Carbon Life Cycle Assessment of United States Cotton:
A View of Cotton Production Practices and their Associated Carbon Emissions for Counties in 16 Cotton Producing States

Prepared for:
Cotton Incorporated
World Headquarters
6399 Weston Parkway
Cary, North Carolina 27513

Final Project Report
Project 07-254

Prepared by:
Marty Matlock, Ph.D., P.E., C.S.E.
Lanier Nalley, Ph.D.
Zara Clayton-Niederman

Center for Agricultural and Rural Sustainability
University of Arkansas Division of Agriculture
233 Engineering Hall
Fayetteville, AR 72701

Submitted February 5, 2009
Revised May 8, 2009

Carbon Life Cycle Assessment of United States Cotton

Table of Contents

List of Figures and Tables

Carbon Life Cycle Assessment of United States Cotton:
A View of Cotton Production Practices and their Associated Carbon Emissions for Counties in 16 Cotton Producing States

Executive Summary

This study estimates the carbon-equivalent emissions (CE) from multiple agronomic production practices to produce one pound of cotton in counties in the United States. Using a life cycle assessment (LCA) approach, we estimate the greenhouse gas (GHG) emitted from cradle to farm-gate. Included in the study is the carbon emitted in manufacturing inputs used in the production of cotton, such as fertilizers and agrochemicals, as well as the emissions from the production itself, such as diesel exhaust. The nitrous oxide emitted from soil due to nitrogen fertilizer application was also included. We assumed soil organic matter, and thus carbon loads in the soil remained constant. The GHG emissions from the manufacturing of the tractors and tools were not included in this analysis, as they are constant across all production practices and were considered negligible (<1 percent) for this comparative analysis.

Production practices included irrigated vs. non-irrigated, genetically modified varieties vs. conventional varieties, and reduced-tillage vs. conventional tillage. County yield data from 2000 to 2007 were obtained from United States Department of Agriculture and input data came from cotton production budgets from each state's cotton extension specialist via personal communications. To account for variability and uncertainty of yield, input and CE metrics, a Monte Carlo simulation was performed using distributions for CE factors, inputs and yield.

Results indicated that while there were significant differences in the amounts of inputs by production practice and hence the CE per acre by region of the country, CEs on a per yield basis were fairly constant. Generally, input intensive production practices resulted in much higher yields, and thus reduced overall CE per pound of cotton.

Fertilizer and nitrogen in particular, contributed the largest portion of the carbon footprint. A significant portion of the carbon emissions was from nitrogen released as soil N_2O. However, in regions that relied on irrigation, fuel use for pumping approached the level of emissions from fertilizer application. Developing methods to reduce soil N_2O emissions could help reduce the impact significantly.

This analysis does not directly compare the efficiencies of production practices with respect to carbon emissions per pound of cotton. However, this may be possible with further analysis using this Life Cycle Inventory. Future analysis could also inform the impact of carbon taxes or carbon cap-and-trade regulations on cropping decisions, in particular how this would relate to cotton production methods and overall acreage. Other analyses could simulate changes in weather; estimate the effects of a reduction in aquifer levels, or differences in carbon emissions in dry versus wet years.

Life Cycle Inventories are the engines of LCAs. This project provides a comprehensive LCI for GHG analysis for US cotton that can be applied to compare different production practices or different locations. In addition, LCA can be used as a predictive tool to see how changes to the production system or supply chain may impact both production as well as the environment.

Carbon Life Cycle Assessment of United States Cotton:
A View of Cotton Production Practices and their Associated Carbon Emissions for Counties in 16 Cotton Producing States

Introduction

Scientists have raised the issue of rising greenhouse gas (GHG) emissions and their impact on global climate change for several decades. As the science underlying the climate models has become more robust, and as people have begun to feel the impacts of environmental stress more acutely, consumers and the general public have become more aware of the need for sustainability of products and their production practices. The meaning of sustainability is not easy to define, although generally people agree that sustainability must incorporate economics, social impacts and environmental impacts. However, there is no consensus on the limits of what should be considered in measuring sustainability in these three broad areas. Nevertheless, greenhouse gas emission, and its global warming potential, is one key metric for sustainability.

The objective of this project was to determine the GHG emissions of cotton production across the range of practices in the United States at a county level. Using a Life Cycle Assessment (LCA) approach, this analysis assessed GHG of cotton production from cradle-to-gate[1]. This analysis included all forms of power, both direct and indirect, required to produce a unit of raw cotton in the field. Direct emissions are those emitted from on farm activities leading to carbon dioxide or other GHG emissions. Indirect emissions are those emissions caused due to inputs used on the farm, but emitted further upstream in the supply chain.

US cotton production practices (tillage to harvest) vary across the US based upon rainfall, soil types, traditional or regional preferences, and sizes of fields. Analyzing sustainability of production processes from a GHG perspective requires equitable comparison of these various practices. This analysis will inform producers and resource managers of the relative impact of various cotton production practices across the US with respect to GHG production. This research is significant in that it will provide resource managers with an ability to rate production practice sustainability on a carbon-equitable basis.

The goal of this project was to develop a life cycle analysis of GHG production from cotton across the range of US cotton production practices (tillage to harvest). The analysis provides the GHG generated in production of a mass of cotton using a range of production practices. Uncertainty and variability are key characteristics of the available data. This analysis assigned a probability distribution function for each input into the model. The objectives of this project were to develop a Life Cycle Inventory (LCI) for cotton in the US for GHG analysis that could be used for a variety of analyses, develop a model of cotton production that reflects the complexity and diversity of cotton production practices, and use Monte Carlo simulation to propagate uncertainty in the

[1] Cradle-to-gate analysis means looking at the process including all of the inputs leading to the production. Typically Life Cycle Analysts will cut off those impacts that are below some threshold, for example less than 1% or 5% of total impact. Cradle-to-grave analysis includes the processing, transportation, use and disposal or recycling of the product.

model in order to determine distributions and statistical differences between mean data points.

Methodology

We estimated both the direct and indirect GHG emissions from the production of cotton. Direct emissions are those emissions that come from farm operations, for example carbon dioxide (CO_2) from the use of diesel and gasoline fuel. Indirect emissions are those emissions from the production of inputs used on the farm, for example the CO_2 emitted from the burning of natural gas to produce inorganic fertilizers. This study did not include the embedded carbon (i.e. carbon emitted upstream in the production) of the tractors and tools used in the production of cotton. We assumed soil carbon to remain at equilibrium and so there was no net carbon sequestration or soil CO_2 emission. We did include soil nitrous oxide (N_2O) emissions from application of nitrogen fertilizer, as nitrous oxide is a potent greenhouse gas[2].

Data were collected from the sixteen largest cotton producing states, which included over three hundred counties[3]. We used annual yield data for lint cotton for each county for the years 2000 to 2007 from National Agricultural Statistics Service (NASS). All cotton producing counties were included for the sixteen states for which NASS provided data. NASS disaggregates yield and acreage by Upland and Pima varieties. Data was collected for both, but given the relatively small number of Pima acres we used only the Upland variety in our analysis. Some states provide data for irrigated acreage, non-irrigated acreage and total acreage. We collected all data where available, but aggregated our results so that we compared only total acreage. However, certain states are predominantly non-irrigated (North Carolina and Alabama), where as others, such as California and Arizona, are exclusively irrigated, according to NASS data.

To determine inputs used for specific production practices in each county and state, we used cotton production budgets produced by University agricultural extension specialists. Extension specialists provided best judgment for the percentage breakdown for each for each crop reporting district (CRD) using a specific production budget, e.g. Roundup Ready (RR), RR Flex, conventional, irrigated, dryland, etc. (Figure 1). We used the major production budgets[4] for each state or crop reporting district. The inputs included: fuel (diesel and gas), irrigation water, fertilizers, herbicides, insecticides, and other agrochemicals such as fumigants, defoliants and growth regulators (Figure 2).

[2] Nitrous Oxide is 296 times as potent as CO_2 according to Intergovernmental Panel on Climate Change (IPCC)
[3] These states are: Alabama, Arizona, Arkansas, California, Florida, Georgia, Kansas, Louisiana, Mississippi, Missouri, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia
[4] Production budgets that were used in less than 5% of the county were not included

Figure 1: Categories of Production Methods for Cotton in the United States

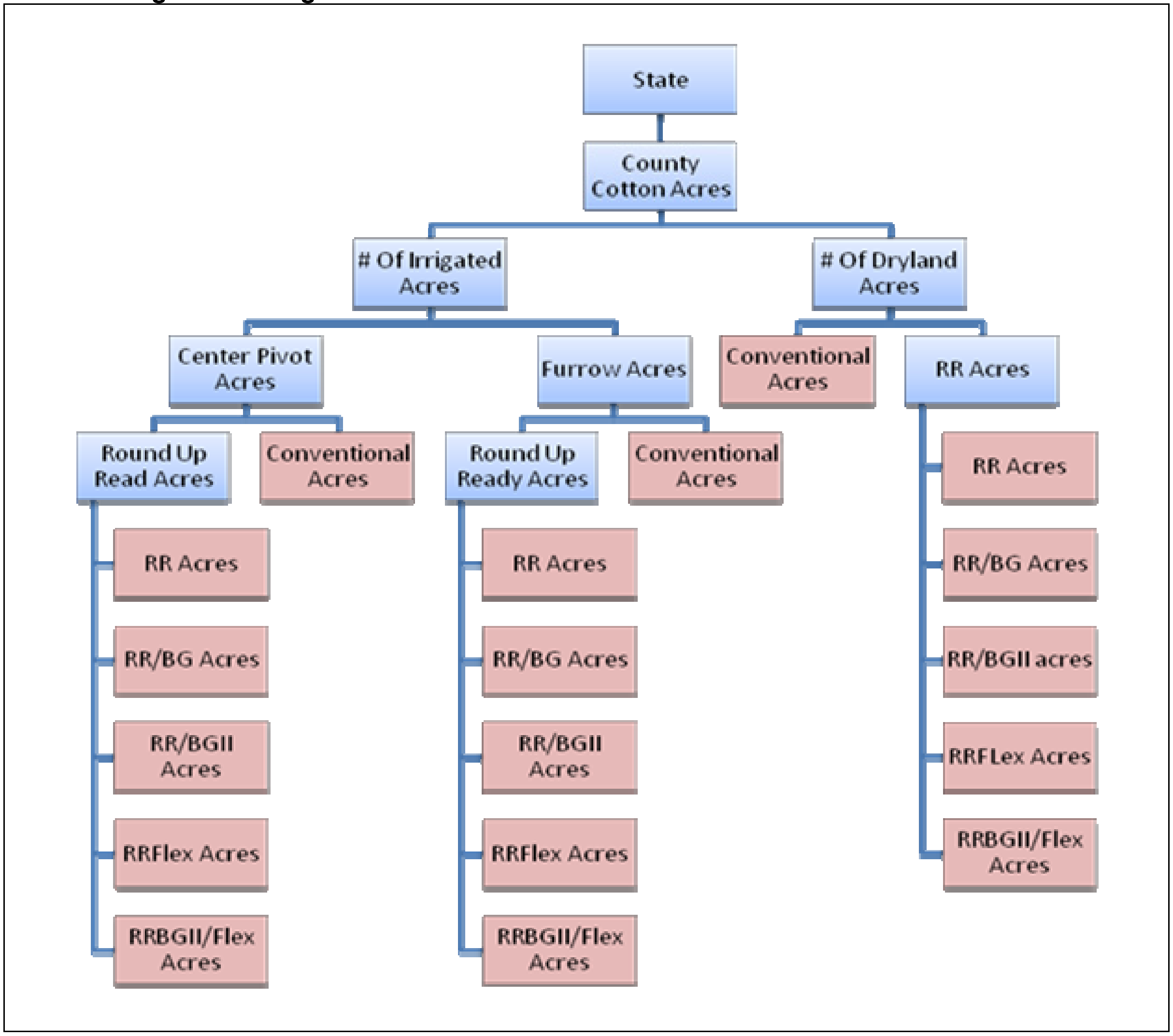
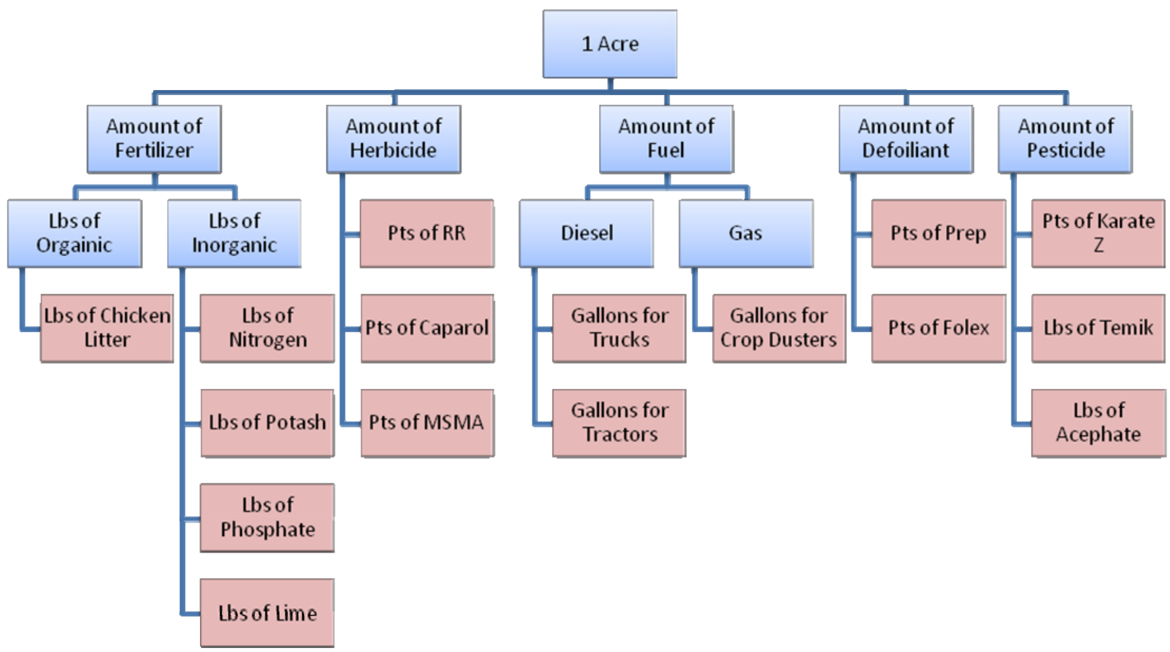


Figure 2: LCA Model Production Inputs for US Cotton



Extension specialists also provided best judgment for the percentage of each county that is irrigated, and the percentage of irrigated land that that implements center pivot, drip, flood, or furrow irrigation techniques. Extension specialists from three states, Mississippi, Arkansas and Louisiana, provided estimates for fuel required to deliver one acre inch of water to the field using either gravity or center pivot. We used these averages to estimate fuel used for irrigation where it was not provided in the budgets[5].

Carbon Emissions Calculations

For each input, we used a carbon emission factor to estimate the amount of carbon or carbon equivalent emitted from the production or use of the input (Table 4). Carbon dioxide is emitted in production or use of all inputs. For diesel and gasoline, we used values provided by the US Environmental Protection Agency (EPA). For all other inputs we used values provided by Lal 2004. Lal provides a synthesis of numerous studies measuring carbon emissions from farm operations. For further discussions of how these values are calculated, please see his article cited below. Some studies cite CO_2-equivalent emitted from production, others cite carbon-equivalent, or CE; we used the carbon-equivalent. One pound of carbon dioxide contains 12/44 lbs. of carbon, using the atomic mass ratio of a carbon molecule to a carbon dioxide molecule.

[5] Some budgets provided total fuel used, some provided fuel used by tractors and irrigation separately, and some provided fuel used for tractors and only the amount of acre inches of irrigation required.

Table 4: Carbon Equivalent Factors for Inputs for US Cotton Production

Input	Carbon-equivalent	Source
Fuel		
Diesel	6.05 lbs C/gal	US EPA
Gasoline	5.29 lbs C/gal	US EPA
Fertilizer		
Nitrogen*	3.30 lbs C/lb	Lal, R. 2004, IPNI 2007
Phosphate	0.20 lbs C/lb	Lal, R. 2004
Potash	0.16 lbs C/lb	Lal, R. 2004
Lime	0.17 lbs C/lb	Lal, R. 2004
Herbicide	6.44 lbs C/lb	Lal, R. 2004
Insecticide	5.44 lbs C/lb	Lal, R. 2004
Defoliant	6.44 lbs C/lb	Using Herbicide Value
Growth Regulator	5.44 lbs C/lb	Using Insecticide Value
Fungicide	5.44 lbs C/lb	Lal, R. 2004

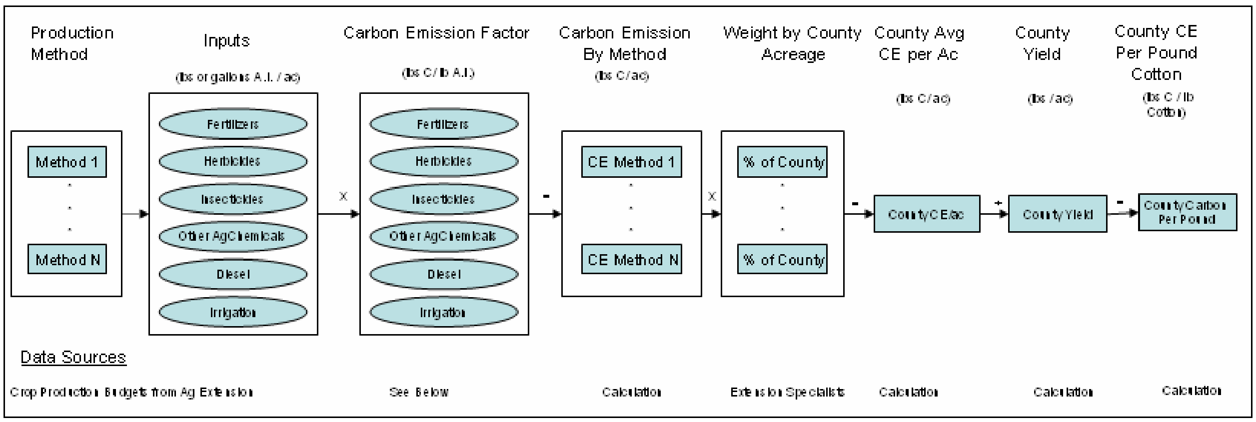
* Nitrogen includes both input value and soil N_2O emissions

Nitrous oxide from soil's atmospheric release of excess applied nitrogen was converted to its carbon equivalent. For this study, we use the IPCC 2001 Third Assessment Report conversion factor of 296 lbs CO_2 per lb N_2O (or 80.7 lbs CE). IPCC estimates that approximately 1% of nitrogen applied to soil is emitted as N_2O, although this amount varies significantly based on soil type, soil conditions and climate, as well as amount and timing of application. We aggregated the CE from nitrogen fertilizer production with soil N_2O release to use one number in the calculation. Although different types of nitrogen fertilizer (e.g. ammonium nitrate or urea) require different amounts of energy, and hence CO_2 emissions from production, we use a generic CE value.

There is validity to the claim that agriculture has the potential to sequester atmospheric carbon. This could come in the form of root mass, woody debris tilled back into the soil, or the in the agricultural product itself. Typically, carbon footprint studies look at the amount greenhouse gasses that will remain in or be removed from the atmosphere for one hundred years or more. Because it is unlikely that carbon sequestered in one year of production remains in the soil for 100 years due to continuous tillage, we did not include sequestration as a possibility. However there may be certain cases where cotton production does sequester carbon. In addition, the production of carbon fabric has the potential to sequester carbon, however, because our life-cycle analysis only includes farm-to-gate (i.e. only production up until it is harvested, and no further processing), we therefore should not take into account any potential sequestration in cotton fabric.

Using the input values and the CE factor for each input, we were able to calculate the carbon footprint for each production type. For each county, using the estimated percentage of each county using a specific production practice, we calculated the estimated weighted average carbon emission per acre for each county. NASS provides data for both acres planted and acres harvested. Since it is difficult to say when the decision was made not to harvest certain acres, this estimate only includes carbon emissions per harvested acreage. Dividing carbon per acreage by yield data, we were able to calculate a weighted average carbon footprint by county in terms of pounds carbon per pound of cotton produced (Figure 3).

Figure 3: Calculation of Carbon Emission by County for US Cotton Production Practices



Uncertainty Simulation

For our initial analysis we used mean values for all of our input data in our model. However, there is significant variability and uncertainty in these numbers. For example, there is uncertainty in how much carbon emission actually comes from the burning of fuel, either to run tractors, or to produce inputs. Additionally, there is both uncertainty and variability in the amount of inputs used in a production practice. There may be variability for a farm either across fields or years, or variability between farms. Therefore we used a Monte Carlo simulation to determine how large or small the level of certainty is for each of our county and production method results. We used distributions for our input data based on data collected, data estimated elsewhere and best judgment (Table 5).

For each input in the model, we provided a distribution, either triangular where we believed there to be a central tendency, or a uniform distribution where we believed the probable value could vary equally across the range. In each case we included a maximum and minimum vale as a percentage of the mean value. These distributions were based on expert opinions. For yield we used a normal distribution using the mean and standard deviation from the 8-year data provided by NASS. We truncated the distribution to cut off the minimum at 10% of the mean value, and capped yield at 3 times the mean value of the county. For CE factors, we used distributions based on data collected from other sources. For fuel, we used a triangular distribution. For fertilizers and pesticides we had multiple data points so we used a normal distribution with truncation limits. Nitrous oxide has wide variability in emissions from soil. The International Plant Nutrition Institute provided mean values for soil N_2O emissions as well as high values and low values, so we used a lognormal distribution with these truncation limits.

Table 5: Monte Carlo Simulation Distributions for Cotton Production Inputs

Outputs and Inputs	Distributions	Truncation		xMean
Yield	Normal	Truncated	Min	0.1
			Max	3
Fertilizer	Uniform	Truncated	Min	0.9
			Max	1.1
Herbicides	Triangle		Min	0
			Max	2
Defoliant	Triangle		Min	0.5
			Max	1.5
Diesel Tractors	Triangle		Min	0.75
			Max	1.25
Irrigation Diesel	Uniform		Min	0.5
			Max	1.5
CE Factors	**Distributions**	**Truncation**		**xMean**
Fuel	Triangle		Min	0.75
			Max	1.25
Fertilizer	Normal	Truncated	Min	0.5
			Max	1.5
Pesticides	Normal	Truncated	Min	0.5
			Max	1.5
N2O	Lognormal		Min	0.4
			Max	3.8

The Monte Carlo simulation was performed for 10,000 iterations in order to achieve stable conversion of estimates of the distributions for carbon emissions. We collected results for variability by county CE per acre and CE per pound. We also produced results for variability across production practices. In addition we created distributions for each major input (e.g. fertilizer, pesticides and fuel) within a production practice.

Results

Carbon by County

We compared all counties by their weighted average carbon footprint. We looked at both the carbon emissions on a per acre basis, as well as on a per pound basis. While we are directly comparing counties, it is important to note that there are numerous factors that go into carbon emissions, such as soil fertility and climate, and hence yield. Carbon per acre is an important measure, in particular, as a baseline. This can be seen in Figure 4. Arizona, for example, has a very high carbon footprint per acre, due mainly to their high levels of irrigation and nitrogen fertilizer application.

Comparing across counties on carbon per acre does not take into account the physical amount of lint and seed produced, and therefore, it may not be appropriate to compare different states, regions, or counties by their carbon per acre. However, carbon per acre, and hence total carbon emitted (Figure 5) is an important issue and as discussed below, carbon emissions per acre may be a key metric for potential carbon tax or cap-and-trade policies.

Carbon per pound of lint produced is a direct measure of the carbon footprint that can be used on a comparative basis across time and space. See Figure 6. As inputs remain constant and yield increases, carbon per pound will decrease, showing the increased efficiencies. While Arizona has high levels of inputs, it also has a very high yield, and so their CE per pound of cotton is much closer in line with that of other states. On the same note, as new seed technologies are adopted which lower input usage and maintain yield, carbon per pound of cotton will reduce as well.

In both the above measures we used Monte Carlo simulation to assess the variability and uncertainty. We were able to look across counties to see if there was a statistically significant difference between them (see Figure 7). We can see that for the most part, mean carbon emissions are roughly 0.5 to 1.0 pounds of carbon per pound of cotton. Given the level uncertainty, most counties are not statistically different from one another. However, there are several counties, namely counties in California that have low mean values and small uncertainties that appear to be significantly different from several counties with much higher means. Further analysis is needed to determine what is causing these differences.

If we compare counties within one state, we may be able to tease out further differences, however, in general, it appears that most counties within a state remain with a common band. For example, in Arkansas, we can see the CE varying from roughly 0.5 to 0.75 pounds of carbon per pound of cotton (see Figure 8). However, the uncertainty levels are to great to assume that they are significantly different, statistically.

Figure 4: Carbon Emitted from Cotton Production in the US (Pounds per Acre)

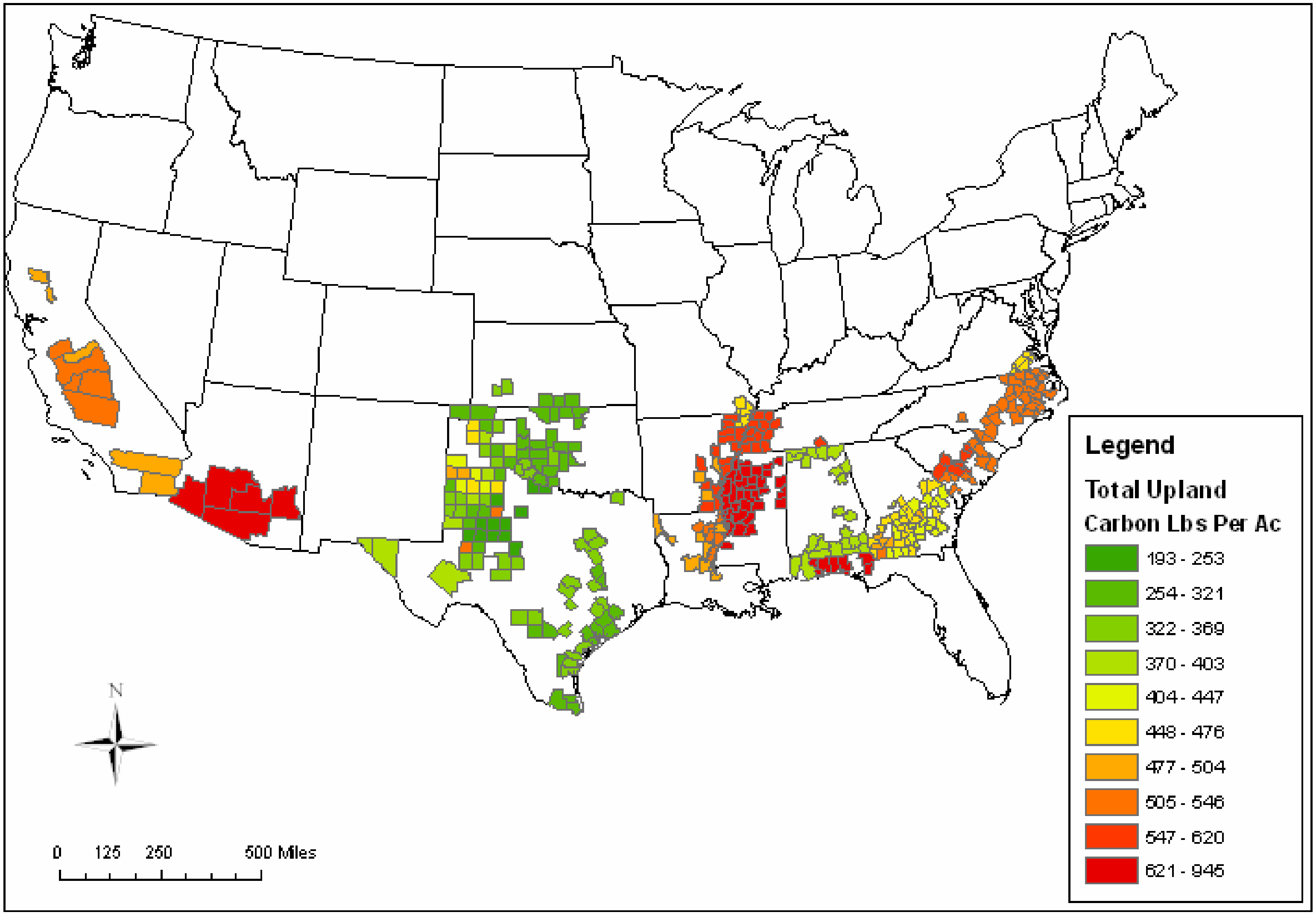


Figure 5: Total Carbon Emitted from Cotton Production per County (pounds), Using 2007 Acres Harvested

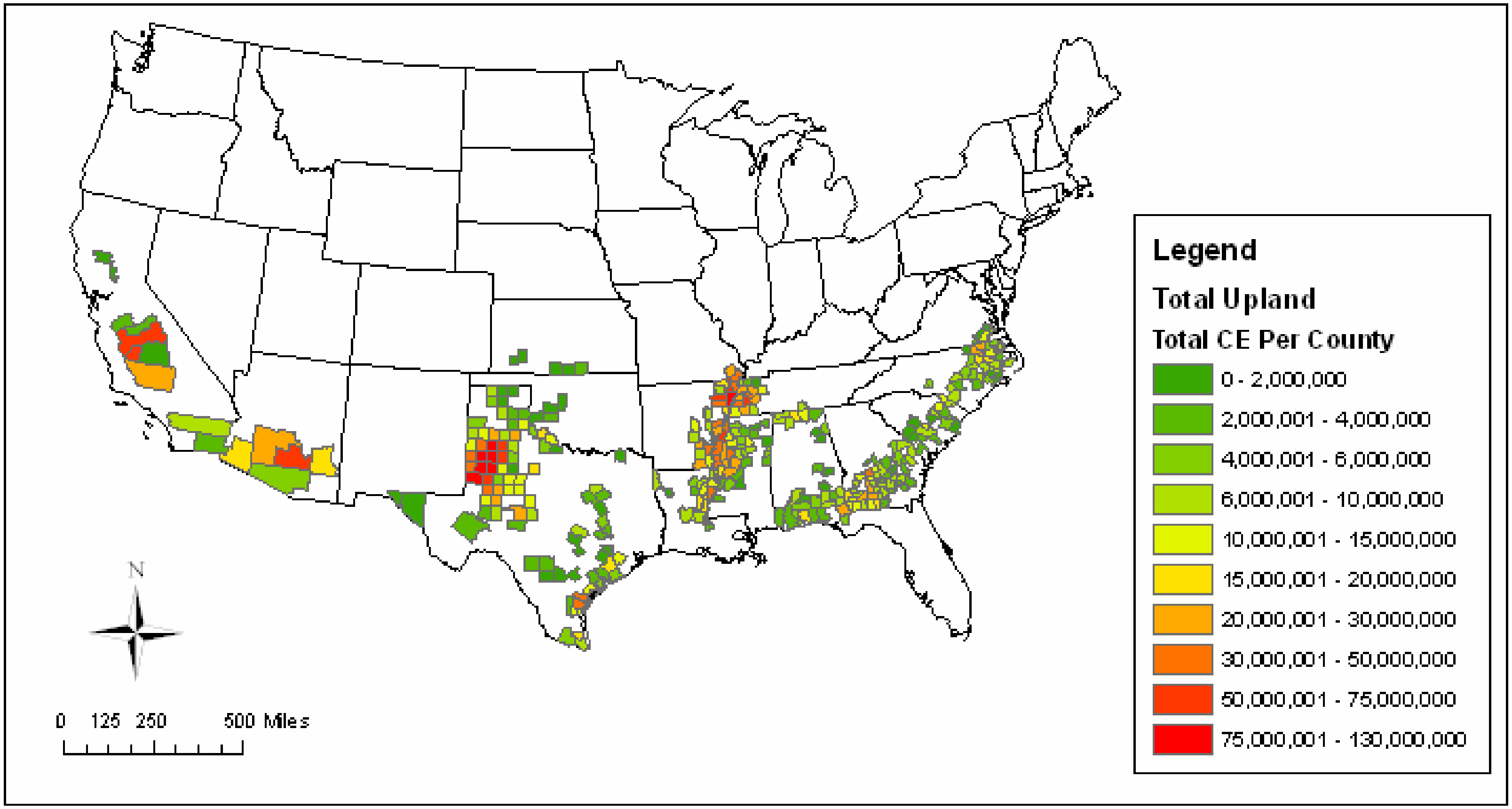


Figure 6: Carbon Emitted From Cotton Production (Pounds CE per pound of Cotton), Using Average Yield from 2000-2007

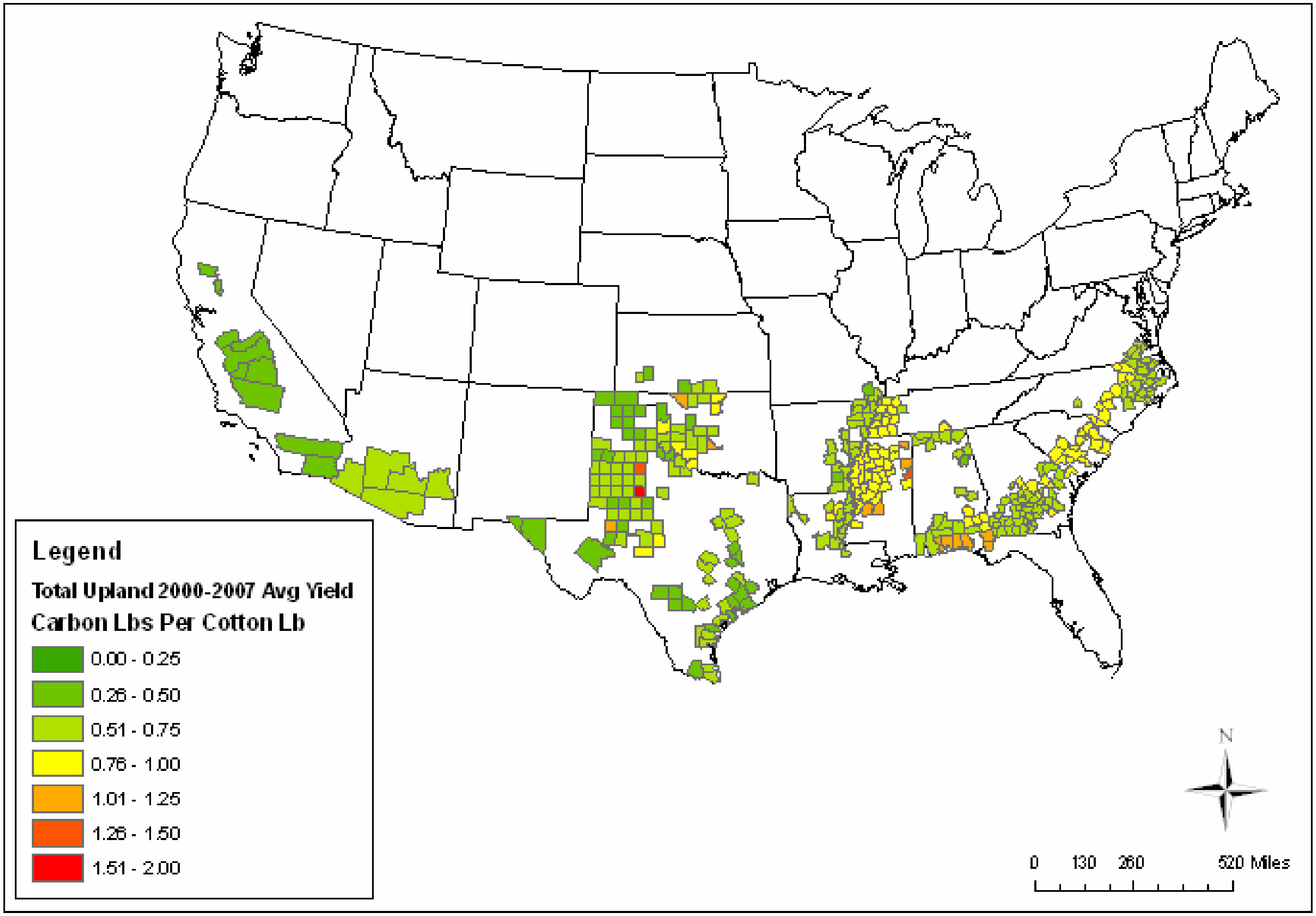


Figure 7: Carbon Emission from Cotton Production by County, Mean and 90% Confidence Levels

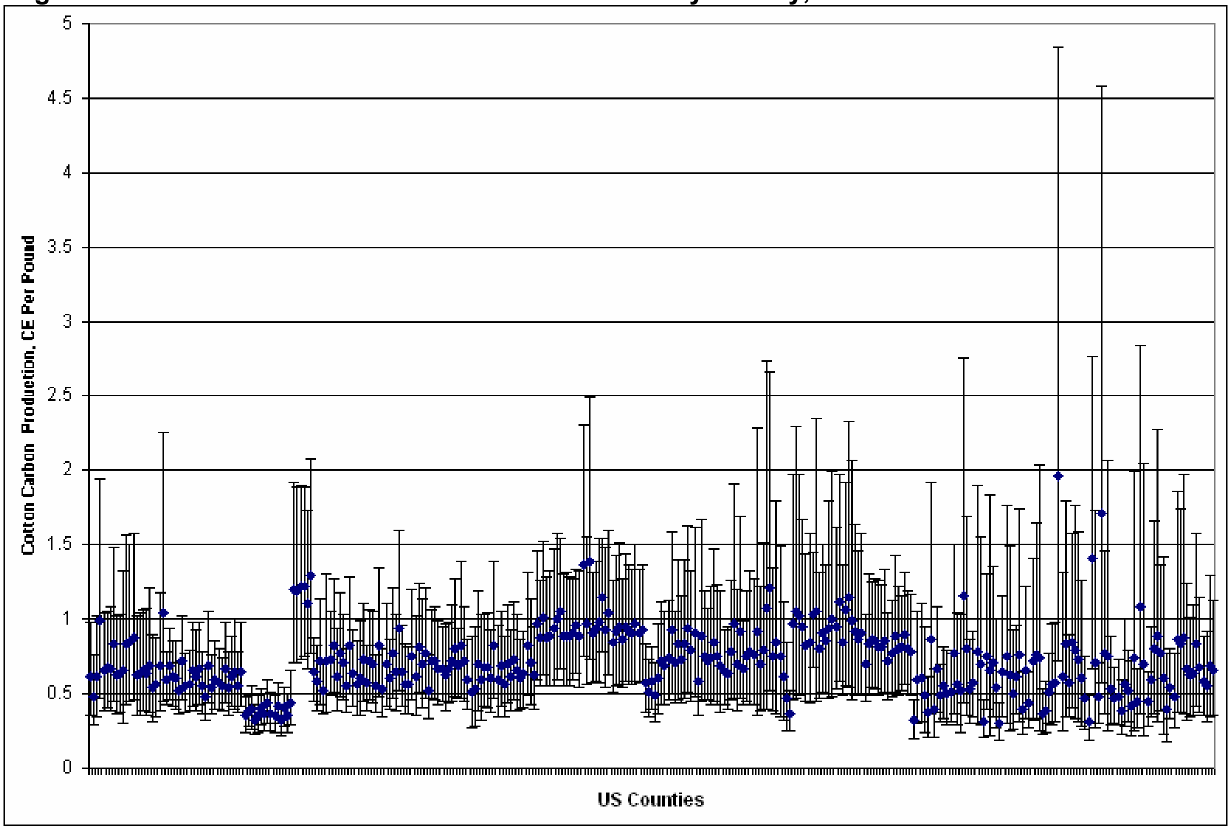
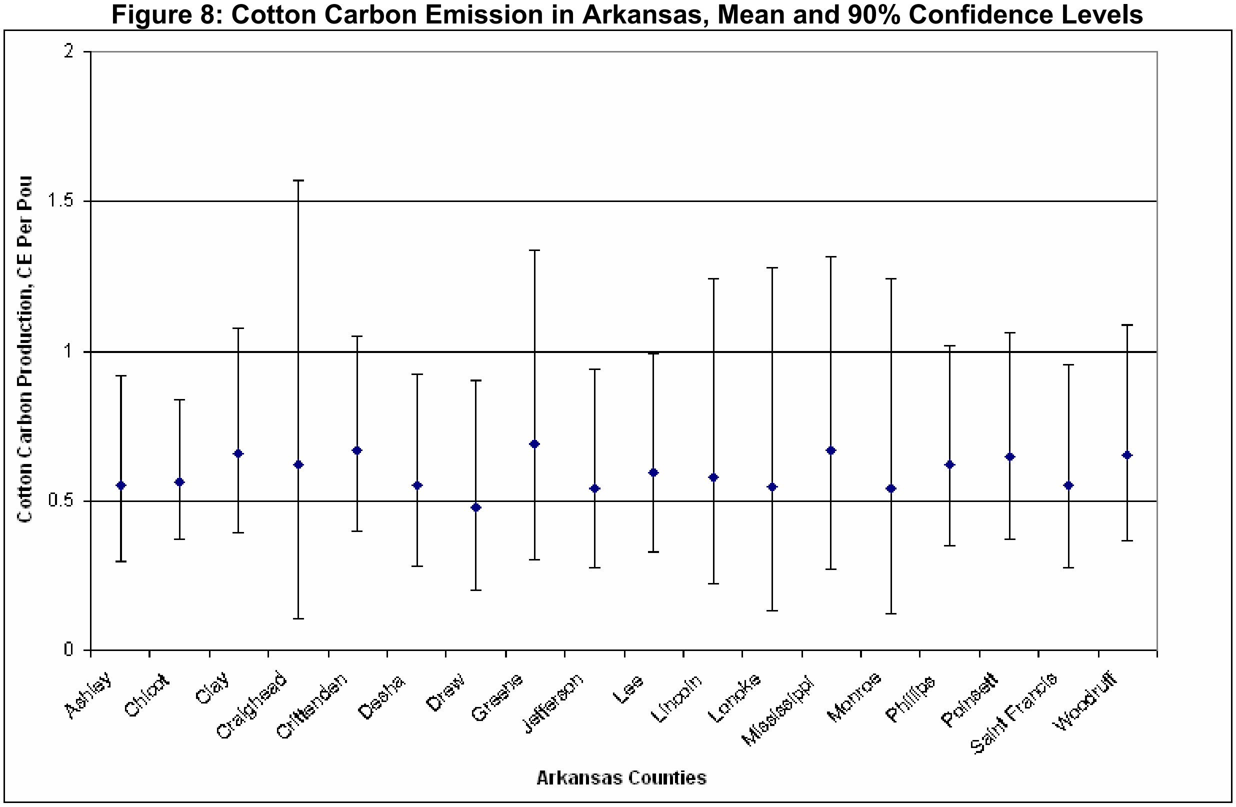


Figure 8: Cotton Carbon Emission in Arkansas, Mean and 90% Confidence Levels



Carbon by Production Method

We compared the CE per acre by each production method (Appendix A). Ideally we would have been able to compare CE per pound by production method, but because yield data is county specific and often there were multiple production practices within a county, our results are confounded. We can see that there is a wide variability in CE per acre (Figure 9). We further analyzed the data to estimate the contribution of each class of inputs, e.g. fertilizers, pesticides, and fuel (and in some cases fuel for tractors vs. fuel for irrigation). Some production methods were high input and typically high yielding. Others were low input and primarily low yielding. Further analysis with the LCI may distinguish where high input with lower yields, or lower inputs with higher yields, occurs. The variability or uncertainty in these numbers can be substantial (Figure 10). In most cases, fertilizers appear to contribute most to the CE. In areas with heavy irrigation, fuel and fertilizers vie for the largest factor. The variability for each of these inputs within each production practice can be large (Figures 11 - 14). Using these distributions, it becomes clear that there are significant differences across production practices with respect to the amount of inputs used and the carbon emissions related with that usage. While this analysis does not segregated practices to compare all similar practices with each other, for example all irrigated, Roundup Ready, strip till, and others, this sort of analysis is possible with this LCI. A more difficult task would be to assess the differences in production practices by carbon emissions per pound of cotton produced.

Figure 9: Total CE per Acre by Production Practice and Input

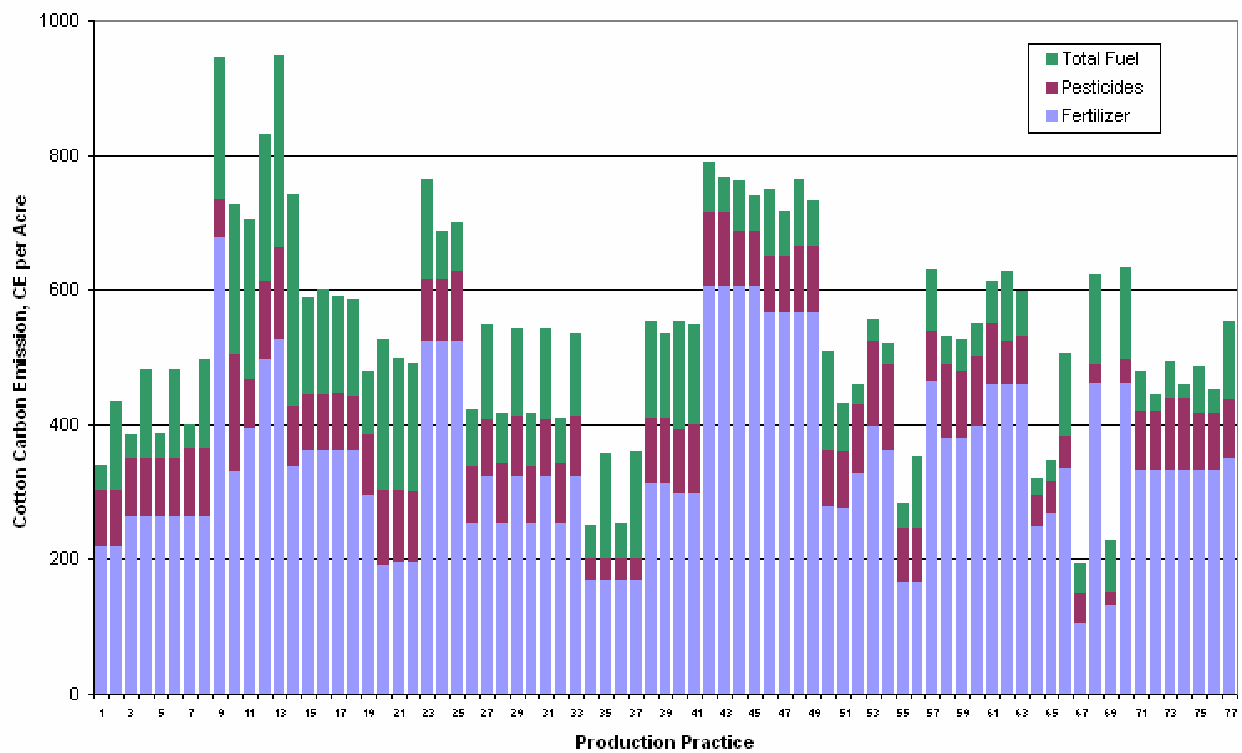


Figure 10: Distributions for Total CE per Acre by Production Practice, Mean and 90% Confidence Levels

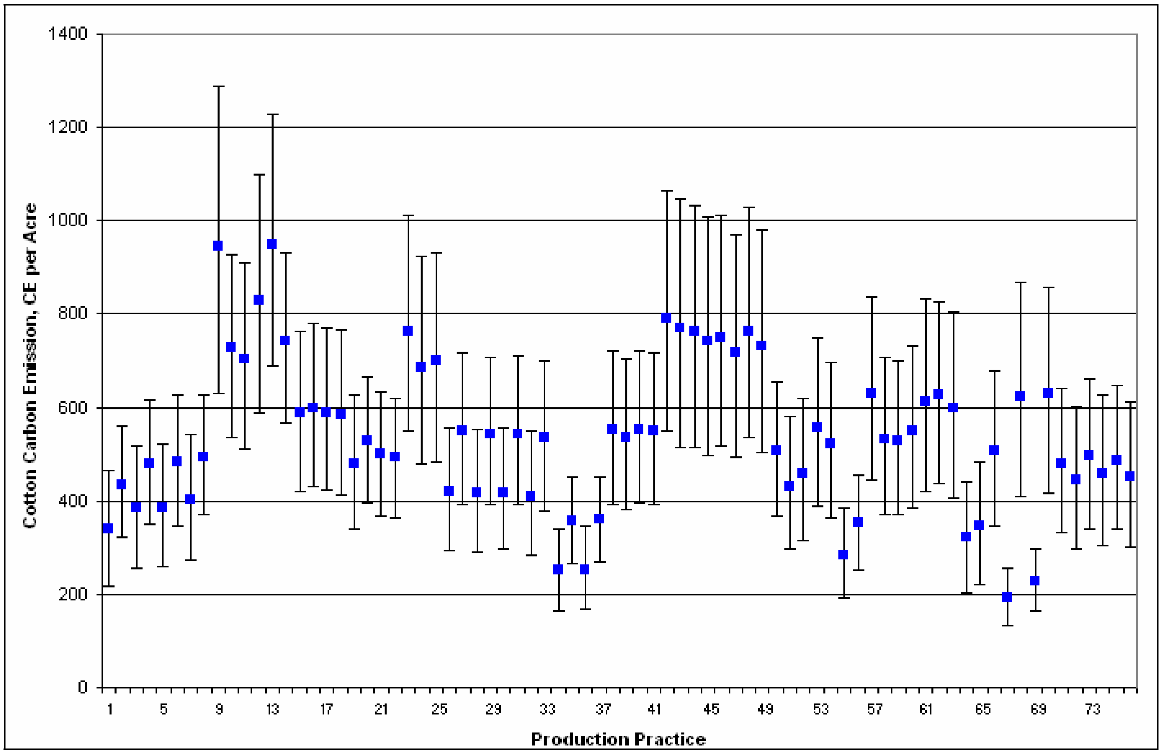


Figure 11: Distributions for CE per Acre from Fuel by Production Practice, Mean and 90% Confidence Levels

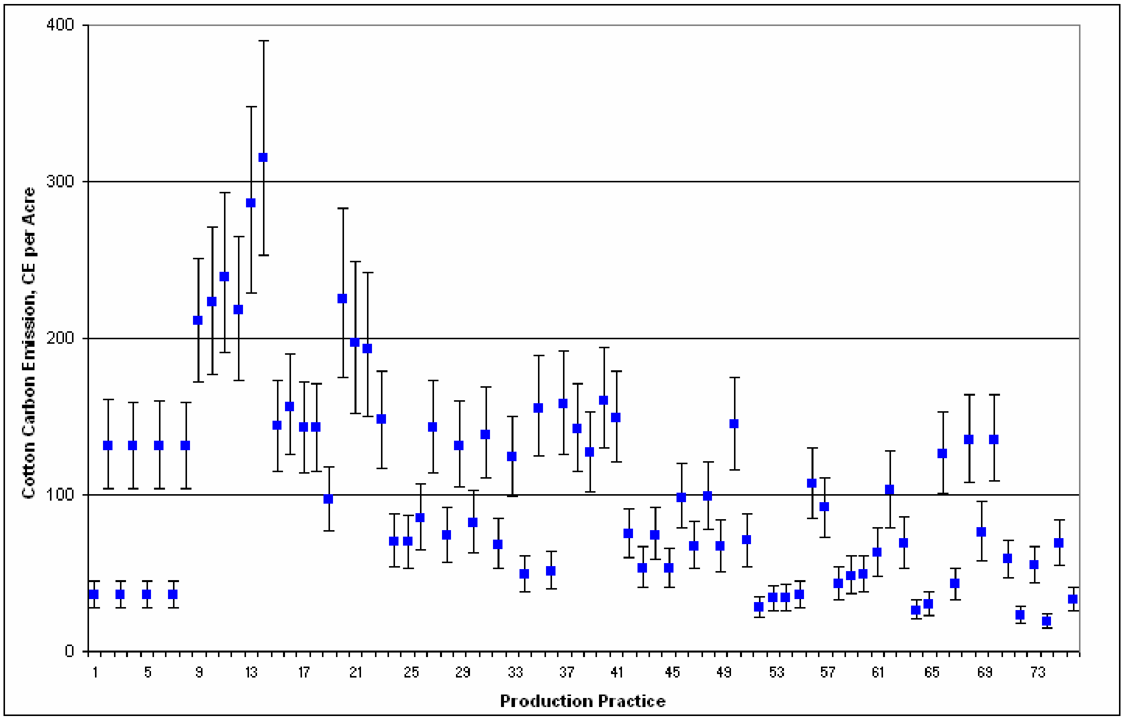


Figure 12: Distributions for CE per Acre from Pesticides by Production Practice, Mean and 90% Confidence Levels

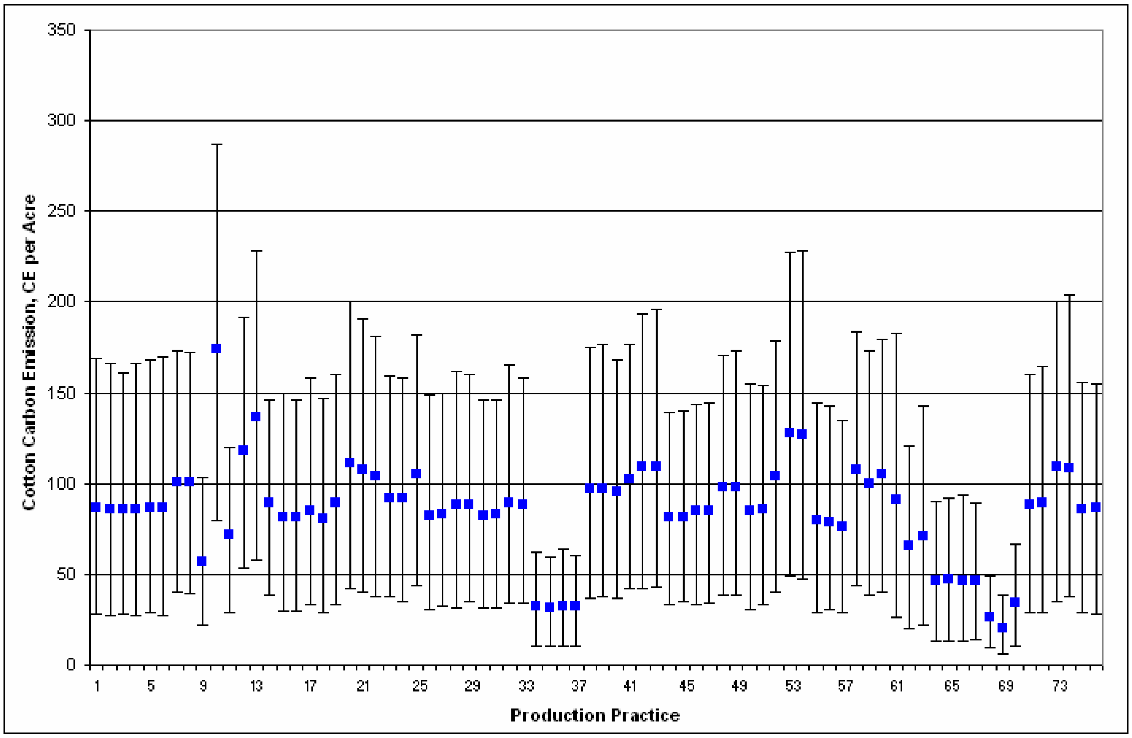


Figure 13: Distributions for CE per Acre from Fertilizer by Production Practice, Mean and 90% Confidence Levels

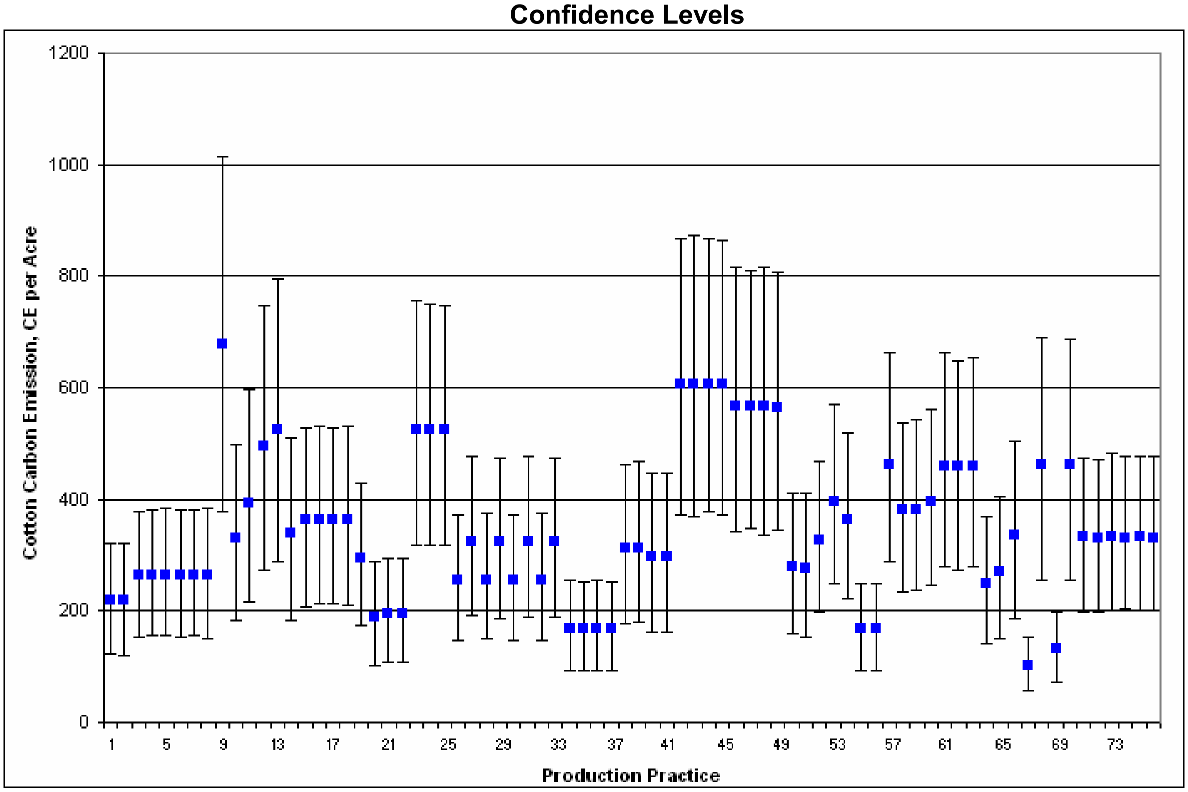
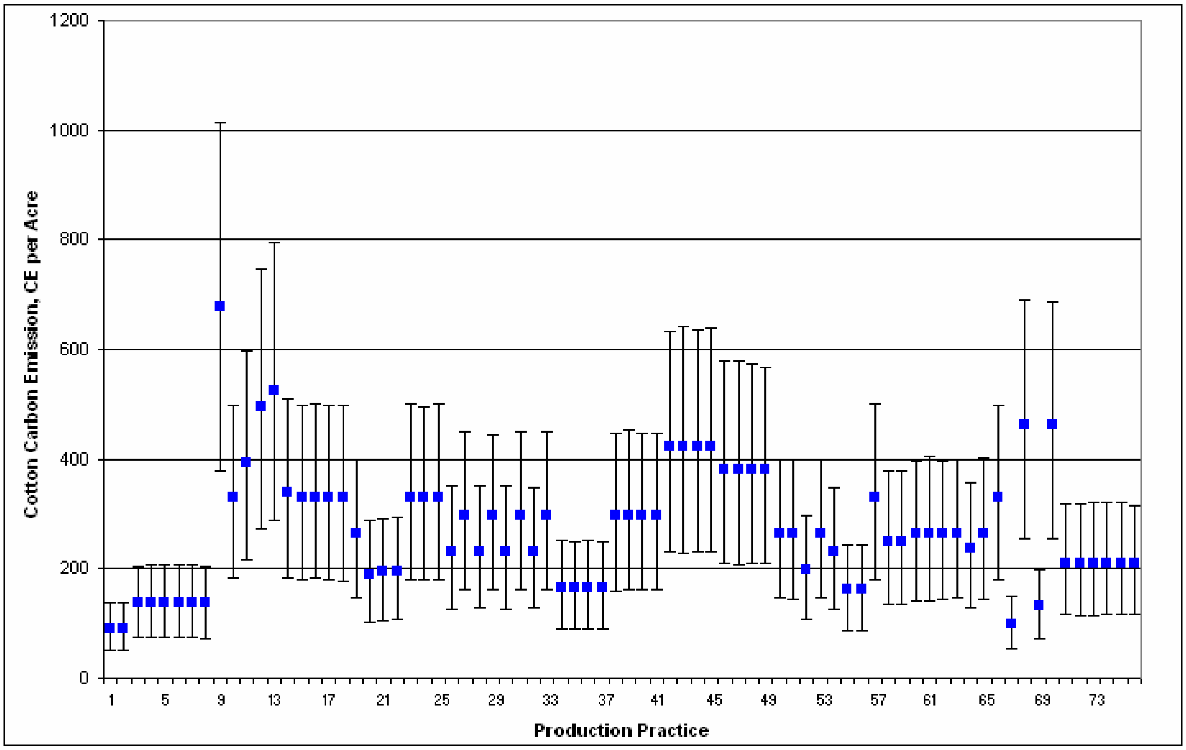


Figure 14: Distributions for CE per Acre from Nitrogen by Production Practice, Mean and 90% Confidence Levels



Analysis

There are significant differences across production practices. Some are clearly high input, while others are low input. Often the high input practices result in high yields, which ends up bringing the overall carbon emissions per pound close in line with the lower input and lower yielding production practices.

In looking at the differences between specific inputs, it is interesting to note that pesticides are fairly constant across all production practices, with the exception of several. Those exceptions are in Kansas and several practices in Texas, presumably due to the cooler temperatures, and hence lower pest pressure. While organic cotton may currently be a niche market, if demand increases, we may see increasing acreage in locations with lower pest pressure such as Kansas.

Fuel on the other hand has significant differences between production practices. Pumping for irrigation can use significant amounts of fuel. Therefore we can see major differences between dryland farming and irrigated farming. For example in Figure 11, we can see the difference in the first 8 production practices. These low numbers are dryland farming in Alabama, while the higher numbers are irrigated farming practices. The highest level of fuel use comes from those areas with the highest level of irrigation, Arizona (practices 9-14), which uses between 42” and 65” of water per year. Next highest is California (practices 20-22) which uses 30” per year on average. However, these two states have the highest production yield, which reduces their carbon emissions on a per-pound of cotton basis. Low-till and no-till options also typically reduce fuel usage, but they generally have much less impact on overall fuel use than the difference between irrigated and non-irrigated acreage.

Fertilizer in general causes the largest emissions of GHG from a life cycle perspective. Nitrogen is typically the major source of emissions within this category. This is due in part from the amount of energy required to produce nitrogen fertilizer (the energy required to produce nitrogen fertilizer is roughly five times as much as is required for phosphate or potash). In addition, nitrogen fertilizer application typically releases nitrous oxide emissions from the soil, adding to the overall total in GHG emissions. Arizona is the heaviest user of nitrogen fertilizer, applying between 100 and 200 pounds per acre per year, probably in part due to the heavy irrigation which may cause leaching of nutrients out of the soil. Mississippi (practices 42-49) is the second highest user of nitrogen fertilizer. Meanwhile, two non-irrigated practices in Texas (67 and 69) use the least amount of nitrogen fertilizer. High nitrogen application in Mississippi is the cause for higher carbon emission per acre and per pound of cotton than the neighboring states with roughly similar climates and yields.

Applications of the LCA

Life Cycle Analysis provides the ability to make both a comparative measure and predictive assessments. In this analysis, we looked only at comparative measures, however, in other studies we have looked at predictive outcomes. The above results provide a baseline for comparison. They allow us to look across counties and across production practices to see how inputs and yield by spatially specific production practices impact CE in production of cotton. They also provide us with a baseline for which to compare changes in production practices. Equally importantly, they provide a framework upon which to build future discussions, models and studies.

With further analysis, we may be able to discern which production practices are most efficient, with regard to greenhouse gas emissions. We may be able to estimate the differences in CE by tillage practice; conventional till versus reduced or no-till. We may be able to estimate the GHG differences between conventional vs. genetically engineered seeds. It may possible to estimate and compare across irrigated vs. non-irrigated production, or more specifically across the different methods of irrigation. This is currently possible given the existing data for those states for which yield data is broken out by irrigated and non-irrigated acres. Combining all we may be able to compare high input with medium or low input methods.

It has been shown that yield plays a major role in the CE per pound of cotton. Weather anomalies for example, drought, late frost or inopportune rains may severely impact yield in a given year. Therefore weather can play a major role in the CE. We have not attempted to capture the impacts of weather in this model. However, using yield data from multiple years, we have attempted to mitigate the weather effect. For example, compare the carbon emission per pound in Figure 15 and Figure 16. A much higher CE per pound in North and South Carolina counties using just 2007 yield was observed. This was likely due to a severe drought that negatively impacted yield in 2007.

Figure 15: Carbon Emissions from Cotton Production Using 2000-2007 Average Yields (Lbs C per Lb Cotton)

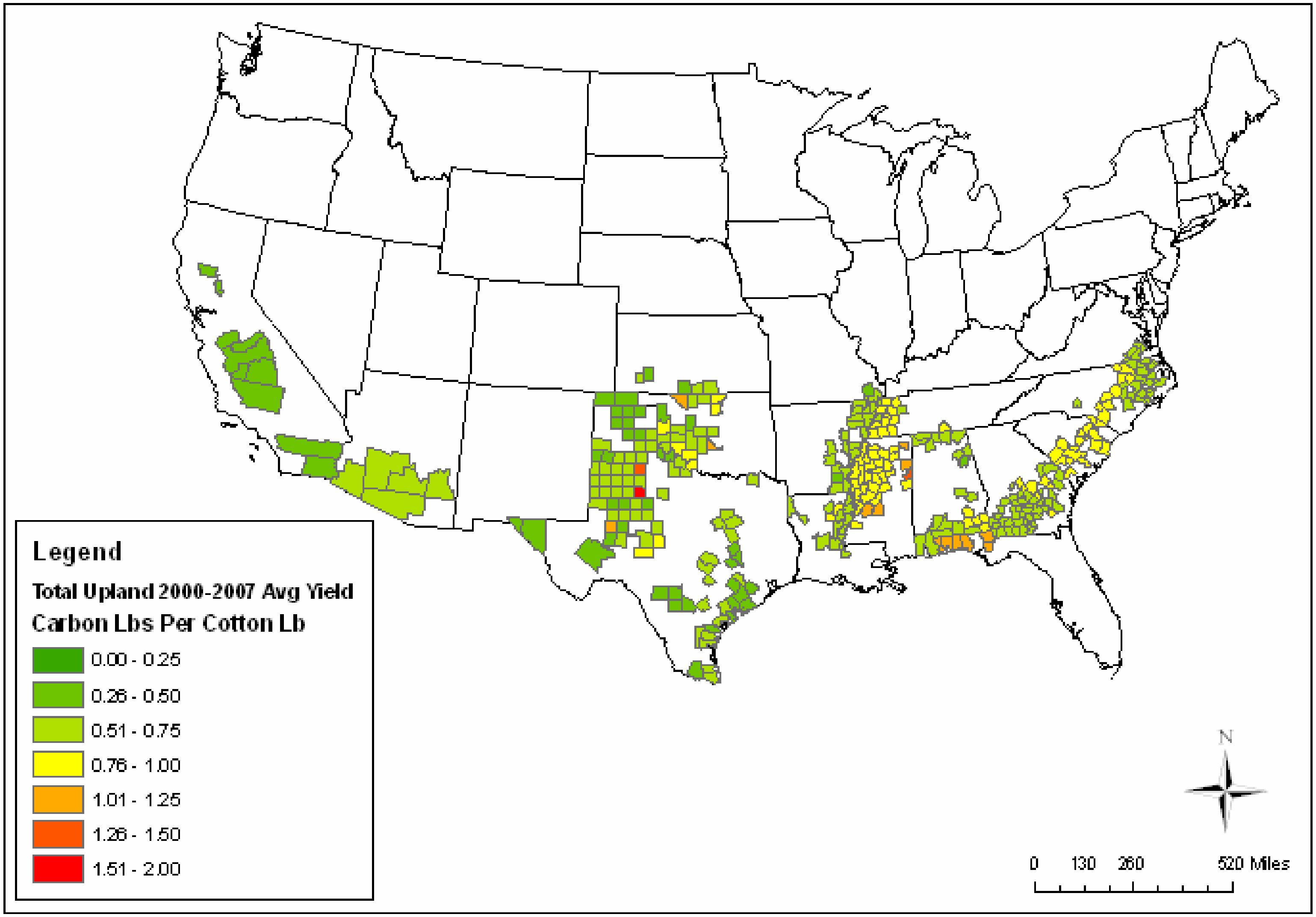
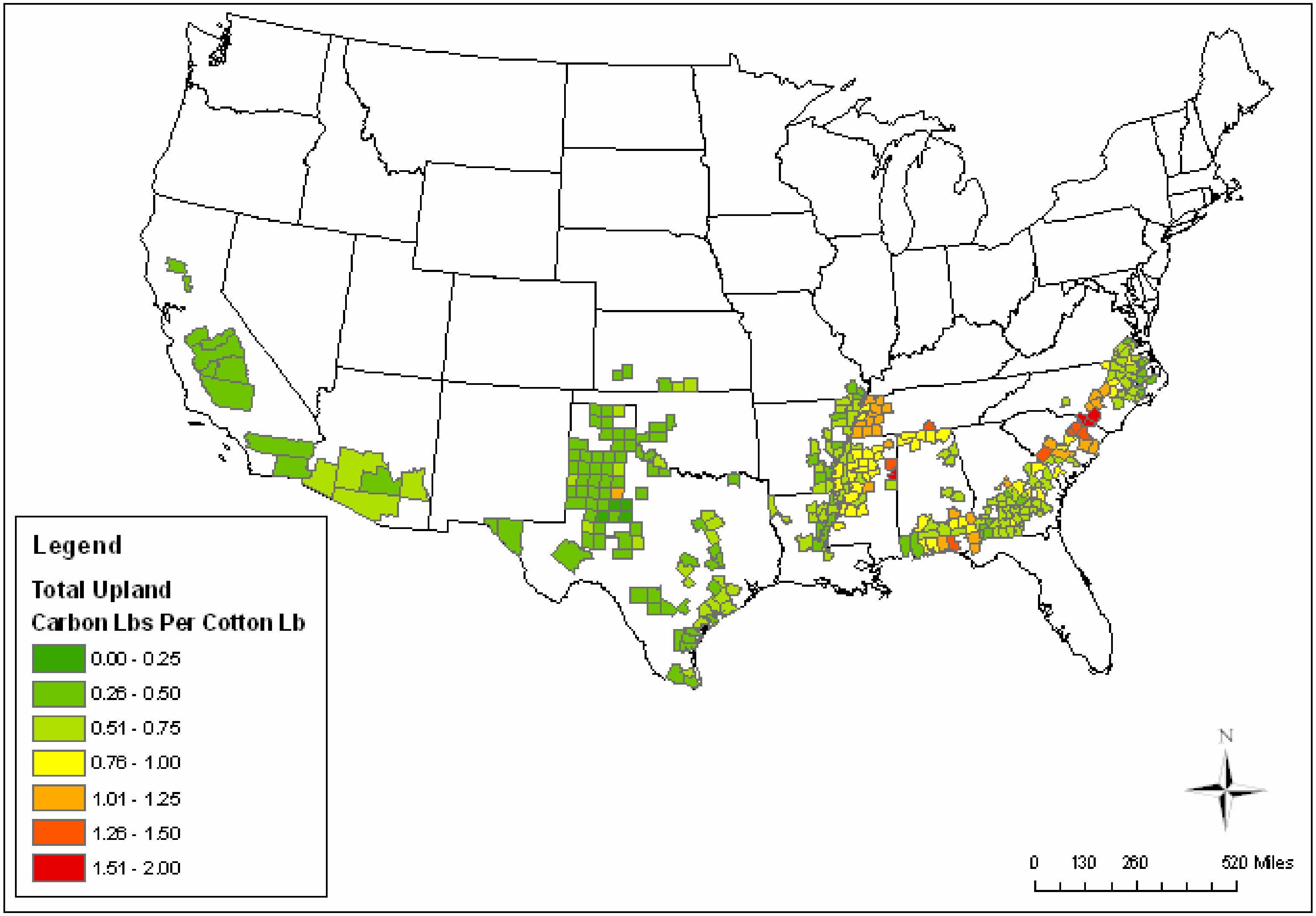


Figure 16: Carbon Emissions from Cotton Production Using 2007 Yield (Lbs C per Lb Cotton)



Carbon Market Impacts Analysis

The utility of the LCA to make predictions on future outcomes given new regulations or scenarios was examined. If we assume that there may be new regulations that limit the amount of carbon emitted, either through a tax, or a cap-and-trade system, we can use this data, along with other models to estimate the effects of such a policy on cropping decisions within specific counties.

Nalley et al. (forthcoming) created a partial equilibrium model for the state of Arkansas to estimate change in cropping decisions across all 75 counties for all major agricultural commodities produced in Arkansas when a carbon cap and trade policy is implemented. Assuming regulations requiring a state to reduce agricultural emissions by 10% or 20% from a 2007 baseline, we can see how producers and counties will alter their cropping patterns to meet this regulation. A county level profit maximization model was built to include input and output prices for all crops including hay and pasture land; CRP rates; and water, labor, fertilizer, agrochemical and other input usage rates.

A carbon footprint was calculated using this method for soy beans (dry, irrigated and double cropped), rice, wheat, cotton (dry and irrigated), corn and sorghum (dry and irrigated). These carbon emissions were based on a carbon per acre basis. The model maximized Arkansas' net returns based on 18 production methods for the crops mentioned above across 75 counties subject to several constraints. Preliminary results showed the change in pounds of carbon per county with a 20% overall reduction in carbon emission (Figure 17). Results also show dryland cotton acreage increases significantly (Figure 18). Overall we see a migration from corn and rice to dryland cotton and beans (Table 3).

Table 6: Predicted Change in Cropping Decisions in Arkansas Based on Carbon Cap-and-Trade Regulation, Requiring 10% and 20% Overall Reductions in State Agricultural Carbon Emissions

Acres	2008 Baseline	10% Reduction	Change from Baseline to 10%	20% Reduction	Change from Baseline to 20%
Corn	321,694	146,100	-55%	146,100	-55%
Dry Cotton	221,717	285,900	29%	328,164	48%
Irr Cotton	582,003	595,100	2%	591,893	2%
Wheat	1,011,763	987,563	-2%	961,329	-5%
Rice	1,550,869	1,486,308	-4%	1,266,200	-18%
Dry Beans	949,928	1,064,019	12%	1,090,128	15%
Irr Beans	1,680,637	1,872,401	11%	1,712,398	2%
State Net Returns	$1,460,945,628	$1,422,350,669	-3%	$1,296,255,109	-11%
Ac-In Water Use	84,419,709	82,873,777	-2%	73,058,641	-13%

Figure 17: Change in Pounds of Carbon Emissions from 2008 Baseline to 20% Reduction in Carbon

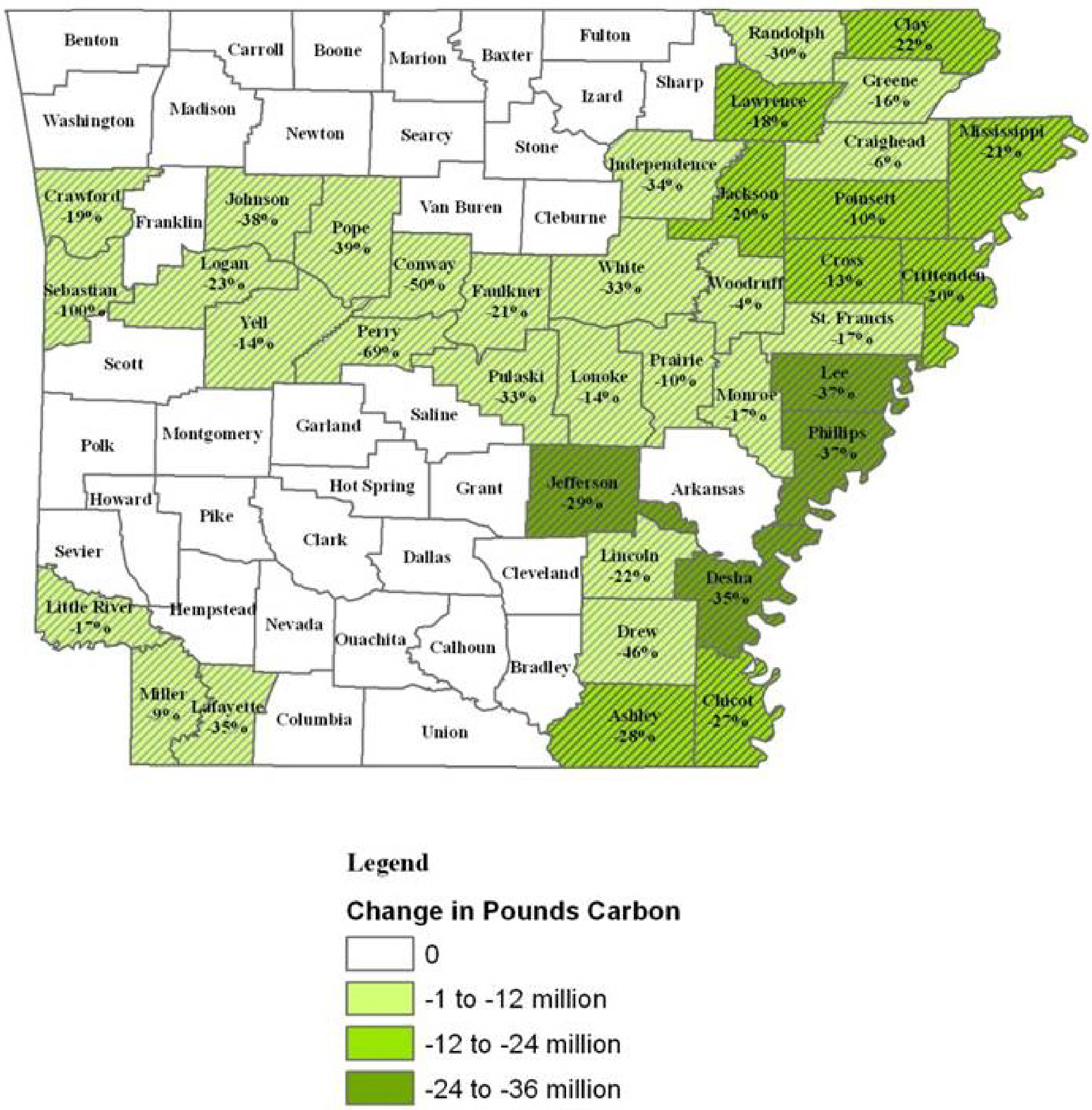
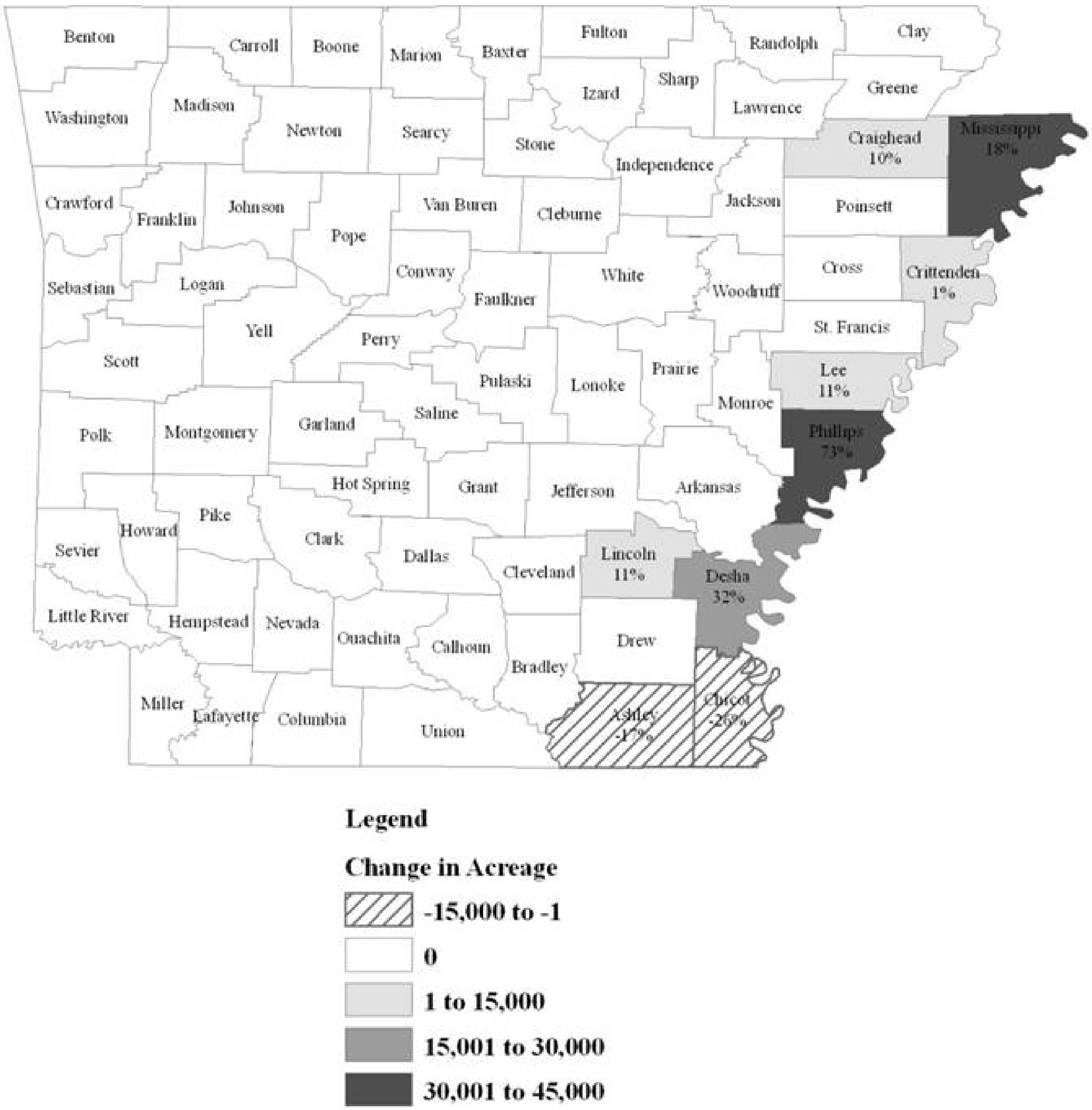


Figure 18: Change in Total Cotton Acres Planted - from 2008 Baseline to 20% Reduction in Carbon



Conclusions

The objective of this study was to estimate the amount of carbon-equivalent greenhouse gas emitted in the production of cotton. Using a cradle-to-gate Life Cycle Analysis, carbon was estimated for both direct and indirect emissions. Carbon emissions were estimated per acre as well as per pound of raw cotton. Results of this analysis showed the differences in emissions on a county by county basis, as well as by production practice.

Nitrogen fertilizer appears to play the largest role in GHG emissions due to the very high amounts of energy required in production. In addition, nitrogen applied to soil may be converted to nitrous oxide, a potent greenhouse gas. Fuel was generally the second largest source of GHG emissions. Pumping water for irrigation takes a significant amount of energy and so contributes significantly to GHG emissions. Dryland farming therefore used much less fuel than irrigated farming. Reduced tillage practices also generally lowered fuel use, although to a lesser extent than the impact of irrigation. Pesticides generally were consistent across all production practices.

Cotton yield, however, made the largest impact when looking at the carbon emissions per pound of cotton. High input production practices with high carbon emissions were mitigated when they produced high yields. Therefore, given the uncertainty in the data most counties, it was generally difficult to distinguish to a great extent the difference between overall carbon emissions per pound of cotton by county. Nevertheless there are clear differences between the most efficient and least efficient producers, with respect to carbon emitted per cotton produced. A similar conclusion would probably be made with regard to production practices; however, due to lack of data with respect to specific yields for specific production practices, the confounding data would not directly allow such a comparison.

Uncertainty in the data causes uncertainty in the results. Monte Carlo simulation was used to propagate uncertainty into the model to assess the uncertainty in the results. While yield data per county is variable from year to year, and within the county itself, the data itself is fairly reliable. Input data however may be less reliable. Cotton production budgets from state cotton specialists were used. However, it is unclear the level to which these recommendations, or rough guidelines are used. Production budgets were typically provided for a given year. However, with changing prices for both inputs such as fuel or fertilizer, as well as the price of cotton, as well as weather patterns, farmers may adhere closely, or not to the recommended guidelines. A national study can not easily move to this level of detail.

Fuel use for irrigation poses another significant level of uncertainty. Energy for pumping depends directly on the water depth and pumping head. In some areas depth to groundwater may be well over 100 feet, whereas other locations may use surface water with only minimal pumping required. It is a possible task if the data is available, using a geographic information system. At a national level study though, this becomes a difficult task.

A final level of uncertainty comes in the carbon emission factors. With regard to carbon emissions from inputs, there should be a fairly narrow band of certainty, given that a certain level of energy is required for production. What is much less certain is the level of emissions of soil N_2O from nitrogen fertilizer application. Soil N_2O emission is a fairly new research topic and so the literature is fairly limited. Research has shown that rates of emission vary widely based upon soil type, climate and weather, as well as amount and time of application. Some regions in the U.S. may have high levels of emissions, relative to level of application, whereas others may have much less. We used the same level of emissions across all regions, using a probability distribution function to capture this uncertainty. However, each region may have its own specific distribution functions. Because N_2O is such a potent greenhouse gas, and because it has a relatively large level of uncertainty, statistically significant differences in results become difficult to discern.

Further research and analysis into regional or more localized estimates of both irrigation energy and soil N_2O emissions could significantly reduce the uncertainty. In addition, further statistical analysis into the differences between production practices could provide meaningful results towards promoting those practices with the most efficient production, with regard to cotton produced per carbon emitted.

Finally, using the LCI and the GHG model, along with existing and new crop production and economic models, one could move beyond a comparative analysis towards predictive analyses. This could include cap-and-trade models or carbon tax models. Using a similar approach, one could predict changes in production patterns based on restrictions in energy use or water, due either to economic factors, or regulatory factors. In addition, one could use a Life Cycle Assessment to analyze changes due to weather patterns, for example wet or dry year simulations. This LCI could be used with similar models to simulate change cropping decisions based on the impacts of climate change on temperature and precipitation.

References

Lal, R. *Carbon Emission from Farm Operations* Environment International (30) 2004

Nalley et al. *Predicted Change in Cropping Decisions in Arkansas Based on Carbon Cap-and-Trade Regulation* Forthcoming

Snyder, C.S. et al. *Greenhouse Gas Emissions from Cropping Systems and the Influence of Fertilizer Management* International Plant Nutrition Institute, 2007

US Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), *QuickStats* USDA NASS, Washington, D.C. http://www.nass.usda.gov/QuickStats/index2.jsp

US Environmental Protection Agency. 2007. *Inventory of US Greenhouse Gas Emissions and Sinks*: 1990-2005. EPA 430-R-07-002. US EPA, 1200 Pennsylvania Ave., N.W. Washington, DC 20460.

Appendix

Table A-1: Production Practices

No.	ST	Input	Tillage[6]	Seed[7]	Water
1	AL	Reduced Tillage RR/BT North AL Non Irrigated	RT	RR/BT	Dry
2	AL	Reduced Tillage RR/BT North AL Irrigated	RT	RR/BT	Irr
3	AL	Reduced Tillage RR/BT Central AL Non Irrigated	RT	RR/BT	Dry
4	AL	Reduced Tillage RR/BT Central AL Irrigated	RT	RR/BT	Irr
5	AL	Reduced Tillage RR/BT South Alabama Non Irrigated	RT	RR/BT	Dry
6	AL	Reduced Tillage RR/BT South Alabama Irrigated	RT	RR/BT	Irr
7	AL	Reduced Tillage RR/Flex South and Central AL Non Irrigated	RT	RRFLEX	Dry
8	AL	Reduced Tillage RR/Flex South and Central AL Irrigated	RT	RRFLEX	Irr
9	AZ	Yuma County 1400 lb Yield Flood Irrigated Conventional tillage RR.	CT	RR	Irr
10	AZ	Pinal County 1400 lb Yield Flood Irrigated Conventional tillage RR.	CT	RR	Irr
11	AZ	Pima County 1400 lb Yield Flood Irrigated Conventional tillage RR.	CT	RR	Irr
12	AZ	Maricopa County 1200 lb Yield Flood Irrigated Conventional tillage RR.	CT	RR	Irr
13	AZ	La Paz County 1200 lb Yield Flood Irrigated Conventional tillage RR.	CT	RR	Irr
14	AZ	Graham County 900 lb Yield Flood Irrigated Conventional tillage RR.	CT	RR	Irr
15	AR	Furrow 12 Row RRFLEX (1144)	CT	RRFLEX	Irr
16	AR	Center Pivot 12 Row BG/RR(1145)	CT	BG/RR	Irr
17	AR	Center Pivot No Till 12 Row BGII/RRFlex (1149)	NT	BGII/RRFLEX	Irr
18	AR	Furrow Irrigated 12 row LL Conventional Till(1141)	CT	Liberty Link	Irr
19	AR	Dryland 8 row RR Conventional Till(1119)	CT	RR	Dry
20	CA	Pima Cotton Production San Joaquin Valley	CT	Pima	Irr
21	CA	Upland 30 in Cotton Production San Joaquin Valley	CT	RR	Irr
22	CA	Upland RR Cotton Production San Joaquin Valley	CT	RR	Irr
23	FL	BT/RR Strip Till Irrigated 12 Row	ST	BT/RR	Irr
24	FL	BT/RR Stirp Till DRYLAND 12 Row	ST	BT/RR	Dry
25	FL	RR Stirp Till DRYLAND 12 Row	ST	RR	Dry
26	GA	South & East Boll Guard BR Conventional Tillage Dryland	CT	BG/RR	Dry
27	GA	South & East Boll Guard BR Conventional Tillage Irrigated	CT	BG/RR	Irr
28	GA	South & East Boll Guard BR Strip Tillage Dryland	ST	BG/RR	Dry
29	GA	South & East Boll Guard BR Strip Tillage Irrigated	ST	BG/RR	Irr
30	GA	South & East Boll Guard Roundup Ready Conventional Tillage Dryland	CT	BG/RR	Dry
31	GA	South & East Boll Guard Roundup Ready Conventional Tillage Irrigated	CT	BG/RR	Irr
32	GA	South & East Boll Guard Roundup Ready Strip Tillage Dryland	ST	BG/RR	Dry
33	GA	South & East Boll Guard Roundup Ready Strip Tillage Irrigated	ST	BG/RR	Irr
34	KS	South Central and Southeast Kansas 500 lbs an acre Dryland	LT	RR	Dry

[6] Tillage Codes RT: Reduced Till; CT: Conventional Till; ST: Strip Till; NT: No Till; LT: Low Till;
[7] Seed Codes RR: Roundup Ready; BG: BollGuard; RRFLEX: Roundup Ready Flex; BT: Bacillus Thuringiensis

35	KS	South Central and Southeast Kansas 500 lbs an acre Irrigated	LT	RR	Irr
36	KS	Southwest Kansas 500 lbs an acre Dryland	NT	RR	Dry
37	KS	Southwest Kansas 500 lbs an acre Irrigated	NT	RR	Irr
38	LA	Red River and Central La. BGII/Flex	CT	BGII/RRFLEX	Irr
39	LA	Red River and Central La. BG/RR	CT	BG/RR	Irr
40	LA	Northeast La. BG/RR	CT	BG/RR	Irr
41	LA	Northeast La. BGII/Flex	CT	BGII/RRFLEX	Irr
42	MS	BGII/Flex RR Conservation Tillage 12 row Delta Area Irrigated	LT	BGII/RRFLEX	Irr
43	MS	BGII/Flex RR Conservation Tillage 12 row Delta Area Dryland	LT	BGII/RRFLEX	Dry
44	MS	Bt RR Conservation Tillage 12 row Delta Area Irrigated	LT	BT/RR	Irr
45	MS	Bt RR Conservation Tillage 12 row Delta Area Dryland	LT	BT/RR	Dry
46	MS	Bt RR Conservation Tillage Brown Loam Area 8 row Irrigated	LT	BT/RR	Irr
47	MS	Bt RR Conservation Tillage Brown Loam Area 8 row Dryland	LT	BT/RR	Dry
48	MS	BGII/Flex RR Conservation Tillage Brown Loam Area 8 row Irrigated	LT	BGII/RRFLEX	Irr
49	MS	BGII/Flex RR Conservation Tillage Brown Loam Area 8 row Dryland	LT	BGII/RRFLEX	Dry
50	MO	Center Pivot Irrigation BG II/RR Flex	CT	BGII/RRFLEX	Irr
51	MO	BGII/RR Flex DRYLAND	CT	BGII/RRFLEX	Dry
52	NC	Ultra Narrow Row	ST	RR	Dry
53	NC	RR conventional Till	CT	RR	Dry
54	NC	RR Strip Till	ST	RR	Dry
55	OK	Non Irrigated	LT	RR	Dry
56	OK	Irrigated	LT	RR	Irr
57	SC	Conventional Tillage IRRIGATED Center Pivot 1000 lb Yield	CT	RR	Irr
58	SC	RR 750 lb yield	CT	RR	Dry
59	SC	RR/BT Conventional 750 lb yield	CT	BT/RR	Dry
60	SC	RR/BT Strip Till 750 lb yield	ST	BT/RR	Dry
61	TN	RR Flex No Till 850 lb Yield	NT	RRFLEX	Dry
62	TN	RR Conventional Till 12 row 850 lb yield	CT	RR	Dry
63	TN	RR No Till 850 lb yield 12 row	NT	RR	Dry
64	TX	RR 12 Row ConvTill Dryland Upper Coastal 750 lb yield	CT	RR	Dry
65	TX	RR 12 Row Conv Till Dryland Lower Coastal 800 lb yield	CT	RR	Dry
66	TX	CRD 1 (N&S) and 2 (N&S) Irrigated	CT	BG/RR	Irr
67	TX	CRD 1 (N&S) and 2 (N&S) DRYLAND	CT	RR	Dry
68	TX	CRD 6 RR 12 Furrow Irrigated	CT	RR	Irr
69	TX	CRD 6 RR 40 inch DRYLAND skip row	CT	Conv	Dry
70	TX	CRD 6 RR 12 Furrow Irrigated PIMA	CT	RR	Irr
71	VA	Round Up Ready FLEX Strip Tillage 750lb Irrigated	ST	RRFLEX	Irr
72	VA	Round Up Ready FLEX Strip Tillage 750lb Dryland	ST	RRFLEX	Dry
73	VA	Round Up Ready Strip Tillage 750lb Irrigated	ST	RR	Irr
74	VA	Round Up Ready Strip Tillage 750lb Dryland	ST	RR	Dry
75	VA	Round Up Ready Conventional Tillage 750lb irrigated	CT	RR	Irr
76	VA	Round Up Ready Conventional Tillage 750lb Dryland	CT	RR	Dry