others

A troublesome, complicating factor is the abundance of numerical values for some of these parameters, particularly available cropland and crop yield. Below we argue that to a first approximation, carbon offset potential is related to cropland acreage and crop yield through a simple mathematical relationship involving algebraic topology and that these two parameters are in fact fungible. This is particularly important in light of recent advances in genetically modified (GM) crops that hold the promise of increased crop yield and the possibility of a reduction in the number of acres required to produce historical yields. Sources of available cropland include cultivated land, revegetated or set-aside land, pastureland, rangeland, and degraded land (Bruce et al. 1998; Frommer et al. 1999).

Consider the following algebraic equation that describes a three-dimensional surface:

$$Z = XY.$$

For our purposes, X = cropland acres and Y = crop yield. Z represents the product of these two parameters. Figure E1 shows how cropland acres and crop yield are related on a three-dimensional surface. For demonstration purposes, Figure E1 has been drawn using equal values of X and Y, but this is not a restriction.

As an illustrative example, we will locate points on the surface using values given for cropland and crop yield in the reference identified as National Research Council 1999. In that reference it is estimated that there are approximately 35-million acres of marginal cropland in the U.S. that could provide additional land to grow biomass crops. The authors assume a very low yield of biomass (2.5 tons/acre) but project that the crop yield could increase four-fold (up to 10 tons/acre) with some crops (e.g., switchgrass) and that the total biomass thus produced is sufficient to easily meet current demands for biobased industrial chemicals and materials.

These two sets of numbers locate the following points on the surface shown in Figure E1:

$$Z = (35) \times (2.5) = 87.5 \text{ and } Z = (35) \times (10) = 350.$$

But these points are not unique, since they can be reached by the following combinations of X and Y:

$$Z = (17.5) \times (5.0) = 87.5$$
$$Z = (50) \times (1.75) = 87.5$$
$$Z = (50) \times (7.0) = 350$$

From this simple example we conclude that it is the product of (cropland acres)x(crop yield) that is the important factor in determining carbon offset potential, and not necessarily either parameter taken by itself.
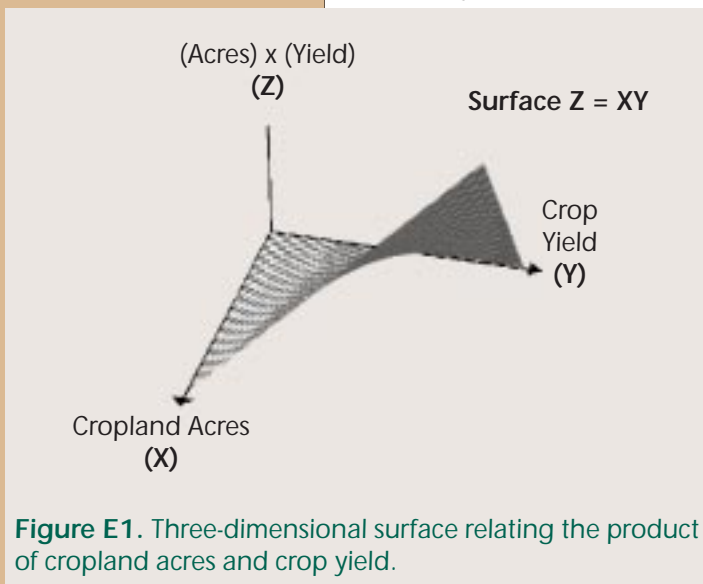
Figure E1. Three-dimensional surface relating the product of cropland acres and crop yield.

(Acres) x (Yield)
(Z)

Surface Z = XY

Crop Yield
(Y)

Cropland Acres
(X)

FOR MORE INFORMATION:

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