HOW POTENTIAL CARBON POLICIES COULD AFFECT COTTON LOCATION AND PRODUCTION PRACTICES IN THE UNITED STATES

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Abstract

This study conducts a life cycle assessment (LCA) for the carbon emissions and estimates the carbon sequestered in cotton production in the USA. Given the uncertainty regarding the type of future carbon legislation, this study presents a suite of estimates to analyze how potential carbon policies would affect cotton producers across the United States. From a cap-and-trade stand point the ratio of dollars of profit to pounds of carbon emitted per acre ($/lb of C) appears to be the driving factor in which areas will experience a loss/addition of cotton acreage. From a carbon-offset standpoint the estimates generated in this study do not indicate, even under high carbon prices, that an offset market will change tillage methods within an area. It would appear that if a carbon market did develop it would more likely affect where cotton is produced rather than affecting the tillage type.

Introduction

With the Waxman-Markey Bill passing the House and the administration's push to reduce carbon emissions, the likelihood of the implementation of some form of a carbon policy is increasing. In addition to government policy, many businesses are attempting to gain a "green" advantage by marketing products with smaller greenhouse gas (GHG) footprints. Agricultural and other raw materials production and processing industries are thus attempting to identify how to increase GHG efficiency. To that end, agricultural modeling efforts to date have focused either on global or national estimates on agriculture (Reilly, 2009; Outlaw et al., 2009; Beckman et al., 2009; McCarl, 2007), individual field test plots, or soil and climate based models that work at the field level (Century Model and DAYCENT models); the former lack detail at the local level while being representative and relevant at the macro level; while the latter prove too myopic as they typically lack the aggregation that will be needed to form policy.

The thrust of this analysis is to perform a life cycle assessment (LCA) for the carbon emissions and the carbon sequestered in cotton production in the USA. The analysis includes the five largest cotton-producing counties in the ten largest cotton-producing states in the USA. Further, the analysis quantifies the likely distribution of carbon footprint by production method and county by utilizing ranges of parameter responses expected for soil, tillage and plant growth parameters. County level detail can thus be tracked across the US to provide a detailed comparison of estimated carbon footprints across states and production practices for a comprehensive analysis of US cotton production. In addition, given the uncertainty regarding the type of future carbon legislation, this study presents a suite of estimates (emissions per acre, farm gate dollars per unit of carbon emitted, carbon sequestered per acre) to analyze how potential carbon policies would affect cotton producers across the United States in a relative sense. Analyzed are over 50 different production practices relevant in 59 counties across the US.

This study provides timely information about spatial and production practice related differences in GHG emissions and sequestration from cotton production. It is unique in that it analyzes the effects of a national carbon policy on county level production. In particular, differences of low/no-till and conventional tillage on carbon sequestration as well as the effects of a hypothetical carbon market on the relative profitability of competing tillage practices are analyzed. These issues are deemed important for producers, industry and policy analysts interested in potential ramifications of the two most widely discussed carbon policies, cap-and-trade, and carbon offset programs. This study thus sets out a framework for estimating the carbon footprint of cotton production and likely producer responses for improving net carbon emissions under varying incentive systems or a mandatory carbon reduction regulation.

Material and Methods

Life Cycle Analysis

A life-cycle assessment is a systematic, cradle-to-grave process that evaluates the environmental impacts of products, processes, and services. An LCA tracks a product's environmental impact from resource extraction through production, processing, transportation, use and disposal. Life cycle assessment examines the energy and other inputs it uses and the resulting pollution they create. The interpretation of an LCA helps to evaluate the processes and impact indicators and determines how to reduce environmental impacts. LCAs benefit producers, scientists, policy makers, and government agencies when alternative practices can be evaluated by addressing the environmental impact of the production of a good. LCA's are thus useful for determining environmental hot spots within a production system or for comparing the environmental impacts of two or more similar products or for comparing two or more production systems for the same product. For a carbon offset program in agriculture, LCA's are also useful for establishing a "baseline" carbon footprint by crop and production practice, such that future modifications in production practices can either be rewarded or discouraged on the basis of changing environmental impact by way of GHG emissions or sequestration.

The Carbon Life Cycle Analysis (LCA) put forth in this study includes both direct and indirect GHG emissions of cotton production in the United States. Direct emissions are those that come from farm operations. Examples are carbon dioxide (CO_2) emissions from the use of diesel by tractors and irrigation equipment and the use of gasoline by farm trucks as well as N_2O emissions from the application of nitrogen fertilizer. Indirect emissions are emissions generated off-farm as a result of the manufacturing of inputs used on the farm. Examples are GHG emissions from the use of natural gas and other energy sources in commercial fertilizer and agrochemical production.

Included in the LCA are GHG emissions of agricultural inputs involved in the production of cotton up to placement of a module at the side of the field (e.g. fertilizer, herbicides, pesticides, fuel, agricultural plastics and other chemicals). Excluded are emissions generated from ginning, transport or processing of cotton that occurs after the farm gate. Also excluded from this study are embedded carbon emissions because of upstream production of equipment and tools used on-farm for agricultural production.

Table 1. Carbon Equivalent Emission Factors.

Input (v_k)	Pounds of Carbon Equivalent Per Unit Of Input Used (CE_k)	Source
Fuel (gal.)		
Diesel	7.01	Sima Pro, 2009 EPA, 2007& 2009
Gasoline	6.48	Sima Pro, 2009, EPA, 2007&2009
Fertilizer (lb.)		
Nitrogen	1.30	Lal, R. 2004
Phosphorus	0.20	Lal, R. 2004
Potassium	0.16	Lal, R. 2004
Lime	0.06	Lal, R. 2004
N_2O emissions	1.27	IPCC 2007
Herbicide/Harvest Aid (pt. or lb.)	6.44	Lal, R. 2004
Insecticide/Fungicide (pt. or lb.)	5.44	Lal, R. 2004

Given the complexities in dealing with the estimation of GHG emissions (be it CO_2, N_2O or other GHGs) previously reported carbon equivalent (CE) emission factors were used to estimate the amount of emissions generated as a result of input use by production practice (Table 1). In essence, multiple GHG's associated with global warming, were converted to their carbon equivalents to obtain a "carbon footprint" – a process stemming from a rich engineering literature on carbon equivalence.

A carbon emission factor was used to estimate the quantity of carbon or carbon equivalent for each cotton production input. Values from the US Environmental Protection Agency were used for diesel and gasoline combustion emissions (EPA 2009). The LCI database ecoinvent 2.0 (Ecoinvent, 2009) as viewed in SimaPro 7.1 (Pre, 2009) was used to calculate the upstream emissions from the production of fuel. The emission factor for lime came from West and McBride (2005). All other inputs were from Lal (2004).

Nitrous oxide (N_20) from soil has been identified as a major contributor to greenhouse gas emissions from crop production (Bouwman, 1996; Del Grosso et al., 2006). While N_2O emissions vary extensively based on environmental conditions as well as timing of tillage and fertilization, method and form of N (Snyder et al., 2009), a conversion factor of 298 units CO_2 per unit N_2O (or 81 units CE) was used based on a 1 percent direct loss from nitrogen applied (IPCC, 2007). A process-based method for estimating N_2O such as DAYCENT (Del Grosso, 2006) would likely reduce N_2O emission uncertainty, but the data input with spatial resolution required for such an analysis were out of the scope of this study.

County Emission Data

Data were collected from five of the largest cotton producing counties in the ten largest cotton producing states in the United States, which included 59 counties in Alabama, Arkansas, California, Georgia, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas. Given its large role in the US cotton market, this analysis includes the top 15 counties in Texas compared to the five top counties in the other states. In addition, there are only four cotton-producing counties in Missouri and hence the total number of counties analyzed sums to 59 counties. Table 2 shows the summary statistics for the annual yield data for lint cotton collected for each county for the years 2000 to 2007 from National Agricultural Statistics Service (NASS) (2009). Weather anomalies including drought, early frost or early/late rains may severely affect yield and thus multiple years of data were included. This mitigates the impact of a single year's outcome to affect spatial comparisons and simultaneously allows for empirical risk analysis by analyzing a range of outcomes based on observed yields. To capture additional detail, county cotton acreage was disaggregated by irrigated and non-irrigated production practice where available.

To calculate the inputs used for specific production practices in each county and state, data were collected from the cotton cost of production budgets produced by university agricultural extension specialists specific to the spatially diverse growing conditions (climatic and agronomic) within a state. Further, county level agricultural extension agents were contacted for every county in the study to determine which production practices (e.g. tillage type and irrigation method by soil type) were most prevalent in each county. The budgets included the following inputs: fuel (diesel and gas), irrigation water applied, fertilizers, herbicides, insecticides, and other agrochemicals such as fumigants, defoliants and growth regulators. From these extension recommendations, input amounts by production practice and their associated carbon equivalents were summed for one acre to obtain a carbon footprint per acre by production practice.

NASS reports the number of acres under irrigation for most states, while university extension budgets provide the recommended acre-inches applied by county. Again, regional extension agents provided their best judgment for the percentage of irrigated land in each county that used center pivot, drip, flood, or furrow irrigation techniques. Energy for irrigation is location-specific based on pumping depths and power sources. Given the variance of groundwater depth within a county this variability could not feasibly be accounted for. Where not specifically provided in the budgets, diesel required to deliver one acre inch of water to the field was thus estimated from Arkansas, Louisiana and Mississippi cost of production budgets and applied to all irrigated acre estimates of fuel use per acre inch applied.

This study complied with ISO 14040 (2006) standards of one percent impact threshold for inclusion of inputs and thus did not include the embedded carbon (i.e. carbon emitted upstream in the production) of the tractors and other equipment used in the production of cotton. This study did not allocate any of the emissions to cottonseed, although cottonseed is a secondary product that does have economic value as animal feed or oil, since GHG embodied in lint was the purpose of the analysis.

Carbon Efficiency and Probabilistic Inputs

The weighted average carbon footprint by county in terms of lbs of CE per lb of cotton lint produced was estimated by dividing carbon per harvested acre by yield per acre. Total carbon emission per acre simply indicates the amount of GHG emitted and not the efficiency of or benefit derived from each unit of GHG. By dividing the total GHG by the mass of cotton harvested on each acre an efficiency measure per unit of cotton was established.

Quantifying variability and uncertainty for this analysis was performed using Monte Carlo simulation with the Microsoft Excel add-in program @Risk (Palisade, 2009). Distributions were assigned by production experts for input data based on characteristics of the data collected. A uniform distribution with an upper and lower boundary was applied where the probable value varied equally across the range; a triangular distribution was used when some central tendency existed between upper and lower boundaries. When more than five observations were available a truncated normal or lognormal distribution was estimated from the observations, with truncation using maximum and minimum values as a percentage of the mean value. Variability across all 52 production practices was thus calculated and included distribution functions for yield, fertilizer, fuel and chemical use. Distributions were also created for each major input (e.g. fertilizer, pesticides and fuel) within a production practice.

Specifically, then, carbon equivalent emissions per acre of production was calculated for each production method and county as follows:

(1) $$E_{in} = \sum_k v_k \cdot CE_k$$

where E_{in} are carbon equivalent emissions per acre in county i for production practice n, v_k are input quantities of k inputs used in production per acre like fuel and fertilizer, and CE_k are the carbon equivalent emissions per unit of input v.

Carbon Sequestration Calculations

Using a methodology similar to Prince et al. (2001), pounds of carbon sequestered from above ground biomass (ABG) per acre in county i under tillage method t was estimated as follows:

(2) $$AGB_{it} = \left[(Y_i \cdot \lambda) \cdot \left(\frac{1}{H} - 1 \right) \cdot \beta \ \cdot \delta_t \cdot \eta_t \right]$$

where Y_i are county level lint yields in conventionally reported units per acre for cotton, λ converts said yield to lbs per acre by assigning an average 2.625 ratio of lint to total seed plus lint weight at negligible moisture content, H is the harvest index (boll to total above ground biomass ratio by weight), β is the estimated carbon content of above ground biomass and δ_t is the estimated amount of above ground biomass incorporated in the soil that depends on the chosen tillage method t and η_t is the estimated fraction of plant residue in soil contact that is sequestered in the soil, again dependent on tillage. Note that only stems and leaves are thus considered above ground residue that is not harvested and hence left on the field in this study.

Pounds of carbon sequestered from below ground biomass (BGB) per acre for cotton in county i under tillage method t was estimated as follows:

(3) $$BGB_{it} = \left[\chi \cdot \eta_t \cdot \left(\frac{\phi \ \cdot [Y_i \cdot \lambda]}{H} \right) \right]$$

where χ is the carbon content of below ground biomass and Φ is the root to shoot ratio with the other variables as defined above.

Both above and below ground biomass carbon sequestration is multiplied by a soil factor ξ_{is}, an acreage weighted estimate by county, that adjusts soil carbon sequestration potential based on soil texture. Thus total carbon sequestration S_{its} per acre for cotton in county i under tillage method t and soil texture s can be estimated by:

(4) $$S_{its} = \left(ABG_{it} + BGB_{it} \right) \cdot \xi_{is}$$

Harvest indices and root to shoot ratios are reported in Table 3. Estimates of the carbon contents of above and below ground biomass were taken from Pinter et. al (1994) at 42 and 41%, respectively. Crop residue soil incorporation factors and below ground biomass sequestration factors by tillage method are reported in Table 3. Soil factor adjustments for clayey, loamy and sandy soils are reported in Table 3.

Harvest Index

The harvest index was used to determine the amount of biomass remaining on the field post-harvest. Since harvest index values can vary significantly by seed variety, planting season, production practice, and location, the model used an average value reported from the literature and from county agents for each state as cited in Table 3. The study averages reported in Table 3 also contain added variation based on the range of data reported in the literature and from expert opinion from state extension agents. The use of the harvest index was necessary to adjust biomass production by lint yield across space given available yield information as described in Table 2. Harvested lint, which is 42% carbon, is not modeled to contribute to carbon sequestration in this methodology even though ultimate use of cotton may lead to products that could trap carbon to a similar extent as soil. The use pattern (long term storage and reuse) along with its high C:N ratio when lint reaches the end of useful life, could result in carbon trapping superior to soil. With regards to carbon sequestration of harvested products, cotton is unlike food or feed crops because its intended commercial use does not return the embedded C to the atmosphere. The use pattern (long term storage and reuse) along with its high C:N ratio when lint reaches the end of useful life, could result in carbon trapping superior to soil. With regards to carbon sequestration of harvested products, cotton is unlike food or feed crops because its intended commercial use does not return the embedded C to the atmosphere.

Root to Shoot Ratio

The root to shoot ratio was used to determine yield dependent below ground biomass production. Since root material and above ground biomass have slightly different carbon content they are modeled separately. Again, root to shoot ratios reported in the literature vary considerably, hence a range of estimate was modeled in this analysis using a triangular distribution.

Tillage Effects

It is well known that plant growth and productivity are greatly affected by agronomic practices. Tillage is a common agronomic practice used to prepare a seedbed for planting and managing crop residues. Tillage affects water infiltration into, storage within, and movement through a soil profile. Tillage also affects soil compaction with direct effects on plant establishment and above- and belowground biomass production. Crop residues, often considered a hindrance to establishing a crop, are a prime source of organic matter and nutrients that maintain a soil's natural level of fertility. Tillage provides a mechanism to break down and physically mix crop residue with the soil and breaks down roots already in the soil. This enhances the interaction of plant residues with soil microorganisms that mineralize the organic matter and recycle essential nutrients from the plant residue for use by subsequent crops. Since soils can only accept a fixed amount of carbon (C), a portion of the more readily obtainable C from cellulose and hemi-cellulose is respired back to the atmosphere as carbon dioxide (CO_2), while lignin, a more resistant source of C in the plant residue, remains in the soil as humus. To summarize, tillage increases the potential for soil erosion, incorporates residue, and stimulates microbial activity with attendant increases in soil respiration and loss of CO_2 decreasing the amount of C that can be sequestered in the soil. With soil erosion a detriment to long-term sustainability, producers have adopted less tillage to mitigate soil loss at the potential cost of reduced short-term nutrient recycling from the lack of residue incorporation.

To model the above effects, conventional tillage was assigned as leaving 30 % of the residue and its C at the soil surface with the remainder mixed into the soil for potential C sequestration (Table 3). At the other extreme, no-tillage production leaves nearly all residue at the soil surface although machinery traffic is expected to incorporate approximatley10% into the soil. Some producers have adopted an intermediate level of tillage referred to here as low-tillage and is defined as leaving 60 % of the residue above-ground and mixing 40 % into the soil.

Once incorporated in the soil, however, not all of the C contained in the above ground residue and roots can be considered sequestered. Since many types of crop residues contain approximately 50 % of lignin (Sylvia et al., 2005), it is the fraction of residue that remains in the soil once the microbes have been able to mineralize the more readily available C fractions that are eventually respired as CO_2 to the atmosphere. Thus, in the absence of tillage, approximately 50 % of the C from plant residue below ground is potentially sequestered in a no-tillage setting

(Table 3). However, when the belowground root biomass is disturbed due to tillage and the incorporated aboveground residue is mixed into the soil and becomes readily available for microbial oxidation, there will be some additional loss of C from elevated microbial activity, hence C sequestration potential was conservatively assigned to be 45 and 40% for low-tillage and conventional tillage.

A complicating factor is that there is no consensus in the soils and agronomic literature as to the true affects of tillage on soil C sequestration due to the issues of sampling depth (VandenBygaart et al., 2003; Baker et al., 2007; Needelman et al., 1999) and time (Hansmeyer et al., 1997; Angers and Eriksen-Hammel, 2008). In general, most long-term C sequestration studies usually show the most dramatic changes in C content in the top 6 to 12 inches of the soil profile, which is the layer directly affected by tillage. However, C can move to lower soil layers over time and that would maintain a soil's C sequestration potential for some time in the future. In addition to the issues of sampling depth and time, soil C sequestration is also highly dependent on the initial C content of the soil. Soils with a relatively low initial C content generally have a greater potential to store more C than do soils with a relatively high initial C content (VandenBygaart et al., 2003). Considering the long history of cultivated agriculture throughout most of the Southern United States, the soils of the row-cropped acreage are expected to have relatively low initial C contents. Therefore, it stands to reason that the soil C sequestration potential (annual accumulations of C in the soil) may not be exhausted for decades on crop land due to the generally low soil organic matter and C contents (Brye, 2009). The latter statement makes an annual, static model, a reasonable framework, albeit a simplification of true C accumulation.

Soil Texture Effects

The effects of tillage on soil C sequestration and soil C sequestration itself are both affected by soil texture (i.e., the relative mixture of sand, silt, and clay that makes up a soil). Once tillage practice has been accounted for in the model, the effect of texture on soil C sequestration is addressed. Soil texture affects soil aggregation, which in turn affects soil water content and the degree to which the soil water content fluctuates. In general, frequent wet and dry fluctuations will enhance the breakdown of soil organic matter by physical, chemical, and biological means. In other words, a soil that holds water longer will generally experience less frequent and less intense wetting and drying cycles. This occurs more with fine-textured (i.e., clayey) soils. Therefore, once the model has estimated the amount of C that can be potentially sequestered after accounting for tillage effects, the effect of soil texture is accounted for by assuming that there is only an average of 5% additional C loss from the soil if the soil texture is clayey (Table 3). However, as the soil texture gets more coarse (i.e., loamy or sandy), the frequency and intensity of wetting and drying cycles will generally increase microbial activity to promote C respiration in the form of CO_2. Thus, the amount of potentially sequesterable soil C is farther reduced by 30 and 60 % for a loamy and sandy soil, respectively (Table 3). These reduction factors due to soil texture match the general relationship between soil texture and soil C content, whereby soil C content tends to increase from coarse- to medium- to fine-textured soils for a variety of reasons (Parton et al., 1987; Burke et al., 1989).

Results

Table 2 presents the results of the average carbon emissions per acre for each of the 59 counties in the study. The average carbon emissions are the sum of the weighted average for each of the production methods used in a specific county. Comparison of CE per acre across all 52 production methods indicated that across most methods, fertilizers were the highest contributors to total cotton carbon emissions, particularly when including N_2O emissions from N-fertilizer application (Figure 1). Nitrogen generally plays the largest role due to its energy intensive production, its heavy use, and the potency of N_2O released from its application. Lime use in the Southeast also had a sizeable impact given the high application rates in some states (namely Mississippi). In areas such as California with heavy irrigation, diesel for pumping made a large relative contribution. On average California irrigated 31.5 acre inches per year whereas Arkansas, for example, applies an average of 10.5 acre inches annually (9 for center pivot and 12 for furrow irrigated).

Emissions per Acre and Pounds of Lint/Pound of Carbon

There were significant differences across states as well as differences across regions within states (namely Texas given its large size). Some production methods and regions (center pivot, conventional tillage, etc.) were highly input intensive and in the case of center pivot irrigation typically high yielding. Others (dryland and low-till) were not as input intensive, and often lower yielding, dryland production in particular. Table 4 presents the county level average carbon emissions per lb of lint produced, which is a direct measure of GHG use efficiency that can be used on a comparative basis across time and space. As inputs remain constant and yield increases, carbon per lb of lint decreases, a direct measure of increased production efficiency. While California had high levels of inputs it also produced a relatively high yield, and so CE per lb of lint was much closer to the mean of other states which have lower inputs (e.g. dryland production). Counties in North Carolina typically had a low lbs of carbon / lbs of lint ratio even though their yield was relatively lower than the rest of the country (the nationwide average in this study was 815 lbs cotton/acre and the average in N. Carolina was 731 lbs/acre). This can be attributed to the fact that nearly all cotton acres in North Carolina are dryland, which reduces their carbon emissions per acre (national average in this study was 380 lbs CE /acre and N. Carolina averaged 318 lbs. /acre). Conversely, a state like Mississippi that has higher than average yield (883 lbs/acre) has a higher than average lbs of carbon/lbs of lint ratio or lower carbon efficiency because of above average emissions per acre (535 lbs/acre). So, improvements to carbon use efficiency can either be sought through increased yield per unit of input or reduced input per pound of cotton produced.

Sequestration and Net Emissions Per Acre

Table 4 presents all counties by their weighted average pounds of carbon sequestered per acre. While this study directly compares sequestration across counties, it is important to note that there are numerous factors that go into carbon emissions and sequestration, such as soil fertility and climate, and hence yield. Therefore, when comparing across counties one needs to be careful when making broad statements about environmental impacts of cotton production. One needs to look at what decisions are endogenous and which are exogenous. California for instance has some of the highest carbon emissions per acre due mainly to their high levels of irrigation and nitrogen fertilizer application (endogenous decisions made by the producer). However; given the fact that California has a relatively good production climate and clay soils (exogenous factors) all of the counties in California are estimated to be net sequesterers (Table 5).

Solely comparing across counties on carbon emissions per acre does not take into account the physical amount of lint and seed produced, or the amount of carbon that is sequestered by production, and therefore, it may not be appropriate to compare different states, regions or counties by their carbon emissions per acre. That is, you can change production practices to improve your carbon emissions but you cannot change soil types and climate, which are two large factors in the amount of carbon sequestered. That being said, carbon per acre, and hence total carbon emitted is an important issue when talking about a potential cap-and-trade policy analysis.

Table 4 presents the net (emissions – sequestration) carbon footprint by county. Of the 59 counties in the study, only 14 (24%) were net emitters of carbon on average, with 7 of those located in Mississippi and Georgia. Mississippi production budgets provided by Mississippi State University recommend 1,000 lbs of lime per year. This recommendation is what is causing the large difference between its emissions and the other Delta (Arkansas, Tennessee, and Louisiana) cotton producing states. When the lime recommendation is removed the Mississippi emissions average decreases by 60lbs/acre (1000 lbs times 0.06 of CE/lb of lime), which places Mississippi in line with the other Delta States emissions per acre average. Even those counties, which were net emitters only averaged emitting 105 lbs CE/acre. (To put that in to context, 105 lbs of CE emissions are comparable to using 15 gallons of diesel fuel). One of the main reasons the Georgia counties proved to be net emitters is the soil composition in South Georgia, which is a sandy and loamy mix. Because sandy and sandy/loam soils are relatively coarse, the frequency and intensity of wetting and drying cycles increases microbial activity to promote C respiration in the form of CO_2, which reduces sequestration potential. Net emissions are driven by both the amount of emissions per acre (a function of inputs) as well as the amount of sequestration per acre (a function of endogenous and exogenous factors such as tillage and soil type, respectively). California had the highest levels of net sequestration with an average of 583 lbs/acre. This would indicate that on average the five California counties in this study would reduce the CE in the atmosphere by 583 lbs for each acre of cotton they produce per year, thus sequestering more carbon than they emit. So, although California had a relatively high emissions rate per acre it has favorable conditions for sequestration given high yields or biomass that capture carbon. Figure 2a illustrates the high variability within a state in regard to a state being considered a net emitter or net sequesterer. Only California can be assumed to be a net sequesterer and only Mississippi can be assumed to be a net emitter. The range of carbon footprint within a county is less, compared to the nation, which would indicate that if gins sourced cotton from specific counties or, more specifically, dictated production practice to minimize footprint within a county, they would have more confidence in labeling a bale of cotton as "carbon neutral" to the gin than they if they sourced cotton from producers across multiple counties. Information such as this could be valuable as consumers are becoming more aware of and increasing their demand for "environmentally friendly" products.

Economic Comparisons

While some factors affecting sequestration in cotton production are exogenous like soil type, producers do have methods, mainly through tillage, to increase the quantity of carbon sequestered in the soil. Table 5 illustrates the profitability by production practice for three Delta Region cotton producers, Tennessee, Arkansas, and Mississippi. Profits by production practice were calculated by subtracting reported operating or cash costs of each method from the NASS reported yield for each county times a price of 56.6 cents per pound of cotton. (It was assumed that there were no yield differences between till and no-till production. This assumption warrants further research. This also assumes that any enacted carbon policy would not alter input prices). Under a cap-and-trade policy, those producers/production practices/regions which have the highest profit per pound of carbon emitted ($/ lb of C) would have a comparative advantage in a relative sense. That is, those producers/production practices/regions which had the lowest $/ lb of C should theoretically be the first to stop producing or start producing an alternative crop given cap and trade restrictions on carbon emissions. Table 4 illustrates that within a state there can be a large range in the $/ lb of C ratio. For example, in Arkansas, Poinsett County has favorable agronomic and climatic conditions for cotton production and thus high yields. Therefore, Poinsett county has a high $/lb of C ratio compared to Mississippi County which has lower yields and higher costs of production. This would indicate that under a cap and trade policy that solely targets reduction of carbon emissions, cotton producers in Mississippi county would theoretically reduce acreage before producers in Poinsett county given the disparity in $/lb of C ratio since carbon sequestration is not rewarded. (This assumes that all producers have the same supply elasticity and does not take into account cross price elasticities of other crops). Further, if it is assumed that input cost price changes occur to the same extent regardless of cotton production region, then the largest driver in the $/lb of C ratio across time is yield. That being said, those states/counties with high yields look to be better positioned to handle an emissions policy.

While the cap and trade type system is based on carbon emissions efficiency, an offset policy rewards production practice differences based on net sequestration status. Hence, production practices that produce a lower net carbon footprint are rewarded with a carbon payment/permit as long as carbon sequestration exceeds emissions. Hence a carbon offset policy is more comprehensive than a cap and trade system as it not only tracks emissions but also takes into account regional and production practice differences in CO_2 sequestration. Figure 2a and 2b illustrates the disparity between carbon emissions per acre and net carbon emissions per acre. Arkansas, California, Louisiana, and Missouri are estimated to have higher average emissions per acre than the national average, but have a lower than average (sequester more) net average footprint (emissions – sequestration) per acre. This suggests that if a policy sets out to reduce GHG per acre and myopically analyzes only the amount of emissions per acre the policy could have countervailing results. That is, the above-mentioned states have higher emissions per acre but lower net emissions per acre than the national average. Conversely, Alabama and Texas have lower than the national average emissions per acre but higher than average footprint as they sequester less (Figure 2a and 2b). So, if a policy sets out to lower GHG and is only emissions based, acreage in Texas and Alabama could increase and there could actually be an increase in net GHG since acreage in Arkansas, California, Louisiana, and Missouri could decrease given higher emissions. A carbon offset policy attempts to address this important issue.

Carbon offset program

This study assumes that a carbon offset market would be constructed such that producers could only sell net carbon footprint (emissions – sequestration), not total carbon sequestered, and only if sequestration is greater than emissions per acre. This is important because unlike the emissions policy which solely focused on emissions per acre the offset policy looks at both the amount of carbon emitted to produce an acre of cotton as well as how much carbon is sequestered from the atmosphere during that production. Table 4 illustrates both the total sequestration and net weighted average footprint by county. On average, those counties that had a clay soil profile tended to sequester more carbon per acre than those with loam or sand. (The soil profile breakdown for each county used in the study is available from the authors upon request). Since biomass, and thus potential carbon to sequester, is correlated with yield, those counties who historically have had a higher yield typically sequester more carbon, *ceteris paribus*.

This study assumes that producers are paid on the amount of net carbon that is sequestered and not on additionality. Calculating payments based off additionality would require historical cropping rotations and what the net carbon footprints are for the cropping substitutes, which is out of the scope of this study but warrants further research. That is, if a producer sequesters a ton of carbon the value of the sequestered carbon, either selling to a carbon bank or to a broker, would be worth some specific amount set by the Chicago Climate Exchange or another monitoring entity. While cotton producers have the ability to alter their cropping patterns to other crops that may be more profitable when a carbon offset market is introduced, this study focuses solely on the spatial and production level differences of cotton. Table 4 and Figure 2b show the state and county weighted average net carbon footprint GHG emissions and their associated confidence intervals. If these numbers are taken as fact, then an estimate of the financial opportunity for cotton producers to take advantage of the offset market could be determined under different carbon prices. At the current carbon price of $0.10 per ton on the Chicago Climate Exchange (CCX), even the California producers who sequester the highest estimated amount of carbon at an average of 583.4 (Table 4) lbs/acre would only receive approximately $0.03 per acre for their sequestered carbon. These market signals would not be enough to change production methods or locations. However, at a price of $20.00 per ton, (the EPA estimates that in 2005 dollars, carbon prices will be $13 per ton in 2015 and increase to $26 per ton by 2030) producers in California would receive on average a permit/offset worth roughly $5.83 per acre.

Table 5 disaggregates counties in Mississippi, Tennessee, and Arkansas by their production practices (tillage types) and profitability to analyze if a carbon price of $20 per ton would change the relative rankings of profitability of different production methods used. These states were chosen given their close proximity and because they had disaggregated costs of production. Some states did not disaggregate cost of production between low and no-till production. Thus, a profit per pound of carbon emitted could not be calculated for all states. In all instances on table 5 the introduction of a carbon offset market with carbon permits trading at $20 per ton does not change the relative profitability between tillage methods. It would appear that given the relatively low amount of net carbon sequestered even paired with a high carbon price is not enough to change tillage methods within a county. Soil texture seems again to be the driving factor to capture the benefits of sequestration. In Craighead county Arkansas for instance, the profitability per acre for loam/low-till and clay/low-till is the same initially at $60.30 per acre. Because clay soils on average sequester more carbon than loam soils when offsets of $20 are introduced the profitability of the clay/low-till increases more to $68.09 compared to the $66.65 of the loam/low-till production (table 5).

The data on Table 5 can also be used to estimate the inflection point at which a carbon price could hypothetically make a producer change production practices. In Mississippi County, Arkansas, for instance, low-till is more profitable than conventional tillage on loam soils by an estimated $6.23 ($53.51 and $47.28, respectively) per acre but sequesters an estimated 58.51 (623.77 – 565.26) fewer lbs of carbon per acre. Therefore, carbon offset price would need to rise to $212.96 per ton for a producer to be indifferent between production practices. ($6.23/58.51 = 0.164 dollars per pound * 2,000 = $212.96 per ton). Not included in this price is the cost of soil erosion or other offsetting benefits (environmental and economic) associated with no-till. A lesser carbon price of $133.50 per ton would be required on clay soils in the same county to get producers to become indifferent between the lower profitability conventional tillage and higher profitability (but higher net carbon footprint) low-tillage production, *ceteris paribus*. Given this, it would appear that if a large carbon market were to develop it would more likely affect where cotton is produced (soil type) rather than affecting the tillage type. It is also worth noting that competing crops such as corn and beans could also alter the acreage of cotton based on their relative profitability with and without a carbon policy.

Conclusions

This study set out to estimate the amount and variability of carbon-equivalent greenhouse gas emitted and the amount of carbon sequestered from cotton production on a mass per mass basis for the five largest cotton producing counties in the ten largest cotton producing states. From these estimates a suite of parameters (emissions per acre, dollars per unit of carbon emitted, carbon sequestered per acre) allow for comparisons across states and within states by production practice and county to analyze how a potential carbon policy could affect cotton producers across the United States. Using a cradle-to-farm 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 lint cotton at the side of the field as a built module. In general, nitrogen fertilizer was the largest component of cotton's GHG emissions from a life cycle perspective, due to the energy required to produce nitrogen fertilizer as well as soil N_2O emitted. Results of this analysis illustrated the differences in emissions on a spatial basis, as well as by input and production (tillage, irrigation, etc.) practice.

This study empirically highlights the differences between a cap-and-trade policy and an offset policy. The emissions-based cap and trade policy could actually increase emissions by rewarding those practices/regions based solely off emissions while ignoring the amount of carbon that was sequestered from the atmosphere during biological life cycle of cotton. That is, Texas was found to have lower than the national average emissions per acre but had higher than national average net (emissions- sequestration) carbon footprint. This would indicate that a shift in acreage from a state like California, which had a higher than national average emissions per acre but a lower than average net emissions per acre, to Texas could increase net GHG even though Texas has lower emissions per acre than California. Since agriculture is one of the few industries that can actually sequester carbon, issues like this need to be given careful scrutiny when developing a policy aimed at improving environmental welfare.

From a cap-and-trade stand point, the ratio of dollars of profit to pounds of carbon emitted per acre ($/lb of C) appears to be the driving factor in which areas will experience a loss/addition of cotton acreage. Intuitively, one would think those acres with the highest GHG emissions per acre would experience a decrease if a cap-and-trade policy would be implemented. However, some cotton production methods (center pivot irrigation for example) have high levels of inputs (fuel) like California, which also have a relatively high yield, and so the GHG emissions per lb of cotton is much closer to the mean of low-input and low-yielding production practices of non-irrigated cotton like in Alabama. In this manner, cap-and-trade will not necessarily reduce acreage in those counties with the highest inputs but rather reduce acreage in those counties with the lowest profit per unit of carbon released.

From a carbon offset standpoint the estimates generated in this study, do not indicate, even under high carbon prices, that an offset market will change tillage methods within a county. It would appear that if a carbon market did develop it would more likely affect where cotton is produced (soil type) rather than affecting the tillage type. Given the differences in soil characteristics clay soils would seem more advantageous for carbon sequestration than sandy or loamy soils. While the estimates of emissions by production type are relatively straightforward, estimating sequestration will prove more problematic with a larger margin of error. Further research, highlighting this uncertainty as well as an investigation of various definitions of carbon offset policies should prove useful for further policy insights.

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Table 2. County Level Per Acre Emissions and Yield (2000-2007) Average in Pounds of GHG and Lint per Acre

State	County/Parish	Average Carbon Emissions Per Acre	Stdev Per Acre	Average Yield Per Acre	Stdev Per Acre
Texas	Lynn	241.04	35.58	468.63	192.99
-	Dawson	227.95	33.85	524.88	127.24
-	Gaines	350.33	53.12	687.75	198.08
-	Hockley	316.55	47.28	574.63	221.05
-	Lubbock	339.07	51.15	607.88	249.80
-	Terry	291.01	43.06	722.25	243.02
-	Crosby	315.59	47.11	542.75	204.52
-	Hale	416.32	65.14	813.75	163.81
-	Martin	190.95	29.73	430.00	160.23
-	Floyd	362.99	55.38	676.13	224.10
-	Yoakum	314.11	46.86	608.13	158.87
-	San Patrico	283.95	51.67	785.50	106.94
-	Lamb	362.18	55.23	761.25	154.56
-	Cochran	320.26	47.90	552.00	184.26
-	Nueces	283.95	51.67	687.29	152.28
Arkansas	Mississippi	477.42	65.58	888.88	151.19
-	Craighead	477.42	65.58	966.38	181.51
-	Lee	469.16	63.92	973.88	152.47
-	Desha	467.04	64.58	1,047.00	153.33
-	Poinsett	477.42	65.58	930.75	190.68
Mississippi	Cahoma	534.80	114.80	893.38	144.97
-	Tunica	533.70	114.78	844.63	151.27
-	Leflore	536.98	114.83	904.88	154.80
-	Bolivar	534.29	114.79	899.00	121.26
-	Washington	533.22	114.78	875.13	140.80
Georgia	Dooly	386.17	51.19	681.75	130.01
-	Colquitt	385.17	50.17	835.38	166.78
-	Worth	378.23	49.84	766.38	121.58
-	Mitchell	411.20	52.51	880.38	149.13
-	Brooks	366.47	50.25	738.38	144.67
California	Fresno	422.29	82.24	1,414.00	127.75
-	Kings	422.29	82.24	1,368.63	154.40
-	Kern	422.29	82.24	1,385.13	138.12
-	Merced	422.29	82.24	1,405.00	160.00
-	Tulare	422.29	82.24	1,394.13	156.12
Tennessee	Haywood	402.00	99.03	748.13	154.35
-	Crockett	402.00	99.03	765.38	156.04
-	Tipton	429.53	97.78	798.38	134.21
-	Gibson	402.00	99.03	780.25	158.31
-	Lauderdale	429.53	97.78	831.00	136.79
Louisiana	Tensas	445.68	62.79	902.75	176.91
-	Catahoula	387.68	60.48	885.88	198.98
-	Concordia	445.68	62.79	837.50	178.77
-	Franklin	432.54	62.10	797.50	167.36
-	Caddo	397.27	60.33	863.63	170.90
Missouri	Dunklin	410.85	57.46	844.63	138.01
-	New Madrid	410.85	57.46	939.88	133.59
-	Pemiscott	410.85	57.46	825.13	103.10
-	Stoddard	410.85	57.46	996.00	156.34
North Carolina	Halifax	349.89	77.29	688.25	178.06
-	Northampton	349.89	77.29	753.38	179.91
-	Martin	190.95	77.29	757.63	179.83
-	Edgecombe	349.89	77.29	688.00	179.99
-	Bertie	349.89	77.29	770.38	161.17
Alabama	Limestone	261.07	67.06	665.25	173.02
-	Madison	261.07	67.00	769.13	179.10
-	Lawerence	261.07	67.06	631.13	142.44
-	Houston	260.23	65.62	514.63	154.32
-	Geneva	260.23	65.62	545.50	172.84

Table 3. Parameters Used in the Estimation of Carbon Sequestration per Acre

	Minimum Value	Mean Value	Max Value
Shoot-to-Root Ratio (Φ)[1]	0.10	0.17	0.21
Harvest Index (H)			
Texas	0.24	0.47	0.57
Arkansas	0.24	0.44	0.57
Mississippi	0.24	0.46	0.57
Georgia	0.24	0.49	0.57
California	0.24	0.51	0.57
Tennessee	0.24	0.44	0.57
Louisiana	0.24	0.30	0.57
Missouri	0.24	0.44	0.57
North Carolina	0.24	0.49	0.57
Alabama	0.24	0.48	0.57
Percent of Above Ground Biomass Incorporated in the Soil (δ)[2]			
No-Till	0.04	0.10	0.12
Low-Till	0.24	0.40	0.56
Conventional	0.40	0.70	0.72
Percent of Below Ground Biomass Incorporated in the Soil (η)[2]			
No-Till	0.40	0.50	1.00
Low-Till	0.35	0.45	1.00
Conventional	0.30	0.40	0.90
Holding Potential of Soil as Percentage of Total Sequestered Carbon(ξ)[2]			
Sand	0.30	0.35	0.70
Loam	0.60	0.65	1.00
Clay	0.80	0.95	1.00

[1] Mauney et al. (1994) and West (2009).
[2] Brye (2009).

Table 4. County Level Weighted Average Carbon Emissions, Sequestration, and Net Carbon Emissions in Pounds Per Acre.

State	County/ Parish	Average Carbon Emissions (lbs per acre)[1]	Pounds of Carbon Emitted Per Pound Of Lint	Average Sequestration (lbs per acre)[2]	Average Net Carbon Emissions (lbs per acre)[3]
Texas	Lynn	241	0.51	327	-86
-	Dawson	228	0.43	353	-125
-	Gaines	350	0.51	285	65
-	Hockley	317	0.55	353	-37
-	Lubbock	339	0.56	437	-98
-	Terry	291	0.40	423	-132
-	Crosby	316	0.58	382	-66
-	Hale	416	0.51	579	-163
-	Martin	191	0.44	274	-83
-	Floyd	363	0.54	554	-191
-	Yoakum	314	0.52	306	8
-	San Patrico	284	0.36	672	-388
-	Lamb	362	0.48	477	-115
-	Cochran	320	0.58	296	25
-	Nueces	284	0.41	592	-308
Arkansas	Mississippi	477	0.54	753	-276
-	Craighead	477	0.49	715	-237
-	Lee	469	0.48	663	-194
-	Desha	467	0.45	734	-267
-	Poinsett	477	0.51	669	-191
Mississippi	Cahoma	535	0.60	359	176
-	Tunica	534	0.63	342	192
-	Leflore	537	0.59	371	166
-	Bolivar	534	0.59	366	169
-	Washington	533	0.61	351	182
Georgia	Dooly	386	0.57	327	59
-	Colquitt	385	0.46	451	-66
-	Worth	378	0.49	363	15
-	Mitchell	411	0.47	459	-48
-	Brooks	366	0.50	319	48

State	County/ Parish	Average Carbon Emissions (lbs per acre)	Pounds of Carbon Emitted Per Pound Of Lint	Average Sequestration (lbs per acre)	Average Net Carbon Emissions (lbs per acre)
Tennessee	Haywood	402	0.54	273	129
-	Crockett	402	0.53	289	113
-	Tipton	430	0.54	556	-126
-	Gibson	402	0.52	280	122
-	Lauderdale	430	0.52	571	-142
Louisiana	Tensas	446	0.49	888	-442
-	Catahoula	388	0.44	757	-370
-	Concordia	446	0.53	850	-404
-	Franklin	433	0.54	749	-316
-	Caddo	397	0.46	655	-257
Missouri	Dunklin	411	0.49	607	-197
-	New Madrid	411	0.44	670	-259
-	Pemiscott	411	0.50	430	-19
-	Stoddard	411	0.41	748	-337
North Carolina	Halifax	350	0.51	450	-100
-	Northampton	350	0.46	475	-126
-	Martin	191	0.25	460	-269
-	Edgecombe	350	0.51	420	-70
-	Bertie	350	0.45	491	-141
Alabama	Limestone	261	0.39	276	-15
-	Madison	261	0.34	322	-61
-	Lawrence	261	0.41	263	-2
-	Houston	260	0.51	372	-112
-	Geneva	260	0.48	391	-131
California	Fresno	422	0.30	987	-565
-	Kings	422	0.31	1,045	-623
-	Kern	422	0.30	984	-562
-	Merced	422	0.30	949	-527
-	Tulare	422	0.30	1,062	-640

[1] Numbers taken from column one on Table 2.

[2] Average of Monte Carlo Simulation not including the carbon sequestered in lint.

[3] Net is equivalent to emissions per acre – sequestration per acre. A negative number indicates a net sequester.

Table 5. Profitability by Production Type with and without Carbon Offsets, and Dollars of Profit Per Pound of Carbon Released.

State	County	Production Type[1]	Profit Per Acre[2]	$/lb of C	Net Sequestration[3] lbs/acre	Offset + Profit Per Acre[4]
AR	Mississippi	Loam/Low-till	$53.51	$0.11	565.26	$59.16
		Loam/Conventional	$47.28	$0.10	623.77	$53.52
		Clay/Low-till	$53.51	$0.11	795.55	$61.47
		Clay/Conventional	$47.28	$0.10	888.88	$56.17
	Craighead	Loam/Low-till	$60.30	$0.13	614.54	$66.45
		Loam/Conventional	$73.81	$0.15	678.16	$80.60
		Clay/Low-till	$60.30	$0.13	778.42	$68.09
		Clay/Conventional	$73.81	$0.15	859.00	$82.40
	Lee	Loam/No-till	$171.10	$0.36	+131.13	$171.10
		Loam/Low-till	$171.10	$0.36	150.15	$172.60
		Loam/Conventional	$240.45	$0.51	214.26	$242.59
		Clay/No-till	$171.10	$0.36	+40.99	$171.10
		Clay/Low-till	$171.10	$0.36	315.30	$174.25
		Clay/Conventional	$240.45	$0.51	396.51	$244.41
	Desha	Loam/No-till	$89.59	$0.19	+103.62	$89.59
		Loam/Low-till	$89.59	$0.19	198.78	$91.58
		Loam/Conventional	$158.94	$0.34	267.70	$161.62
		Clay/No-till	$89.59	$0.19	+6.71	$89.59
		Clay/Low-till	$89.59	$0.19	376.33	$93.36
		Clay/Conventional	$158.94	$0.34	463.63	$163.58
	Poinsett	Loam/No-till	$116.76	$0.25	+103.62	$116.76
		Loam/Low-till	$116.76	$0.25	198.78	$118.75
		Loam/Conventional	$186.11	$0.40	267.70	$188.79
		Clay/No-till	$116.76	$0.25	+6.71	$116.76
		Clay/Low-till	$116.76	$0.25	376.33	$120.53
		Clay/Conventional	$186.11	$0.40	463.63	$190.75

State	County	Production Type[1]	Profit Per Acre[2]	$/lb of C	Net Sequestration[3] lbs/acre	Offset + Profit Per Acre[4]
MS	Cahoma	Loam/No-till	$152.77	$0.29	+247.57	$152.77
		Loam/Low-till	$152.26	$0.28	+18.68	$152.26
		Loam/Conventional	$114.30	$0.21	32.42	$114.62
	Leflore	Loam/No-till	$37.87	$0.07	+246.05	$37.87
		Loam/Low-till	$37.36	$0.07	+14.22	$37.36
		Loam/Conventional	$22.00	$0.04	35.12	$22.35
	Bolivar	Loam/No-till	$37.30	$0.07	+245.25	$37.30
		Loam/Low-till	$36.79	$0.07	+14.92	$36.79
		Loam/Conventional	$23.83	$0.04	36.49	$24.20
	Washington	Loam/No-till	$23.72	$0.04	+251.86	$23.72
		Loam/Low-till	$23.21	$0.04	+27.65	$23.21
		Loam/Conventional	$10.25	$0.02	22.40	$10.47
TN	Haywood	Loam/No-till	$99.83	$0.25	+142.32	$99.83
	Crockett	Loam/No-till	$158.13	$0.39	+136.33	$158.13
		Clay/No-till	$158.13	$0.39	+65.49	$158.13
	Tipton	Loam/No-till	$57.95	$0.13	+152.41	$57.95
		Loam/Conventional	$41.97	$0.10	130.73	$43.28
		Clay/No-till	$57.95	$0.13	+78.51	$57.95
		Clay/Conventional	$41.97	$0.10	280.14	$44.77
	Gibson	Loam/No-till	$103.80	$0.26	+131.17	$103.80
	Lauderdale	Loam/No-till	$167.75	$0.39	+141.09	$167.75
		Loam/Conventional	$151.77	$0.35	153.63	$153.31
		Clay/No-till	$167.75	$0.39	+64.17	$167.75
		Clay/Conventional	$151.77	$0.35	309.14	$154.87

[1] Definiation and associated costs for each production type are taken from each states respective extension service.

[2] Profit per acre is calculated by taking the NASS reported yield for each county multiplying it by a price of 56.6 cents per pound and subtracting total reported expenses by production type. These profits do not take into account direct, CCP, or LDP payments. (+) indicates a net emitter of carbon. Fixed costs were subtracted out of total costs which makes conventional tillage relatively more attractive.

[3] The weighted acreage average for each county is the total sequestration value listed on Table 3.

[4] The offset price used in this calculation was $20 per ton of CO_2.

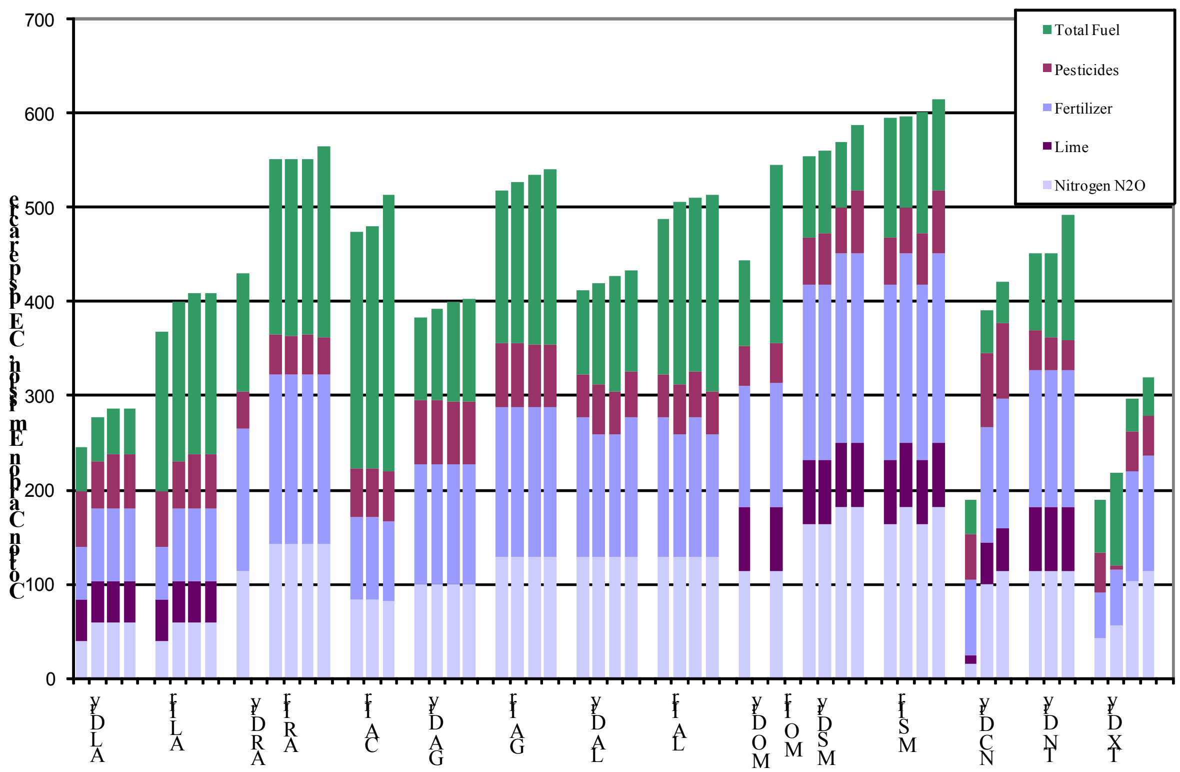

Figure 1. Decomposition of the Total Green House Gas Emission by State and Irrigated and Dryland Production Practices.

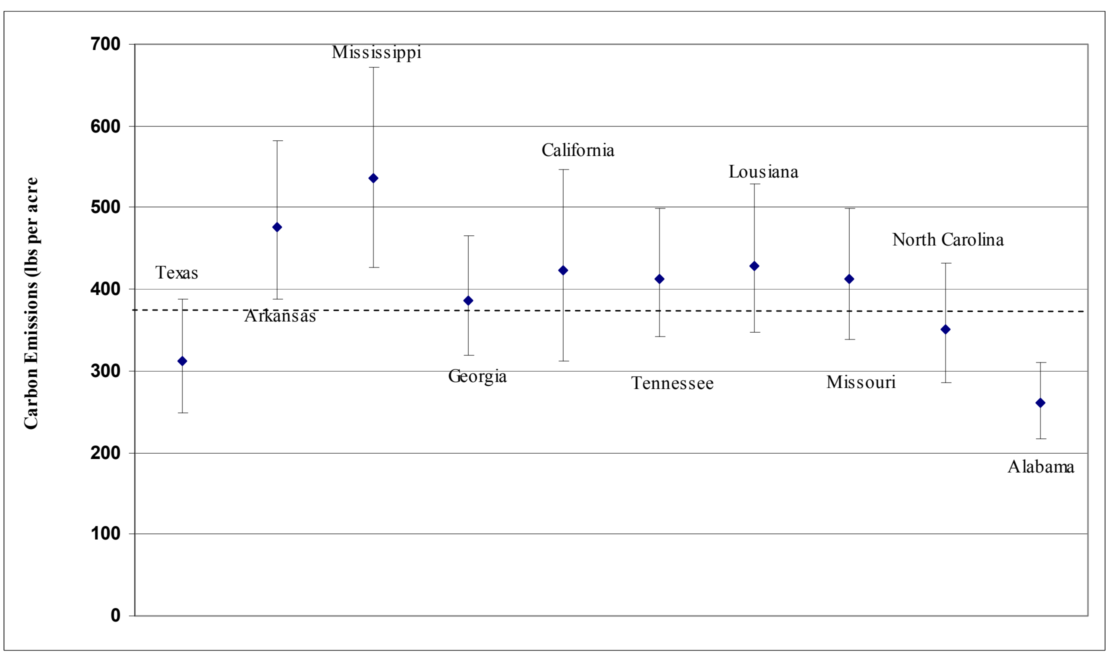

Figure 2a. State Weighted Average and 90% Confidence Interval of Carbon Equivalent Emissions Compared with US Average (dotted line) for Cotton Production in Pounds of Carbon Equivalent Per Acre.

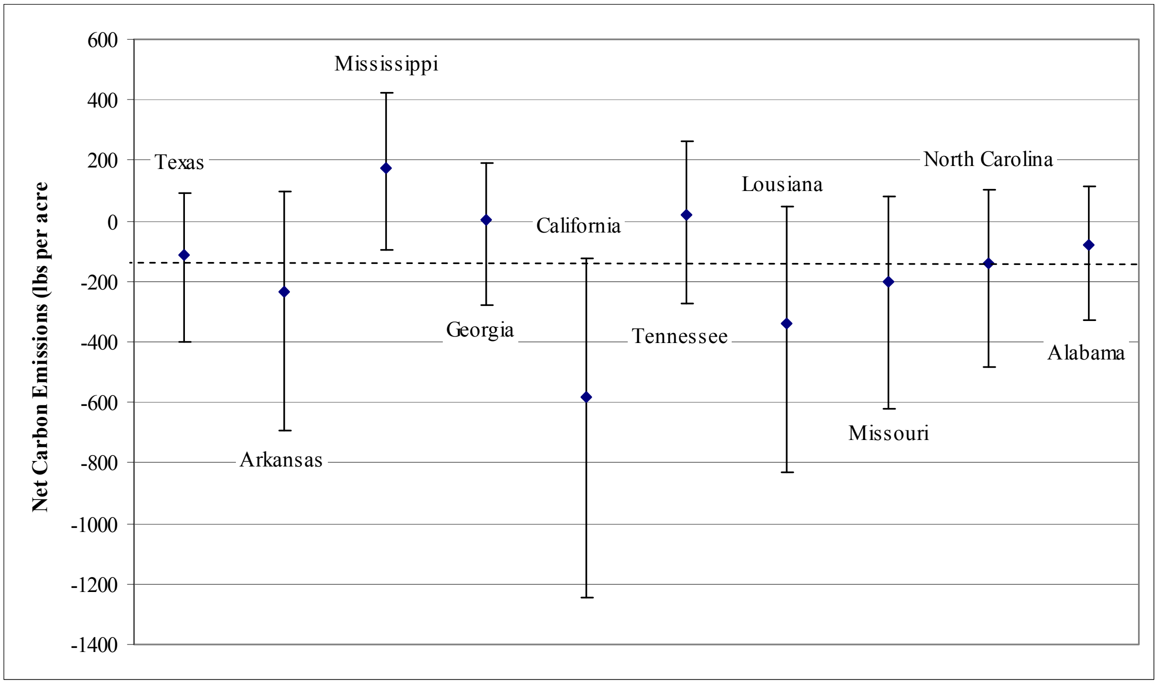

Figure 2b. State weighted average and 90% confidence interval of net carbon footprint (emissions-sequestration) compared with the US average (dotted line) for cotton production in pounds of carbon equivalent per acre