



*Field to Market: The Keystone Alliance for Sustainable Agriculture*

**Environmental Resource Indicators  
for Measuring Outcomes of  
On-Farm Agricultural Production in the United States**

**First Report, January 2009**

(Available online at [http://keystone.org/spp/env-sustain\\_ag.html](http://keystone.org/spp/env-sustain_ag.html))





## Table of Contents

<b>Letter to Readers</b>	<b>ii</b>
<b>Steering Committee Member List</b>	<b>iii</b>
<b>Executive Summary</b>	<b>iv</b>
<b>1. Introduction</b>	<b>1</b>
<b>2. Data and Methods</b>	<b>4</b>
2.1 Overview	4
2.2 Land Use Indicator	7
2.3 Soil Loss Indicator	9
2.4 Water Indicator	11
2.5 Energy Use Indicator	18
2.6 Climate Impact Indicator	22
<b>3. Results: Corn</b>	<b>29</b>
<b>4. Results: Cotton</b>	<b>35</b>
<b>5. Results: Soybeans</b>	<b>41</b>
<b>6. Results: Wheat</b>	<b>47</b>
<b>7. Discussion and Conclusions</b>	<b>53</b>
<b>8. References</b>	<b>56</b>
<b>Appendix A: Literature Review of Sustainability Metrics</b>	<b>A-1</b>
<b>Appendix B: Peer Review Summary Report</b>	<b>B-1</b>
<b>Appendix C: Agricultural Indicators - Total Impact</b>	<b>C-1</b>

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## **To the readers of this report:**

A year and a half ago, a diverse group of leaders from the conservation community, farmer organizations, agribusiness companies and food companies gathered together to attempt to develop a framework for “sustainable agriculture” for production agriculture. It was clear from the start of that meeting that there was a strong consensus about the challenges that lie ahead for agriculture. Predicted global food demands indicate that production will need to double in the next 40 years. At the same time, we are increasingly aware of the need to preserve biodiversity, the challenges of climate change, and the potential degradation of soil and major waterways. Agriculture must meet these and other challenges with the continued leadership, innovation, and performance that have marked the last century in production agriculture. These challenges will further require strong collaboration among farmers, conservation and community leaders, and the entire agricultural supply chain.

As our discussions have progressed, we have learned a few things about sustainability and agriculture. Good practices are key to achieving good outcomes, and yet it is the outcomes—water use, soil loss, yields, to name a few—that will dictate how sustainable our systems are.

Recognizing these tensions, we have devoted our attention first to identifying and measuring systems-wide outcomes that are important to the sustainability of production agriculture in the United States. Tracking these systems-wide measures is a first step at gauging overall performance against key sustainability indicators. We will look to local efforts and initiatives to further inform our work.

One of our axioms has been to build on areas of highest common ground, accomplish what we can, and learn as we go. While it has been no easy task to develop a set of tools and metrics that provide meaningful and credible information and also track and identify trends over time on a broad scale, we recognize that this report is only a starting point. Yet we feel it is an important point that will inform our future work. We know that the local context –environmentally, socially, and economically– is critically important to the decisions growers make every day on an individual level. We are learning how to ensure that tracking national, system-wide performance will create drivers for change at the individual farm level, at the watershed level, and at the regional level.

We have embarked on this complex task by focusing first on environmental indicators and on commodity crops in the United States. Broader economic and societal trends are equally important to track to determine our overall progress towards greater sustainability as we meet the challenges of the next 40 years. We also recognize that these challenges must be met not only by the four crops focused upon in this study, but by all crops and by a full spectrum of practices and technology choices. Our work in those areas will continue.

We recognize that the credibility of this information is critical to its use. We conducted an informal peer review of this information with experts in agriculture. We learned from these experts and will continue to solicit expert feedback as we do additional work. A summary of peer feedback and our response is included as an appendix to this report.

We continue to address these challenges and their various dimensions, and invite you to join us as we learn together how to create more sustainable outcomes for agriculture.

**Sincerely,**

**Jeff Barach, Jason Clay, Bonnie Raquet, Jerry Steiner, Rick Tolman**

The Executive Committee on behalf of *Field to Market: The Keystone Alliance for Sustainable Agriculture*

***Field to Market***  
***The Keystone Alliance for Sustainable Agriculture***

**Steering Committee Members**

Dr. Jeff Barach, Grocery Manufacturers of America  
John Buchanan, Conservation International  
Dr. Jason Clay, World Wildlife Fund  
Daren Coppock, National Association of Wheat Growers  
Michael Doane, Monsanto Company  
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Gene Kahn, General Mills  
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Dr. Greg Wandrey, DuPont  
Andrew Whitman, Manomet Center for Conservation Sciences  
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Dr. Bob Young, American Farm Bureau Federation

***Field to Market***  
***The Keystone Alliance for Sustainable Agriculture***  
**Environmental Resource Indicators Report**

**Executive Summary**

**Background.** Nearly all estimates of future demand for agricultural goods suggest a need to double agricultural production by 2050, if not before, in order to maintain adequate supplies for a growing world population that will use its expanding income to diversify diets with more meat, dairy, fruits and vegetables.<sup>i</sup> *Field to Market: The Keystone Alliance for Sustainable Agriculture* believes this increased production must be accomplished in a manner that does not negatively impact – and actually improves – overall environmental and societal outcomes. *Field to Market* is a collaborative stakeholder group of producers, agribusinesses, food and retail companies, and conservation organizations that are working together to develop a supply-chain system for agricultural sustainability. The group was convened and is facilitated by The Keystone Center, a neutral, non-profit organization specializing in collaborative decision-making processes for environment, energy, and health policy issues.

As an initial step, the group has defined sustainable agriculture as meeting the needs of the present while improving the ability of future generations to meet their own needs by focusing on these specific, critical outcomes:

- Increasing agricultural productivity to meet future nutritional needs while decreasing impacts on the environment, including water, soil, habitat, air quality and climate emissions, and land use;
- Improving human health through access to safe, nutritious food; and
- Improving the social and economic well-being of agricultural communities.

It is within this context that the group is developing metrics to measure the environmental, health, and socioeconomic outcomes of agriculture in the United States. These metrics will ultimately comprise a Sustainability Index that will facilitate quantification and identification of key impact areas and trends over time, foster productive industry-wide dialogue, and promote continued progress along the path toward sustainability. The national-scale environmental resource indicators presented here are a first step in these larger efforts, which are summarized

visually in Table I.I. Table I.I lists the kinds of components that we believe are critical for a complete sustainability index that measures outcomes for a full range of products and practices. The table includes the national scale outcomes that we have modeled to date (the shaded cells) as well as the additional environmental, health, and socioeconomic outcomes at national, regional and local scales that we plan to model in the future. Our future plans and objectives for developing international scale metrics have not yet been defined.

**Table I.I. Components of a Complete Sustainability Index.** *Field to Market* has produced metrics for measuring environmental outcomes at the national scale (shaded cells). Specific socio-economic and health and safety outcomes are given as examples only; future work will determine which outcomes can be measured within these broad categories, as well as how they can be applied at different scales.

	Environmental Outcomes							Social and Economic Outcomes							Health and Safety Outcomes			
	Land Use	Soil Loss	Water Use	Water Quality	Energy Use	Climate Impact	Biodiversity	Producer Income	Labor	Productivity	Competing Land and product uses	Rural Character and Quality of Life	Availability	Post Harvest Loss	Consumer Demand	Return of Value to Producers	Nutrition (access to calories, etc)	Safety
International Scale																		
National Scale	x	x	X		x	x				x								
Regional Scale																		
Local Scale																		

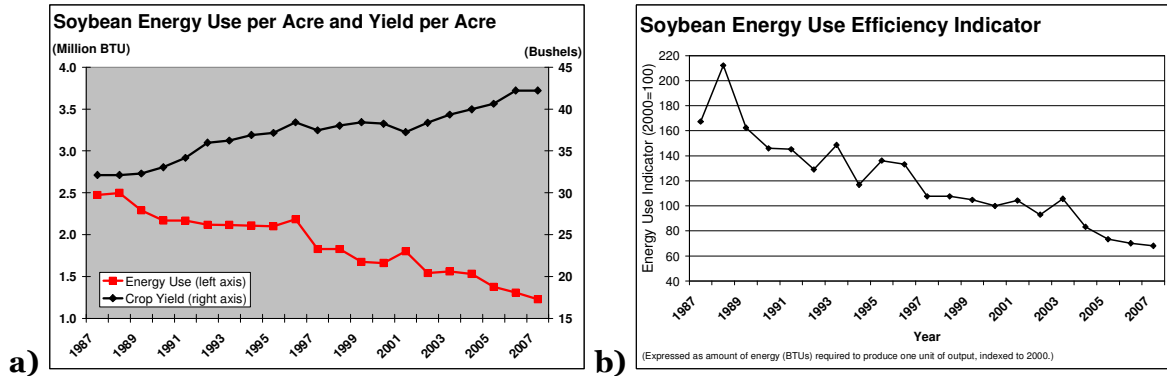
**Methods Overview.** The environmental resource indicator metrics presented here represent a first step in these efforts. Using publicly-available data, national-scale metrics are developed to measure outcomes for five environmental indicators: land use, soil loss, irrigation water use, energy use, and climate impact (greenhouse gas emissions). The metrics are applied to quantify environmental outcomes for four commodity crops –corn, cotton, soybeans, and wheat—produced through agricultural practices in the United States.

The national scale was chosen as a starting point for benchmarking the overall environmental

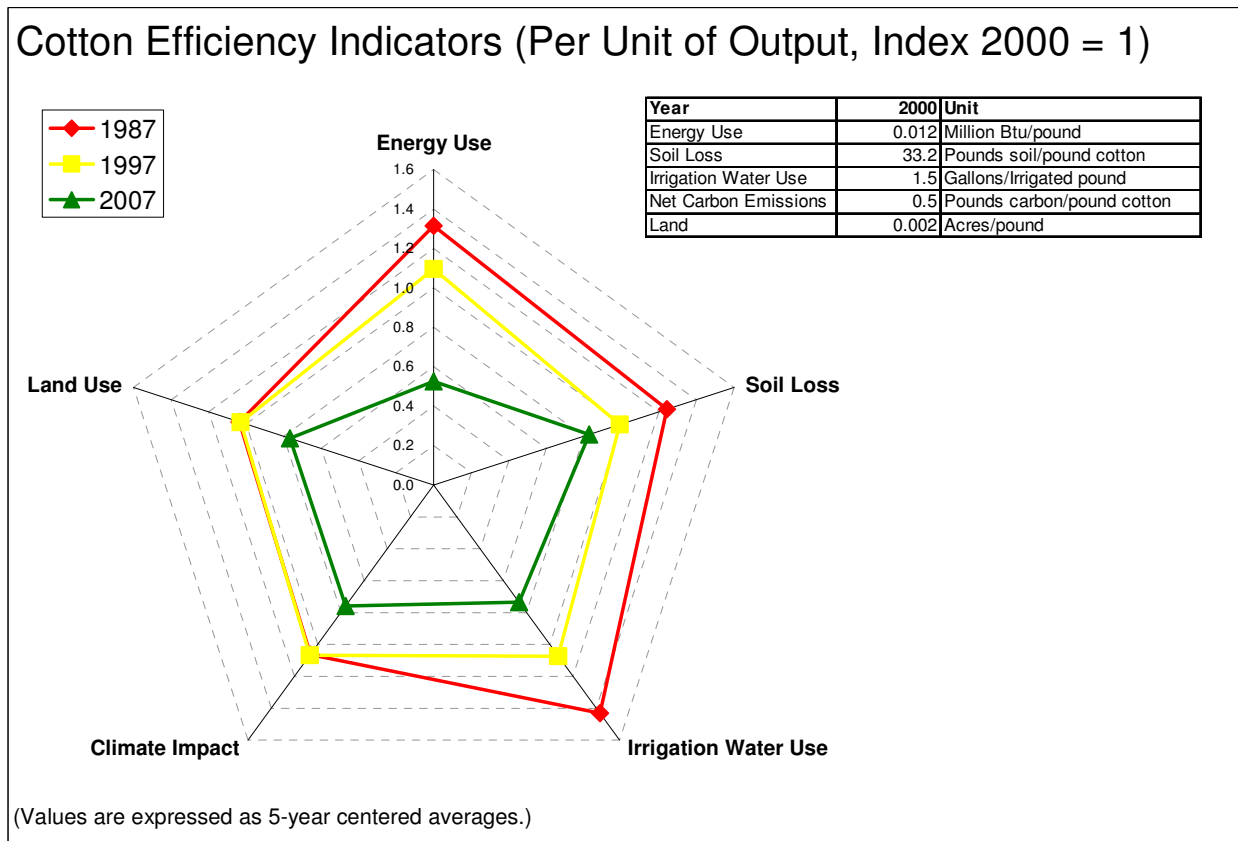
performance of particular crops. We believe that national level environmental indicators can provide perspective and prompt industry-wide dialogue that is ultimately relevant to more localized investigations and efforts. We have focused upon the four commodity crops because they constitute a majority of agricultural crops currently harvested in the United States. An outcomes-based approach was selected because it can provide an inclusive mechanism for considering the actual impacts and sustainability of diverse agricultural products and practices.

We recognize that water quality and biodiversity are key environmental areas of concern for agriculture, and we will need to develop metrics to measure the successes and continued challenges for these areas. In this report, we provide an overview of our progress to-date in developing a water quality indicator.

**Results Overview.** Results are presented for the years 1987-2007. The results for each indicator (land use, soil loss, water use, energy use, and climate impact/carbon emissions) are displayed for each crop in two formats: 1) Resource indicator (use or impact) per acre and crop productivity (yield) per acre (Figure I.Ia), and 2) “Efficiency” indicators showing resource indicator (use or impact) per unit of output, benchmarked to the year 2000 (Figure I.I.b). We believe that both approaches are valuable, as resource use or impact indicators can show change over time independent of yield, and efficiency measures – resource indicator measures over output – can show change in use or impact over time relative to our ability to meet productivity demands. A summary of efficiency indicator results for each crop is also presented in a spidergram that demonstrates the change in “footprint” over time of all of the efficiency indicators (Figure I.II).



**Figure I.I. Examples of Indicator Charts: (a) Per acre resource use or impact and per acre productivity and (b) Resource efficiency (resource use/ unit of output, indexed to the year 2000)**



**Figure I.II. Summary of Cotton Efficiency Indicators**

**Discussion and Conclusions.** The group anticipates that the approaches presented in this report can be refined to better measure impacts on natural resources in addition to the efficiency of use of the resource. The group also anticipates that these approaches can be adapted to quantify environmental outcomes for other crops and agricultural products and be inclusive of a full range of agricultural technologies and practices ranging, for example, from organic to conventional methods. This expectation must be tested through case studies, and the methods must be revised as necessary for other crops and scales, as well as when additional data becomes available. Table I.II conceptualizes our understanding of what each of our current metrics does and does not do, the metrics' potential scalability, and areas for future improvement.

**Table I.II. Evaluation of Environmental Resource Indicators and their effectiveness as metrics for environmental sustainability outcomes at various scales.** The five metrics presented here are believed to be relevant (assuming appropriate available data) at national, regional, and local scales. Land Use, Water Use, and Energy Use indicators measure the efficiency of resource use, while soil loss and climate impact measure actual impact on the natural resource in question. In most cases, the data utilized is not confounded by non-agricultural sources of stressors. Agricultural inputs such as nutrients and pesticides are accounted for in the Energy Use and Climate Impact indicators. Examples of ideas for future areas of improvement are also provided.

Resource Indicator	Type of Measure of Sustainability Outcomes		Scalability (based on appropriateness of use of other available data)			Data confounded by other (non-agricultural) sources of stressors?	Ag Inputs Included? (i.e. nutrients, pesticides)	Areas of Improvement
	Efficiency of Use of Resource	Impact on Natural Resource	National	Regional	Local (grower)			
Land Use	Yes	No	Relevant	Relevant	Relevant	No	NA	
Soil Loss	No	Yes (soil loss specific)	Relevant (data specific to cropland)	Relevant	Relevant	No	NA	Incorporate 2007 data when available through NRI.
Water Use	Yes	No	Relevant	Relevant	Relevant	No	NA	Look for and utilize state level data with greater reporting frequency.
Energy Use	Yes	No	Relevant	Relevant	Relevant	No	Yes	Current approach may not capture energy efficiency improvement over time; include seed production energy.
Climate Impact	No	Yes	Relevant	Relevant	Relevant	Yes – geographic (climate and soil)	Yes	Could be improved with better energy efficiency data over time, possible improvements in the method of fertilizer application analysis, inclusion of NO <sub>2</sub> and CH <sub>4</sub> , and also by incorporating better measurement or estimation of soil organic carbon sequestration for alternative tillage practices and crop rotations (as they become available).

This report does not define a benchmark level for sustainability, and thus cannot conclude whether we have achieved “sustainability” in agriculture or how far we might have to go. However, the environmental resource indicators provide tools by which to describe progress or lack of progress at the national scale in terms of total environmental impacts as well as resource

efficiency. They also provide a context for further focusing in on specific challenges and regions and generating processes for achieving continuous improvement.

It is too soon in this process to draw major conclusions about this data. This report marks our first step in establishing some benchmarks and baselines for overall performance. However, we can begin to see some positive trends emerge and also identify areas where we would like to see stronger trends and continuous improvement. Gains in productivity (yield) per acre over the past decade in most of the crops have generally improved overall efficiency of resource use. Soil loss trends (both per acre and per unit of output) have improved significantly in all crops. In addition, corn has seen modest to significant improvements in water use per acre and in water use, energy use, and carbon emissions per bushel. Cotton and soybeans are making progress in reducing irrigated water use, energy use, and carbon emissions per acre and per unit of output. Wheat's energy use per bushel has decreased, its water use per bushel has remained relatively flat, and its carbon emissions per acre and bushel have seen larger increases. In the future, we hope to better understand the relationship between outcomes trends and the practices and other factors that are driving them. This understanding will enhance our ability to achieve improved outcomes performance.

We view this work as a first step toward developing a complete Sustainability Index. In the future, *Field to Market* will continue to develop and improve metrics for measuring environmental, health, and socioeconomic outcomes at a variety of scales, as we build consensus on an overall methodology for doing so (See Table I.I). We recognize that other stakeholders must be engaged to develop these indicators. The focus of these future indicators will be on outcomes rather than practices, policies, or technologies. The group will utilize these current and future measures to further communicate about and define sustainability and develop practices to promote continuous improvement throughout the agricultural supply chain.

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<sup>i</sup> FAO. (2006). World agriculture: towards 2030/2050. Rome: Food and Agriculture Organization.  
<http://www.fao.org/ES/esd/AT2050web.pdf>

***Field to Market***  
***The Keystone Alliance for Sustainable Agriculture***  
**Environmental Resource Indicators Report**

**1. Introduction**

*Field to Market: The Keystone Alliance for Sustainable Agriculture* is a collaborative stakeholder group involving producers, agribusinesses, food and retail companies, and conservation organizations striving to develop a supply chain system for agricultural sustainability. The alliance was convened and is facilitated by The Keystone Center, a neutral, non-profit organization specializing in collaborative decision-making processes for environment, energy, and health policy issues. The primary objectives of *Field to Market* are:

- To identify criteria for sustainable agriculture that are open to the full range of agricultural technology choices; and
- To support the implementation of production systems that lead to broad performance improvements against these criteria.

We believe that growing food demand, grower needs and desirable land use patterns will require an intensification of agriculture. Nearly all estimates of future demand for agricultural goods suggest a need to double agricultural production by 2050, if not before, in order to maintain adequate supplies for a growing world population that will use its expanding income to diversify diets with more meat, dairy, fruits and vegetables.<sup>1</sup> Agriculture is already the predominant use of all habitable land; however, grain-producing land per capita in 2030 is projected to be just 0.08 hectares (0.2 acres), or just one-third of what was available in 1950.<sup>2</sup>

Increased production must be accomplished in a manner that does not negatively impact – and actually improves – overall environmental and societal outcomes. Globally, agriculture makes an estimated 70 percent of freshwater withdrawals.<sup>3</sup> The World Water Council suggests we will need 17 percent more water than is available to feed the world in 2020.<sup>4</sup> Energy is an important input to agriculture, yet the competition for energy resources is growing. The International Energy Agency (IEA) suggests energy demand will grow by 55 percent by 2030, with 74 percent of the new demand coming from developing countries.<sup>5</sup> Climate change has also emerged as a concern with potential impacts on agricultural productivity. The Intergovernmental Panel on

Climate Change (IPCC) reports that agriculture contributes 13.5 percent of total global greenhouse gases (GHG).<sup>6</sup> The IPCC reports that another 17 percent of global GHG emissions are due to deforestation and land transformation – practices that are associated in part with the demand for new sources of agricultural land. In the United States, the Environmental Protection Agency (EPA) estimates that agriculture is responsible for less than 10 percent of GHG emissions.<sup>7</sup>

While agriculture is necessary in order to sustain human life, the group recognizes the need to address these and other important environmental and natural resource issues while meeting the demands for agricultural goods. Consistent with the Brundtland Report’s definition of sustainable development, we have defined sustainable agriculture as agriculture that “meets the needs of the present without compromising” – and while improving – “the ability of future generations to meet their own needs.”<sup>8</sup> The alliance is focusing on these specific, critical outcomes:

- Increasing agricultural productivity to meet future nutritional needs while decreasing impacts on the environment, including water, soil, habitat, air quality and climate emissions, and land use;
- Improving human health through access to safe, nutritious food; and
- Improving the social and economic well-being of agricultural communities.

It is within this context that the group is developing metrics to measure the environmental, health, and socioeconomic outcomes of agriculture in the United States. These metrics will comprise a sustainability index that will facilitate quantification and identification of key impact areas and trends over time, foster productive industry-wide dialogue and promote continuous improvement along the path toward sustainability. The national-scale environmental resource indicators presented here are a first step in these larger efforts. Table 1.1 lists the components that we believe are critical for a complete sustainability index that measures outcomes for a full range of products and practices. The table includes the national scale outcomes that we have modeled to date (the shaded cells) as well as the environmental, health, and socioeconomic outcomes at national, regional and local scales that we plan to model in the future.

**Table 1.1. Components of a Complete Sustainability Index.** *Field to Market* has produced metrics for measuring environmental outcomes at the national scale (shaded cells). Specific socio-economic and health and safety outcomes are given as examples only; future work will determine which outcomes can be measured within these broad categories, as well as how they can be applied at different scales.

	Environmental Outcomes							Social and Economic Outcomes							Health and Safety Outcomes			
	Land Use	Soil Loss	Water Use	Water Quality	Energy Use	Climate Impact	Biodiversity	Producer Income	Labor	Productivity	Competing Land and product uses	Rural Character and Quality of Life	Availability	Post Harvest Loss	Consumer Demand	Return of Value to Producers	Nutrition (access to calories, etc)	Safety
International Scale																		
National Scale	x	x	X		x	x				x								
Regional Scale																		
Local Scale																		

## **2. Data and Methods**

### **2.1. Overview**

As a part of this effort, studies of existing outcomes-based metrics for sustainability were consulted. Appendix A provides a thorough review of those studies. In May 2008, we conducted a peer review of our methodologies and data uses. Appendix B includes a list of peer reviewers, an overview of the process, and a summary of reviewer feedback as well as our responses. The methodologies presented here represent our attempts to integrate and respond to peer review feedback.

An outcomes-based approach was selected because it can provide an inclusive mechanism for considering the actual impacts and sustainability of a diversity of agricultural products and practices. The national scale was chosen as a starting point for benchmarking the overall environmental performance of particular crops. We believe that national level environmental indicators can provide perspective and prompt industry-wide dialogue that is ultimately relevant to more localized investigations and efforts.

For this study, data has been retrieved and assembled across four primary crops in the United States:

- 1) Corn
- 2) Cotton
- 3) Soybeans
- 4) Wheat

Together, the production of these four crops has comprised approximately 70 percent of the acres of agricultural cropland use in the United States for the past several decades. With the exception of hay production, these land uses would be the four largest acreage allocations of cropland in the United States. In 2007, these crops comprised 69 percent of the 305.7 million acres of U.S. agricultural crops harvested and had combined crop value of \$98.12 billion.<sup>9</sup> It is our intention that the methods utilized could be applied to a full range of technology choices and to other crops produced in the United States or elsewhere assuming sufficient data and, perhaps, with some modification.

In selecting resource indicators, the group has chosen to focus on five important indicator areas.

The five areas are:

- 1) Land use and biodiversity
- 2) Soil loss
- 3) Irrigation water use and water quality
- 4) Energy use
- 5) Climate impact

There is ample evidence to suggest these five indicator areas merit the most consideration when considering the environmental impact and sustainability of agriculture. In 1999, a United Nations Environment Program (UNEP) panel of 200 scientists across 50 countries selected water shortages and climate change potential as the most pressing problems for the 21<sup>st</sup> century.<sup>10</sup> A recent Massachusetts Institute of Technology survey of U.S. citizens reported that climate change, the destruction of ecosystems, and water pollution rank as the top three environmental concerns.<sup>11</sup>

In addition to providing an abundant source of raw commodities for global human consumption, efficient agricultural land use creates less incentive to utilize additional land resources that may harbor sources of biodiversity. Efficient land use also addresses a potential source of climate change – the significant CO<sub>2</sub> emissions resulting from deforestation and land transition – and results in utilizing less marginal land where higher rates of soil loss and applied fertilizer are a co-product of crop production.

The group has evaluated a number of other potential indicators including pesticide and fertilizer use. Consistent with the outcomes approach taken by this group, the impacts of these product inputs are accounted for in the energy use and climate impact outcomes indicators and will be included in the water quality indicator; the methodology for incorporating these inputs into energy and climate indicators is explained in sections 2.5 and 2.6 (below). Another important factor in choosing indicators has been the ability of management practices or technology to impact the observed outcomes. For this reason, the group decided against including a measure of total water use, requiring the use of rainfall as an indicator. Farm managers have no ability to manage the timing or application rates of rainfall. In addition, any undesirable impact of rainfall that can be managed, such as soil loss or water quality, is already assessed. By measuring

applied water, we place priority on the relatively less renewable water resources as well as those that are within the farm management decision process.

We recognize that water quality and biodiversity are also areas that merit considerable attention. Lacking a viable methodology at this time, we do not currently provide water quality and biodiversity metrics in this report. However, following the release of this report, we plan to turn our immediate attention to this issue with the intent of developing robust water quality and biodiversity metrics in the course of the next year. In the meantime, we have included in Section 2.4.2 an overview of our work on water quality to date, including the strengths and weaknesses of an earlier approach.

We present results in three formats: 1) Resource indicator (use or impact) per acre and crop productivity (yield) per acre, 2) “Efficiency” indicators showing resource indicator (use or impact) per unit of output, and 3) Total use and impact indicators, showing the annual use or impact per acre multiplied by total acres harvested. The Total annual indicators methodology and results are presented in Appendix C. We believe that all approaches are valuable, as resource use or impact indicators can show change over time independent of yield, and efficiency measures – resource indicator measures over output – can show change in use or impact over time relative to our ability to meet productivity demands. Total impact indicators show the impacts where increasing crop acreage may offset the benefits from higher yields and lower resource use per acre (Appendix C). A summary of efficiency indicator results for each crop is presented in a spidergram that demonstrates the change in “footprint” over time of all of the efficiency indicators; spidergram values are five-year centered averages.

For the efficiency measures, all indicators and variables are normalized to a unit of production:

Corn: per bushel produced

Cotton: per pound produced

Soybeans: per bushel produced

Wheat: per bushel produced

Yield data are derived from U.S. Department of Agriculture’s Annual Crop Production report.<sup>12</sup> Data used in this analysis are on a harvested area basis. Harvested area, rather than planted area, was used here because it is most often used in data reporting and is most familiar to agriculture producers. The alternative would be to present yield on a planted area basis; this method would account for abandonment due to weather or other adversity that causes the crop

not to be harvested. In parts of the world where abandonment is more pronounced, a measure based on planted area might be necessary. Similarly, resource indicator per acre values for soil loss, water use, energy use, and climate impact are per harvested acre. The per acre land use indicator is an exception, with land area shown as planted area in order to reflect total agricultural land use per crop.

In order to facilitate comparison and evaluate relative changes over time, each efficiency indicator is indexed where actual values observed in the year 2000 are set equal to 100. Therefore, a one unit change in the index value of an individual indicator is equal to a one percent change, based on actual values observed in the year 2000. Other prominent sustainability metrics, both pertaining to agriculture and apart from agriculture, have relied on normalized metrics including measures such as per capita, per unit of production, or per unit of value of production. In the widely acknowledged *2005 Environmental Sustainability Index*,<sup>13</sup> the authors suggest “...sustainability is a characteristic of dynamic systems that maintain themselves over time; it is not a fixed endpoint that can be defined;” under this interpretation, normalization becomes optimal in that it allows us to compare trends over time.

Data and methods have been standardized across all crops. The data utilized in this report have been retrieved from numerous sources – all are within the public domain, with the exception of some information on water quality presented below but not utilized in actual calculations. Data and methods for each environmental resource indicator are further explained below. Data analysis and summary has been completed by Global Insight, an economic, financial analysis, forecasting and consulting firm with more than 40 years of experience.

## **2.2. Land Use Indicator**

Land is a primary requirement to produce agricultural goods. By its very nature, agriculture domesticates the land under production. A 2001 USDA Economic Research Service Report stated, “Land quite literally underlies all economic activity, but nowhere more than for agriculture. Land is the primary input for crop production and grazing livestock, a source of rural amenities, and a store of value for farmland owners.”<sup>14</sup> According to 2002 land use data from the USDA, the United States composes 2.3 billion acres in total; 19.5% of these acres are cropland, or 442 million acres.<sup>15</sup> Other land uses include pasture, forest, special uses and

other.<sup>16</sup> These categories can be divided further into more specific uses such as grassland, urban, rural parks and wildlife, cropland used for pasture, and cropland idled to name a few.<sup>17 18</sup> Each type of land use contributes its own challenges to sustainability, especially agriculture as a result of its high level of productivity per acre and large land use percentage.<sup>19 20</sup> Therefore, in this report the focus is on cropland land use, which will be referred to as agriculture for corn, cotton, soybeans and wheat. In order for valuable crops to survive and thrive, the land must be managed in order that the optimal level of production can be reached. It is desirable to minimize the amount of land under agricultural management in order to sustain the ecosystem services associated with natural habitat. By limiting the amount of land under production, more land is provided for any and all other uses. Such uses might include habitat for wildlife and biodiversity of all forms.<sup>21</sup> Although there is evidence to suggest that agricultural land is being converted to suburban and urban areas,<sup>22 23</sup> at this time, it is our intent is to produce metrics for on-going agricultural production per acre. In future versions of the report we will more explicitly capture biodiversity and habitat measures within the land use metrics.

Data for measuring land use have come from the National Agricultural Statistics Service (NASS), a division of the United States Department of Agriculture (USDA). The data were drawn from the final estimates provided in the Annual Crop Production report released in February 2008.<sup>24</sup> USDA's survey estimates of yield and farmed land area are considered the best measure available for US agriculture, as well as much agriculture around the world.<sup>25 26</sup>

The land use efficiency indicator reflects the desire to minimize land use as a function of production:

$$\text{Land Use Efficiency Indicator} = \text{Harvested Acres} \div \text{Unit of Output}$$

Results are presented in both per acre and output efficiency forms.

$$\% \text{ Output efficiency} = 1 \text{ acre/units of output}$$

In other words, the results are presented in bushels or pounds per acre, as well as by the percentage of each acre that one bushel/pound requires for production. As indicated in the equations above, the land use efficiency indicator utilizes harvested acres, reflecting the productivity of one harvested acre. We recognize that an efficiency indicator utilizing planted area rather than harvested area per unit of output would have the greatest impact on cotton, which has the greatest rate of pre-harvest abandonment (10-11 percent). The impact on the

other three crops would be much smaller as the ratios of planted to harvested area for these three crops are close to 1. Harvested acres were used as the indicator in this report because the industry standard is to report yield based on harvested production.<sup>27</sup> It is also recognized that corn and soybean production go to uses other than the food supply, such as ethanol production. We focus on total harvested acres in this report and do not address post harvest allocation at this time.

For the land use efficiency indicator (land use per unit of output), data were indexed such that the year 2000 equals 100. This year was randomly selected as a reference. In addition, the numbers reported in the results section should be multiplied by a factor of 1000.

### **2.3. Soil Loss Indicator**

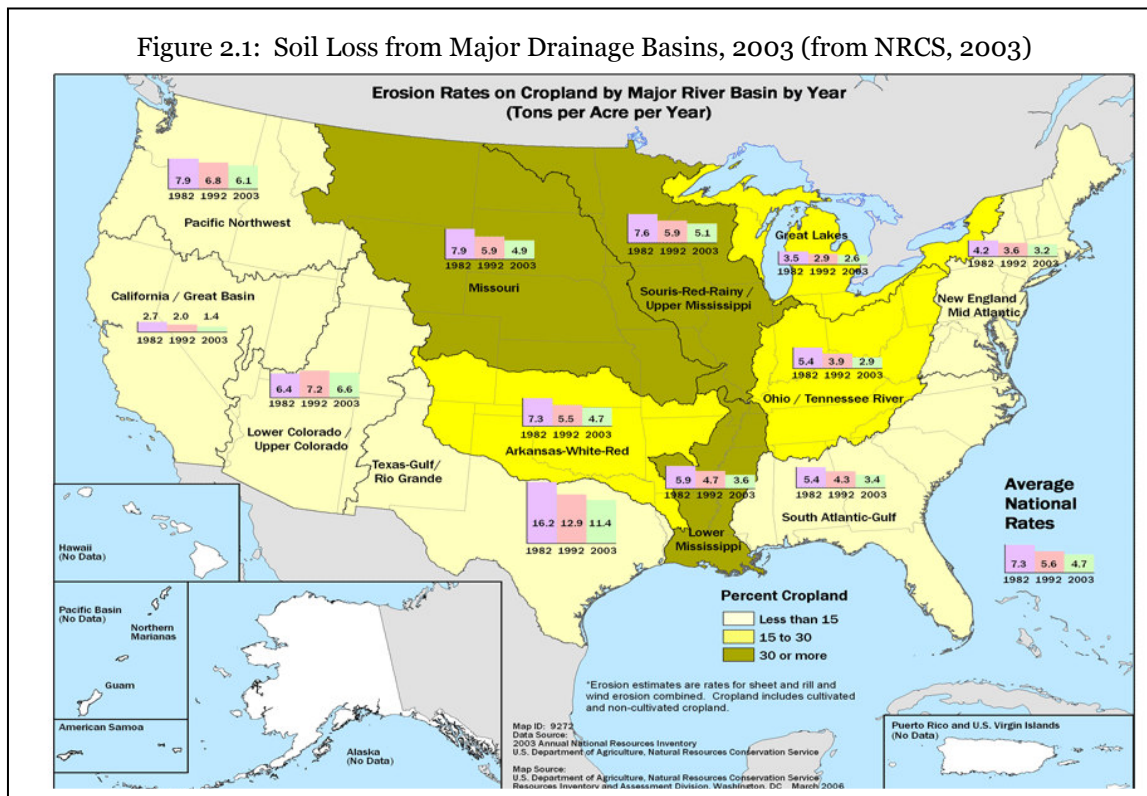
Soil is fundamental to efficient and economical food production. While renewable over the long-run, excessive soil loss can have significant adverse effects on agricultural productivity and environmental health. Beyond the loss of productivity, movement of soil from the field has negative implications on surface water quality and the ecosystems involved.

Soil loss processes are predominantly caused by wind and water, and have been occurring on the land as long as there has been soil. Tillage practices that result in soil exposed to these elements without vegetative cover greatly accelerates these rates of loss. Agricultural practices in the early part of the 20<sup>th</sup> Century coincided with a regional drought to produce the collapse of agro-ecosystems across the Great Plains, commonly referred to as the Dust Bowl. Great storms of soil were transported by wind across Texas, Oklahoma, and Kansas, and became a symbol of the need for conservation practices in agricultural production.

Soil loss is measured in a government report called the National Resource Inventory (NRI) from the Natural Resources Conservation Service (NRCS).<sup>28 29</sup> The most recent data from the NRI is for 2003 (Figure 2.1). From 1982 to 1997 these data were collected on five-year cycles, but beginning in 2000 they were collected annually. The data were collected for 800,000 sample sites from 1982-1997, but in 2000 forward the data were collected from about 200,000 sample sites. Processing these data required aggregation at many levels for comparison. Erosion data were computed using land use based models for water (the Universal Soil Loss Equation) and wind (the Wind Erosion Equation).<sup>30</sup> These land use based models used as independent

variables the impact of crop rotation, tillage practice, field slope, rainfall, and conservation practices.

Data for wind and water (sheet and rill) erosion were summed to estimate total loss from cultivated cropland by state for the reference years 1982, 1987, 1992, and 1997. Working with the statisticians at NRCS and the NRI databases, area-weighted estimates were developed to quantify the soil loss by crop, by state, for the comparison years. Soil loss estimates were calculated as the mass of soil loss greater than the tolerable soil loss level (T). T is a widely recognized measure of the maximum amount of soil loss in tons per acre per year that can be tolerated and still permit a high level of crop productivity to be sustained economically and indefinitely.<sup>31</sup>



While there is currently a debate as to the merits of T as a management tool, it does provide a mechanism for comparing relative impacts of erosion on soils for comparative purposes.<sup>32</sup> Linear interpolation was used to estimate values for non-reporting years. State soil loss levels were held constant from 1997 to present. The resulting data are expressed in units of tons of soil

lost above tolerable levels by crop per acre per year. These data were weighted using annual state planted acreage levels to create a national estimate. Results are presented in both resource impact per acre (soil loss above T per harvested acre) and efficiency (soil loss above T per unit of output) forms. Efficiency data are indexed where the year 2000 equals 100.

## **2.4. Water Indicator**

Water is an important limiting factor for crop production.<sup>33</sup> Without adequate and timely water availability, crop production is not possible,<sup>34 35</sup> which is one reason agriculture is responsible for 80% of the nation's water consumption each year.<sup>36</sup> Water quality is also an important social good – providing for the adequate and safe sources of human consumption, recreation, and biodiversity among others. In this report, we offer a final methodology and results only for an irrigation water use indicator. While we have been working to develop a water quality indicator, we do not offer a final methodology at this time. However, in this section, we review our work to date on the water quality indicator; future work may or may not depart significantly from the water quality approach described below.

### *2.4.1 Irrigation Water Use Indicator*

Water is becoming an increasingly scarce resource <sup>37</sup> because of greater demands from variables such as population growth, urbanization and accessibility.<sup>38 39</sup> Increased population means increased food requirements.<sup>40</sup> These increased demands on water create more competition for this finite resource. Sixteen percent of U.S. agricultural land is irrigated. Irrigated land produces 2.5 times more than non-irrigated land, <sup>41 42</sup> which means that more irrigation water will continue to be demanded. This report presents a method for calculating total irrigation water use and per unit irrigation water use.

Although average annual rainfall is a variable which affects the amount of water utilized by plants, <sup>43</sup> the focus of this project will be on irrigation water. In addition, there is no doubt that water quality is a factor in sustaining water resources, <sup>44</sup> and that water quality is an important social good providing for adequate and safe sources of human consumption, recreation, and biodiversity. <sup>45</sup> Although improvements in efficiency are important, the authors recognize the importance of measuring changes in resource quality over time. Water, air and soil quality are

part of environmental sustainability.<sup>46 47 48</sup> While we have been working to develop a water quality indicator, we do not offer a final methodology at this time. In this report, we offer a final methodology and results only for an irrigation water use indicator.

Irrigation water use is the anthropogenic application of water on land to facilitate the growing of crops, pastures and recreational lands in order to maintain vegetative growth.<sup>49</sup> Although it is recognized that irrigation sources vary,<sup>50</sup> in this report, these differences will not be addressed. Data used for the irrigation analysis for the report were largely pulled from the "Farm and Ranch Irrigation Survey," part of the Census of Agriculture.<sup>51 52 53</sup>

This data source was chosen because it is the only consistent and peer-reviewed source available for national data on water use and water management practices in the United States.<sup>54 55 56</sup> The benchmark years of data used in this analysis are 1988, 1994, 1998, and 2003. These years were selected based on the Census of Agriculture methods of surveying in years ending in "2" and "7". The reference year for the Farm and Ranch Irrigation Survey is generally the year following the census. Survey methodology included a mail-out survey to nearly 20,000 randomly selected operators who had noted irrigation use in previous census years. While participants were randomly selected, leading irrigation states were well represented. The population was stratified into Water Resource Area, state, and the number of irrigated acres in order to increase the probability that an operator would be selected based on irrigation usage.<sup>57</sup>

This survey provides information on the sources and uses of irrigation water for 48 states, not including Hawaii and Alaska. Information obtained from survey participants included the source and amount of water used for irrigation, the number of acres irrigated, the type of distribution system used for irrigation, the number of wells and their characteristics, the amount of water use for each crop type, the average crop yields, the participant's irrigation practices, the capital spent on irrigation, maintenance costs, the type of energy used, and the types of new technologies employed. Data used from the Farm and Ranch Survey for this report include quantity of water applied by crop, acres of irrigated crop, yield for the irrigated crop and yield for non-irrigated production on farms that irrigate. Given that the data presented in the Farm and Ranch Irrigation Survey is collected for farms that do irrigate we feel that it is appropriate to compare the irrigated and non-irrigated yields on these farms and the differential between them.

National average yield for each crop was calculated from the averaging of survey responses for the 4 census years stated above. Using the averages of these four benchmark years, the relationship between the national average yield, irrigated yield and non-irrigated yield was established for each crop. Then, by linear interpolation, the outcomes were used to estimate irrigated and non-irrigated yields, and water applied per acre for years without data. In addition, the average share or portion of total acreage irrigated for each crop was calculated. This was done by dividing the amount of land irrigated by the total amount of land harvested for each crop:

$$\text{Irrigated acres/total harvested area (acres)} = \text{irrigated share}$$

The overall share of irrigated land was found by averaging the irrigated land for the four reference years. The share of irrigated acreage for reference years was used to estimate the irrigated acreage for non-survey years. Between survey values, water application rates after 2003 were assumed to be constant at the 2003 level. A new census was conducted in 2007 and the results have yet to be published.<sup>58</sup>

Non-irrigated yield was subtracted from irrigated yield in order to determine difference in yield between the two practices. Again, data were averaged over all four reference years before the overall differential was established:

$$\text{Irrigated yield} - \text{non-irrigated yield} = \text{Net Impact of Irrigation on Yield}$$

The average amount of water applied was converted to gallons per acre and divided by the irrigation yield differential to determine the gallons of water used per unit of incremental production:

$$\text{Total Gallons H}_2\text{O/difference in yield} = \text{difference in gallons of water/bushel or pound as a result of irrigation}$$

Results are presented in total irrigation water applied per harvested acre, as well as in water use per unit of incremental production (thousands of gallons). Efficiency values were converted to an index where the year 2000 = 100. The year 2000 was randomly selected.

We recognize the limited number of data points as a limitation to our methods. However, at the national level, a suitable alternative was not found. Smaller scale studies may provide more regular annual data at the state or regional level. For the same reason, a small n value for reference years, statistical analyses for significance were not performed.

#### **2.4.2. Water Quality Indicator (Overview of Work to Date)**

Water quality is essential to agriculture and all of life. It is also among the most challenging of the variables to quantify in a consistent and comprehensive manner because of the numerous groups collecting monitoring data and the myriad of methodologies being employed. Due to the complexity of the issue, we have decided to exclude any quantitative measure of water quality from the current assessment. Instead, we are planning to invest the considerable time and effort that we believe is both necessary and appropriate to adequately address water quality. We hope to include such a quantitative analysis within the next year.

As one example of the extensive amount of research that has already been done in this area, we cite monitoring results from the United States Geological Survey (USGS) National Water Quality Assessment (NAWQA) program. For the purpose of this example, we have focused on parameters measured by USGS in surface water, and compared them to human health benchmark concentrations tabulated by USGS. We are investigating additional potential measures of water quality, based on aquatic life benchmarks, hydrology alteration, and ground water. This is just one set of issues that will need to be addressed in the planned water quality research that we mentioned above.

Despite some limitations, the USGS NAWQA database is the only water quality monitoring database with the necessary breadth and scope to uniformly address the potential impacts of crop production practices at both watershed and national scales. Other possible sources of data, such as impaired waters lists or Total Maximum Daily Loads (TMDLs), are far too geographically variable, and they are more representative of state regulatory activity rather than actual water quality.

Within the USGS NAWQA program, we attempted to look at the frequency of detection of a potential water contaminant (Nitrate/Nitrite as N, or pesticides) at a concentration greater than 10 percent of its water quality benchmark concentration to determine trends in overall water quality. The term “detection” as used here does not refer to a mere analytical detection at any level. The benchmark concentrations used for this purpose generally represent annualized mean concentrations intended to be protective of human health. This approach has limitations because it creates a somewhat arbitrary standard that is not necessarily indicative of overall

water quality or sustainability. As noted above, aquatic life benchmarks are being considered for future work providing appropriate availability.

The methodology could be applied using any suitable water quality monitoring data, including local watershed-scale data. However, the national-scale USGS data (NAWQA, 1992-present) are the most useful, due to widespread geographic and temporal coverage and the rigorous uniformity of their analytical methods and reporting procedures. The list of water quality parameters for which queries were performed is given in Table 2.1. Also indicated in Table 2.1 are the benchmark concentrations that were used for each parameter to determine detection frequencies. Most of these are Health-Based Screening Levels as defined by USGS<sup>59</sup> and the rest are mainly Maximum Contaminant Levels as promulgated by the US Environmental Protection Agency.<sup>60</sup>

The 52 pesticide analytes included in the data queries represent the vast majority (by pounds applied) of all pesticide applications to corn, cotton, soybeans, and wheat. As indicated in Table 2.2, the pesticides included in these searches collectively account for 82-96 percent of the total amount of pesticides applied to these crops in the U.S. during the period 1990 to present. The mean concentration (unweighted) was calculated at each sampling site for each year having at least four analytical results for the parameter of interest. The overall detection frequency was then determined annually by comparing these mean concentrations with the benchmark concentration listed in Table 2.1 for that parameter.

The overall average frequencies of detection above the benchmark levels for nitrate-nitrite as nitrogen and pesticides are listed in Table 2.3. Detection rates are very low even when looking at benchmark concentrations of 10 percent below the human health standards for both nitrates and pesticides. While the detection trends over this period are relatively flat, production of these crops has increased over this period, suggesting that the efficiency of nitrogen and pesticide utilization has significantly increased, with the net result of less runoff over the time period that otherwise might have been expected. This finding will be further elaborated and broadened over the next year or so as the more complete water quality assessment is completed.

**Table 2.1. Water Quality Parameters Included in NAWQA Data Warehouse Queries**  
**Benchmarks based on USGS Health Based Screening Levels unless indicated<sup>(1)</sup>**

Water Quality Parameter	Benchmark (PPB)	Water Quality Parameter	Benchmark (PPB)
Nitrate plus nitrite as N	10000 <sup>(1)</sup>	GLUFOSINATE	3
2,4-D	70 <sup>(1)</sup>	GLYPHOSATE	700 <sup>(1)</sup>
ACETOCHLOR	1	IMAZAQUIN	2000
ACIFLUORFEN	90	IMAZETHAPYR	2000
ALACHLOR	2 <sup>(1)</sup>	LINURON	5
ALDICARB	9	MALATHION	50
ALDICARB-SULFONE	7	MCPA	30
ALDICARB-SULFOXIDE	7	METHYL PARATHION	1
ATRAZINE	3 <sup>(1)</sup>	METOLACHLOR	700
AZINPHOS-METHYL	10	METRIBUZIN	90
BENTAZONE	200	NORFLURAZON	10
BROMOXYNIL	10	OXAMYL	200 <sup>(1)</sup>
BUTYLATE	400	PARATHION	0.02
CARBOFURAN	40	PENDIMETHALIN	70
CHLORAMBEN	100	PHORATE	4
CHLORIMURON	600	PROFENOFOS	0.4
CHLORPYRIFOS	2	PROMETRYN	300
CYANAZINE	1	PROPACHLOR	1
DICAMBA	3000	PROPARGITE	1
DICROTOPHOS	0.05	PROPICONAZOLE	70
DIMETHOATE	2	SIMAZINE	4 <sup>(1)</sup>
DISULFOTON	0.9	TEFLUTHRIN	40
DIURON	2	TERBUFOS	0.4
ENDOSULFAN	40	TRIALATE	20
EPTC	200	TRIBENURON METHYL	6
FLUOMETURON	4	TRIFLURALIN	20
FONOFOS	10		

(1) Based on MCL (individual samples for nitrate-N and annualized means for pesticides)

**Table 2.2. Extent to which Monitoring Data represent Crop Pesticide Use.**

	Total Pesticide Used on Crop since 1990 (MM lbs/yr)	Total for which NAWQA Data Exist (MM lbs/yr)	
Corn	207.9	199.7	96.1%
Cotton	40.6	33.1	81.5%
Soybeans	80.3	74.5	92.8%
Wheat	19.8	17.6	88.8%

**Table 2.3. USGS NAWQA Detections above Human Health Benchmark Levels**

Year	Nitrate plus nitrite as N	All Monitored Pesticides
1992	0.0%	4.0%
1993	0.4%	0.7%
1994	0.7%	0.1%
1995	0.4%	0.5%
1996	0.8%	0.3%
1997	0.4%	0.3%
1998	2.9%	0.3%
1999	0.0%	0.2%
2000	0.9%	0.1%
2001	0.9%	1.1%
2002	0.7%	2.1%
2003	0.0%	2.1%
2004	1.1%	2.1%
2005	1.1%	2.1%
2006	2.3%	2.2%

## 2.5. Energy Use Indicator

From the production of nitrogen fertilizer to the drying and transportation of grain, agriculture uses energy in many forms. Our analysis includes the major energy intensive areas of on-farm crop production: direct usage including operation of farm equipment utilizing various energy products (diesel, electricity, gasoline, natural gas, and liquefied petroleum gas) and indirect usage including fertilizer production and crop chemical production. Direct usage includes average energy use for irrigation and transportation energy to move the crop to on-farm storage only. Together, these categories comprise 94.9 percent of total energy requirements for farm inputs.<sup>61</sup> Seed production, which comprises only one percent of on-farm energy requirements, is not included but can be added to future versions of this metric; custom work, input hauling, and purchased water represent the remaining four percent of energy requirements for farm inputs.<sup>62</sup>

Numerous studies have estimated the energy use, both direct and indirect, for crop production (see Piringer and Steinberg 2006, Shapouri 2002, West and Marland 2002, and Lal 2004 for energy estimates and summaries of other studies). However, these studies typically look at energy use at a point in time, rather than as a time-series, as we are doing in this study.

Data from several USDA sources were used to build estimates of the total energy use by crop by year. At the heart of our analysis of the energy used to produce corn, soybeans, wheat, and cotton is a 2004 USDA study titled "The 2001 Net Energy Balance of Corn-Ethanol."<sup>63</sup> While our analysis does not involve ethanol, the work done in this report provides well researched information concerning the energy associated with fertilizer production, seed production, crop protection products, and fuel and energy for equipment operation and crop handling. The most recent update to this study represents its third release. Over time the estimates have continued to be refined. The study ultimately draws its data from USDA's Agricultural Resource Management Survey (ARMS) and the Agricultural Chemical Usage reports as well as the Greenhouse Gas Regulated Emissions and Energy Use in Transportation (GREET) model from Argonne National Laboratory. All energy requirements are converted into British Thermal Units (BTU) for comparison purposes.

### 2.5.1 Fuel and Electricity

Data is not available for how much direct energy is used on farm for growing corn, cotton, soybeans and wheat at the national level. However, USDA's National Agricultural Statistics Service (NASS) has conducted surveys to estimate the dollar cost of energy on farm in the Prices Paid Index.<sup>64</sup> Therefore direct energy for fuel and electricity usage is calculated using estimated costs paid per acre by crop type. Energy costs correlate with energy use, but due to changing prices for energy over time, they do not correlate directly with energy use. In order to correlate energy costs more closely with energy use, costs must be weighted (divided) by a price index for the year given. As energy prices rise, so does the price index, so energy price divided by price index remains close to constant. Because the price index includes prices for many types of energy in locations all across the country with different prices, individual farmers may see a greater or lesser change than the price index. Nevertheless, the index is a good representation of the mean price of energy.

Energy costs paid by farmers are estimated from surveys by USDA. USDA's Prices Paid Index calculates the price index for fuels paid by farmers. Using 2001 as the base year, one can divide the energy cost per acre per crop by this price index in 2001. This results in the estimated real energy cost for 2001. Shapouri 2005 calculates the amount of energy in BTUs from fuel and electricity, averaged over 9 states in 2001, required in the production of one bushel of corn. Using Shapouri's values for BTU's from energy per bushel in 2001 and yield, one can derive the BTU's per real dollar spent on fuel in 2001, in this case 172,913 BTU/Real Dollar of Fuel and Electricity. We assume that the BTU's per real dollar spent on fuel is a constant value over time. Using this constant value of BTU/\$, we can multiply it by the real dollars spent per acre in any given year for a given crop to estimate the BTUs per acre. USDA provides annual national level yield data for each of the crops studied. Dividing the BTU/acre by yield, one can calculate the BTU per bushel or pound for the given year (See Table 2.4).

**Table 2.4. Method of Estimation of Energy used in Production**

Caclulation	Result
Energy Cost in 2001 (\$/ac) ÷ Price Index in 2001	= Real Energy Cost (2001\$/ac)
BTU/Ac in 2001 ÷ Real Energy Cost (2001\$/ac)	= BTU/ Real Energy \$
BTU/ Real Energy \$ * Real Energy Cost/ac in given year	= BTU/ac in given year
BTU/ac ÷ Yield (Bushels/ac or Lbs/ac)	= BTU/Bushel or BTU/Lb in given year

It is possible that as the price for one type of energy increases, farmers may substitute for other types of fuel where possible. This will confound the results and the price index. However, this may be the best proxy for energy use on farm and does not appear to lead to significant bias in either direction.

### 2.5.2 Agricultural Chemicals

Data on the quantity of agricultural chemicals used by crop type are not readily available at the national level. However, USDA's NASS does provide data on costs farmers pay for agricultural chemicals in the Prices Paid by Farmers index and NASS provides an annual price index for agricultural chemicals. Additionally Shapouri 2005 calculated the amount of energy in BTUs, averaged over 9 states, required in the production of agricultural chemicals used to produce one bushel of corn. Therefore, indirect energy from agricultural chemicals can be calculated in a similar manner as fuel and electricity usage (Table 2.5).

Using the average yield of bushels per acre in 2001 across those 9 states, one can obtain the BTUs per acre for agricultural chemicals for corn. Given that we have data on dollar amount spent on agricultural chemicals every year for all four crops, we can estimate the amount of agricultural chemicals used in production of each crop across the years. Using farm expenditures on chemicals over time (prices paid index) divided by the price index will provide the real dollars spent per year per acre. Multiplying real dollars spent by Shapouri's value for BTU's required to produce a given value of agricultural chemicals (in 2001\$) will give the BTU's required per acre for agricultural chemicals per crop. Dividing by USDA's yield data results in BTU's per bushel or pound of crop produced.

**Table 2.5. Method of Estimation of Energy used in Production of Chemical Inputs**

Caclulation	Result
Ag Chemical Cost 2001 (\$/ac) ÷ Price Index in 2001	= Real Ag Chemical Cost (2001\$/ac)
BTU/ac in 2001 ÷ Real Ag Chemical Cost (2001\$/ac)	= BTU/ Real \$ Ag Chemicals
BTU/ Real \$ Ag Chem in given year * Real Energy Cost/ac in given year	= BTU/ac in given year
BTU/ac ÷ Yield (Bushels/ac or Lbs/ac)	= BTU/Bushel or BTU/Lb in given year

Different chemicals may have significantly different energy input requirements for production, so it is not clear how actual usage will differ from this proxy. West and Marland

2002 estimate herbicides require 266.56 GJ/Mg (252,650 BTU/kg) while insecticides and fungicides require 284.82 GJ/Mg (269,957 BTU/kg) and 288.88 GJ/Mg (273,805 BTU/kg) respectively. Shapouri uses values from Wang et al. 1999,<sup>65</sup> somewhat higher at 336,600 BTU/kg for herbicide and 347,600 BTU/kg for insecticide. While these studies vary significantly, it should be noted that the difference between herbicides and insecticides within each study vary only slightly.

These data were used to benchmark the year 2001 and real dollar expenditures were used to back-calculate and project forward from the year 2001. Factors based on corn data are used to project soybean, cotton, and wheat, with the implicit assumption that crop chemical energy per real dollar for these crops are comparable to those for corn. This assumption would seem reasonable given that many of the products are used across several crops. This assumes conservatively that production technology is constant over time. It also assumes that new chemicals used have roughly the same energy requirements for production. It should also be noted that the crop chemicals represented about six percent of the energy for all inputs for corn in 2001 and thus the uncertainty in our assumptions is balanced somewhat by the relatively minor role that crop chemicals contribute to overall energy use. Using this methodology a factor of 18,079 BTUs per real (2001) dollar of crop protection products was calculated.

### 2.5.3 Chemical Fertilizer

USDA’s Economic Research Service (ERS) provides national level data on the acreage and percentage of acreage of major crops that use chemical fertilizers, as well as the rate of fertilizer application.<sup>66</sup> A few missing data points from USDA’s data were estimated by interpolation. By multiplying the percentage of acres fertilized by the application rate, one can calculate fertilizer per acre. Dividing by USDA’s yield data results in the amount of fertilizer per bushel or pound of crop (see Table 2.6)

**Table 2.6. Method of Estimation of Energy used in Production of Fertilizer**

Caclulation	Result
Percent of Acres Fertilized * Fertilizer Application Rate (lbs /ac)	= Fertilizer Used (lbs/ac)
Fertilizer Used (lbs/ac) ÷ Yield (Bushels/ac or Lbs/ac)	= Fertilizer (lbs) /Bushel or Pound
Fertilizer (lbs) /Bushel or Pound * BTU/Fertilizer (lbs)	= BTU/Bushel or BTU/Lb

Shapouri 2005 provides estimates for the amount of energy required to produce nitrogen, phosphorous and potassium fertilizers. The values are reported to be 24,500 BTUs per pound N, 4,000 BTUs per pound phosphate and 3,000 BTUs per pound of potash fertilizer. Multiplying energy in BTUs per pound of nutrient by the number of pounds required per bushel or pound of crop results in the BTUs per pound or crop of product.

While the literature provides a wide range for the energy required for production, the values we use are roughly in the middle of the literature values.<sup>67 68 69</sup> These values are conservatively assumed to be constant over time. If these values are relatively constant over time, then the value used for BTU/lb nutrient should not affect the overall trend of energy use from fertilizer per crop. Fertilizer application rate data was sourced from USDA and missing data points were estimated by linear interpolation. Results are presented in both resource use per acre (energy use per harvested acre) and efficiency (energy use per unit of output) forms. Efficiency values were converted to an index where the year 2000 = 100.

## **2.6. Climate Impact Indicator**

Climate change and its potential impact on agriculture is an important public policy topic. Climate impact measures the net carbon dioxide and other greenhouse gasses emitted both directly and indirectly in the production process. In the US, agriculture is a small but significant source of greenhouse gas, roughly 10% according to the US EPA.<sup>70</sup> According to much of the current literature, energy use and tillage create sources of greenhouse gas emissions. However, some agricultural practices have the potential to sequester carbon dioxide in the soil.<sup>71 72</sup> For example, continuous no-tillage practices for some crops are documented as sources of carbon sequestration.<sup>73</sup> However, the impact of no-till farming on soil organic matter remains poorly understood and is soil specific. Recent studies suggest that no-till may result in change in the distribution of soil carbon—concentrating it into the upper-most soil layer— rather than a significant increase in total soil carbon measured over a larger soil profile.<sup>74 75</sup> We recognize these uncertainties in current scientific understanding of the impacts of tillage practices as limitations to our climate impact methodology.

A net carbon balance was constructed for each of the four crops – corn, soybeans, wheat, and cotton. Most of the available literature on the subject of carbon balance report a single cropping

season.<sup>76</sup> In our effort we are trying to adjust for known, quantifiable changes over time. Some of our measures assume a static carbon contribution over time due to lack of data to make credible adjustments while others use actual application rates to predict carbon balances for years before and after the benchmark year. Our analysis takes no credit for the carbon embedded in the removal of the crop. It is assumed that the crop will ultimately be utilized or consumed and this carbon will be released back into the atmosphere.

There are four major sources of climate impact in crop production: emissions from energy used to power machinery; emissions from energy used to produce agricultural inputs; carbon emissions or sequestration in soil; and soil N<sub>2</sub>O emissions from applied nitrogen fertilizer and manure.<sup>77</sup> Our analysis takes no credit for the carbon embedded in the removal of the crop. It is assumed that the crop will ultimately be utilized or consumed and this carbon will be released back into the atmosphere.

The carbon balance includes carbon dioxide (CO<sub>2</sub>) as well as nitrous oxide (N<sub>2</sub>O) emissions converted to carbon equivalents (CE). One kg of carbon dioxide contains 12/44 kg of carbon, using the atomic mass ratio of a carbon molecule to a carbon molecule. In this study, nitrous oxide (N<sub>2</sub>O), from soil's atmospheric release of excess applied nitrogen, must be converted to its carbon equivalent. For this study, we use the IPCC 2001 Third Assessment Report conversion factor of 296 kg CO<sub>2</sub> per kg N<sub>2</sub>O (or 80.7 kg CE).<sup>78</sup>

The method for constructing the balances in this report relies heavily on West and Marland (2002).<sup>79</sup> Their method calculated the carbon balance for fuel consumption, agricultural inputs and soil carbon due to tillage. West and Marland compare emissions from three tillage practices: conventional till, reduced till and no-till. Tillage practice impacts not only the soil carbon emissions or sequestration, but also the machinery fuel usage, as well as fertilizer and chemical application rates.

We also include N<sub>2</sub>O soil emissions from nitrogen application in this analysis. N<sub>2</sub>O is a major source of greenhouse gas emissions in US agriculture, and agriculture produces roughly 80 percent of US N<sub>2</sub>O emissions according to Synder et al. 2007.<sup>80</sup> Most of the available literature on the subject of carbon balance report a single cropping season.<sup>81</sup> In our effort we are trying to adjust for known, quantifiable changes over time. Some of our measures assume a static carbon

contribution over time due to lack of data to make credible adjustments while others use actual application rates to predict carbon balances for years before and after the benchmark year.

### *2.6.1 Agricultural Inputs*

West and Marland supply national average data from USDA for the year 1995 for each of the three tillage practices, for corn, soybeans and winter wheat.<sup>82</sup> They give values in kg C/ha for herbicides, insecticides, N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O, CaCO<sub>3</sub>, seed and irrigation. In addition they provide values for emissions with irrigation, without irrigation, and average C emissions. The carbon balance for each input is weighted by the percentage of planted acres using that input. All values are then summed to give an average value. West and Marland do not provide data for cotton, so we interpolated using the data on C emissions given for corn and USDA data we had on level of inputs. Using the C emission from corn, multiplied the ratio of cotton input (e.g. N, P, K etc) to corn input gave us a proxy for the C-emissions from cotton.

Using these values from 1995, we extrapolated both forward and backward to estimate values for other years. For herbicides and pesticides, we used the percentage change in real dollars spent on agricultural chemicals (see above discussion in Energy Section) to create the same percentage change in carbon emissions for a given year. For nitrogen, phosphorous and potassium, we similarly used the percentage change in application rate over time for each nutrient, respectively, and created the same percentage change in carbon emission. Because no data for lime is available at the national level over time, we used the percentage change in nitrogen as a proxy. While this may or may not be reflective of actual practice, lime has a small impact on the overall number of the total carbon emissions calculated, between 0.5% for wheat and up to 5% for soybeans in 1995, respectively. Carbon emissions from seed production are a larger portion, between 5% for corn and 20% for soybeans in 1995. Data for emissions from seed production was not available over time so we extrapolated using a 1% increase in carbon emissions every year from 1995, and likewise a 1% decrease every year prior to 1995. This results in approximately a 23% increase over the 20-year time horizon from 1987 to 2007. This may or may not be reflective of reality, but it seems to be a conservative estimate.

For emissions from irrigation, we used a similar method for extrapolation. Data is available for water applied per hectare for several years. First we interpolated across those years to estimate water use by year. Then, using the percentage increase or decrease of water use per hectare over

time from 1995, we used the same value to increase or decrease the carbon emissions in the respective year. Clearly irrigation depends on rainfall, and will not follow the linear trend of interpolation. However, interpolation should work in helping to elicit the trends over a 20-year time frame in C-emissions from water use. While irrigation is a major energy user and carbon emitter, only a certain percentage of fields are irrigated. The total carbon emissions from irrigation are weighted by this share. We assume that the share of irrigated acres remains constant at the 1995 values, 5%, 7%, 15% and 36% for soybean, wheat, corn and cotton, respectively. It is unclear how accurately these numbers reflect reality. It may be that both the percentage of acres irrigated, as well as the energy and hence carbon emissions required to pump water for irrigation may change dramatically over time as cropping patterns change over time. This may be difficult to estimate on a national scale without a much deeper analysis. Without better data, we believe this is the best estimate we can make.

We calculated carbon emissions from agricultural inputs for each of the three tillage practices. We then created a weighted average, weighted by the share of planted acres under each type of tillage practice (see Table 2.6).

**Table 2.6. Carbon Emission by Tillage Practice by input per crop**

Caclulation	Result
Mass applied/Mass applied in 1995 * Lbs C/ac per input in 1995	= Lbs C / ac in reference year
Lbs C / ac ÷ Yield (Bushels/ac or Lbs/ac)	= Lbs C per input /Bushel or Pound
Σ Share of Crop under Tillage Practice * Lbs C per input /Bushel or Pound	= Weighted Average Lbs C per input /Bushel or Pound per crop

### 2.6.2 Emissions from Machinery Operations

The carbon emissions due to equipment operation for alternative tillage systems were reported in the West and Marland study. The three tillage systems are defined in the study as being consistent with the definitions used by the Conservation Technology Information Center (CTIC): Conventional Till, Reduced Till, and No-Till. CTIC provides data over time of the percentage of each crop under the different tillage practices.

Conventional tillage uses the most energy for machinery, and hence produces the largest carbon emissions of the three practices, with respect to machinery usage. No-Till uses the least amount of energy, and hence produces the lease amount of carbon emissions (see Table 2.7). Because we do not have data for cotton, we assumed the tillage contribution to be the same for cotton and

corn. The analysis in this report assumes that these factors have not increased or decreased over time (i.e. no fuel efficiency improvement over time within a tillage system). While the specific impact of this assumption is not known the directional impact is likely that we have understated gains in energy efficiency over time.

Changes over time in the national average emissions from machinery come only from the changing percentages of tillage practices over time. Efficiency gains due to changes in tillage practices are captured by using the CTIC data for the share of each crop under each tillage system.

### 2.6.3 Soil Carbon Emissions and Sequestration from Tillage

The impact of soil sequestration is provided for the three tillage systems but is considered in a three-crop (corn, wheat, and soybean) rotation. This rotation is consistent with the West and Marland method for calculating the net carbon flux. The inclusion of average soil carbon sequestration from corn, soybean, and wheat production was done because these three crops represent the three largest acreage crops produced in the United States. Using the average of all three crops for each of the crops will likely underestimate the soil carbon sequestration of land under a corn/soybean rotation in the Midwest but the results should be generally representative of average values for the three crops across all acres and geographic regions.

**Table 2.7. Carbon Emission from Machinery Operation (West and Marland 2002)**

Carbon Emissions from Machinery Operation	Corn	Soybean	Wheat
Conventional (kgC per hectare)	72.02	67.45	67.45
Reduced Tillage (kgC per hectare)	45.27	40.7	40.7
No-Till (kgC per hectare)	23.26	23.26	23.26

In the case of a no-till system the carbon sequestration is considered to be in a continuous no-till system. Data on the amount of continuous no-till by crop do not exist. The industry standard for tillage system data is the CTIC.<sup>83</sup> CTIC intends to collect continuous no-till estimates in the future but have no data at present. For the purpose of this analysis we assume continuous no-till is 10 percent of annual no-till area reported by CTIC. This 10 percent estimate is based

strictly on professional judgment and serves as a conservative estimate until a better measure becomes available. The West and Marland study reports an average soil carbon sequestration level of 337 kg C/hectare per year assuming the three-crop rotation is maintained under continuous no-till. This data comes from US Department of Energy, Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystem's (CSiTE) database. No appreciable carbon sequestration occurs under a reduced tillage or conventional tillage system, and consequently these systems are assigned a zero value. While corn likely contributes more than twice that level of C in a given year, continuous no-till experts would suggest that strict crop rotation is a very important management practice. For this reason this study assumes 337 kg C/hectare for all crops and assumes a rotation is being followed. In many regions, this crop rotation is not followed, and so for those regions, this is not an accurate assumption. However, when one looks at carbon emissions and sequestration on a national scale, we believe this methodology will approach a national average. West and Marland note that soil carbon sequestration will be significantly higher in the first few years and will slow in the later years. The 337 Kg C/hectare average was considered a realistic average over a 20 year period. Some studies show appreciably higher soil carbon sequestration levels due to tillage practice.<sup>84 85 86</sup> The level we assume is likely conservative. An ideal measure of soil carbon sequestration is the organic matter in the soil but no consistent, broad based data set was found for soil organic matter. If such data becomes available, we will seek to include it in future versions of this report.

#### *2.6.4 Soil N<sub>2</sub>O Emissions from Nitrogen Application*

N<sub>2</sub>O is a potent greenhouse gas, and as such, nitrogen fertilizer application released as N<sub>2</sub>O is an important source of carbon-equivalent emissions. However, the range of estimates for N<sub>2</sub>O as a percent of N applied is very wide depending on the source of N, the method of application, and the soil conditions at the time of application. Data from the December 2007 International Plant Nutrition Institute literature review reports that N<sub>2</sub>O emissions as a percent of N applied can range from near zero to nearly 20 percent of applied N.<sup>87</sup>

For the purposes of our analysis we use a factor of 1.33 percent of all fertilizer N applied. This estimate is consistent with the current IPCC estimates.<sup>88</sup> Bouwman et al (2002) report a global mean of 0.9% of N from fertilizer is released from soil as N<sub>2</sub>O. Data on U.S. mean annual N fertilizer per crop by year is provided by USDA.<sup>89</sup> We used this application rate to estimate N<sub>2</sub>O emissions from synthetic nitrogen fertilizer. We have applied an estimate of 1.79 percent of N

from manure, as currently summarized in recent literature.<sup>90</sup> Manure application data was pulled from USDA's ARMS data concerning tons applied and manure source. The methodology to calculate emissions from soil N<sub>2</sub>O is seen in Table 2.8.

**Table 2.6. Carbon Equivalent Emission from Soil N<sub>2</sub>O Emission**

Caclulation	Result
Percent of Acres N-Fertilized * N- Application Rate (lbs /ac)	= N Used (lbs/ac)
N Used (lbs/ac) ÷ Yield (Bushels/ac or Lbs/ac)	= N (lbs) /Bushel or Pound
N (lbs) /Bushel or Pound * 1.33%	= N <sub>2</sub> O lbs/Bushel or N <sub>2</sub> O lbs /Lb
Percent of Acres Manure Fert * Manure N Application Rate (lbs /ac)	= N Used (lbs/ac)
N Used (lbs/ac) ÷ Yield (Bushels/ac or Lbs/ac)	= N (lbs) /Bushel or Pound
N (lbs) /Bushel or Pound * 1.79%	= N <sub>2</sub> O lbs/Bushel or N <sub>2</sub> O lbs /Lb
N <sub>2</sub> O from N-Fertilizer plus N <sub>2</sub> O from Manure	= Total N <sub>2</sub> O Bu/lb or lbs/lb
N <sub>2</sub> O lbs/Bushel or N <sub>2</sub> O lbs /Lb*296*(12/44)	= C-Equivalent lbs/Bushel or lbs/lb

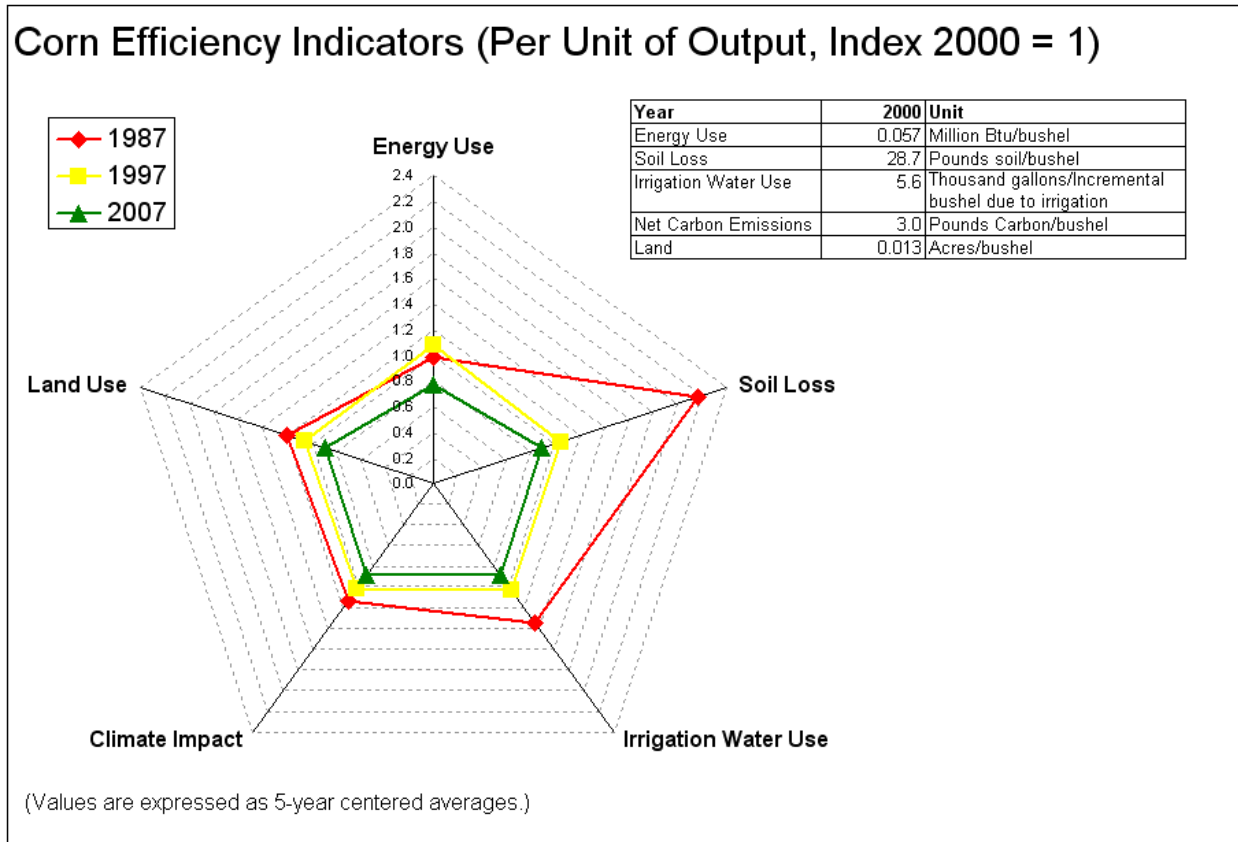
### 2.6.5 Total Carbon Emissions

The basic approach we used was to add the four factors of the carbon balance to create a net carbon balance for each of the crops:

$$\text{Net Carbon Balance by Crop} = (\text{Machinery Operation} + \text{Inputs Used} + \text{Soil Carbon Change} + \text{N}_2\text{O Emissions})$$

We also calculated total emissions per crop as measured by impact per acre times harvested acres. While acres planted but not harvested do contribute to carbon emissions, they do so to a lesser extent. We chose not to include those acres for this analysis. This will underestimate the overall value, but should not affect the overall trend as the unharvested acres remain fairly constant over time for each crop. Results are presented in both resource impact per acre (greenhouse gas emissions per harvested acre) and efficiency (emissions per unit of output) forms. Efficiency values were converted to an index where the year 2000 = 100.

### 3. Results: Corn



**Figure 3.1. Summary of Corn Efficiency Indicators**

#### 3.1. U.S. Corn Supply and Demand

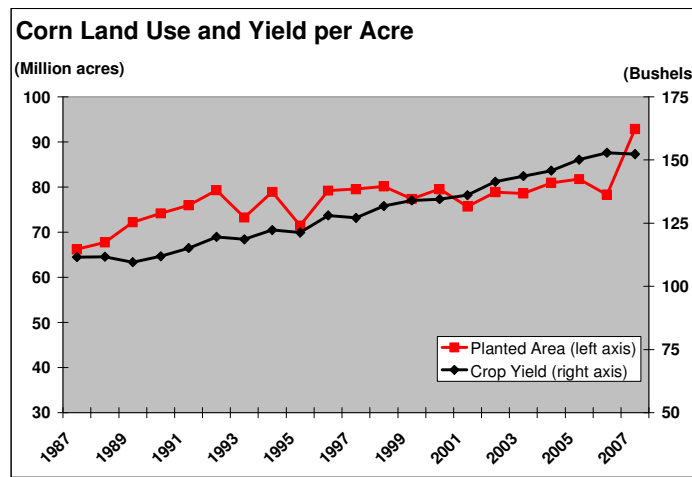
Over the past three decades corn has continued to rise in importance in the mix of U.S. crops. In 1983 the U.S. Government paid farmers not to plant corn and other major crops and corn represented 19 percent of total US cultivated area. Since 1993 corn has increased in prominence and hit its current peak of 29 percent of the total U.S. cultivated area in the current, 2007/08, marketing year. Technology advancements have allowed corn to be planted farther north and south every year. Overall productivity gains in corn have been more robust than any of the other major crops with yield gains averaging 2.2 bushels per acre per year or about 1.5 percent per year based on recent yield levels.

Corn has replaced millions of less productive sorghum acres over time. The continued growth in share of the U.S. and world feed grain market has made corn the standard for livestock feed

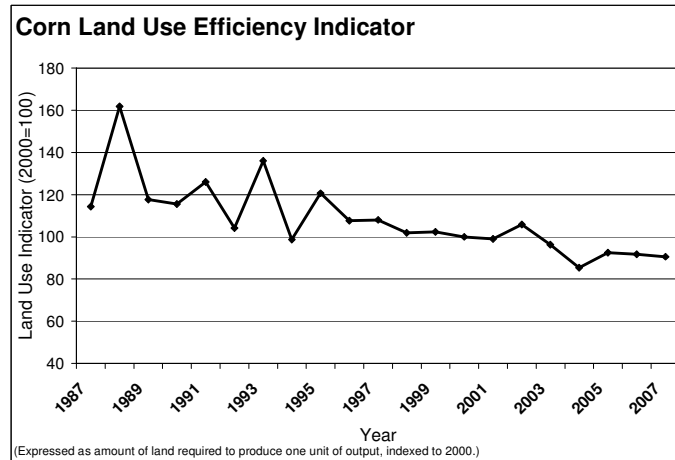
ingredients. More recently the U.S. ethanol industry has adopted corn as its predominate feedstock accounting for nearly 25 percent of total corn demand in 2007, and contributing to sharp increases in land use for corn production in that year.

### 3.2. Land Use

Over the twenty year study period from 1987 to 2007, corn demonstrated a 41 percent increase in productivity (bushels per acre).<sup>a</sup> At the same time, corn's planted area has increased 21 percent (Figure 3.2), with a significant increase in 2007. Corn's productivity gains have allowed for a 37 percent reduction in the land needed to produce one bushel (Figure 3.3).



**Figure 3.2. Corn Land Use and Yield**

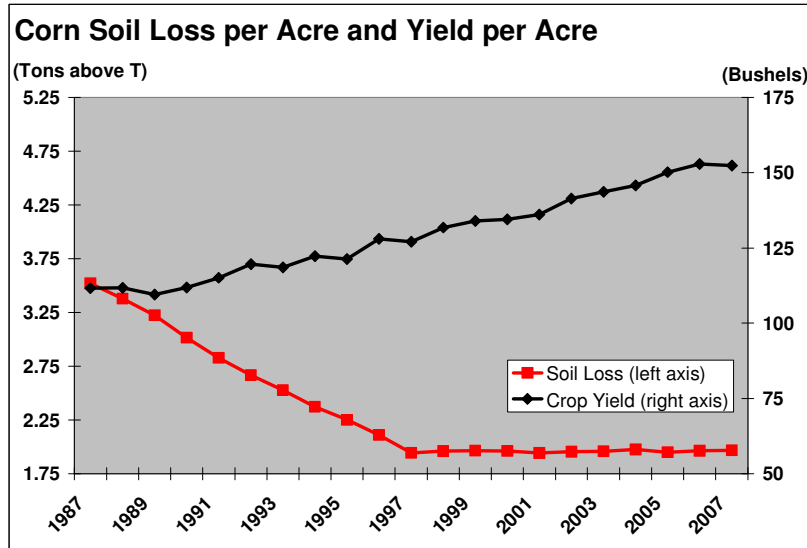


**Figure 3.3. Corn Land Use Efficiency**

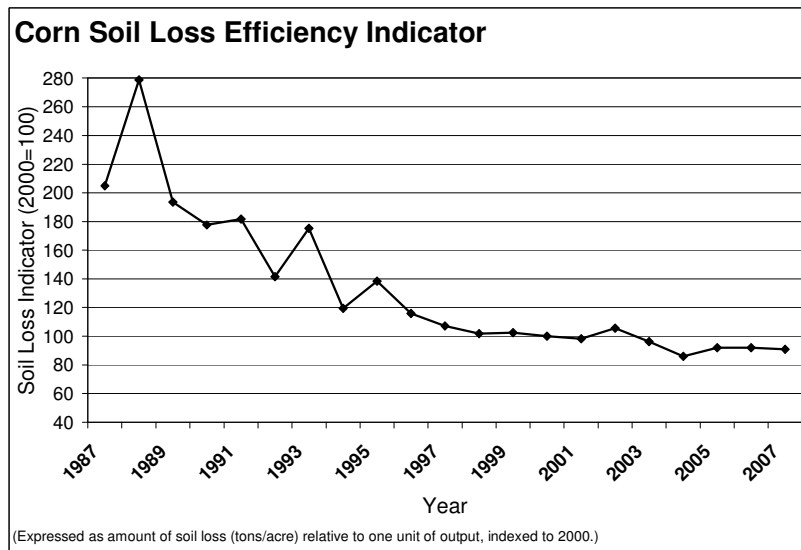
<sup>a</sup> Percent change results for all indicators and crops are based on 20-year least squares trends analyses.

### 3.3. Soil Loss

Soil loss above tolerable level (T) due to corn production has been significantly reduced in all regions of the U.S., with a 43 percent decrease in tons lost per acre (Figure 3.4). When combined with productivity advances, soil loss above T per bushel of corn produced during the period 1987 to 2007 has decreased by 69 percent (Figure 3.5).



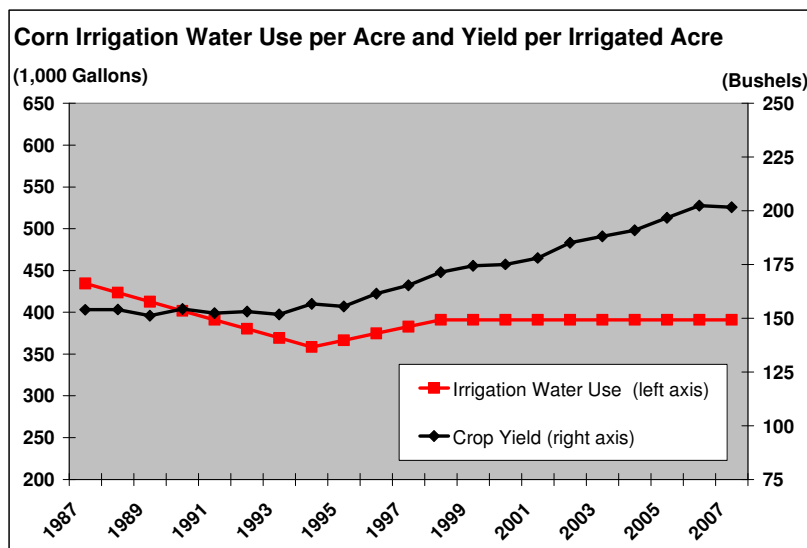
**Figure 3.4. Corn Soil Loss Indicator**



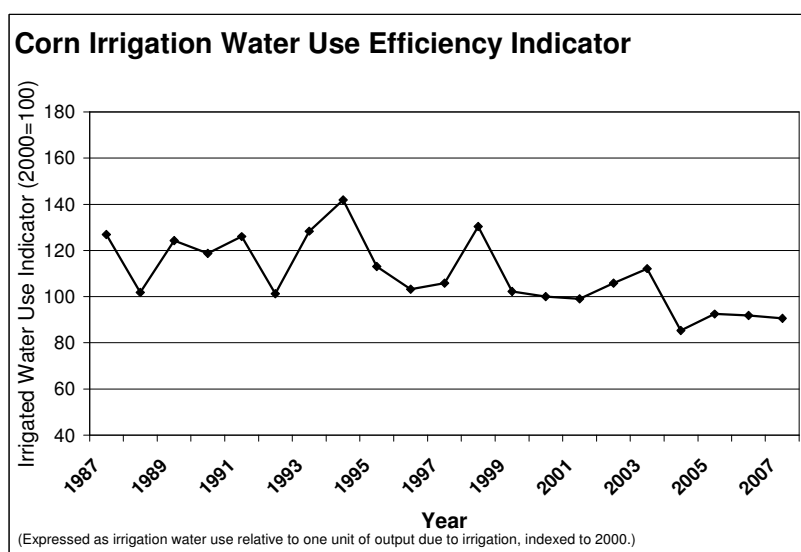
**Figure 3.5. Corn Soil Loss Efficiency Indicator**

### 3.4. Irrigation Water Applied

Over the analysis time period the average amount of irrigation water being applied per acre has declined from about 450,000 gallons per acre to 400,000 gallons per acre in the most recent survey year (2003), with a four percent trend decrease overall (Figure 3.6). During the same period about 14 percent of corn planted area was irrigated annually and the typical yield differential was 64.5 bushels per acre more than non-irrigated acres. Irrigation efficiency per bushel has been variable over this time period, with a decrease of 27 percent (Figure 3.7).



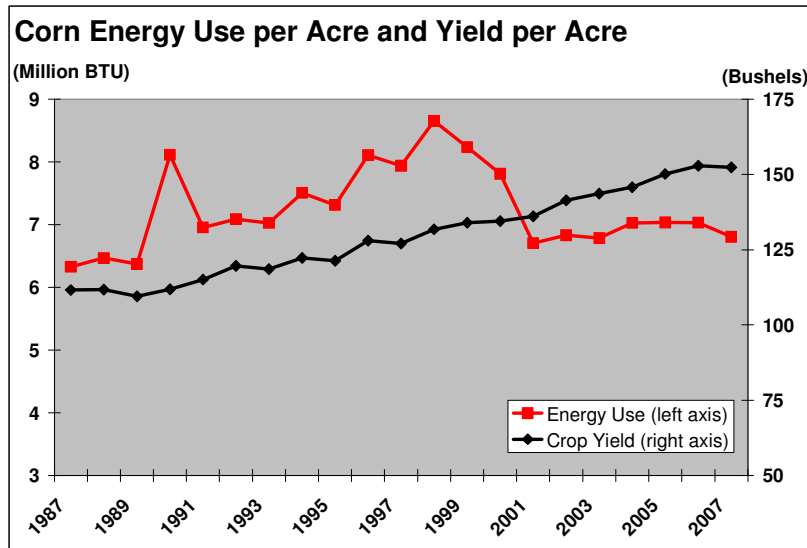
**Figure 3.6. Corn Irrigation Water Use Indicator**



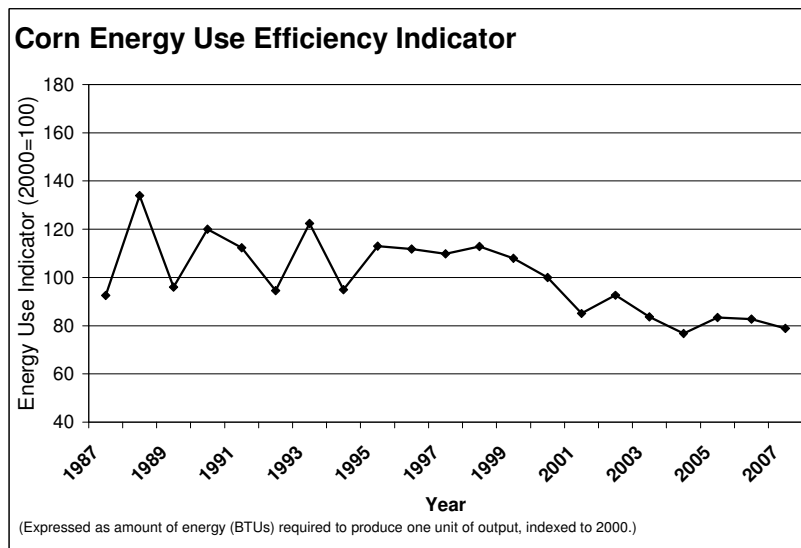
**Figure 3.7. Corn Irrigation Water Use Efficiency Indicator**

### 3.5. Energy Use

Over the study period, corn's energy use per acre increased by three percent, with improvement since 1999 (Figure 3.8). The energy used to produce a bushel or unit of corn has decreased by 37 percent (Figure 3.9).



**Figure 3.8. Corn Energy Use Indicator**



**Figure 3.9. Corn Energy Use Efficiency Indicator**

### 3.6. Climate Impact

Measurement data for change in greenhouse gases (GHG) from the production of corn and other crops are very limited. Changes in the application methods for nitrogen fertilizer as well as the true change in energy use over time are difficult to approximate and consequently efficiency gains over time may not be captured in our analysis. Given the heightened awareness of climate change in recent years, we can expect data availability in the area to improve rapidly. During the study period, corn has seen an increase in emissions per acre of eight percent (Figure 3.10) and a 30 percent decrease in emissions per bushel (Figure 3.11).

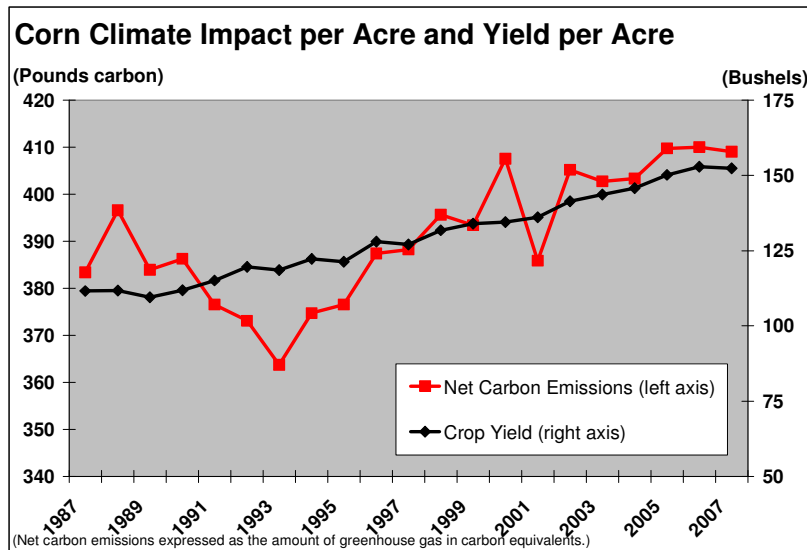


Figure 3.10. Corn Climate Impact Indicator

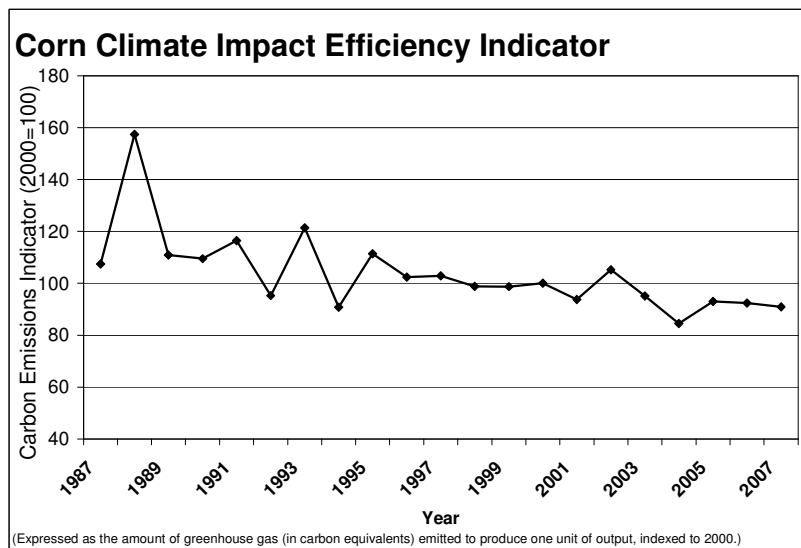
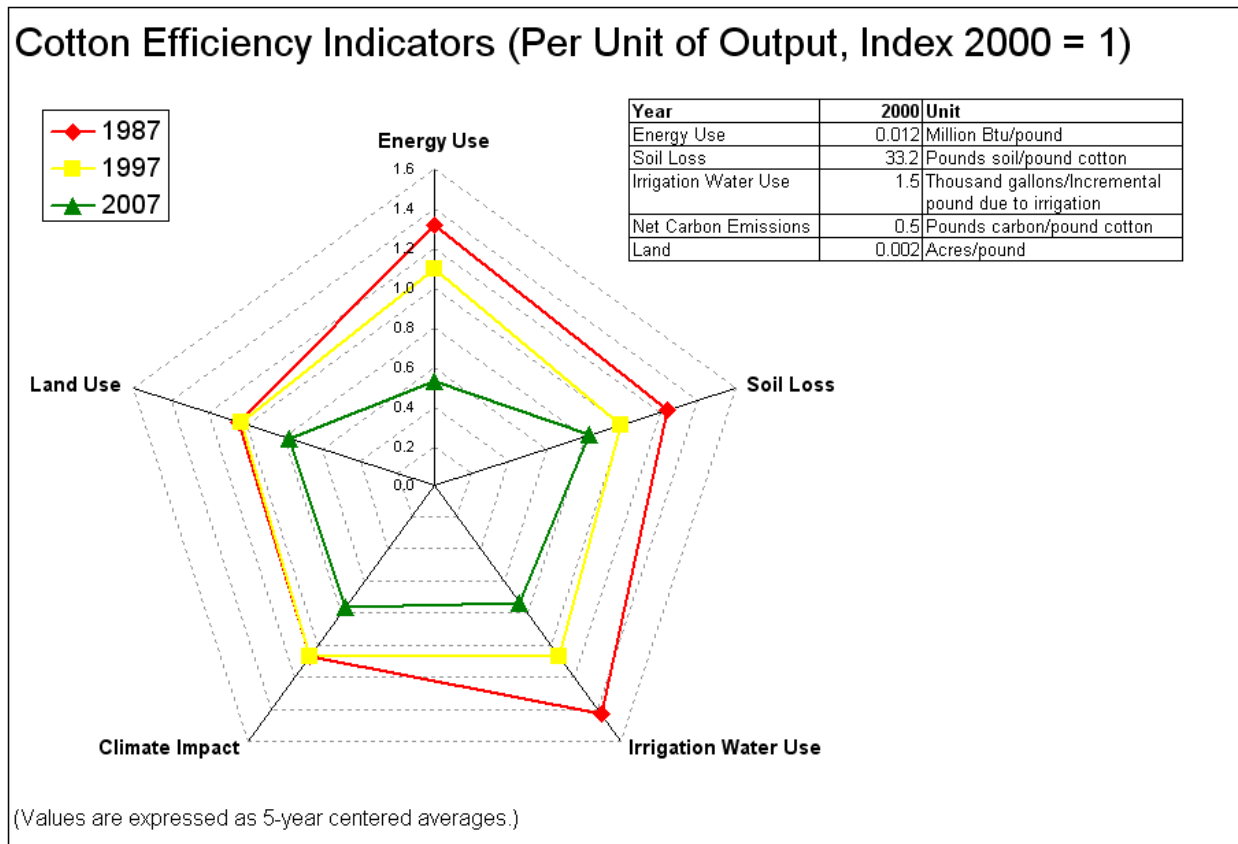


Figure 3.11. Corn Climate Impact Efficiency Indicator

#### 4. Results: Cotton



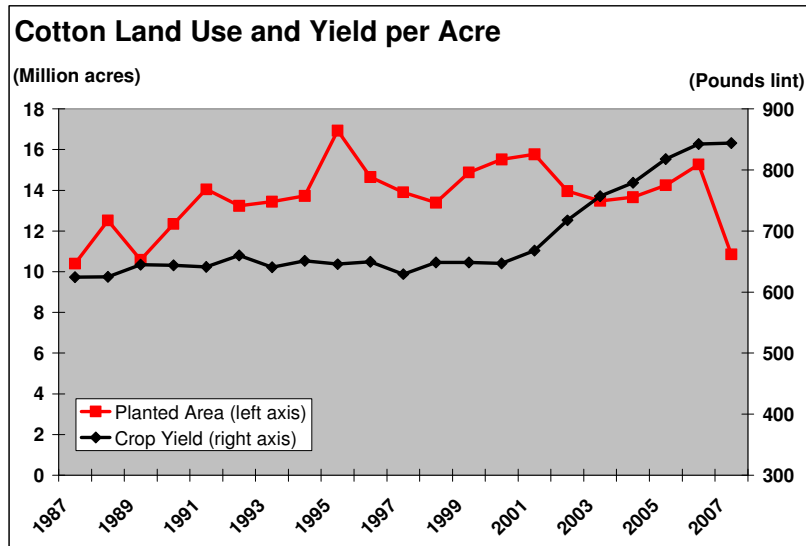
**Figure 4.1. Summary of Cotton Efficiency Indicators**

#### 4.1. U.S. Cotton Supply and Demand

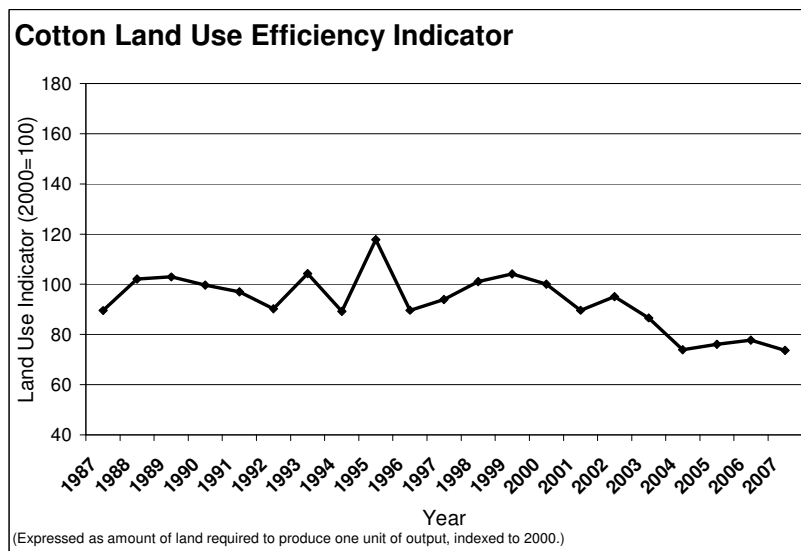
The U.S. cotton market has seen considerable change over the past 20 years. Growth in domestic demand for cotton products, particularly clothing, caused a significant increase in domestic demand/milling of raw cotton in the early years of our 1987 to 2007 time frame. More recently, strong competition from foreign mills has caused demand to shift significantly to exports of raw cotton. Exports as a share of total cotton demand have increased from 30 percent in 1998 to roughly 75 percent in 2007. Cotton is grown in the southern states with Texas growing the largest number of acres - about five million acres of the 10 to 15 million acres typically grown. Recent advances in commodity prices have had much less impact on cotton compared to soybeans, wheat, and corn. This change in relative prices led to a significant loss in cotton planted area in 2007 and 2008. Cotton plantings in 2007 totaled 10.8 million acres compared to a peak of nearly 17 million in 1995 and a low of eight million in 1983.

## 4.2. Land Use

In recent years cotton yields have frequently reached record levels, and productivity (yield per acre) increased 31 percent over the study period (Figure 4.2). While some of this growth has been the result of favorable weather in Texas, there has also been significant advancement in seed technology. Cotton land use has fluctuated over time, with an overall increase of 19 percent (Figure 4.2). The amount of land required to produce a pound of cotton has decreased by 25 percent over the study period (Figure 4.3).



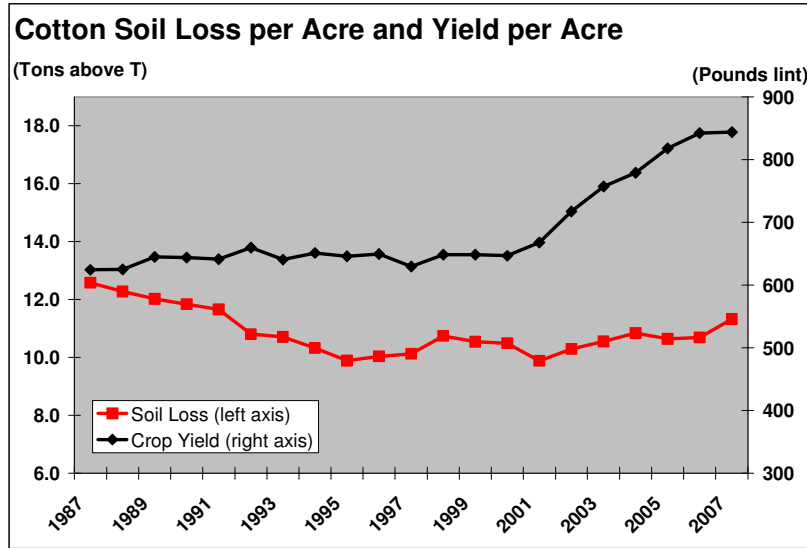
**Figure 4.2. Cotton Land Use Indicator**



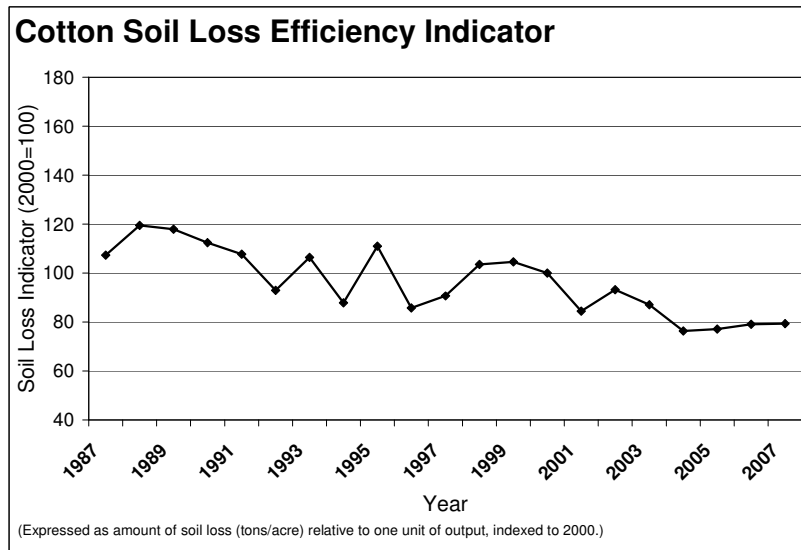
**Figure 4.3. Cotton Land Use Efficiency Indicator**

### 4.3. Soil Loss

Soil loss per acre due to cotton production decreased 11 percent over the study period (Figure 4.4). Meanwhile, soil loss per pound of cotton decreased 34 percent (Figure 4.5).



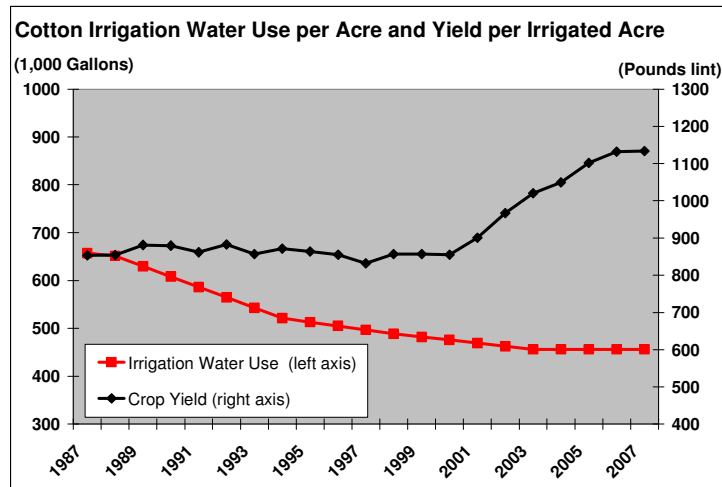
**Figure 4.4. Cotton Soil Loss Indicator**



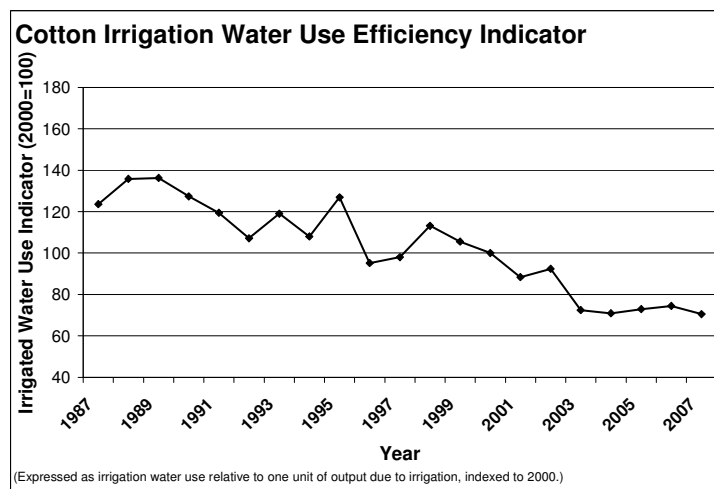
**Figure 4.5. Cotton Soil Loss Efficiency Indicator**

#### 4.4. Irrigation Water Applied

Among the major crops produced in the U.S., cotton is one of the most intensely irrigated. During the analysis period the share of total cotton planted acreage that was irrigated has typically been around 33 percent but has been as high as 45 percent in 1998. Beyond the number of acres irrigated, the amount of water applied has also been substantial with levels as high as two acre-feet in past years. The quantity of water applied to cotton has seen a precipitous decline from roughly 650,000 gallons per acre at the beginning of the study period to less than 500,000 gallons per acre in the most recent survey year (2003), with an overall 32 percent reduction over the study period (Figure 4.6). This reduction in water use occurred at the same time that cotton yields hit record levels. Cotton has seen dramatic improvement in this regard, with irrigated water use per pound of cotton reduced 49 percent during the past 20 years (Figure 4.7).



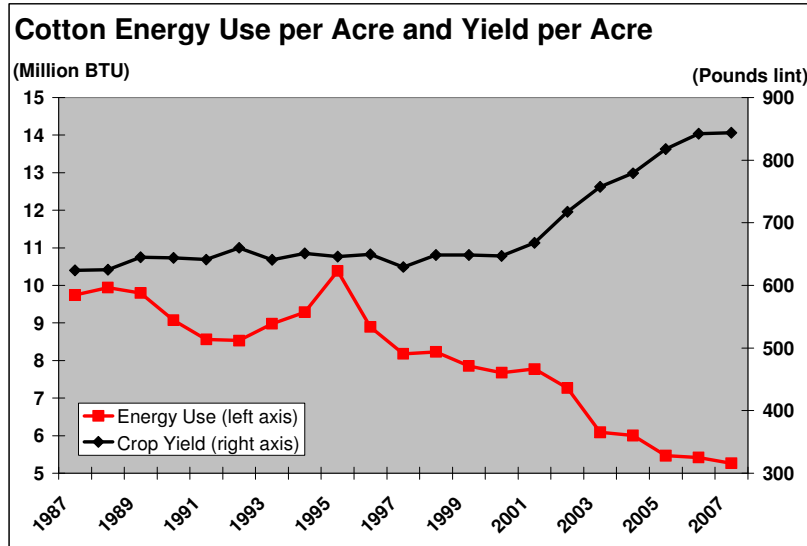
**Figure 4.6. Cotton Irrigation Water Use Indicator**



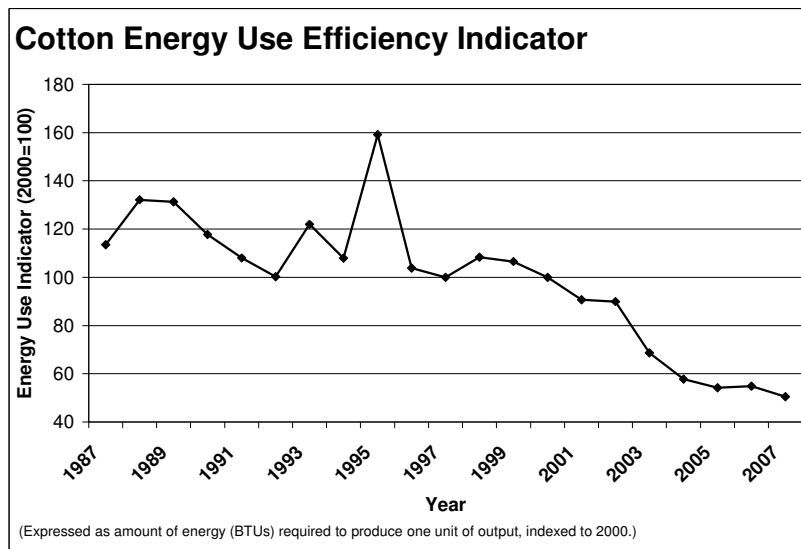
**Figure 4.7. Cotton Irrigation Water Use Efficiency Indicator**

## 4.5. Energy Use

Increased cotton yields coinciding with 47 percent reduction in per acre energy use (Figure 4.8) has led to a 66 percent decrease in energy use per pound of lint (Figure 4.9).



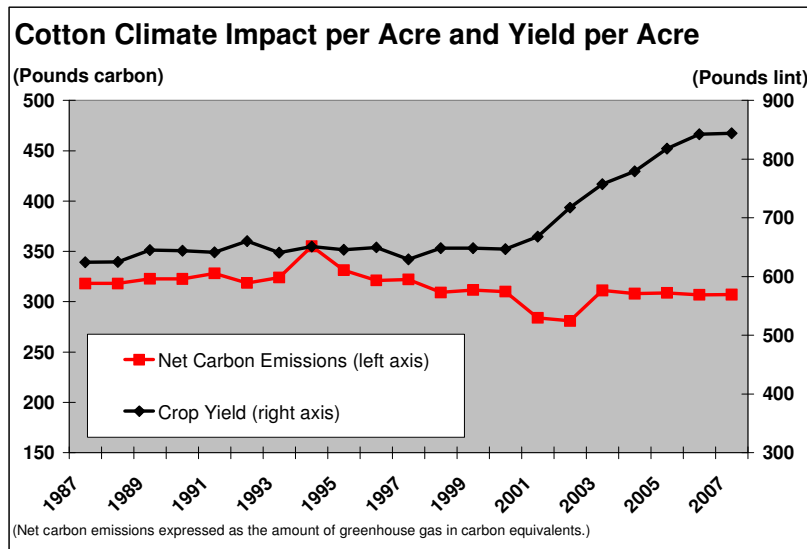
**Figure 4.8. Cotton Energy Use Indicator**



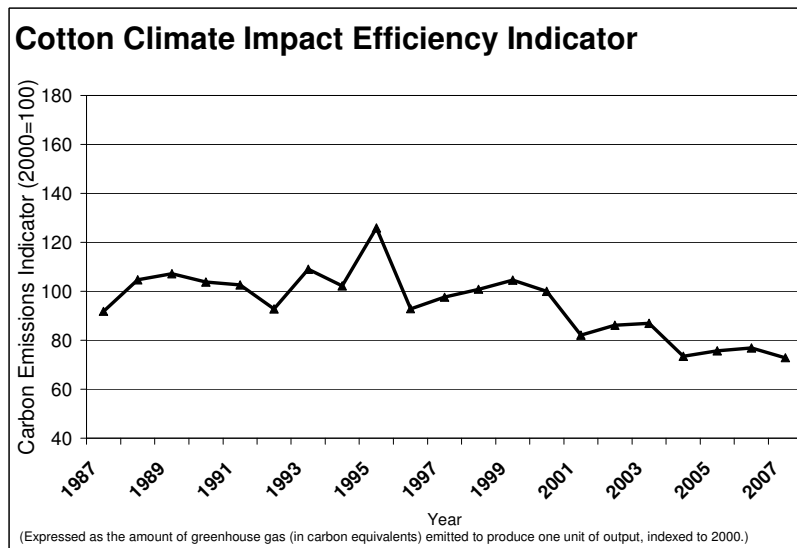
**Figure 4.9. Cotton Energy Use Indicator**

#### 4.6. Climate Impact

Emissions per acre decreased nine percent over the study period (Figure 4.10) while emissions per pound of lint fluctuated, with more recent improvements resulting in a 33 percent decrease between 1987 and 2007 (Figure 4.11). Since 1995, nitrogen application has leveled off and carbon emissions have decreased. Strong adoption of no-till over the past decade has also helped reduce net carbon emissions.

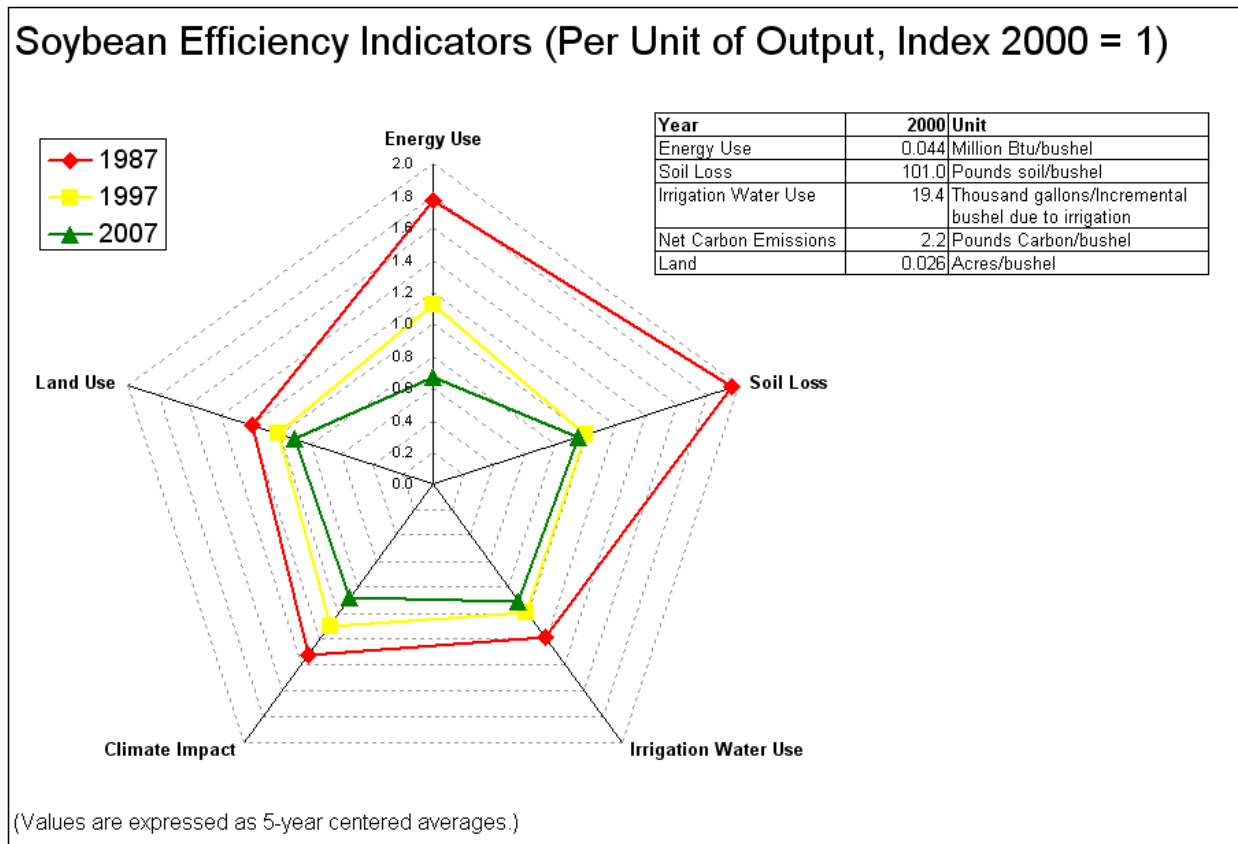


**Figure 4.10. Cotton Climate Impact Indicator**



**Figure 4.11. Cotton Climate Impact Efficiency Indicator**

## 5. Results: Soybeans



**Figure 5.1. Summary of Soybean Efficiency Indicators**

### 5.1. U.S. Soybean Supply and Demand

U.S. soybean demand has benefited from steady growth in both domestic demand (crush) and export demand for whole beans. Domestic demand has increased over time due to increased meat consumption, particularly poultry and pork. A similar phenomenon has occurred in China, resulting in that country importing more soybeans for animal feed use. These demand increases have led to increased soybean planted area from a low of 58 million acres in 1990 to a recent high of 75 million acres in 2006. The acreage expansion has altered geographically where soybeans are grown within the U.S., with the greatest change being expansion of planted acreage in northern and western areas of the cornbelt where spring wheat and barley have traditionally been grown.

Soybean yields have not seen rapid growth like corn, but significant technology changes have

occurred during the period. The use of herbicide resistant seeds for weed control has become the standard while at the same time significant adoption of no-till farming practices has taken place. Simultaneous with these changes, there has been a more efficient use of resources as well as direct growth in yields. Soybean yield growth has been about 0.37 bushels per acre or 1.0 percent annually.

## 5.2. Land Use

Soybean productivity (yield per acre) increased by 29 percent over the study period while planted area for soybeans increased by 31 percent (Figure 5.2). Increasing yields have resulted in soybean land use per bushel decreasing by 26 percent over the past 20 years (Figure 5.3).

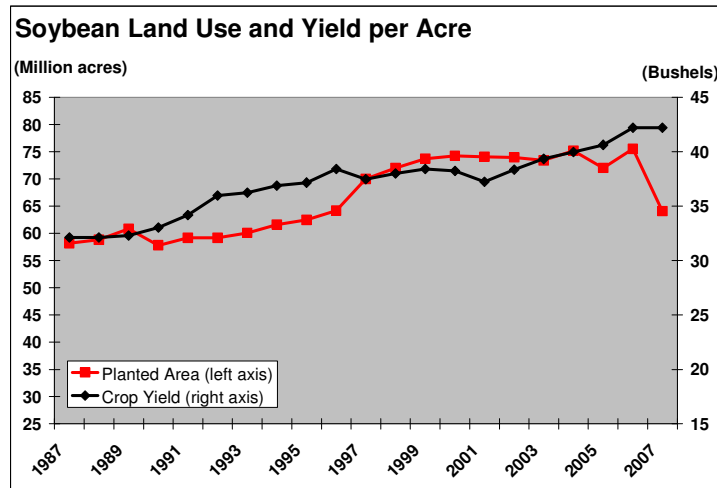


Figure 5.2. Soybean Land Use Indicator

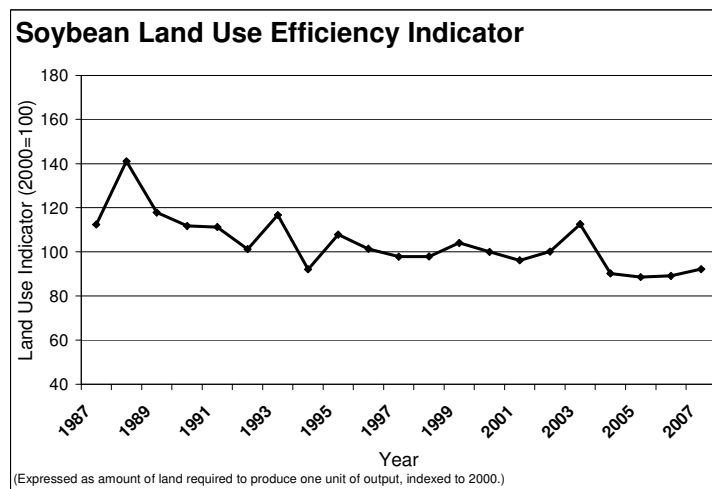
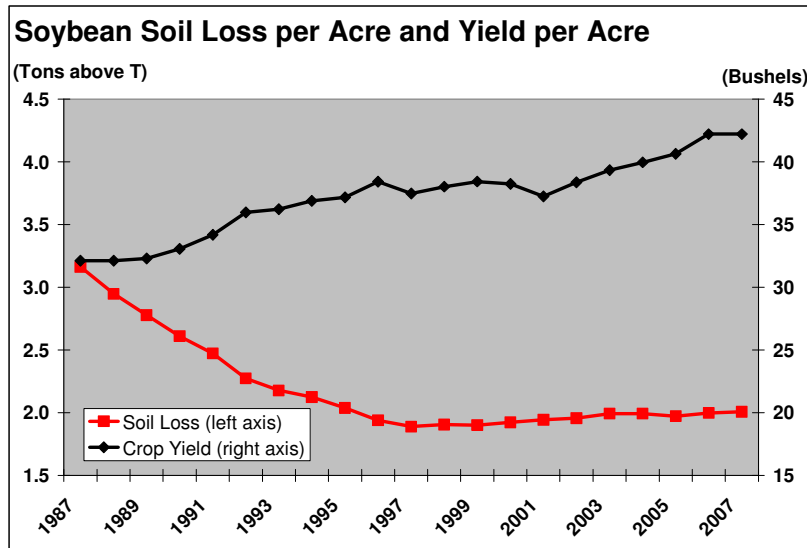


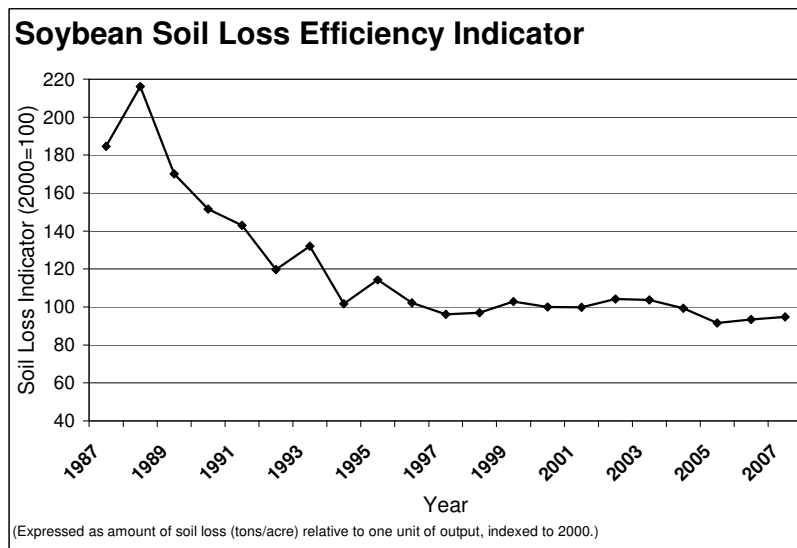
Figure 5.3. Soybean Land Use Efficiency Indicator

### 5.3. Soil Loss

The soybean soil loss indicators (per acre and efficiency) have improved dramatically over time, with a 31 percent reduction in soil loss per acre and 49 percent reduction in soil loss per bushel. These trends coincide with significant changes in farming practices in states that grow the bulk of U.S. soybeans (Figures 5.4 and 5.5).



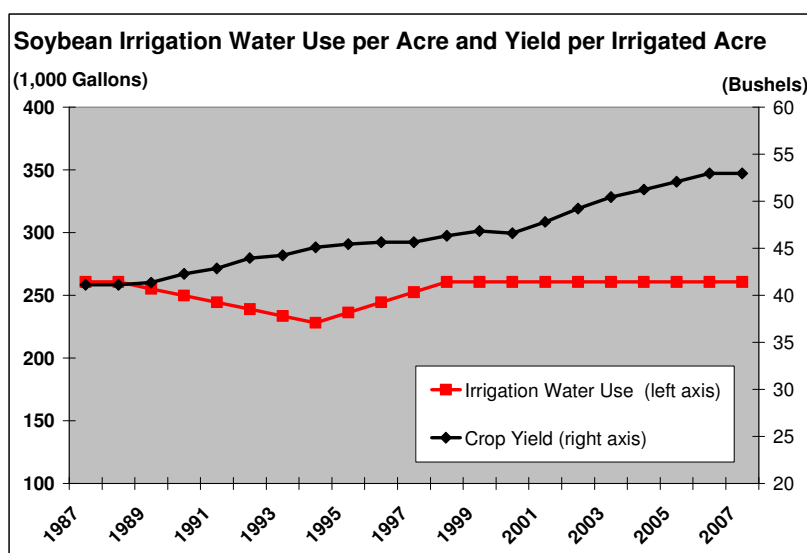
**Figure 5.4. Soybean Soil Loss Indicator**



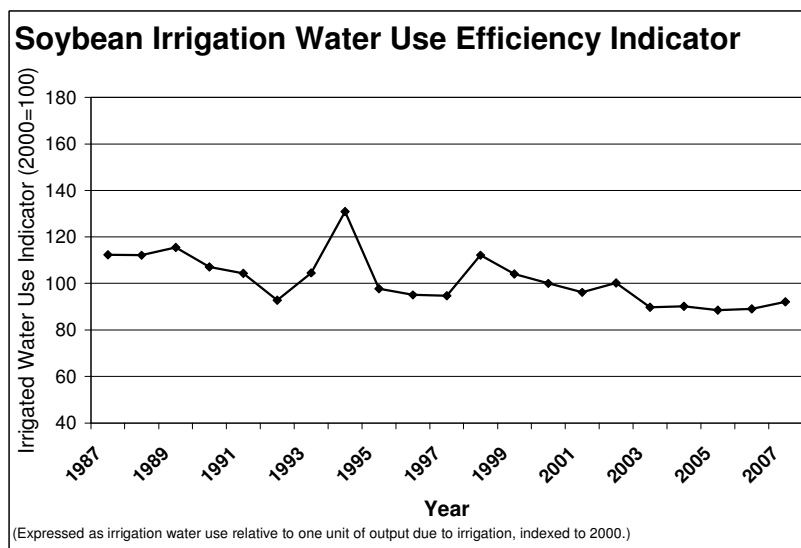
**Figure 5.5. Soybean Soil Loss Efficiency Indicator**

## 5.4. Irrigation Water Applied

Irrigation use on soybeans is relatively limited. Only four to seven percent of the crop utilizes supplemental water. Consistent with the lower share of area being irrigated the amount of water per acre is typically less at about 260,000 gallons per acre per year. The amount of water applied per acre has changed very little over time (Figure 5.6), while water use efficiency per bushel fluctuated over time, showing an overall 20% improvement between 1987 and 2007 (Figure 5.7). Irrigated yields average 40 percent above non-irrigated yields on farms that irrigate at least part of their crop.



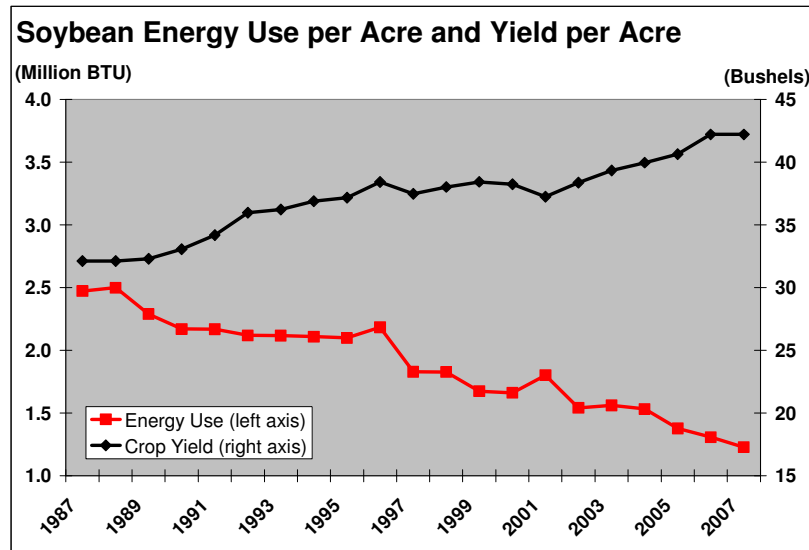
**Figure 5.6. Soybean Irrigation Water Use Indicator**



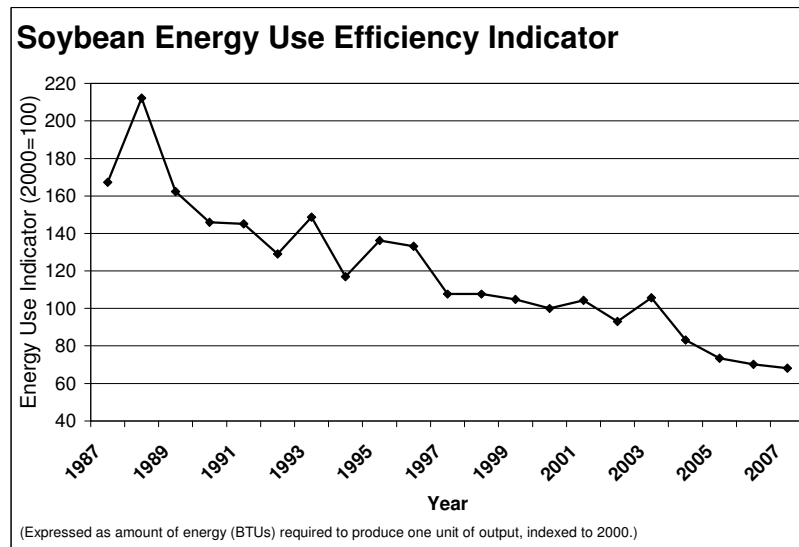
**Figure 5.7. Soybean Irrigation Water Use Efficiency Indicator**

## 5.5. Energy Use

Over the study period, the energy use per acre for soybeans has decreased by 48 percent (Figure 5.8) while energy use per bushel has decreased by 65 percent (Figure 5.9). Soybeans utilize a very limited amount of nitrogen fertilizer and this considerably reduces the total amount of energy used to produce the soybeans, especially in comparison with more nitrogen-intensive crops. Soybeans have seen the most dramatic shift in inputs used, particularly herbicides and fuel for tillage. These factors have allowed the per-unit energy requirements to decline substantially over time.



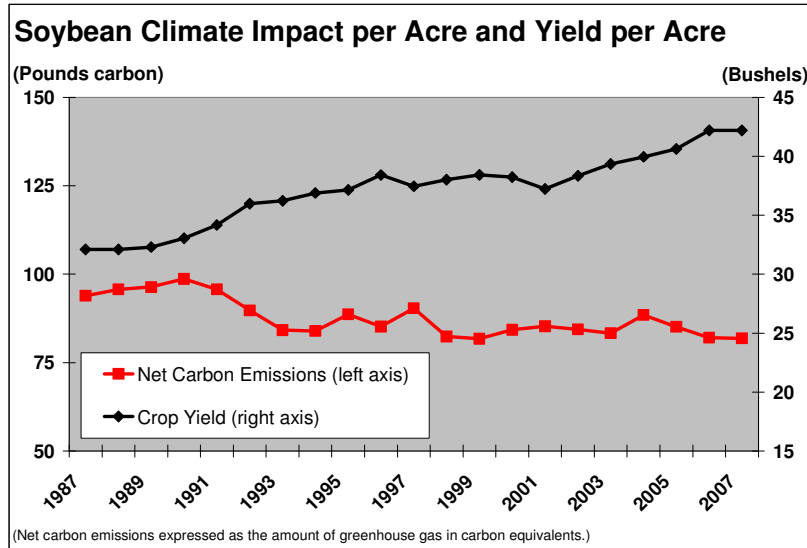
**Figure 5.8. Soybean Energy Use Indicator**



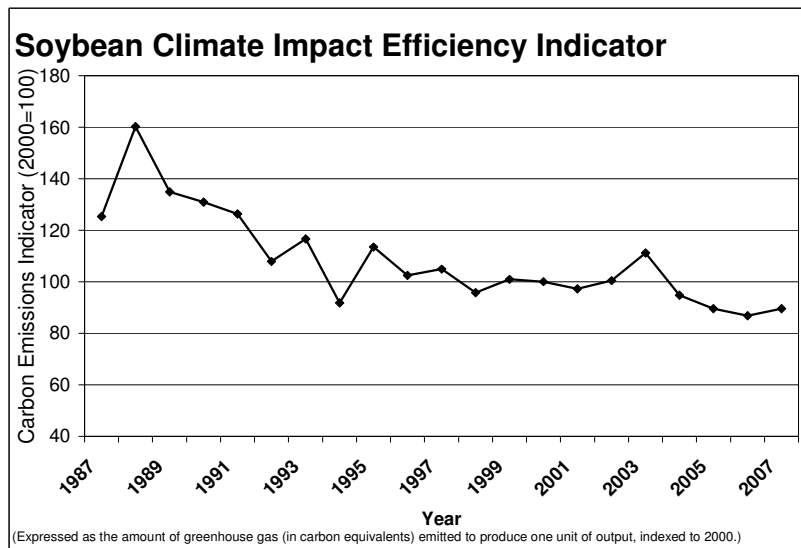
**Figure 5.9. Soybean Energy Use Efficiency Indicator**

## 5.6. Climate Impact

Soybean tillage practices have moved heavily toward no-till over the years. Even with the assumption that only 10 percent of the annual no-till is continuous, as measured by CTIC, the net carbon balance per acre decreased for most of the study period, by 14 percent overall (Figure 5.10). Emissions per bushel decreased 38 percent (Figure 5.11).

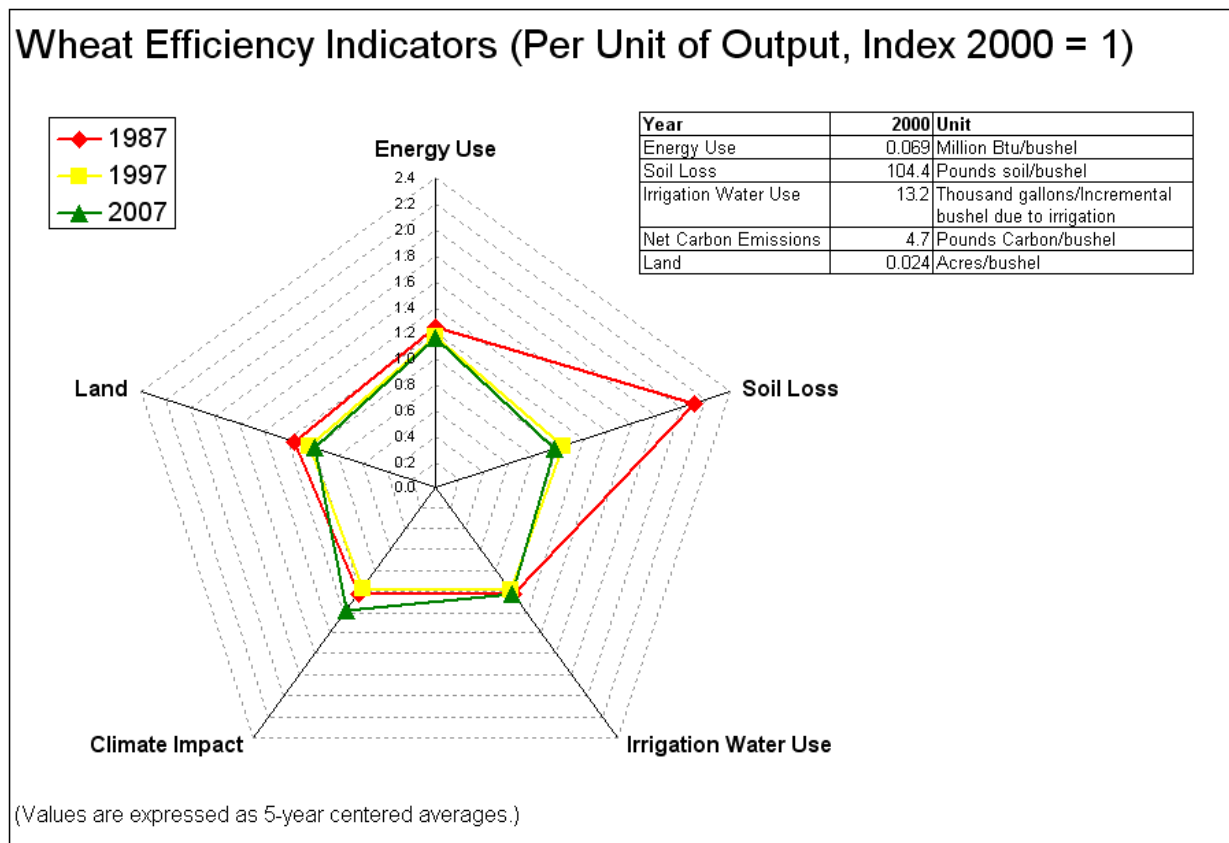


**Figure 5.10. Soybean Climate Impact Indicator**



**Figure 5.11. Soybean Climate Impact Efficiency Indicator**

## 6. Results: Wheat



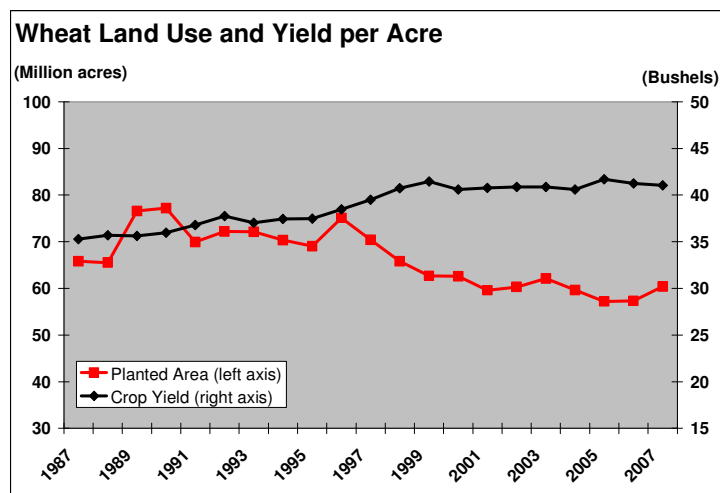
**Figure 6.1. Summary of Wheat Efficiency Indicators**

### 6.1. U.S. Wheat Supply and Demand

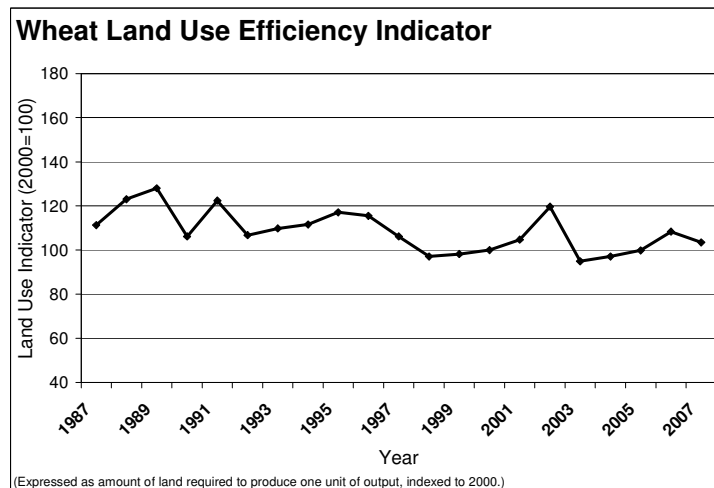
U.S. wheat acreage has generally declined over the past 20 years due to acreage competition from other crops, primarily corn and soybeans. Minimal growth in yields has reduced wheat's competitiveness with alternative crops and has contributed to the acreage loss. During the 1990s, the impact of the low-carbohydrate diet caused consumption of bread, pasta, and other wheat based products to decline in absolute and per-capita terms. Only in the last couple years has there been an increase in domestic demand, albeit relatively small. Export demand has been highly variable over the years with large swings often being the result of lower quality wheat being purchased as feed for livestock. At present several crop supply disruptions have fueled dramatic commodity price increases and relatively strong international demand for U.S. wheat. High prices may encourage expansion in the U.S. and globally during subsequent growing seasons.

## 6.2. Land Use

Wheat productivity (yield per acre) increased by 19 percent over the study period. U.S. wheat land use decreased 24 percent over the past 20 years (Figure 6.2) while land use per bushel was variable, with an average overall decrease of 17 percent (Figure 6.3). Wheat yields have increased very marginally over the period with the greatest productivity increases occurring in the soft red winter varieties. The much larger market segment, comprised of the hard red types, has seen very slow growth in yield and durum wheat has seen almost no productivity advancement over the period. Much of the research on wheat seed has focused on quality considerations rather than yield or technology advancements.



**Figure 6.2. Wheat Land Use Indicator**



**Figure 6.3. Wheat Land Use Efficiency Indicator**

### 6.3. Soil Loss

The indicator of soil loss for wheat made significant progress during the period 1987 through 1997 as soil loss above T decreased from approximately four tons to two tons per acre; reductions in the soil lost per acre have been relatively modest from 1997 forward. Over the twenty year study period, tons per acre decreased 39 percent (Figure 6.4). Similarly, soil loss efficiency improved dramatically, roughly 50 percent, with most improvements over the first half of the study period and more gradual improvements in the second half (Figure 6.5). A major source of soil lost in large wheat growing areas is wind erosion.

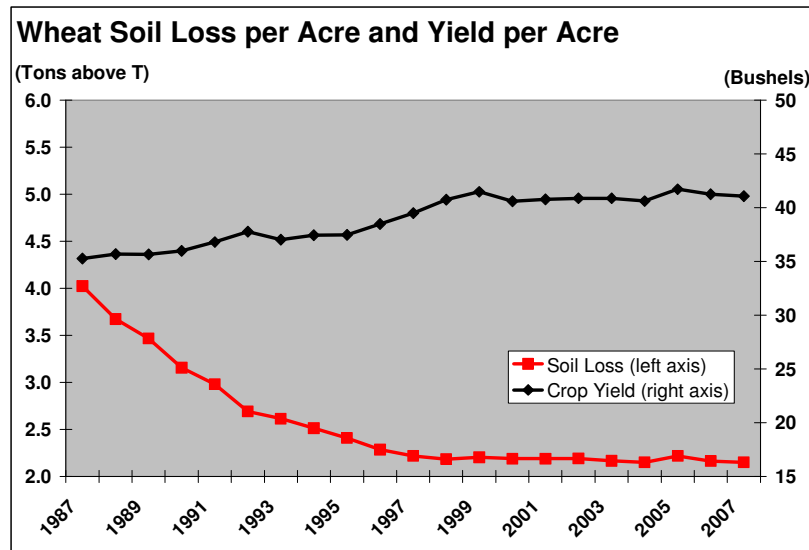


Figure 6.4. Wheat Soil Loss Indicator

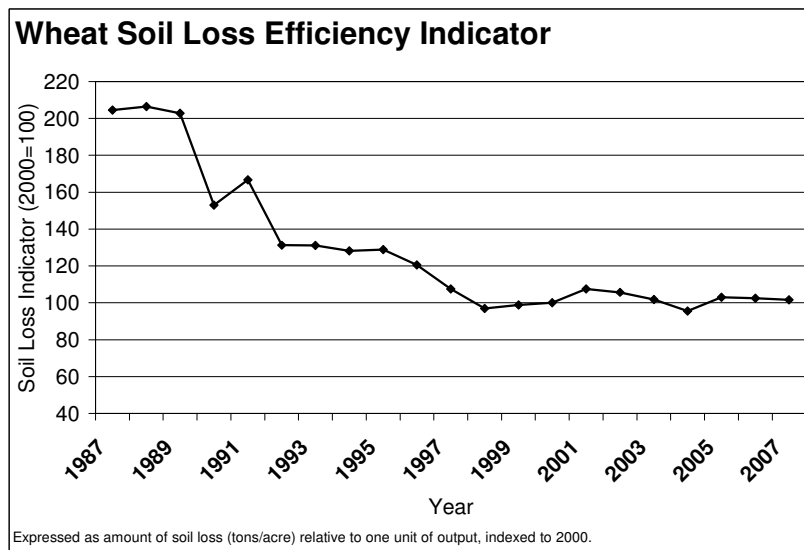
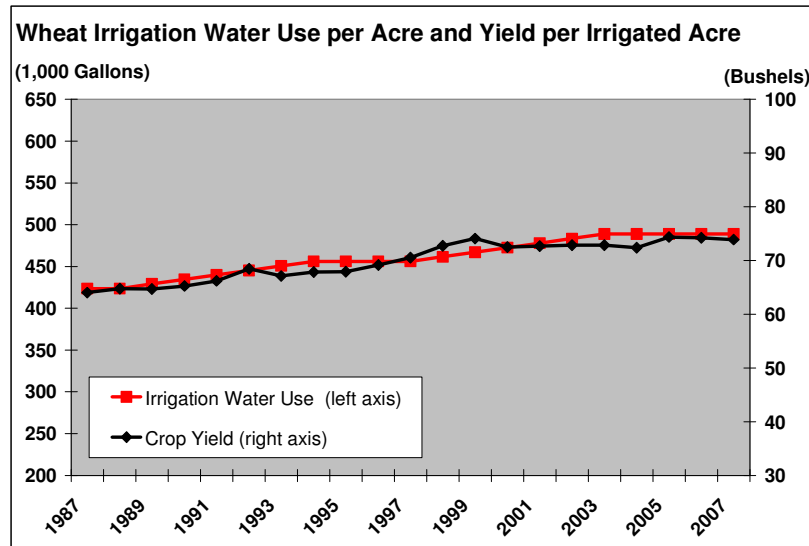


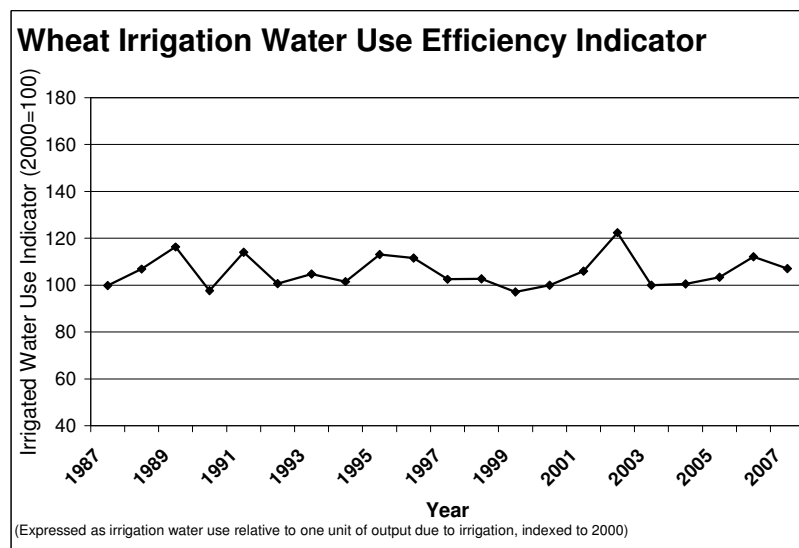
Figure 6.5. Wheat Soil Loss Efficiency Indicator

## 6.4. Irrigation Water Applied

Water applied per acre of wheat increased 17 percent over the past 20 years from roughly 420,000 gallons per acre to 490,000 gallons per acre (Figure 6.6). The portion of total planted area that is irrigated has varied from 5.5 percent to nearly seven percent over the years. Irrigated wheat yields are nearly twice that of non-irrigated yields, a larger yield response than with many other crops. The impact of marginal yield growth offsets the increase in application rates and the efficiency indicator trend is generally flat (Figure 6.7).



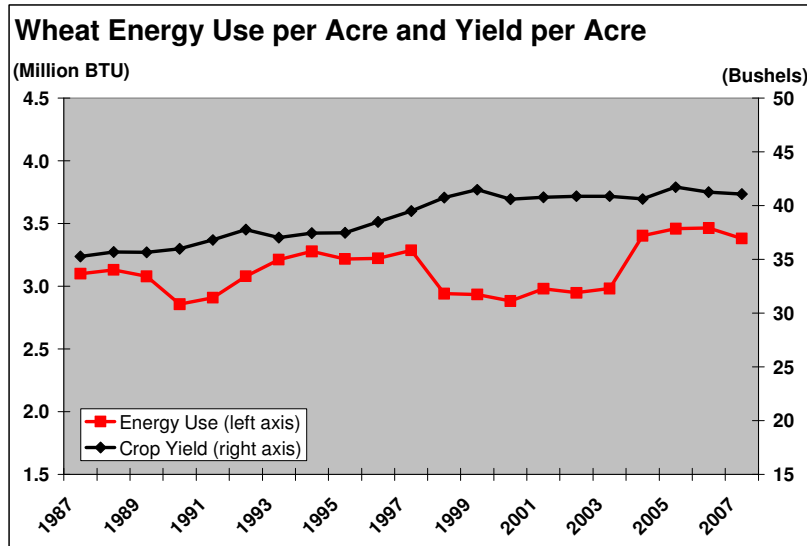
**Figure 6.6. Wheat Irrigation Water Use Indicator**



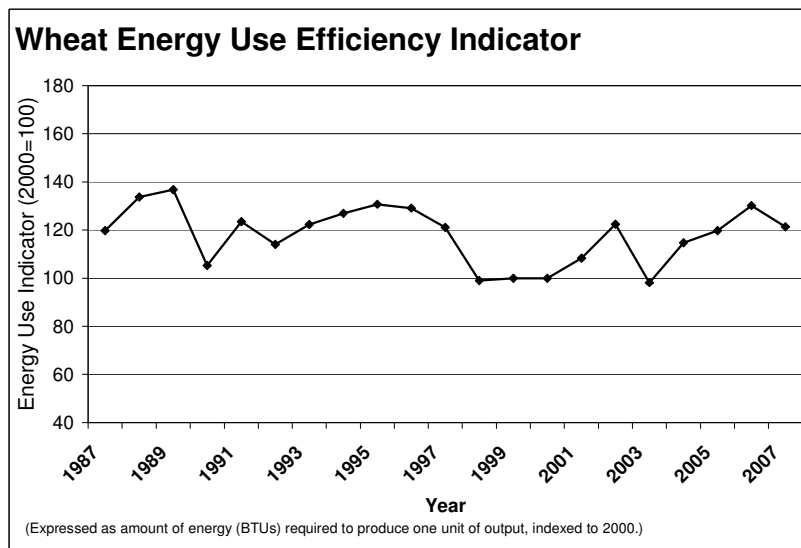
**Figure 6.7. Wheat Irrigation Water Use Efficiency Indicator**

## 6.5. Energy Use

Increased applications of nitrogen over the study period, coupled with relatively limited yield response, resulted in fluctuation of wheat's energy use per acre and per bushel of output, with an overall eight percent increase in energy per acre and a nine percent decrease in energy per bushel (Figures 6.8 and 6.9).



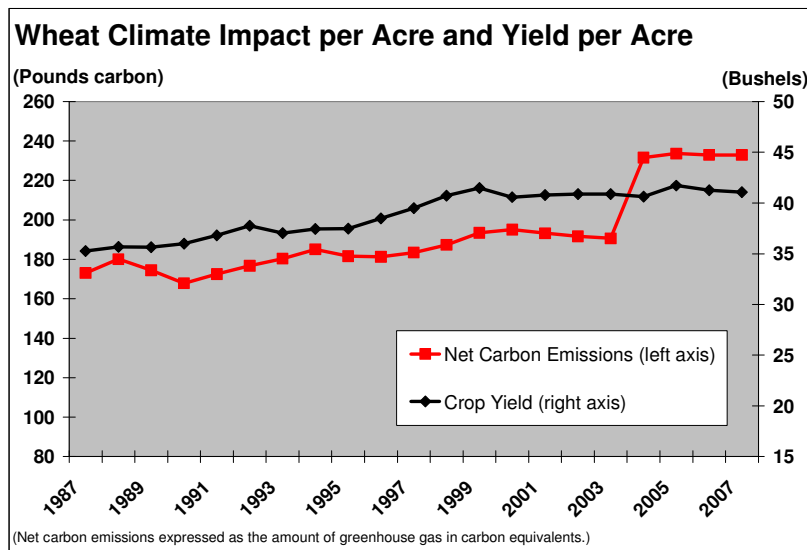
**Figure 6.8. Wheat Energy Use Indicator**



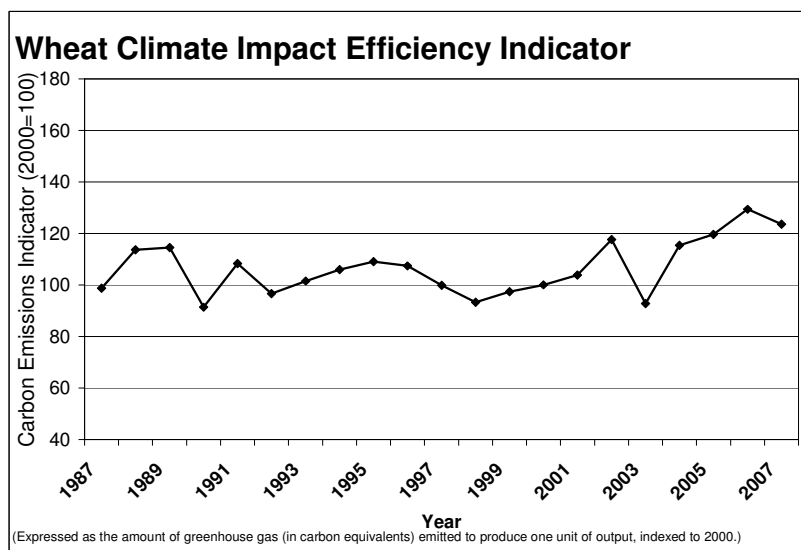
**Figure 6.9. Wheat Energy Use Efficiency Indicator**

## 6.6. Climate Impact

The wheat climate indicator indicates increase in emissions per acre and per bushel of output over time, with the largest increases occurring in the last ten years, resulting in a 34 percent increase in emissions per acre and 15 percent increase in emissions per bushel between 1987 and 2007 (Figures 6.10 and 6.11). The primary factors affecting this indicator are increased nitrogen application with only a small increase in yields. While no-till is being readily adopted by wheat farmers, given the assumption of only 10 percent being continuous no-till, the soil carbon sequestration is inadequate to offset the nitrogen use.



**Figure 6.10. Wheat Climate Impact Indicator**



**Figure 6.11. Wheat Climate Impact Efficiency Indicator**

## 7. Discussion and Conclusions

The findings in this report represent an initial but significant step toward evaluating agricultural sustainability and tracking progress over time. The members of this alliance expect the methodology to be modified and improved as research, time and better data allow. In this report, the sustainability index is applied to corn, cotton, soybeans, and wheat production at the national scale. In theory, this methodology can also be applied to other crops and to regional, local, and farm-scales. However, this theory must be tested through case studies, and the methods must be revised as necessary for other crops and scales. We also recognize that our metrics fall into two categories: measures of the efficiency of the use (land use, irrigation water use, and energy use) of the resource as well as measures of the actual impact on the resource (soil loss and climate impact). Table 7.1 conceptualizes our understanding of what each of our metrics does and does not do, the metrics' potential scalability, and areas for future improvement.

**Table 7.1. Evaluation of Environmental Resource Indicators and their effectiveness as metrics for environmental sustainability outcomes at various scales.** The five metrics presented here are believed to be relevant (assuming appropriate available data) at national, regional, and local scales. Land Use, Water Use, and Energy Use indicators measure the efficiency of resource use, while soil loss and climate impact measure actual impact on the natural resource in question. In most cases, the data utilized is not confounded by non-agricultural sources of stressors. Agricultural inputs such as nutrients and pesticides are accounted for in the Energy Use and Climate Impact indicators. Examples of ideas for future areas of improvement are also provided.

Resource Indicator	Type of Measure of Sustainability Outcomes		Scalability (based on appropriateness of use of other available data)			Data confounded by other (non-agricultural) sources of stressors?	Ag Inputs Included? (i.e. nutrients, pesticides)	Areas of Improvement
	Efficiency of Use of Resource	Impact on Natural Resource	National	Regional	Local (grower)			
Land Use	Yes	No	Relevant	Relevant	Relevant	No	NA	
Soil Loss	No	Yes (soil loss specific)	Relevant (data specific to cropland)	Relevant	Relevant	No	NA	Incorporate 2007 data when available through NRI.
Water Use	Yes	No	Relevant	Relevant	Relevant	No	NA	Look for and utilize state level data with greater reporting frequency.
Energy Use	Yes	No	Relevant	Relevant	Relevant	No	Yes	Current approach may not capture energy efficiency improvement over time; include seed production energy.
Climate Impact	No	Yes	Relevant	Relevant	Relevant	Yes – geographic (climate and soil)	Yes	Could be improved with better energy efficiency data over time, possible improvements in the method of fertilizer application analysis, inclusion of NO <sub>2</sub> and CH <sub>4</sub> , and also by incorporating better measurement or estimation of soil organic carbon sequestration for alternative tillage practices and crop rotations (as they become available).

At this point, a benchmark level for sustainability by crop is not defined, and thus we cannot state whether we have achieved “sustainability” or, if not, how far we have to go. However, these

indicators begin to provide tools by which to describe progress or lack of progress in making efficient use of resources and the environment. Our results demonstrate increasing efficiency over time in many of the indicator areas for each of the major crops, suggesting positive progress toward achieving meeting increasing agricultural demand while achieving lesser environmental impacts per unit of output.

It is too soon in this process to draw major conclusions about this data. This report marks our first step in establishing some benchmarks and baselines for overall performance. However, we can begin to see some positive trends emerge and also identify areas where we would like to see stronger trends and continuous improvement. Gains in productivity (yield per acre) over the past decade in most of the crops have generally improved overall efficiency of resource use. Soil loss trends (both per acre and per unit of output) have improved significantly in all crops. In addition, corn has seen modest to significant improvements in water use per acre and in water use, energy use, and carbon emissions per bushel. Cotton and soybeans are making progress in reducing irrigated water use, energy use, and carbon emissions per acre and per unit of output. Wheat's energy use per bushel has decreased, its water use per bushel has remained relatively flat, and its carbon emissions per acre and bushel have seen larger increases. In the future, we hope to better understand the relationship between outcomes trends and the practices and other factors that are driving them. This understanding will enhance our ability to achieve improved outcomes performance.

We will also work to be more inclusive of other indices important to sustainability and agriculture. We know that water quality and biodiversity are key areas of concern for agriculture, and developing metrics to measure trends over time for these crucial areas will be one of our immediate next steps. Overall land use trends are important in determining the ways agriculture is contributing to open space and habitat, and whether intensification on existing acres in production is truly lessening pressures on other lands. Tracking agricultural sustainability may also involve comparing the sustainability indices presented here against a world population growth and agricultural demand growth index. The results of such a comparison would demonstrate whether agricultural efficiency – in terms of both environmental outcomes and yield – outpaces or lags behind global per capita demand. Given that the U.S. is a significant producer of agricultural goods for consumers around the globe, such a comparison is worthwhile and may be appropriate. This and other approaches will be

considered and attempted in the future.

Finally, the indicators reported here consider only one dimension of agricultural sustainability. In addition to environmental outcomes, human health and socio-economic outcomes are also key indicators of sustainability, and must be considered in the future. In the meantime, this report provides an initial step toward defining and measuring sustainability and creating awareness of agricultural outcomes.

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