Climate Science Initiative

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AgMRC agricultural marketing resource center

http://www.agmrc.org/

Global Warming *September 2008*

Climate Change and Agriculture*

The Iowa State University Climate Science Initiative (CSI) is established in response to urgent needs and opportunities for authoritative information supporting research, state agencies, and the private sector in response to rapidly emerging public concern over global climate change and its regional implications. Because of its impact on every segment of society, and most directly the basic resources of soil and water and their role in food (and now fuel) production, climate change is a quintessential land-grant-university research issue.

Iowa State University with its wide range of expertise in engineering, agriculture, basic sciences, and cyberinfrastructure, is well positioned to lead both regionally and nationally in conducting forefront research in climate science that draws on this research capacity. This initiative complements and draws synergy from recent University focused attention to biofuels, basic plant sciences, and cyberinnovation. Weather/climate arguably is the most common societal topic of discussion, which means that every citizen can relate in a personal way to climate change and hence the activities of CSI. What this means is that there will be a very broad range of interest in its work, particularly if it is recognized as a source of authoritative information. While the initial focus of CSI for the first few years will be on developing a broad and substantial base of externally funded research, the eventual opportunities for adding educational and outreach components are self-evident.

The vision is that the ISU Climate Science Initiative will have a broad range of expertise that could be marshaled to provide authoritative, scientifically based information for short-term and long-term decision-making that would be consistent with long-term resilience to climate change and climate variability.

*Climate Change and Agriculture: Reprints of a series of articles currently appearing on the Ag Marketing Resource Center (http://www.agmrc.org/agmrc/renewables/) and Ag Decision Maker (http://www.extension.iastate.edu/agdm) Web sites.

IOWA STATE UNIVERSITY
University Extension


Global warming – the science

by Eugene Takle, Professor of Atmospheric Science and Professor of Agricultural Meteorology, 515-294-9871, gtakle@iastate.edu and Don Hofstrand, value-added agriculture specialist, co-director AgMRC, Iowa State University Extension, 641-423-0844, dhof@iastate.edu

This series of articles will focus on global warming, the science behind it and the impact global warming may have on Midwestern agriculture. Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity.

The warming and cooling cycles

The earth has been going through periods of global warming and cooling for hundreds of thousands of years. With the use of "ice cores" of ancient ice layers, scientists have determined ancient temperature fluctuations in our atmosphere. The bottom line in Figure 1 shows temperature fluctuations over the most recent 430,000 years. Temperature during this period shows a rather regular cycle lasting about 100,000 years. The variation in temperature during a cycle is about 10 to 12 degree centigrade. Although the temperature line appears to move up and down abruptly, in reality the rate of change is very gradual over thousands of years due to the enormous time span covered by the chart.

During the last 15,000 years, we have been in a period of global warming with temperature rising. If we follow the traditional cycle, we would expect temperature to start a gradual decline over the next 70,000 to 80,000 years.

Two of the major greenhouse gases are carbon dioxide (CO2) and methane (CH4). Scientists have been able to track the historic concentration of these two greenhouse gases in our atmosphere. As shown in Figure 1, they track closely with the changes in temperature. The central question facing the science community is what will happen to temperature due to the recent and expected future increase is greenhouse gases.

Temperature variations over the last 1,000 years are shown in Figure 2. This figure shows a comparison of ten different published reconstructions of average temperature changes. A pattern emerges of very gradual cooling over the first 900 years followed by a period of rapid warming during the last 100 years.

Temperatures over just the last 150 years since 1850 are shown in Figure 3. The annual average temperature varied greatly from year to year. However, by using a five year moving average, a trend can be deciphered. The trend was relatively flat from 1850 to 1900. Then it increased significantly during the 20th Century (although it dipped briefly from 1900 to 1910 and 1940 to 1950).

Global climate models

The scientific community creates complex climate computer models in an attempt to predict future global temperature changes. The accuracy of a model can be verified by its ability to predict past global temperature changes. Figure 4 shows the accuracy of a model based on five known climate change factors. As can be seen, temperature estimates made by the model tracked quite closely with the actual temperature levels during the period of 1900 to 1990.

The five climate change factors contributing to departures from long-term global average temperatures are greenhouse gas concentration, solar intensity, ozone levels, volcanic activity and sulfate levels. Three of these factors are anthropogenic and two of them are naturally occurring.

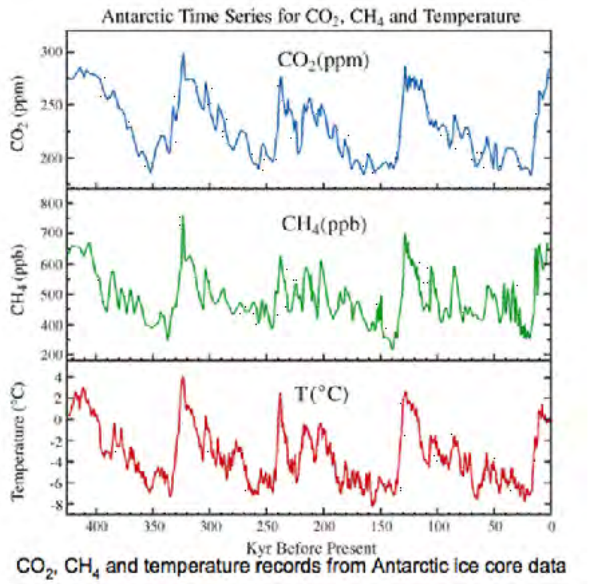
> Anthropogenic effects are those that are derived from human activities, as opposed to those occurring in natural environments without human influences.

The natural factors are:

1) Solar

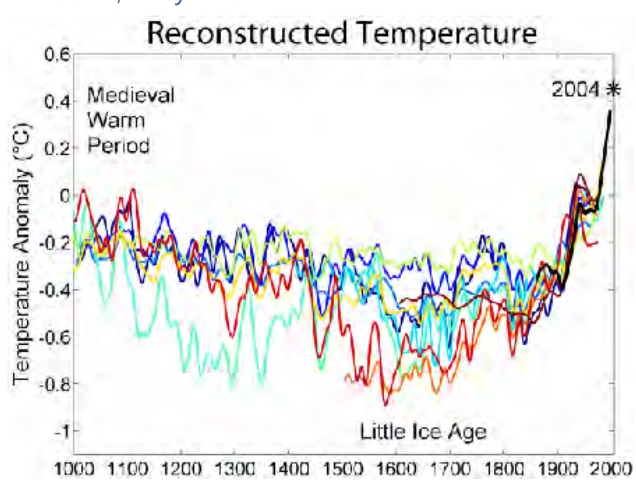
The absorption of solar energy heats up our planet's surface and atmosphere and makes life on Earth possible. Sunspots correlate to the changes in intensity of solar radiation reaching the earth. Sunspot activity goes through variations and cycles, so it has the ability to warm and cool the earth compared to the long-term average. As shown in Figure 4, solar activity has contributed to warming (tracks above the dashed line) over the last century. Future sunspot activity will influence the amount of solar radiation reaching the earth and will impact global warming.

Figure 1. Antarctic time series for CO2, CH4 and temperature variations over the last 430,000 years.



Source: Vimeux, F., K.M. Cuffey, and Jouzel, J., 2002, "New insights in Southern Hemisphere temperature changes from Vostok ice cores using deuterium excess correction", Earth and Planetary Science Letters, 203, 829-843.

Figure 2. Reconstructed temperature variations over the last 1,000 years.



Source: Global Warming Art, http://www.globalwarmingart.com/wiki/Image:1000_Year_ Temperature_Comparison_png

2) Volcanic

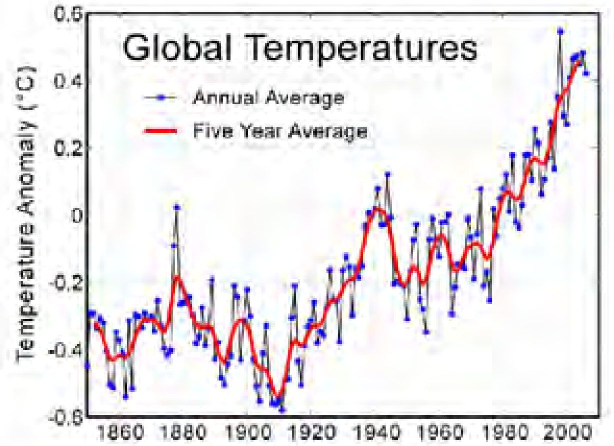
Volcanoes temporarily cool the earth. A decrease in volcanic activity during the first half of the century led to temperature increases, but more volcanoes during the last half contributed to cooling.

The anthropogenic factors are:

1) Greenhouse gases

Solar energy heats up the earth's surface. But the energy does not stay bound up in the Earth's

Figure 3. Temperature variations over the last 150 years.



Source: Source: Global Warming Art, http://www.globalwarmingart.com/wiki/Image:Instrumental_ Temperature_Record_png
Compiled by the Climatic Research Unit of the University of East Anglia and the Hadley Centre of the UK Meteorological Office.

environment forever. Instead, as the earth warms, it emits thermal radiation (heat). This thermal radiation, which is largely in the form of long-wave infrared rays, eventually finds its way out into space, leaving the Earth and allowing it to cool. However, instead of passing into space, some of the infrared rays (heat) are absorbed by greenhouse gases and held in the atmosphere. Higher concentrations of greenhouse gases hold more heat in the atmosphere.

The major anthropogenic greenhouse gases are carbon dioxide, methane, nitrous oxide and chlorofluorocarbons. As shown in Figure 4, greenhouse gases in the atmosphere have increased substantially, especially since 1960. More information on greenhouse gases will be presented in the next article.

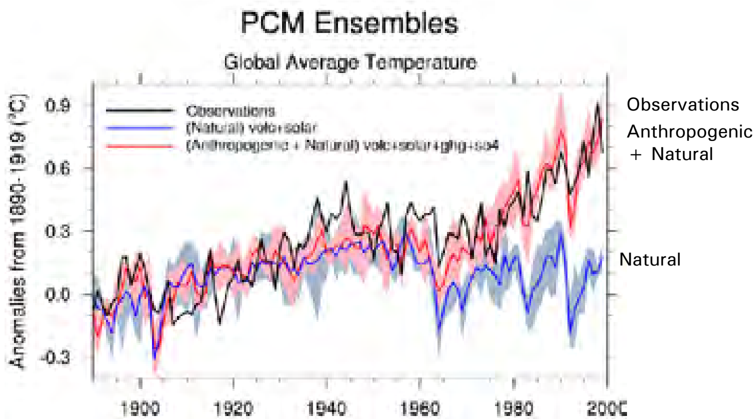
2) Ozone

Ozone is a gaseous atmospheric constituent. In the troposphere (layer of the atmosphere closest to earth), ozone is created primarily by human activity. In the stratosphere (atmospheric layer above the troposphere), ozone filters potentially damaging ultraviolet rays from reaching the Earth's surface. Ozone acts as a modest greenhouse gas, As shown in Figure 4, the contribution due to atmospheric ozone has changed modestly over the last century, with warming due to increase in tropospheric ozone partially offset by cooling due to loss of stratospheric ozone.

3) Sulfate

Sulfates occur as microscopic particles (aerosols). They increase the acidity of the atmosphere and form acid rain. They are known to reduce the effects of global warming. Sulfate particles have the capacity to scatter light rays, effectively increasing the earth's albedo (surface reflectivity). Also, the particles act as "cloud condensation nuclei". Essentially, these are particles around which cloud and rain droplets form. The abundance of these nuclei means that more and smaller water droplets form which diffuses light rays. As shown in Figure 4, the global increase of sulfate particles in the atmosphere due to industrial emissions (primarily in developing countries) is contributing to a cooling of the global atmosphere, which offsets part of the warming due to greenhouse gases.

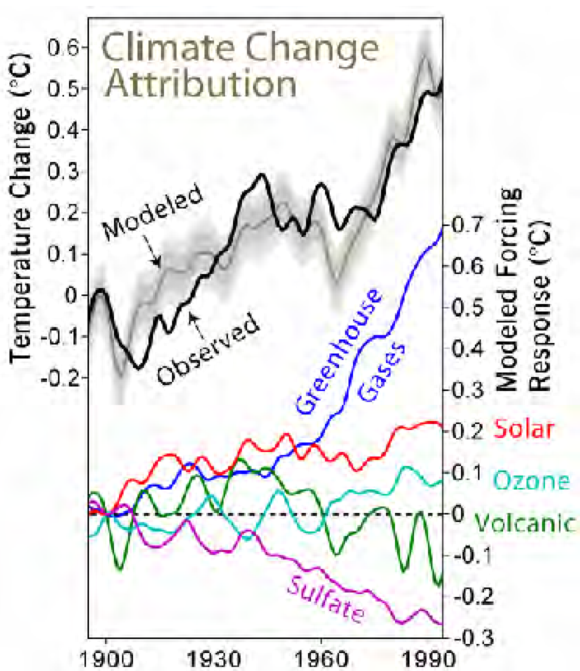
Figure 5. Global average temperatures (observed temperature versus predicted temperature)



Source: Jerry Meehl, National Center for Atmospheric Research

The model shown in Figure 5 also estimates global temperature. When both natural and anthropogenic factors are included in the model, the prediction is closely correlated with the actual observations. However, when just the natural factors (solar and volcanic activity) are included in the model, a discrepancy emerges. Although the natural factors are a good predictor of actual warming in the early part of the century, in about 1960 they start to diverge. By themselves the natural factors do not account for the rise in global temperatures since 1960. Only when they are combined with the anthropogenic factors of greenhouse gases and sulfate does the model predict relatively accurately the actual temperature levels. This leads us to believe that anthropogenic factors have a significant role in the recent increase in global temperature.

Figure 4. Natural and anthropogenic contributions to global warming.



Source: Global Warming Art. http://www.globalwarmingart.com/wiki/Image:Climate_Change_Attribution_png.
Natural and anthropogenic contributions to global temperature change (Meehl et al., 2004). Observed values from Jones and Moberg 2001. Grey bands indicate 68% and 95% range derived from multiple simulations.

The next two articles in this series focus on the role of greenhouse gases in global warming and the potential impact of global warming on Midwestern agriculture.

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Global warming – impact of greenhouse gases

Global warming will have a profound impact on global agriculture, with yet unknown influences on Midwest agriculture. As with most changes, this will provide both opportunities and threats for Midwest agricultural producers. This article discusses the role greenhouse gases play in global warming.

Solar energy heats the earth's surface. But the energy does not stay bound up in the earth's environment forever. Instead, as the earth warms, it emits thermal radiation. This thermal radiation, which is largely in the form of long-wave infrared rays, eventually finds its way out into space, leaving the earth and allowing it to cool. However, not all of the infrared rays pass into space. Some of the infrared rays are absorbed by greenhouse gases and warm the atmosphere. So the amount of greenhouse gases in the atmosphere is directly related to the temperature of the atmosphere. Increased concentrations of greenhouse gases increase the temperature of the atmosphere leading to the warming of the earth's surface.

The natural carbon cycle

Carbon dioxide and other greenhouse gases go through a natural cycle. Large amounts of carbon pass back and forth between the atmosphere and the earth's surface. For example, growing crops and trees take in carbon dioxide (CO_2) during photosynthesis. The carbon is the feedstock for making the plant and the oxygen (O_2) is released into the atmosphere. When the plant dies and deteriorates or is processed, the carbon is combined with oxygen by microbial processes to become CO_2 and is returned to the atmosphere. So these processes tend to keep the amount of carbon dioxide relatively constant over time.

However, burning fossil fuels takes carbon that has been stored deep in the earth and emits the carbon into the atmosphere in amounts that are too large for the earth's plants to absorb. This is "new" carbon dioxide that is being pumped into the atmosphere.

Changing land-use has the effect of slightly increasing carbon dioxide atmospheric concentrations. Human activities such as burning fossil fuels, releasing chlorofluorocarbons, and deforestation have raised levels of greenhouse gases far above natural levels. Nature requires hundreds of years to remove these excessive amounts of greenhouse gases.

Types of greenhouse gases

Water vapor is the most prevalent greenhouse gas in the atmosphere. Water vapor doesn't stay in the atmosphere very long. Although concentrations can change rapidly on a local basis, globally concentrations remain quite constant. The greenhouse gases that impact the gradual warming of the earth's surface are those that stay in the atmosphere for a long period of time and build-up over time. In spite of their relatively low atmospheric concentrations, their long lifetime makes their influence on global warming large.

The warming impact of different types of greenhouse gases varies according to the warming power of the gas and the length of time it stays in the atmosphere. As shown in Table 1, carbon dioxide has an atmospheric life of 50 to 200 years. So once emitted into the atmosphere, it has a warming effect over a long period of time. Methane, for example, has a life of about 12 years, much shorter than carbon dioxide.

The warming power of each gas varies greatly. For example, methane is a much more powerful greenhouse gas than carbon dioxide. Over a 100 year period, a molecule of methane (CH_4) has 21 times the warming effect as a molecule of carbon dioxide (CO_2), even though it stays in the atmosphere for only about 12 years of the 100 year period.

Table 1. Global Warming Potentials and Atmospheric Lifetimes (years).

	Atmospheric Lifetime	GWP*
Carbon Dioxide (CO_2)	50-200	1
Methane (CH_4)	12	21
Nitrous Oxide (N_2O)	114	289
Other	1-50,000	5-22,800

** Global warming potential over 100 year lifetime*
Source: Intergovernmental Panel on Climate Change, 2007 Report.

To compare the impact of each gas, the warming potential of each gas is computed over a 100 year period as shown in Table 1. The Greenhouse Warming Potential (GWP) is computed for each gas based on its warming power and atmospheric lifetime. As a basis of comparison, carbon dioxide is assigned a GWP of one and the GWP of the other gases are computed in relationship to carbon dioxide. For example, relative to carbon dioxide, nitrous oxide has about 300 times the warming effect. The other gases (halocarbons, perfluorocarbons and sulfur hexafluoride) are also powerful gases. Although the warming potential of the other gases is more powerful than carbon dioxide, carbon dioxide emissions dwarf those of the other gases due to its large volume of emissions.

Atmospheric levels of greenhouse gases

The current rate of increase of greenhouse gas levels in the atmosphere is unprecedented. Focusing specifically on the major greenhouse gas, carbon dioxide, it has traditionally fluctuated from about 180 parts per million (ppm) to about 300 ppm. Carbon dioxide emissions have increased from less than 320 ppm in 1960 to 380 presently. The atmosphere now contains more carbon dioxide than at any time in the last 420,000 years and possibly the last 20 million years.

We can calculate with confidence that, even with severe limits on emissions, carbon dioxide concentrations will be at least 450 ppm by 2050. If we allow for rapid economic growth based on continued use of fossil fuels, carbon dioxide concentrations will reach 600 ppm by 2050 and about 950 ppm by the end of the century (Intergovernmental Panel on Climate Changes, 2007 Report).

Impact on global temperatures

Average global temperature will rise 0.7 to 2.2 degrees Fahrenheit by 2030 and a 2.5 to 10.4 degrees Fahrenheit over the next 100 years (Intergovernmental Panel on Climate Change). Recent scientific reports conclude there is a 40% chance that warming will exceed this range and only a 5% chance that it will be less. There is no scientific evidence to suggest that global average temperatures will remain constant or decline in the next 100 years.

Although the earth has warmed and will continue to warm, the temperature increase has not and will not be distributed evenly. The warming tends to be concentrated in certain parts of the world, especially the northern areas. There were also areas that actually cooled slightly.

Projected temperatures increases over the next 100 years are once again not expected to be distributed evenly. The warming tends to be concentrated in the far north. Also, because land is more responsive to atmospheric temperature changes than the oceans, the temperature increase will be greater over the continents than the oceans

This article has focused on the role of greenhouse gases in global warming. The next article will focus on agriculture's role in greenhouse gas emissions.

Global warming – agriculture's impact on greenhouse gas emissions

In this article we will examine the size and sources of greenhouse gas emissions from the agricultural sector. We will also discuss greenhouse gas sinks (the removal or sequestration of gases). Finally, we will examine ways agriculture can reduce emissions and increase sinks.

Greenhouse gas emissions (primarily carbon dioxide, methane and nitrous oxide) by sector of the U.S. economy are shown in table 1. Electric power generation accounts for one-third of all greenhouse gas emissions. Although wind and hydroelectric generation are very clean technologies, half of U.S. electricity is generated by coal fired plants.

Table 1. U.S. Greenhouse Gas Emission by Economic Sector (2005) (percent)

Sector	Percent
Electric power industry	33.5%
Transportation	27.7
Industry	18.6
Agriculture	8.2
Commercial	5.9
Residential	5.2
Other	.8
Total	100.0%

Source: EPA, U.S. Inventory of Greenhouse Gas Emissions and Sink (1990 – 2005), Trends in Greenhouse Gas Emissions, Table 2-14.

The transportation sector produces over one-fourth of the greenhouse gas emissions, primarily from gasoline and diesel fuel. Agriculture produces about eight percent of emissions.

Agricultural greenhouse gas emissions

Agricultural greenhouse gas emissions come from several sources as shown in table 2. Each of the sources is discussed along with possible ways of reducing emissions.

Table 2. U.S. Agricultural Greenhouse Gas Emissions by Source (2005) (percent)

Source	Percent of Total Emissions	Percent of Agricultural Emissions
Agricultural soil management	5.0%	61%
Enteric fermentation	1.5	18
Manure management	.7	9
CO_2 from fossil fuel consumption	.6	7
Other	.3	4
Total	8.2%	100%

Source: EPA, U.S. Inventory of Greenhouse Gas Emissions and Sinks (1990 – 2005), Trends in Greenhouse Gas Emissions, Table 2-14.

Agricultural soil management

These are nitrous oxide emissions and account for about 60 percent of the total emissions from the agricultural sector. Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and de-nitrification. During nitrification, ammonium (NH_4) produces nitrates (NO_3). During de-nitrification, nitrates (NO_3) are reduced to nitrogen gas (N_2). An intermediate step in both of these processes is the creation of nitrous oxide (N_20).

The large increase in the use of nitrogen fertilizer for the production of high nitrogen consuming crops like corn has increased the emissions of nitrous oxide. Although nitrogen fertilizer is essential for profitable crop production, the development of practices for more efficiently using nitrogen fertilizer has the potential to significantly reduce nitrous oxide emissions while also reducing production costs and mitigating the nitrogen contamination of surface and ground waters.

Enteric fermentation

Methane is produced as part of the normal digestive processes in animals. During digestion, microbes in the animal's digestive system ferment feed. This process, called enteric fermentation, produces methane as a by-product which can be emitted by the exhaling and belching of the animal.

Because of their unique digestive system, ruminant animals (e.g. cattle) are the major emitters of methane. Beef cattle account for about 70 percent and dairy cattle for about 25 percent of these methane emissions. If beef and dairy cattle numbers increase, methane emissions will also increase.

Feed qualify and feed intake influence the level of methane emissions. In general, lower feed quality and higher feed intake lead to higher methane emissions.

Manure management

Methane is produced by the anaerobic (without oxygen) decomposition of manure. When manure is handled as a solid or deposited naturally on grassland, it decomposes aerobically (with oxygen) and creates little methane emissions. However, manure stored as a liquid or slurry in lagoons, ponds, tanks or pits, decomposes anaerobically and creates methane emissions. Dairy cattle and swine produce about 85 percent of the methane emissions. Methane emissions will increase as the number of large scale livestock confinement systems increases.

Methane emissions can be reduced through the application of technologies designed to capture the methane and use it as an energy source. In addition to reducing methane emissions, methane capture will improve the profitability of the livestock operation by offsetting the need for fossil fuel energy from outside sources.

Carbon dioxide from fossil fuel consumption

The use of fossil fuels in agricultural production accounts for eight percent of the emissions from agriculture. These emissions are primarily from combustion of gasoline and diesel fuel. Using renewable fuels can reduce the carbon dioxide emissions from agriculture production.

Other

A variety of other sources produce greenhouse gas emissions. For example, most of the world's rice and all of U.S. rice is grown on flooded fields, which prevents atmospheric oxygen from entering soil. When rice is grown with no oxygen, the soil organic matter decomposes under anaerobic conditions and produces methane that escapes into the atmosphere.

Agricultural greenhouse gas sinks

A sink is a reduction in atmospheric greenhouse gases by storing (sequestering) carbon in another form. A traditional carbon sink is underground coal and oil deposits where millions of year ago living plants (and other organisms) used atmospheric carbon to build the plant. When the plants died, instead of decomposing and releasing carbon back into the atmosphere, they were stored under high pressure and became oil and coal. When oil and coal are recovered and consumed, the sequestered carbon is emitted into the atmosphere as carbon dioxide.

Greenhouse gas sinks reduce annual greenhouse gas emissions by 11.4 percent. Ten percent of these offsets are due to forests and soils as shown in Table 3.

Table 3. Greenhouse Gas Sinks (2005) (percent of total emissions)

	Sink
Forest management practices	9.6%
CO_2 flux from agricultural soils	.4
Other	1.3
Total	11.4%

Source: EPA, U.S. Inventory of Greenhouse Gas Emissions and Sinks (1990 – 2005), Trends in Greenhouse Gas Emissions, Table 2-14.

Forest management practices
Growing trees sequester large amounts of carbon dioxide from the atmosphere through photosynthesis. The carbon is used to build the plant and the oxygen is released back into the atmosphere. An increase in biomass from the growth of forests (both above ground and below ground) provides a carbon sink. As long as the wood does not decompose or is not burned or otherwise destroyed, the carbon is maintained in the wood and the wood continues to be a carbon sink. Trees harvested for building materials maintain the carbon in the new structure (houses, etc.) for decades. Wood disposed of in a solid waste disposal site provides an almost permanent carbon sink. The growth of new trees planted on harvested areas sequesters additional carbon.

The carbon sink created by forests and forest products (9.6 percent) more than offsets the greenhouse gas emissions from agriculture (8.2 percent). Although most forested areas are not located in the Midwest, sinks do occur in Midwest agriculture. Agroforestry practices such as managed shelterbelts and forested riparian zones enhance carbon emission offsets and provide other wildlife and aesthetic benefits.

CO_2 flux from agricultural soils
The soil is a great storehouse (sink) of carbon in the form of organic matter. Currently agriculture soils provide a small (.4%) positive flux (soil sequestration slightly exceeds soil emissions) of carbon dioxide.

Midwest topsoil was created by the decomposition of prairie grasses that grew on these soils. Over the centuries, carbon was stored (sequestered) in the soil. When the prairie was plowed, soil carbon oxidized and became atmospheric carbon dioxide. Tillage of the soil over the decades released more carbon than was added by crop residue and thereby reduced soil organic matter. However, equilibrium has been reached in most soils where the amount of carbon sequestration approximately equals the amount of carbon released. In individual situations, however, excessive tillage continues to release carbon and no-till practices sequester carbon.

No-till farming practices provide a great potential for the future sequestration of atmospheric carbon and building soil organic matter while also minimizing soil erosion and reducing production costs. Carbon sequestration programs created by organizations such as the Iowa Farm Bureau provide the opportunity for farmers to transform the sequestered carbon into “carbon credits” that can be sold (AgDM Newsletter, Aug. 2007). These programs provide a way for farmers to generate revenue while also reducing atmospheric carbon dioxide levels.

Other
Other sinks include the planting of trees in urban areas and landfilled yard trimmings and food scraps.

Opportunities for midwest agriculture
If federal and state governments create incentives for lowering greenhouse gas emissions and expanding sinks, Midwest agriculture will be uniquely positioned to take advantage of these by:

1) Sequestering carbon in agricultural soils by reducing tillage,
2) Reducing nitrous oxide emissions through more efficient use of nitrogen fertilizer,
3) Developing viable technologies for creating ammonia (nitrogen fertilizer) from feedstocks other than natural gas.
4) Capturing methane emissions from anaerobic manure handling facilities,

5) Substituting renewable fuels for gasoline, diesel fuel and natural gas used on the farm,
6) Increasing the generation of electricity from wind and other renewable sources,
7) Expanding the use of practices like managed shelterbelts and forested riparian zones,
8) Others we haven't thought of yet.

The next article in this series will deal with the issues of greenhouse gases from renewable fuels.

Global warming – are bio-fuels good or bad?

The emergence of bio-fuels such as ethanol has been touted as the answer to our energy problems and a boon for the agriculture sector. By defining the energy problem as the danger of relying on foreign sources of oil, domestically produced renewable fuels provide a logical solution. So, the question facing domestically produced renewable fuels is not "if it provides a solution" but "how much of a solution does it provide".

Net greenhouse gas emissions

Another dimension of the energy problem has emerged. Scientific investigation has confirmed the dangers of global warming from greenhouse gas (GHG) emissions. Our reliance on energy from fossil fuels contributes to GHG emissions. Early analysis determined that bio-fuels, while not exempt from carbon emissions, emit less (GHG) emissions than gasoline. As shown in Table 1, corn ethanol results in a 20 percent reduction in emissions versus gasoline. Biomass ethanol shows a 70 percent reduction. Other studies provide similar results.

Although growing corn and biomass and refining them into ethanol produces as much or more emissions than pumping, transporting and refining crude oil into gasoline, the source and amount of carbon contained in the feedstock is the most important component. The carbon in crude oil has been sequestered from the atmosphere and now is being released into the atmosphere during consumption. So, it adds to the amount of atmospheric carbon. Conversely, the carbon contained in corn and biomass that is released during consumption was recently pulled out of the atmosphere during photosynthesis. So this carbon is part of the natural carbon cycle and does not increase the level of atmospheric carbon.

Carbon in the soil

A carbon sink is a place where carbon is stored or sequestered. We are aware that crude oil and coal are natural sinks where carbon was removed from the atmosphere millions of years ago. As we consume oil and coal, this carbon is released back into the atmosphere. We are also aware that forests, especially tropical rain forests, are natural carbon sinks where large amounts of carbon are stored in the wood. When forests are burned or otherwise destroyed through deforestation, the carbon is released into the atmosphere.

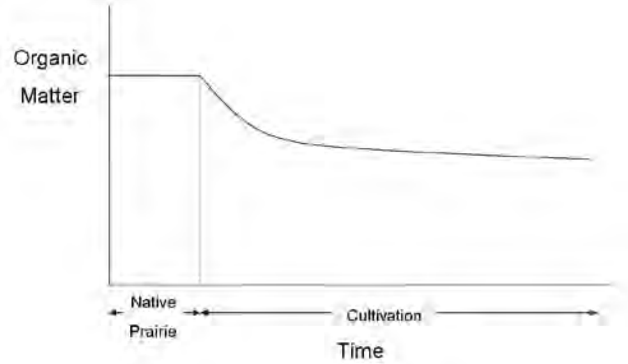
A less well-known but important carbon sink is soil. Large amounts of carbon are stored in the soil in the form of undecayed plant and organic matter. When virgin soils are disturbed by plowing or other tillage, large amounts of carbon stored as organic matter are released into the atmosphere. This causes a reduction in soil organic matter as shown hypothetically in Figure 1. However, over time the balance of emissions and sequestration is restored, but at a lower level of soil organic matter. Part of the organic matter loss from tillage is replaced by the organic matter increase from the decomposition of crop residue. Crop residue includes

Table 1. Gasoline and ethanol greenhouse gas (GHG) emissions (not considering land use changes) (grams of GHGs CO_2 eq. per MJ of energy in fuel)

Fuel Source	Making Feedstock	Refining Fuel	Vehicle Operation	Feedstock Uptake	Land Use Change	Total GHGs	Percent Change
Gasoline	+4	+15	+72	0	--	+92	--
Corn Ethanol	+24	+40	+71	-62	--	+74	-20%
Biomass Ethanol	+10	+9	+71	-62	--	+27	-70%

Source: Use of U.S. Cropland for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change, www.sciencexpress.org, Feb. 2008

Figure 1. Depletion of organic matter and carbon from midwest soils.



the stalks, stems, leaves, chaff, cobs, etc. left in the field after the grain is harvested.

Crop residue has been touted as a major biomass source for the production of cellulosic ethanol. However, removing residue for ethanol production will change the organic carbon balance in the soil. By removing the crop residue, it is not available for decay and sequestration as carbon in the soil. The soil will once again become a net emitter of carbon into the atmosphere.

Is there a limited amount of residue that can be removed for ethanol production without reducing soil organic matter levels further? This is a topic of current discussion and future research. Regardless of the answer, it appears that the potential of crop residues as a major ethanol feedstock is not as great as previously believed.

High levels of organic matter are also important for maintaining soil productivity and retaining soil moisture. In addition, crop residue contains important crop nutrients that are returned to the soil during decomposition. Crop residue left on the soil surface also helps reduce soil erosion.

This article has focused on the "direct" GHG emissions from both corn and cellulosic ethanol production. More controversial are the "indirect" emissions from "land use" changes that may be attributed to corn, biomass and ethanol production. In the next article we will explore these indirect effects and endeavor to shed light on the issues involved in this debate.

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Global warming – more on bio-fuels

In the previous article we discussed the greenhouse gas emissions from corn and biomass (cellulosic) ethanol. If only the "direct" effects of producing ethanol on existing cropland are considered, ethanol produces fewer greenhouse gas emissions than gasoline. In this article we will examine the controversy over the "indirect land use" effects of using existing cropland for ethanol production. We will also examine the emissions from converting native ecosystems to ethanol production.

The world's demand for food and feed and the world's agricultural capacity to produce food and feed are roughly in balance. If large areas of agriculture's production capacity are switched from food production to fuel production, either food shortages will arise or agriculture's production capacity must expand. Production capacity can expand in two ways – through increased yields per acre or more acres. Although increasing yields is a powerful way to expand production, it tends to occur gradually over time. Agriculture's production will expand more rapidly by increasing the land area under cultivation.

Native ecosystems

As the global ethanol industry expands, it is likely that native soils and ecosystems will be converted to farmland for bio-fuel production. In some parts of the world this process has already started. Estimates have been made of the impact on greenhouse gas emissions of producing ethanol on native ecosystems in different parts of the world. Three examples are shown in Table 1.

The carbon "debt" shows the soil carbon emissions created by transforming virgin land into bio-fuel production (the carbon emissions from this process were discussed in the previous article). Next, the percent of emissions "allocated to bio-fuels" represents the portion of the production that goes to bio-fuel production. For example, 39 percent of Brazilian soybean production is allocated to the oil used for bio-diesel production with the remainder allocated to soybean meal. The "annual repayment" represents the annual reduction in equivalent CO^2 emissions from using bio-fuels rather than gasoline to repay the carbon debt. The "repayment period" is the number of years required for the annual payment to repay the carbon debt.

For example, it will take 86 years of "annual payments" from palm biodiesel production to repay the "carbon debt" from converting tropical rainforest to palm biodiesel production. Only after the year 2094 (2008 + 86 = 2094) will the cumulative emissions from palm biodiesel production be less than those of gasoline.

Converting central US grasslands to corn ethanol production will require almost 100 years to repay the carbon debt (emissions) from converting grassland to corn production. Converting Brazilian grasslands to biodiesel production will require 37 years.

According to the calculations by Fargione et al., unless a way can be found of maintaining soil carbon, converting native ecosystems to bio-fuels production as a replacement for gasoline will not reduce greenhouse gas emissions.

Indirect emissions

It appears that, in general, bio-fuels produced on existing US farmland (discussed in our previous article) produces fewer emissions than gasoline while bio-fuels produced on converted land (Table 1) produces more greenhouse gas emissions.

However, the picture is somewhat more complex. Recent scientific research has focused on the indirect change in land use from using corn for energy instead of food. Changing land use from feed/food to fuel in one location may trigger a change in land use to feed/food in another location. For example, what is the indirect effect of converting an acre of Midwest from corn for feed and food production to corn for ethanol production?

Transitioning this acre of Midwest cropland may mean that somewhere in the world an acre of virgin land is converted to farmland for feed and food production to make up for the lost acre in the Midwest. Market prices are the mechanism causing this transition. Reducing the feed supply will raise feed prices which will provide an incentive to increase feed production somewhere else.

Table 2 shows the "indirect land use" changes from using farmland for fuel production rather than feed production. This change in land use triggers substantial greenhouse gas emissions. Table 2 is the same chart as shown in the previous article except that the indirect effect of carbon emissions from land use change is taken into effect. By including land use changes, corn

Table 1. Greenhouse gas emissions for selected examples of bio-fuels production

	Palm Biodiesel in Indonesia/Malaysia (Tropical Rainforest)	Soy Biodiesel in Brazil (Cerrado Grassland)	Corn Ethanol in Central U.S. (Grassland)
Carbon Debt [1/]	702	85	134
Allocated to Bio-fuels (%) [2/]	87	39	83
Annual Repayment [3/]	7.1	0.9	1.2
Repayment Period (yrs) [4/]	86	37	93

[1/] *Carbon debt, including CO^2 emissions from soils and aboveground and belowground biomass due to habitat conversion (Mg CO^2 ha-1)*

[2/] *Proportion of total carbon debt allocated to biofuel production*

[3/] *Annual life-cycle GHG reduction from bio-fuels, including displaced fossil fuels and soil carbon storage (Mg CO^2eha-1 yr-1)*

[4/] *Number of years after conversion to biofuel production required for cumulative biofuel GHG reductions, relative to fossil fuels they displace, to repay the biofuel carbon debt.*

Source: Fargione, et al. (2008)

Table 2. Gasoline and ethanol greenhouse gas (GHG) emissions considering land use changes (grams of GHGs CO^2 eq. per MJ of energy in fuel)

Fuel Source	Making Feedstock	Refining Fuel	Vehicle Operation	Feedstock Uptake	*Land Use Change*	Total GHGs	Percent Change
Gasoline	+4	+15	+72	0	***--***	+92	--
Corn Ethanol	+24	+40	+71	-62	***+104***	+177	+93
Biomass Ethanol	+10	+40	+71	-62	***+111***	+138	+50

Source: Searchinger, et al. (2008)

ethanol produces 93 percent more emission than gasoline. Cellulosic ethanol produces 50 percent more.

The production of 15 billion gallons of ethanol (the current mandate for corn-starch ethanol) will cause a large shift in corn acres from feed production to energy production. This conversion from feed production to fuel production could trigger a large acreage shift of virgin land into farmland for feed production in other parts of the world.

Not so fast

While the logic used in the scenario above seems reasonable, other scientists raise questions about the underlying assumptions used to obtain these results. The analysis provides one scenario of what might happen, but this is not the only one. Other scientists have questioned whether global markets for agricultural commodities are as tightly coupled as is assumed in the previous analysis. And enhanced yields on both existing high-yielding land and marginally producing land need to be considered, as do biofuel sources other than food/feed grains. Further research is needed to assess to what extent a change of the proposed magnitude in one part of the world will trigger the projected response in another part of the world. The conversion of native ecosystems to agricultural production started well before the emergence of the bio-fuels demand.

Implications

Research to assess the indirect impact of converting agricultural production from food/feed production to fuel production is just beginning. Additional research is forthcoming to improve our understanding of this relationship and its impact. However, measuring the carbon loss from the conversion of the myriad of different types of ecosystems around the world is daunting. The implementation of a world-wide carbon tax or cap-and-trade system, along with good data on carbon loss and gain under different land-use scenarios, will help balance the cost of carbon emissions with the need for food and fuel. Although this may seem like a distant goal, it does provide the framework for a viable solution.

As discussed in the previous articles, efforts to curb greenhouse gas emissions will impact the world our children and grandchildren will inherit. However, in the short term (present time to 2030), we will have little impact on global warming and will need to adapt to the climate changes that are coming. The next article will focus on how global warming may impact the production capacity of Midwest agriculture.

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Global warming – impacts of global climate change on the Midwest

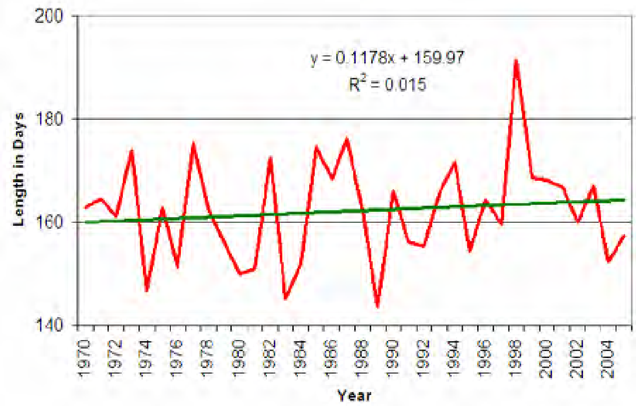
In previous articles we discussed the science of climate change and how agriculture is impacting it. However, in the short term (next 50 years) we can do little to mitigate the effects of climate change. Changes during this period have already been set in motion by past greenhouse gas emissions. Limiting greenhouse gas emissions in the future will only impact climate change in the long-term (beyond 50 years). So we must learn to adapt to the changes in climate that will occur over the next 50 years. In this article we discuss some of the ways that climate change may impact Midwest agriculture. A better understanding of these climate changes will help us harden agriculture to adverse changes and find new opportunities that might emerge from favorable changes.

The study of global climate change discussed briefly in previous articles is an important first step in understanding Midwest climate because the atmosphere links our region with changes going on elsewhere such as tropical sea-surface temperature changes and shrinking Northern Hemisphere ice masses. However, farmers and agribusinesses are affected by local and regional – not just global – climate change. So, what changes can we expect here in the Midwest? How confidently can we make such statements? Below is a list of changes likely to occur in the Midwest as gleaned from the most recent report of the International Panel on Climate Change 2007 4th Assessment Report and from the US Climate Change Science Program Synthesis and Assessment Report of 2008. In each case we give the level of confidence (high or medium) of the scientific consensus. In some cases we have combined more than one indicator to provide factors relevant to agriculture.

Temperature-related changes:

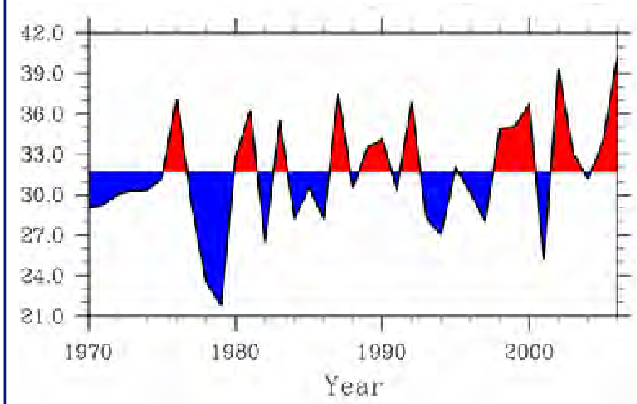
- Longer frost-free period (Figure 1) (high)
- Higher average winter temperatures, both daily maximum (Figure 2) and daily minimum (Figure 3) (high)
- Fewer extreme cold temperatures in winter (high)
- Fewer extreme high temperatures in summer in short term but more in long term (medium)
- Higher nighttime temperatures both summer and winter (high)
- More freeze-thaw cycles (high)
- Increased temperature variability (high)

Figure 1. Trend in length of the frost-free season in Iowa (statewide average)



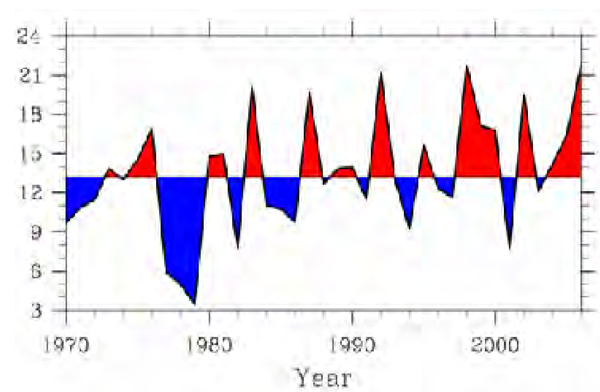
Source: D. Herzmann, Iowa Environmental Mesonet

Figure 2. Trend in average winter (Dec-Jan-Feb) daily maximum temperature (statewide average).



Source: D. Herzmann, Iowa Environmental Mesonet

Figure 3. Trend in winter (Dec-Jan-Feb) average daily minimum temperature (statewide average).



Most plant processes are accelerated under higher (except extreme) temperature. So, even though the frost-free period will be longer, the growing season required by the plant may be shortened. Nighttime temperatures have risen more than daytime temperatures over the last 30 years. This trend is likely to continue. Although it seems counter-intuitive, summer daytime maximum temperatures in Iowa have gone down in the last 30 years. We rarely have extended periods of 100+ oF temperatures. This is in part due to more precipitation and likely slightly more cloudiness.

Over-wintering of pests may be more of a problem in the future. It is already happening in the Rocky Mountains where the pine-bark beetle is expanding its range northward and to higher elevations due to fewer extreme cold events.

More freeze-thaw cycles might be better for breaking down hard-pan soils and allowing more winter recharge of soil moisture. They may be detrimental to animal health, however, and certainly will create more challenges for road maintenance.

Higher day-to-day and year-to-year variability in temperatures (2007: warm March followed by widespread freeze in early April; 2008: cold March-May) can damage agricultural and fruit crops as happened in 2007 or delay spring planting and crop growth as happened in 2008.

Precipitation-related changes:

- More (~10%) precipitation annually (Figure 4) and during the growing season (Figure 5) (medium)
- Most of the increase will come in the first half of the year (wetter springs, drier or little change in summers) (high)
- More water-logging of soils (medium)
- More variability of summer precipitation (high)
  - –More intense rain events and hence more runoff (high)
  - –Higher episodic streamflow (medium)
  - –Longer periods without rain (medium)
- Higher absolute humidity (Figure 6) (high)
- Stronger storm systems (medium)
- Snowfall increases (late winter) in short term but decreases in long run (medium)
- More winter soil moisture recharge (medium)

Precipitation is much more difficult for climate models to simulate. So we have less confidence in the predictions of changes in precipitation due to climate change (more "mediums" and fewer "highs" in the confidence levels). A complicating issue of assessing changes in precipitation in the Midwest is that we are located close

Figure 4. Trend in Iowa total annual precipitation

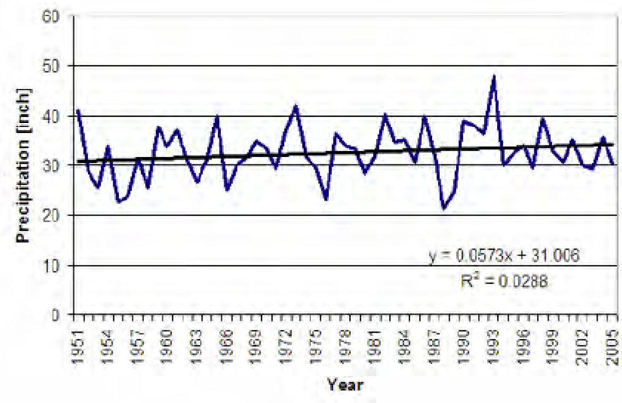


Figure 5. Trend in Iowa growing season precipitation.

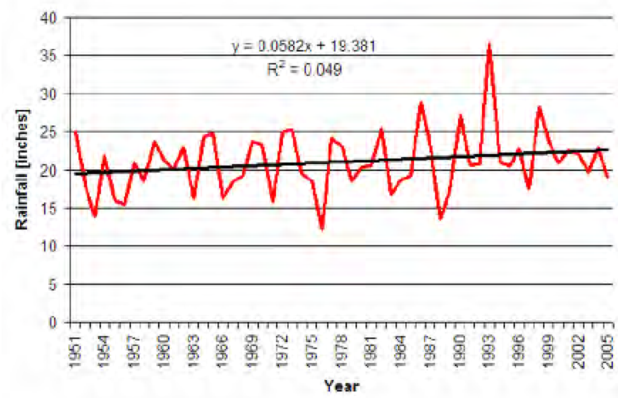
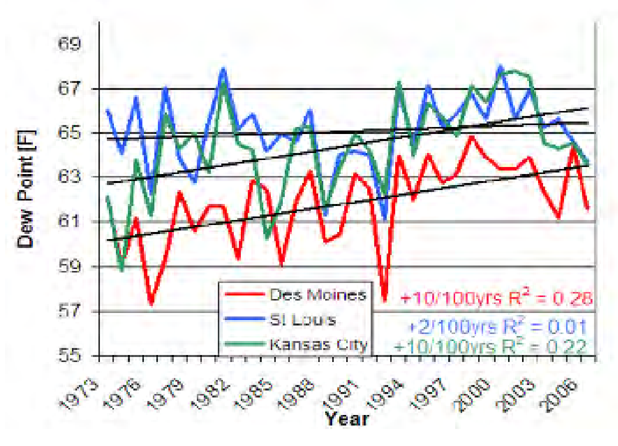


Figure 6. Trends in summer (Jun-Jul-Aug) dew-point temperature at three locations in the Midwest.



to regions of high precipitation gradients. That is, annual precipitation is much less in western Iowa than eastern Iowa and less in northern Iowa than southern Iowa. In Illinois, there is less in the north than the south, but east-west differences are small. So if precipitation patterns shift eastward, for instance, in a future climate, Iowa will be more affected than Illinois, but both will be affected by a northward shift of higher rainfall.

Other changes:

- Reduced wind speeds (high)
- Reduced solar radiation (medium)
- Increased tropospheric (atmospheric layer next to the earth) ozone (high)
- Accelerated loss of soil carbon (high)
- Faster plant growth and development to maturity (high)
- Weeds and vines grow more rapidly under elevated atmospheric CO_2 (high)
- Weeds migrate northward and are less sensitive to herbicides (high)
- Plants have increased water used efficiency (high)
- Combinations of conditions and pathogens more favorable for development of toxins (medium)

Reduced wind speeds can impact pollination and dispersion of pests and pathogens and, of course, influence wind power generation. At ISU we are examining the impact of climate change on wind speeds.

Increased precipitation in our region likely would be accompanied by more cloudiness and hence less solar radiation, particularly in spring. This likely would slow early-season crop growth.

Higher temperatures promote conditions that allow for the generation of tropospheric (atmospheric layer next to the earth) ozone from automobile exhaust. Ozone near the ground now likely accounts for a small reduction in yield, but may rise to as much as 30% over the next century.

Higher temperatures and more soil moisture accelerate the microbial action in soil. This leads to a faster breakdown of plant materials to form carbon dioxide out of soil carbon, increasing the loss of soil carbon.

Plant biological processes also are accelerated, which may be good or bad. A shortened pollination period for corn, for instance, might increase its vulnerability to drought – even short period droughts.

Many weeds, particularly C_3 weeds [1/], respond more quickly to elevated CO_2 than crops. Herbicides are, in some cases, less effective on weeds grown under these conditions.

Crops grown under high CO_2 environments do not require stomatal (minute pores in the epidermis of a leaf or stem through which gases and water vapor pass) opening as wide as those grown under lower CO_2. A positive side effect of this is that plants tend to conserve water better and thereby increase their water-use efficiency.

A plant that is stressed, by whatever cause, is more vulnerable to succumb to other biotic (living) or abiotic (non-living) stresses. For example, if humidity levels increase, corn encountering drought during the grain-filling phase may be more vulnerable to micotoxin or aflatoxic growth. We are only beginning to understand how such combinations of stress factors interact to challenge the flourishing of agricultural crops.

In our next article we will look internationally at how climate change may be affect other regions of the world where crops are grown for export.

[1/] C_3 plants show greater photosynthetic response to elevated levels of CO_2 than C_4 plants (e.g. corn).

Global warming - impact of climate change on global agriculture

Our efforts to mitigate the effects of climate change, urgent as they are, will have little effect over the next 50 years. Changes during this period have already been set in motion by past greenhouse gas emissions. Limiting greenhouse gas emissions will only affect climate change in the long-term (beyond 50 years). So we must learn to adapt to the changes in climate that will occur over the next 50 years.

In the previous article we listed several estimated changes we may expect to see in the Midwest and possible impacts on Midwest agriculture. In this article we will examine the rest of the world. We will identify expected changes in major agricultural regions around the world.

and the rim of Australia. These are the traditional agricultural producing regions of the world that have allowed human population to flourish and grow.

The population density of various parts of the world is shown in Figure 2. In many instances, areas suitable for rainfed agriculture match the areas of high population density. This includes Europe, Eastern U.S., India, China and Southeast Asia. Other regions, such as southern Mexico, the Middle East, parts of China, and regions bordering the Nile River, have high populations but low suitability for rainfed agriculture and therefore must rely on either irrigation or food imports. Changes in the suitability index for rainfed agriculture due to climate change can impact the ability of large areas of the world to feed themselves.

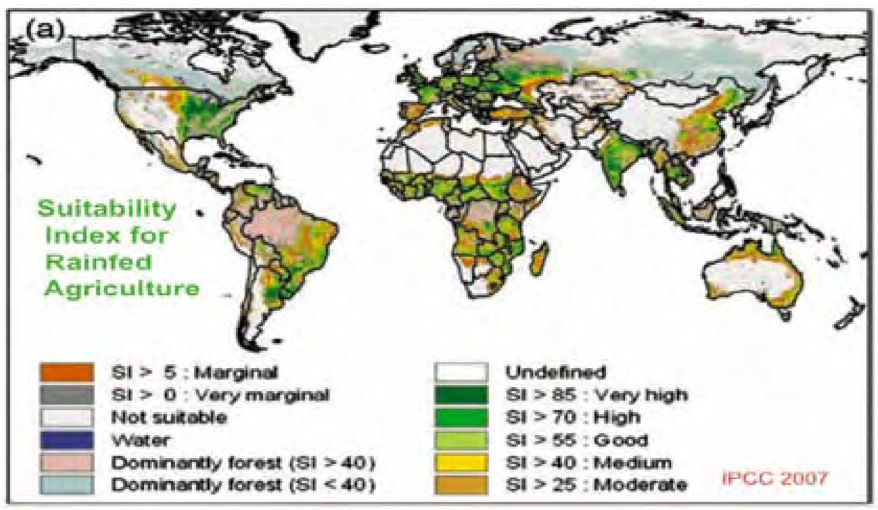
Suitability for rainfed agriculture

It takes large amounts of water to produce grain. But suitable soil and terrain are also necessary for successful agricultural production. Let's take a look at regions of the world that have a "high suitability for rainfed agriculture". This suitability factor depends on the amount of precipitation, the availability of soils suitable for agriculture, and terrain that allows for agricultural production.

An index of the suitability for rainfed agriculture is shown on the world map in Figure 1. The various shades of green show a high suitability index. The yellows and golds indicate a more moderate suitability index. The other colors show areas that are generally not suitable.

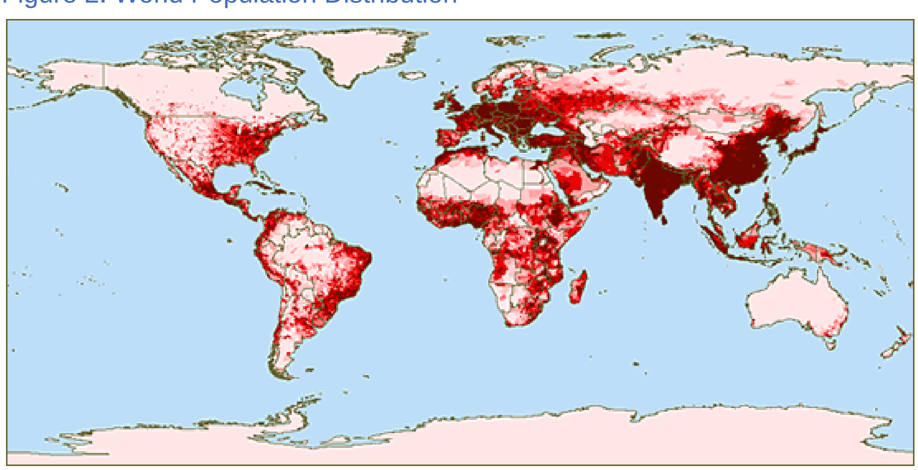
From this we can see the regions of the world that are highly suitable for rainfed agriculture. They include the U.S. Midwest and Great Plains, Europe and European Russia, India, Southeast Asia, southern and eastern Brazil including the Pampas of Argentina, sub-saharan Africa

Figure 1. Suitability Index for rainfed agriculture



Source: (Fisher et al., 2001; IPCC, 2007b)

Figure 2. World Population Distribution



Source: BigPicture - Smallworld

Projected precipitation changes

The latest International Panel on Climate Change (IPCC) report outlines potential changes in rainfall patterns over the 21st Century. Although this represents the best available science, there are still uncertainties about the projections. However, considerable research is currently focused on this issue. So, more reliable estimates will be forthcoming.

By looking at the projected changes in precipitation due to climate change over the next hundred years (Figure 3), we see there will be winners and losers. Shades of blue indicate increases in precipitation. Shades of red indicate declines.

Since soils and terrain will not change, changes in the suitability index for rainfed agriculture depend on changes in rainfall during the growing season. The suitability index will increase in some areas and decrease in others. A decrease in precipitation will usually result in a decline in the suitability index. However, an increase in precipitation may or may not improve the suitability index. If the precipitation increase leads to more flooding or water-logging of soils, the suitability index will decline. Also, changes in precipitation will increase a region's suitability index only if it has suitable soils and terrain.

To help us focus on the areas with suitable soils and terrain, we have circled these areas in Figures 3 and 4. Areas with increased rainfall are circled in green. Areas with decreased rainfall are circled in red.

The IPCC has not evaluated how the suitability index will change due to climate change rainfall projections. Discussions are underway to launch such an effort. However, we can at least make a simplistic estimate of the future of global agricultural production based on projected changes in precipitation.

Of the seven major regions with a high or moderate suitability index (Figure 1), we can see that:

1) The central U.S. will likely experience a modest decrease, particularly in the Great Plains,
2) Mexico and Central America will likely experience a significant decrease. This decline in precipitation is a feature of all global climate models. Because of the magnitude of this impact on our neighbors to the south, our U.S. national policy makers should monitor climate change over this region through the coming years.
3) Brazil, Uruguay and Argentina might see an increase in rainfall that likely will be beneficial,
4) Southern and eastern Europe likely will see a substantial decrease,
5) Central Africa likely will see an increase and southern Africa a decrease,
6) India probably will experience an increase.
7) China and East Asia will probably experience an increase. However, the likelihood of extreme increases in precipitation in these areas may be detrimental to agricultural production.
8) Australia is projected to see an increase in the east and a decrease in the west. Regions with a long history of cereal production, such as Australia, are already facing new challenges (Reuters, 2008).

Figure 3. Projected precipitation changes between 1980-1999 and 2080-2099 for the Northern Hemisphere summer (June-July-August) (energy-conserving scenario of greenhouse gas emissions -- IPCC 2007a).

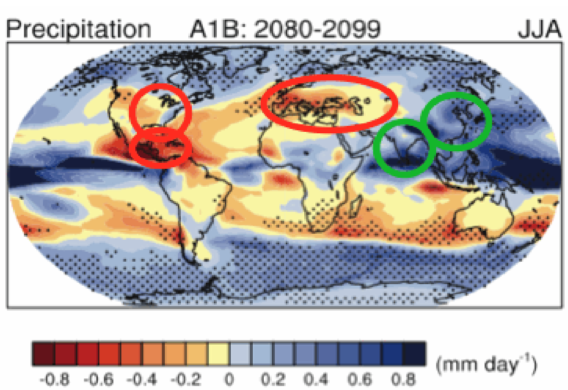
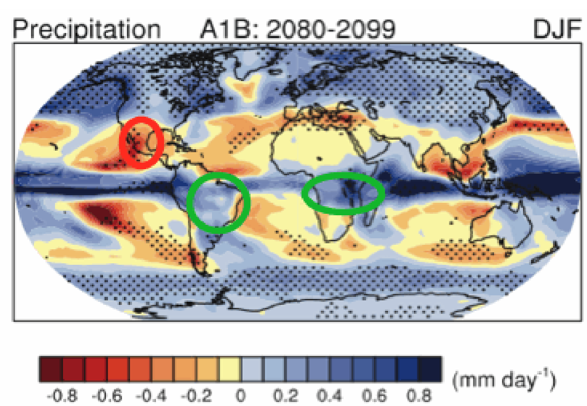


Figure 4. Projected precipitation changes between 1980-1999 and 2080-2099 for the Southern Hemisphere summer (December-January-February) (energy-conserving scenario of greenhouse gas emissions -- IPCC 2007a).



> Six continuous years of drought have reduced Australia's rice crop by 98 percent and has shut down processing plants (Bradsher, 2008).

Climate change will also lead to an increase in temperature that will impact agricultural production. However, it is difficult to evaluate whether temperature increases due to climate change will allow new regions such as northern Russia and Canada to expand production.

Adapt by using irrigation

Can we adapt to reduced rainfall by irrigating? Although irrigation can provide a short-term solution (a few decades), it does not provide a permanent or sustainable solution. A colleague made the observation that, of all former civilizations that depended on irrigated agriculture for their food supply, none have survived. In the modern world we see numerous regions with widespread irrigation facing challenges relating to water supply (e.g., aquifer depletion, competing uses for reservoir water) or salinization of land under long-term irrigation.

A recent example is Saudi Arabia (Elhadj, 2008), which, having an annual rainfall of only 3-4 inches per year, discovered in the early 1980s what was thought to be substantial groundwater reserves. By 1992 they were irrigating about 2.5 million acres and producing 4.1 million tons of wheat. But by 2000, the average cost of raising wheat in Saudi Arabia rose to $500 per ton – four times what it cost to buy it on the world market. On January 8, 2008, the Saudi government abandoned its food independence strategy and decided instead to import the country's entire wheat needs by 2016.

So, in the long-term, we will depend on rainfed agriculture. This means we must adapt our agricultural systems to the changes that a changing climate has in store for us.

Implications

We emphasize that, although the research summarized by the latest IPCC report represents the best available science, there are still uncertainties in the projections summarized here. However, climate change will have a significant impact on world agriculture regardless of the specific implications for various growing regions.

Because of the global nature of agricultural markets, agricultural trade patterns may shift. U.S. producers must address both the impact of climate change on their own operations and respond to market signals created by the impact of climate change on agricultural production around the world.

These projected changes in rainfall patterns and the resulting changes in the suitability index for rainfed agriculture provide us with a tool for anticipating the impact of climate change on various agricultural regions of the world. By focusing our attention on the regions of the world where climate change will negatively impact agricultural production, we can develop strategies for adapting to these changes that will help mitigate the negative impact on food production in the coming decades.

These strategies must focus on agricultural research and development, including investment in new technologies that can mitigate the impact of climate change. Although countries must make these investments individually, a need will arise for a world-wide collaboration to address these issues on a global basis.

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