How Potential Carbon Policies Could Affect Where and How Cotton Is Produced in the United States

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Using life cycle assessment methodology, this analysis evaluates how two carbon reduction strategies affect cotton plantings regionally and methods used to produce cotton. Because cotton production emits large amounts of carbon, the design of a reduction policy as either excluding soil sequestration through cap-and-trade or including it through carbon offset is likely to affect the success of the policy. A cap-and-trade program that ignores the amount of carbon cotton would sequester in the soil during its life cycle could increase net emissions by rewarding producers whose crops emit limited carbon directly but also sequester little carbon in the ground.

Key Words**:** carbon, cotton, greenhouse gas, life cycle assessment, sequestration, tillage

Given the U.S. administration's current goal of reducing carbon emissions, some form of federal carbon policy may be implemented. In addition, many businesses are attempting to gain a "green" advantage by marketing products that have lower greenhouse gas (GHG) footprints. Industries that produce and process agricultural and other raw materials are thus attempting to identify ways to increase GHG efficiency. As a result of these business and governmental initiatives, agricultural modeling efforts to date have focused either on (i) global, national, or regional estimates for agriculture (Reilly 2009, Outlaw et al. 2009, Beckman et al. 2009, McCarl 2007, and Nalley et al. 2011) or on (ii) individual field test plots or soil- and climate-based models that work at the field level (i.e., the Century and DAYCENT models). Regional estimates typically lack detail at the local level but are representative and relevant at the macro level while the field-based models require so much detailed input information that they prove difficult to parameterize for policy analyses of larger regions. As an example, Nalley et al. (2011) attempted to bridge the gap between county-level crop production details and an aggregation of policy effects to the state level for a cap-and-trade analysis. A multitude of conventional crop production methods for rice, soybeans, cotton, wheat, corn, and grain sorghum were investigated, along with pasture and hay production methods, in Arkansas' 75 counties. Results suggested that crops that have net carbon emissions will suffer acreage losses, particularly crops that are only marginally profitable.

While Nalley et al. (2011) used a significant body of production cost detail, it lacked the national scope required by many crop commodity organizations to identify regional production processes and environments that lead to the lowest net carbon emissions. The thrust of the study outlined here, therefore, was to perform a life cycle assessment for net carbon emissions from cotton produced in the United States and thereby evaluate how different carbon reduction

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strategies might affect cotton production regionally. Our analysis examined data for the top five cotton-producing counties in each of the top ten cotton-producing states, and county-level information for 52 production practices that were relevant in 59 counties across the United States allowed for a comprehensive national analysis of cotton's carbon footprints and production practices. The model quantified the likely distribution of the cotton's carbon emissions by production method and county using a range of expected soil, tillage, and plant growth parameters. Therefore, the analysis presents greater detail on cotton production methods and conditions than a national carbon policy study but excludes the ramifications of a national policy across crops. This tradeoff was deemed reasonable given that there are few substitutes for cotton fiber. In addition, considering current uncertainty about the type of carbon-limiting legislation that may be enacted, this study presents a suite of estimates (i.e., emissions per acre, farmgate dollars per unit of carbon emitted, and carbon sequestered per acre) to analyze how potential carbon policies could affect cotton producers across the United States as they compete domestically.

The two carbon reduction policies analyzed were a cap-and-trade and a carbon offset program. As modeled here, a cap-and-trade program would only limit direct emissions of carbon and other GHGs and would ignore carbon sequestration. In contrast, a carbon offset program would provide monetary incentives for *net* reductions of carbon generated by GHG emissions and soil sequestration. Because agriculture in general and cotton production in particular emit large amounts of GHGs, a governmental policy's exclusion (through cap-and-trade) or inclusion (through carbon offset) of soil carbon sequestration is expected to make a significant difference in the outcome of that policy.

This study is unique in that it analyzes the effects of a national carbon policy on county-level production of cotton. In particular, we examine differences between low or no tillage and conventional tillage on carbon sequestration. In addition, we study the effects of a hypothetical carbon market on the relative profitability of competing tillage practices in terms of both cost of production and the effect of the tillage method on carbon sequestration.

Material and Methods

Life Cycle Analysis

A life cycle analysis (LCA) is a systematic, cradle-to-grave process that tracks a product's environmental impact from resource extraction through production, processing, transportation, use, and disposal, examining energy and other inputs used and the resulting pollution created. Interpretation of a LCA is useful in evaluating production processes and guiding efforts to reduce environmental impacts. Such analyses benefit producers, scientists, policymakers, and government agencies because the environmental impacts of alternative practices of production can be evaluated. LCAs are also useful, therefore, for determining environmental hotspots within a production system and for comparing the environmental impacts of two or more similar products or two or more production systems for a single product.

For an agricultural carbon offset program, LCAs can establish a baseline carbon footprint by crop and production practice. In this sense, the program can reward or discourage future modifications in production practices according to those practices' ability to reduce GHG emissions or add soil carbon sequestration relative to a baseline.

The LCA put forth in this study includes both direct and indirect GHG emissions from cotton production in the United States. Direct emissions come from the primary production process. Examples are carbon dioxide (CO_2) from the burning of diesel and gasoline by tractors, irrigation equipment, and farm trucks and nitrous oxide (N_2O) from applications of nitrogen fertilizers. Indirect emissions are generated upstream or off-farm by manufacturing of inputs used on the farm. Examples are GHG emissions from natural gas and other energy sources used in commercial fertilizer and agrochemical manufacturing

Included in our LCA are GHG emissions from agricultural inputs involved in the production of cotton to the point of placement of a lint module at the side of the field (e.g., fertilizers, herbicides, pesticides, fuel, agricultural plastics, and other chemicals). Data were not available on ginning efficiencies, sizes of gins and their distances from fields, or power sources they use. Consequently, emissions generated from ginning, transporting, and processing the cotton, which occur outside the farmgate, were excluded. Also excluded were embedded carbon emissions that result from upstream manufacturing of equipment and tools used on-farm for production. The impact of a governmental carbon policy would have to be included in a LCA of equipment manufacture, and the GHG impact of equipment use at the farm level is quite small relative to the use of fertilizers, fuel, and agricultural chemicals.

Given the complexity of dealing with estimations of GHG emissions, whether CO_2, N_2O, or other GHGs, we used previously reported carbon equivalent (CE) emission factors to estimate the emissions generated as a result of input use by production practice (Table 1). In essence, multiple GHGs associated with global warming were converted to CEs to obtain a "carbon footprint"—a process that is based on a rich engineering literature on carbon equivalence. Hence, a carbon emission factor was used to estimate the quantity of carbon or CE for each cotton production input. Values from the U.S. Environmental Protection Agency (EPA) were used for diesel and gasoline combustion emissions (EPA 2009). The life cycle inventory database Ecoinvent 2.0 (Ecoinvent Center 2009) as viewed in SimaPro 7.1 was used to calculate upstream emissions from the production of fuel. The emission factor for lime came from West and McBride (2005). All other input conversion factors in the analysis were reported by Lal (2004).

Nitrous oxide from soil has been identified as a major contributor of GHG emissions from crop production (Bouwman 1996, Del Grosso et al. 2006). Emissions of N_2O vary extensively based on environmental conditions, the timing and method of tillage and fertilization, and the form of nitrogen applied (Snyder et al. 2009). This study used a conversion factor of 298 units of CO_2 per unit of N_2O (81 units of CE per unit of N_2O) based on a 1 percent direct loss from nitrogen applied (IPCC 2007). Process-based methods 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 was beyond the scope of this study.

County Emission Data

This study examined data from the top five cotton-producing counties in each of the top ten cotton-producing states: Alabama, Arkansas, California, Georgia, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas. In Missouri, only four counties produce cotton. Texas, on the other hand, holds a relatively large share of U.S. cotton production so 15 of its top-producing counties were analyzed. In total, then, 59 counties were included in the study. Table 2 shows summary statistics for annual yield data for lint cotton collected for each county for the years 2000 through 2007 from the U.S. Department of Agriculture's National Agricultural Statistics Service (NASS) (2009). Weather anomalies, including drought, early frost, and early/late rains, can severely impact cotton yields so multiple years of yield data were included to mitigate the impact of a single year's outcome on spatial comparisons. This approach also allowed for an empirical risk analysis on a range of outcomes on the basis of observed yields. To capture additional detail, county cotton acreages

Table 1. Carbon Equivalent Emission Factors

Input (v_k)		Pounds of Carbon Equivalent per Unit of Input Used (CE_k)	Source
Fuel (gallons)	Diesel	7.01	SimaPro (2009), EPA (2007, 2009)
	Gasoline	6.48	SimaPro (2009), EPA (2007, 2009)
Fertilizer (pounds)	Nitrogen	1.30	Lal (2004)
	Phosphorus	0.20	Lal (2004)
	Potassium	0.16	Lal (2004)
	Lime	0.06	Lal (2004)
	N_2O emissions	1.27	IPCC (2007)
Herbicide / Harvest Aid (pints or pounds)		6.44	Lal (2004)
Insecticide / Fungicide (pints or pounds)		5.44	Lal (2004)

Table 2. County-level Averages of Emissions in Pounds of GHG per Acre and Yields in Pounds of Lint per Acre for 2000–2007

State	County / Parish	Average Carbon Emissions per Acre	Std Dev. per Acre	Average Yield per Acre	Std Dev. per Acre
Texas	Cochran	320	48	552	184
	Crosby	316	47	543	205
	Dawson	228	34	525	127
	Floyd	363	55	676	224
	Gaines	350	53	688	198
	Hale	416	65	814	164
	Hockley	317	47	575	221
	Lamb	362	55	761	155
	Lubbock	339	51	608	250
	Lynn	241	36	469	193
	Martin	191	30	430	160
	Nueces	284	52	687	152
	San Patricio	284	52	786	107
	Terry	291	52	550	204
	Yoakum	314	47	608	159
Arkansas	Craighead	477	66	966	182
	Desha	467	65	1047	153
	Lee	469	64	974	152
	Mississippi	477	66	889	151
	Poinsett	477	66	931	191
Mississippi	Bolivar	534	115	899	121
	Coahoma	535	115	893	145
	Leflore	537	115	905	155
	Tunica	534	115	845	151
	Washington	533	115	875	141
Georgia	Brooks	366	50	738	145
	Colquitt	385	50	835	167
	Dooly	386	51	682	130
	Mitchell	411	53	880	149
	Worth	378	50	766	122
California	Fresno	422	82	1,414	128
	Kern	422	82	1,385	138
	Kings	422	82	1,369	154
	Merced	422	82	1,405	160
	Tulare	422	82	1,394	156
Tennessee	Crockett	402	99	765	156
	Gibson	402	99	780	158
	Haywood	402	99	748	154
	Lauderdale	430	98	831	137
	Tipton	430	98	798	134
Louisiana	Caddo	397	60	864	171
	Catahoula	388	60	886	199
	Concordia	446	63	838	179
	Franklin	433	62	798	167
	Tensas	446	63	903	177
Missouri	Dunklin	411	57	845	138
	New Madrid	411	57	940	134
	Pemiscot	411	57	825	103
	Stoddard	411	57	996	156
North Carolina	Bertie	350	77	770	161
	Edgecombe	350	77	688	180
	Halifax	350	77	688	178
	Martin	350	77	758	180
	Northampton	350	77	753	180
Alabama	Geneva	260	66	546	173
	Houston	260	66	515	154
	Lawrence	261	67	631	142
	Limestone	261	67	665	173
	Madison	261	67	769	179

were disaggregated by irrigated and nonirrigated production practice where sufficient data were available to do so.

Data used to calculate inputs for specific cotton production practices in each county came from cost-of-production budget estimates by university agricultural extension specialists who provided specific detail about spatially diverse growing conditions (climatic and agronomic) within a state. County extension agents in each county in the study also provided information on the production practices (e.g., type of tillage and irrigation method by soil texture) that were prevalent in each county. The budgets incorporated costs for fuel (diesel and gas), irrigation water applied, fertilizers, herbicides, insecticides, and other agrochemicals such as fumigants, defoliants, and growth regulators. From these recommendations, input amounts by production practice and associated CEs 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 Cooperative Extension budgets provide recommended acre inches of water to apply by county. Again, regional extension agents provided their best estimates for percentages of irrigated land in each county that used center pivot, drip, flood, and furrow irrigation techniques. The amount of energy required for irrigation varies by location based on pumping depths and power sources.[1] Because of a large degree of variability within each county, the model could not feasibly account for groundwater depth. Where not specifically provided in a budget, the amount of diesel required to deliver one acre inch of water to the field was estimated from average diesel requirements in cost-of-production budgets from Arkansas, Louisiana, and Mississippi, and that amount was applied to estimates of fuel use per acre inch for all irrigated acres.

This study complied with the International Organization of Standardization's (ISO's) 14040 standards (ISO 2006) of a 1 percent impact threshold for inclusion of inputs. Consequently, it omitted the carbon embedded in the manufacturing of tractors and other equipment used in the production of cotton. Further, this study did not allocate any emissions to cottonseed, although cottonseed is a secondary product that has economic value as animal feed and high-value cooking oil, since the GHGs embodied in cotton lint were the focus of the analysis.

Carbon Efficiency and Probabilistic Inputs

Weighted-average carbon footprints by county (pounds of CE per pound of cotton lint produced) were estimated by dividing the number of pounds of carbon emitted per harvested acre by the yield in pounds of cotton per acre. Total carbon emission per acre simply indicates the physical amount of GHG emitted and not benefit derived (i.e., cotton yield or income) or the efficiency of producing that benefit with respect to its emissions. Dividing the amount of GHG emitted by the mass of cotton harvested on each acre established an efficiency measure per unit of cotton.

Variability and uncertainty for this analysis were quantified by Monte Carlo simulations with Microsoft Excel's add-in program @Risk (Palisade 2009). Production experts (county extension agents) assigned distributions for input data based on characteristics of the data collected. A uniform distribution with an upper and lower boundary was applied when the probable value varied equally across the range; a triangular distribution was used when some central tendency existed between the 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 the 52 production practices included in the study was thus calculated with 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, CE emissions (pounds per acre) were calculated for each production method and county as follows:

$$(1) \qquad E_{in} = \sum_{k} v_k \cdot CE_k$$

where E_{in} represents CE emissions per acre in county i for production practice n, v_k represents per acre input quantities of k inputs (such as fuel and fertilizer), and CE_k represents CE emissions per unit of input v. We also assumed that producers

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[1] Given the relatively large amount of uncertainty regarding the response of input prices to implementation of such a policy, we assumed that input prices were fixed at the time of planting and independent of a carbon policy. This assumption warrants further research.

do not alter their production behavior. However, a carbon tax could raise energy prices, which could raise fertilizer prices. In the face of such costs increasing, producers might choose to apply less fertilizer or convert to a less carbon intensive energy source. Our model excludes the effect of a carbon tax on input costs and production practices.

Carbon Sequestration Calculations

Using a methodology similar to Prince et al. (2001) and most recently utilized by Popp et al. (2011), we estimated the number of pounds of carbon sequestered from aboveground biomass per acre (*AGB*) in county *i* under tillage method *t* as follows:

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

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

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

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

where χ is the carbon content of belowground biomass and Φ is the root-to-shoot ratio. The other variables are as previously defined.

Carbon sequestration for both aboveground and belowground biomass was multiplied by a soil factor, ξ_{is}, that represents an acreage-weighted estimate by county and adjusts soil carbon sequestration potential based on soil texture. Thus, total carbon sequestration per acre, S_{its}, for cotton in county *i* under tillage method *t* and soil texture *s* can be estimated by

$$S_{its} = (AGB_{it} + BGB_{it}) \cdot \xi_{is}. \tag{4}$$

Harvest indices and root-to-shoot ratios are reported in Table 3, and estimates of the carbon

Table 3. Parameters Used in Estimations of Carbon Sequestration per Acre

	Minimum Value	Mean Value	Maximum Value
Root-to-Shoot Ratio (Φ)[a]	0.10	0.17	0.21
Harvest Index (*H*)[b]			
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 Aboveground Biomass Incorporated in the Soil (δ)[c]			
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 Belowground Biomass Incorporated in the Soil (η)[c]			
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)[c]			
Sand	0.30	0.35	0.70
Loam	0.60	0.65	1.00
Clay	0.80	0.95	1.00

[a] Mauney et al. (1994) and West (2009).

[b] State-specific indices are available from the authors upon request.

[c] Brye (2009).

content of aboveground biomass (42 percent) and belowground biomass (41 percent) used in the analysis come from Pinter et al. (1994). Table 3 also reports the crop-residue soil-incorporation factors and belowground-biomass sequestration factors by tillage method plus the soil factor adjustments used for clayish, loamy, and sandy soils.

Harvest Index

A harvest index was used to determine the amount of biomass remaining on the field postharvest. Since harvest index values can vary significantly by seed variety, planting season, production practice, and location, our model used not only an average value reported from the literature and from county extension agents for each state as cited in Table 3 but also a range of estimates for Monte Carlo simulations. In our model, the harvest index adjusted values for biomass production by lint yield across space based on the yield information that was available (described in Table 2). Harvested lint, which on average is 42 percent carbon, was not modeled as a contribution to carbon sequestration in this methodology even though the use of cotton can lead to products that trap an amount of carbon similar to that of soil.[2]

Root-to-Shoot Ratio

The root-to-shoot ratio was used to determined yields dependent on belowground biomass production. Since root materials and the aboveground biomass have slightly different carbon concentrations, they were modeled separately. Again, root-to-shoot ratios reported in the literature vary considerably so a range of estimates was used in this analysis under a triangular distribution.

Tillage Effects

To model tillage effects, we denoted conventional tillage as leaving behind 30 percent of the carbon residue on the soil surface and the remaining 70 percent as mixed into the soil for potential carbon sequestration (Table 3). At the other extreme, no-till production leaves nearly all of the residue at the soil surface; only about 10 percent is expected to get incorporated into the soil by machinery traffic. Some producers have adopted an intermediate level of tillage referred to here as low tillage and defined as leaving 60 percent of the residue aboveground and mixing 40 percent into the soil.

Once incorporated into the soil, however, not all of the carbon contained in the aboveground residue and roots can be considered sequestered. Since many types of crop residue contain approximately 50 percent lignin (Sylvia et al. 2005), it is the fraction of residue that remains in the soil once microbes have mineralized the more readily available carbon fractions that are eventually respired as CO_2 to the atmosphere. Thus, in the absence of tillage, approximately 50 percent of the carbon from belowground plant residue is potentially sequestered in a no-till setting (Table 3). However, when the belowground root biomass is disturbed through tillage and the aboveground residue gets incorporated into the soil and becomes readily available for microbial oxidation, there is some additional loss of carbon from elevated microbial activity. Consequently, we conservatively assigned the carbon sequestration potential as 45 percent for low tillage and 40 percent for conventional tillage.

Soil Texture Effects

How tillage affects soil carbon sequestration and the sequestration process in general are both influenced by soil texture (the relative mixture of sand, silt, and clay that makes up a soil). Once the amount of carbon that could be sequestered based on tillage was estimated, the model accounted for the effect of soil texture by assigning an average of just 5 percent additional carbon loss for clay-type soils (Table 3). As the soil texture became more coarse (loamy or sandy), the model reduced the amount of potentially sequesterable soil carbon 30 percent for loamy soil and 60 percent for sandy soil (Table 3). These soil-texture reduction factors match general relationships established in the literature between a soil's texture and its carbon content: soil carbon tends to increase as the soil progresses from a coarse texture to a fine one for a variety of reasons (Parton et al. 1987, Burke et al. 1989).

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[2] How such cotton is used (long-term storage and reuse) along with a high carbon-to-nitrogen ratio when the lint reaches the end of its useful life could result in carbon-trapping that is superior to that of soil. With regard to carbon sequestration by harvested products, cotton lint is unlike food or feed crops because its intended commercial use does not return the embedded carbon to the atmosphere in the near term.

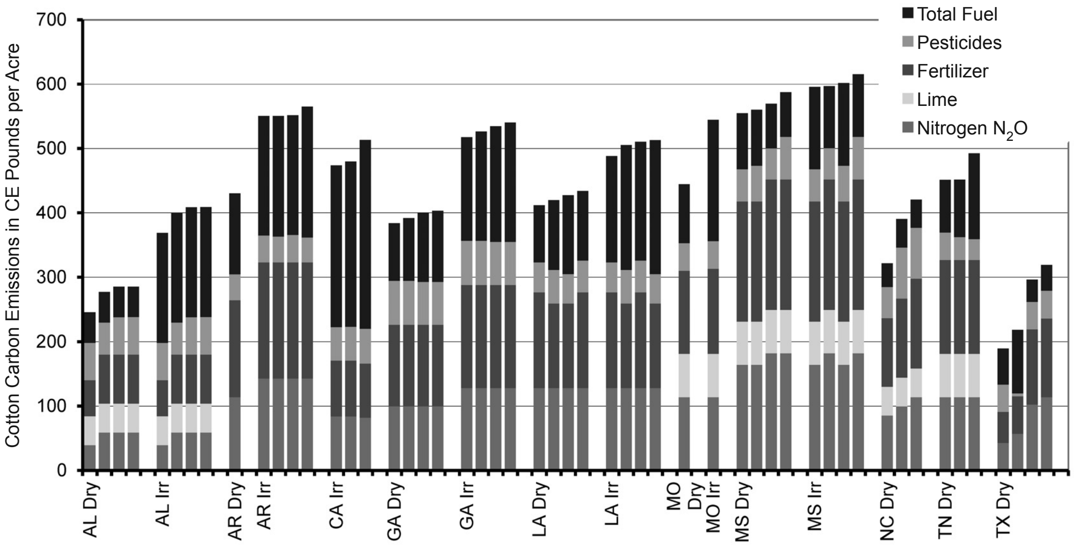

Figure 1. Decomposition of Total Green House Gas Emissions by State and by Irrigated and Dryland Production Practices

Notes: AL is Alabama, AR is Arkansas, CA is California, GA is Georgia, LA is Louisiana, MO is Missouri, MS is Mississippi, NC is North Carolina, TN is Tennessee, and TX is Texas. "Irr" denotes irrigated crops and "Dry" denotes nonirrigated crops.

Results

Table 2 presents estimates of average carbon emissions per acre for each county in the study calculated as the sum of the acre-weighted average for each production method used in the county. A comparison of CEs per acre for the 52 cotton production methods demonstrated that fertilizers were the greatest contributor to total carbon emissions for most methods, particularly when N_2O emissions from nitrogen fertilizer applications were included (Figure 1). Nitrogen generally plays the largest role in carbon emissions because it requires a large amount of energy to produce, is used heavily in most cotton production, and releases potent N_2O emissions when applied. Lime use in the southeastern United States also had a sizeable impact because of high rates of application in some states, namely Mississippi. In areas such as California, where heavy irrigation is prevalent, diesel for pumping made a large relative contribution. On average, California cotton growers irrigate 31.5 acre-inches per year while Arkansas growers, for example, apply an average of 10.5 acre-inches annually (9 inches with center pivot irrigation and 12 inches with furrow irrigation).

Emissions per Acre and Pounds of Lint per Pound of Carbon

Individual states and regions within states varied substantially in the amount of emissions per acre and pounds of lint per pound of carbon. Texas, in particular, was responsible for more emissions than other states because of its physical size and amount of cotton production. Some production methods (center pivot irrigation and conventional tillage) and regions were particularly input-intensive and, in the case of center pivot irrigation, also produced large yields. Other production methods (dryland production and low tillage) were less input-intensive and generated smaller yields; this was particularly true for dryland production. Table 4 presents county-level average carbon emissions per pound of lint produced, which is a direct measure of GHG-use efficiency that can be used comparatively across time and space. When inputs remain constant and yield increases, carbon per pound of lint decreases—a direct measure of improved efficiency in reducing emissions. While California used fewer inputs, the state also produced a relatively high yield so the CE per pound of lint was much closer to the mean of states that use a smaller number of inputs (e.g., dryland

Table 4. County-level Weighted-average Carbon Emissions, Sequestration, and Net Carbon Emissions in Pounds per Acre

State	County / Parish	Average Carbon Emissions in Pounds per Acre[a]	Pounds of Carbon Emitted per Pound of Lint	Average Sequestration in Pounds per Acre[b]	Average Net Carbon Emissions in Pounds per Acre[c]
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 Patricio	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	Coahoma	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

[a] Numbers taken from column 1 in Table 2.

[b] Average of Monte Carlo simulation not including the carbon sequestered in lint.

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

production). Counties in North Carolina typically had a low carbon-to-lint ratio even though the yield was generally smaller than those of other states. The nationwide average in this study was 815 pounds of cotton per acre, and the average in North Carolina was 731 pounds per acre. This can be attributed to the fact that nearly all cotton grown in North Carolina is not irrigated—not having to pump water reduces carbon emissions per acre. The national average in this study was 380 pounds of CE per acre, and North Carolina averaged 318 pounds. Conversely, a state like Mississippi that has higher than average yields (883 pounds per acre) generates a greater than average ratio of pounds of carbon per pound of lint—is less carbon efficient—because of greater than average emissions per acre (535 pounds per acre in Mississippi). Therefore, improvements to carbon-use efficiency can be sought either through increased yield per unit of input or reduced input per pound of cotton produced.

Sequestration and Net Emissions per Acre

Table 4 presents weighted averages for pounds of carbon sequestered per acre for each county.

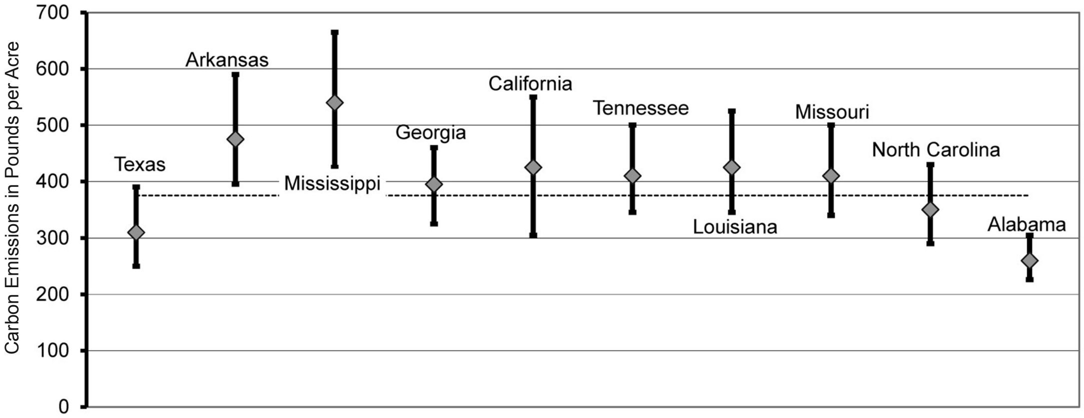

Figure 2a. State Weighted Averages and 90% Confidence Intervals for Carbon Equivalent Emissions Compared with the U.S. Average (dotted line) for Cotton Production in Pounds of Carbon Equivalent per Acre

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, including soil fertility and climate, that affect yield. Therefore, when comparing across counties, one must be careful when making broad statements about the environmental impacts of cotton production. It is important to determine which production variables are endogenous and which are exogenous as well as the yields associated with emissions. California, for instance, has relatively large carbon emissions per acre due mainly to high levels of irrigation and nitrogen fertilizer application (i.e., endogenous decisions made by producers). However, given that California has a relatively good production climate and clay soils (exogenous factors) with high yields, all of the state's counties are estimated to be net sequesterers (Table 4). Therefore, it may not be appropriate to compare states, regions, or counties by their carbon emissions per acre. That is, one can change production practices to improve carbon emissions but cannot change soil textures and climate, which are two significant factors in the amount of carbon sequestered. Nonetheless, carbon per acre and, hence, total carbon emitted are important issues when examining a potential cap-and-trade policy.

Table 4 presents net carbon footprints (emission minus sequestration) by county. Of the 59 counties in the study, only fourteen (24 percent) were net emitters of carbon on average and seven of those were located in Mississippi and Georgia.[3] Even the counties that were net emitters averaged only 105 pounds of CE per acre.[4] A main reason that Georgia's counties were estimated to be net emitters was the soil composition in southern Georgia, which is a mix of sand and loam. Because sandy and sandy/loamy soils are relatively coarse, the frequency and intensity of wetting and drying cycles generally increases microbial activity, which promotes oxidation of a soil's organic matter. That oxidation increases carbon respiration from the soil in the form of CO_2, which reduces the carbon sequestration potential. Net emissions are driven by both the amount of direct emissions per acre (a function of inputs) and the amount of sequestration per acre (a function of endogenous (e.g., tillage) and exogenous (e.g., soil texture) factors). California's levels of net sequestration were greatest, averaging 583 pounds per acre. This indicates that, on average, the five California counties evaluated in this study would reduce CEs emitted to the atmosphere by 583 pounds for each acre of cotton produced per year, thus sequestering more carbon than was emitted. So, although California had a relatively large emission

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[3] Production budgets from Mississippi State University recommend 1,000 pounds of lime per year, causing the large difference in emissions between Mississippi and other delta states (Arkansas, Tennessee, and Louisiana). When the lime recommendation is removed, Mississippi's average emissions decrease 60 pounds per acre (1,000 pounds times 0.06 CEs per pound of lime) and place it in line with the other delta states.

[4] To put that amount of carbon into context, 105 pounds of CE emissions are comparable to using 15 gallons of diesel fuel.

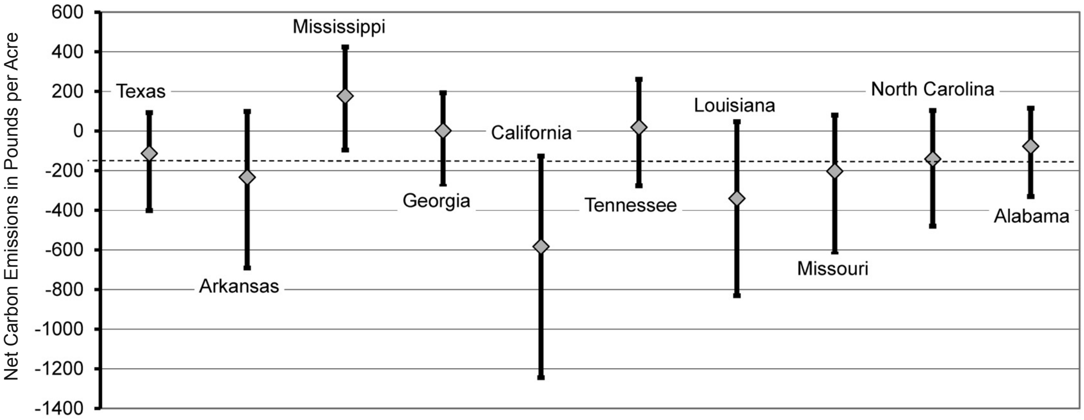

Figure 2b. State Weighted Averages and 90% Confidence Intervals for Net Carbon Footprints (emissions minus sequestration) Compared with the U.S. Average (dotted line) for Cotton Production in Pounds of Carbon Equivalent per Acre

rate per acre, favorable conditions for soil carbon sequestration and high yields or biomass production were sufficient to offset those emissions. Figure 2a shows a relatively large variation in emissions within each state but fairly similar ranges across states. Figure 2b illustrates the large amount of variability within a state in regard to being considered a net carbon emitter or net carbon sequesterer. From this conservative analysis, only California appears to be a net sequesterer and only Mississippi appears to be a net emitter.

The variability of carbon footprints within a county is also important. If a county's carbon footprint varied only slightly from the national average, indicating that gins sourced cotton from specific counties to minimize footprint within a county, they would have more confidence in labeling a bale of cotton as "carbon neutral" to the gin than if they sourced cotton from producers across multiple counties. Information on the source of cotton and the footprint of its production could be valuable since consumers are becoming more aware of and increasing their demand for "environmentally friendly" products.

Economic Comparisons

While some factors that affect sequestration in cotton production are exogenous (such as soil texture), producers can use various practices, particularly related to tillage, to increase the quantity of carbon sequestered in the soil. Table 5 illustrates profitability by production practice for three delta-region cotton-producing states: Tennessee, Arkansas, and Mississippi. Profit by production practice was calculated by multiplying the NASS-reported yield for each county by a price of 56.6 cents per pound of cotton and then subtracting the reported operating or cash cost for each method.[5] Under a cap-and-trade policy, producers, production practices, and regions that have the greatest profit per pound of carbon emitted would have a comparative advantage in a relative sense. That is, the producers and regions that had the lowest profit per pound of carbon theoretically should be the first to stop or start producing an alternative crop in the face of possible cap-and-trade restrictions on carbon emissions. Table 5 illustrates that within a state there can be considerable variation in the ratio of profit per pound of carbon. For example, in Arkansas, Poinsett County has favorable agronomic and climatic conditions for cotton production so it generates large yields. As a result, Poinsett County's profit per pound of carbon is high compared to that of Mississippi County, where yields are lower and production costs are greater. Under a cap-and-trade policy that ignores sequestration, cotton producers in Mississippi County theoretically would reduce acres committed to cotton before producers in Poinsett County because carbon sequestration

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[5] We assumed that there were no yield differences between till and no-till production. This assumption warrants further research. We also assumed that any enacted carbon policy would not alter input prices.

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

County	Production Type[a]	Profit per Acre[b]	Profit per Pound of Carbon	Net Sequestration[c] in Pounds per Acre	Profit per Acre + $1 Offset[d]	Profit per Acre + $20 Offset[e]
ARKANSAS						
Mississippi	Loam/Low-till	$53.51	$0.11	565.26	$53.79	$59.16
	Loam/Conventional	$47.28	$0.10	623.77	$47.59	$53.52
	Clay/Low-till	$53.51	$0.11	795.55	$53.91	$61.47
	Clay/Conventional	$47.28	$0.10	888.88	$47.73	$56.17
Craighead	Loam/Low-till	$60.30	$0.13	614.54	$60.61	$66.45
	Loam/Conventional	$73.81	$0.15	678.16	$74.15	$80.60
	Clay/Low-till	$60.30	$0.13	778.42	$60.69	$68.09
	Clay/Conventional	$73.81	$0.15	859.00	$74.24	$82.40
Lee	Loam/No-till	$171.10	$0.36	+131.13	$171.10	$171.10
	Loam/Low-till	$171.10	$0.36	150.15	$171.17	$172.60
	Loam/Conventional	$240.45	$0.51	214.26	$240.56	$242.59
	Clay/No-till	$171.10	$0.36	+40.99	$171.10	$171.10
	Clay/Low-till	$171.10	$0.36	315.30	$171.26	$174.25
	Clay/Conventional	$240.45	$0.51	396.51	$240.65	$244.41
Desha	Loam/No-till	$89.59	$0.19	+103.62	$89.59	$89.59
	Loam/Low-till	$89.59	$0.19	198.78	$89.69	$91.58
	Loam/Conventional	$158.94	$0.34	267.70	$159.08	$161.62
	Clay/No-till	$89.59	$0.19	+6.71	$89.59	$89.59
	Clay/Low-till	$89.59	$0.19	376.33	$89.78	$93.36
	Clay/Conventional	$158.94	$0.34	463.63	$159.18	$163.58
Poinsett	Loam/No-till	$116.76	$0.25	+103.62	$116.76	$116.76
	Loam/Low-till	$116.76	$0.25	198.78	$116.86	$118.75
	Loam/Conventional	$186.11	$0.40	267.70	$186.25	$188.79
	Clay/No-till	$116.76	$0.25	+6.71	$116.76	$116.76
	Clay/Low-till	$116.76	$0.25	376.33	$116.95	$120.53
	Clay/Conventional	$186.11	$0.40	463.63	$186.34	$190.75
MISSISSIPPI						
Coahoma	Loam/No-till	$152.77	$0.29	+247.57	$152.77	$152.77
	Loam/Low-till	$152.26	$0.28	+18.68	$152.26	$152.26
	Loam/Conventional	$114.30	$0.21	32.42	$114.31	$114.62
Tunica	Loam/No-till	$149.94	$0.28	+247.57	$149.94	$149.94
	Loam/Low-till	$149.43	$0.28	+18.68	$149.43	$149.43
	Loam/Conventional	$111.47	$0.21	32.41	$111.48	$111.79
Leflore	Loam/No-till	$37.87	$0.07	+246.05	$37.87	$37.87
	Loam/Low-till	$37.36	$0.07	+14.22	$37.36	$37.36
	Loam/Conventional	$22.00	$0.04	35.12	$22.02	$22.35
Bolivar	Loam/No-till	$37.30	$0.07	+245.25	$37.30	$37.30
	Loam/Low-till	$36.79	$0.07	+14.92	$36.79	$36.79
	Loam/Conventional	$23.83	$0.04	36.49	$23.85	$24.20
Washington	Loam/No-till	$23.72	$0.04	+251.86	$23.72	$23.72
	Loam/Low-till	$23.21	$0.04	+27.65	$23.21	$23.21
	Loam/Conventional	$10.25	$0.02	22.40	$10.26	$10.47

continued on following page

Table 5. (continued)

County	Production Type[a]	Profit per Acre[b]	Profit per Pound of Carbon	Net Sequestration[c] in Pounds per Acre	Profit per Acre +$1 Offset[d]	Profit per Acre +$20 Offset[e]
TENNESSEE						
Haywood	Loam/No-till	$99.83	$0.25	+142.32	$99.83	$99.83
Crockett	Loam/No-till	$158.13	$0.39	+136.33	$158.13	$158.13
	Clay/No-till	$158.13	$0.39	+65.49	$158.13	$158.13
Tipton	Loam/No-till	$57.95	$0.13	+152.41	$57.95	$57.95
	Loam/Conventional	$41.97	$0.10	130.73	$42.04	$43.28
	Clay/No-till	$57.95	$0.13	+78.51	$57.95	$57.95
	Clay/Conventional	$41.97	$0.10	280.14	$42.11	$44.77
Gibson	Loam/No-till	$103.80	$0.26	+131.17	$103.80	$103.80
Lauderdale	Loam/No-till	$167.75	$0.39	+141.09	$167.75	$167.75
	Loam/Conventional	$151.77	$0.35	153.63	$151.85	$153.31
	Clay/No-till	$167.75	$0.39	+64.17	$167.75	$167.75
	Clay/Conventional	$151.77	$0.35	309.14	$151.93	$154.87

[a] Definitions and associated costs for each production type are taken from each state's respective extension service.

[b] Profit per acre was calculated by taking the NASS-reported yield for each county and (1) multiplying it by a price of 56.6 cents per pound and (2) subtracting total reported expenses by production type. These profits did not take into account direct payments, counter-cyclical payments (CCPs), or loan deficiency payments (LDPs). A "+" indicates a net emitter of carbon. Fixed costs were subtracted from total cost, which makes conventional tillage relatively more attractive. The adjoining column to the right divides profit by CE emissions.

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

[d] The offset price used in this calculation is $1 per ton of CE. If we impose additionality, the payments are smaller.

[e] The offset price used in this calculation is $20 per ton of CE. If we impose additionality, the payments are smaller.

is not rewarded.[6] Further, if one assumes that a change in input cost does not vary by region, then the largest driver of profit per pound of carbon is yield. Therefore, states and counties with high yields should be better positioned to handle an emission policy.

While a cap-and-trade system is based on carbon emission efficiency, an offset policy rewards changes in production practices that improve net carbon sequestration with a carbon payment/permit as long as the level of sequestration exceeds the level of emission. Thus, a carbon offset policy is more comprehensive than a cap-and-trade system because it simultaneously tracks emissions and differences in soil carbon sequestration both regionally and by production practice. Figures 2a and 2b illustrate the disparity between gross and net carbon emissions per acre. Gross average emissions per acre for Arkansas, California, Louisiana, and Missouri exceed the national average but those states' net footprints (emissions minus sequestration) are smaller than the national average (they sequester more). In Alabama and Texas, on the other hand, gross emissions per acre are lower than the national average but net average footprints are larger because they sequester less. Consequently, a policy that sets out to reduce the amount of carbon produced per acre and myopically analyzes only gross emissions could generate countervailing results. Cap-and-trade's reward for smaller emissions could encourage producers in Texas and Alabama to expand and net sequestering areas like California to shrink cotton production, increasing the net level of GHGs. A carbon offset policy attempts to address this important issue.

Carbon Offset Program

This study assumed that a carbon offset market would be constructed such that producers could sell only their net carbon footprints (emissions minus sequestration), not the carbon sequestered, and that the amount of carbon sequestered would have

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[6] This assumes that all producers have the same supply elasticity and does not take into account cross-price elasticities of other crops.

to exceed emissions per acre. These restrictions are important. Unlike a cap-and-trade policy that focuses solely on emissions per acre, the offset policy looks at both the amount of carbon emitted to produce an acre of cotton and the amount of carbon sequestered from the atmosphere during that production. Table 4 provides both average sequestration and net weighted-average emissions by county. Counties that had clay soils tended to sequester more carbon per acre than those with loamy or sandy soils.[7] Since biomass, and thus potential carbon to sequester, is correlated with yield, counties that historically have had greater yields typically sequester more carbon, *ceteris paribus*.

This study also assumed that producers are paid for the amount of net carbon that is sequestered and not for additionality.[8,9] That is, if a producer sequestered a ton of carbon, the value of that sequestered carbon, whether sold to a carbon bank or to a broker, would be worth an amount set by a monitoring entity. As previously mentioned, while cotton producers have the ability to switch to other crops that may be more profitable when a carbon offset market is introduced, this study focused solely on spatial and production differences in cotton. Table 4 and Figure 2b show state- and county-weighted average net GHG emissions and the associated confidence intervals. If these numbers are taken as fact, one can generate estimates of the financial opportunity for cotton producers in the offset market under different carbon prices. Given the historic average carbon price of $0.10 per ton on the Chicago Climate Exchange (CCX), even California producers who sequester the greatest amount of carbon (estimated as an average of 583.4 pounds per acre) (Table 4) would receive only approximately $0.03 per acre for their sequestered carbon. That degree of market signal likely would not be enough to change production methods or growing locations for a profit-maximizing producer. However, at a price of $20 per ton (EPA estimates that carbon prices in 2005 dollars 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 but would receive less if the additionality concept was employed. So even with a presumably unrealistic carbon price two hundred times greater than the current price, there would be only a marginal market signal to producers to change either the location where cotton is grown or the method of its production.

Table 5 disaggregates the counties in Mississippi, Tennessee, and Arkansas by production practice (tillage type) and profitability to determine whether a carbon price of $1 per ton of CE, which may be a more realistic short-term estimate than $20 per ton, would change the profitability rank of the production methods used.[10] In all instances, introduction of a carbon offset market with credits trading at $20 per ton does not change the relative profitability of tillage methods (nor does $1 per ton) (Table 5). Given the relatively small amount of net carbon sequestered, even a carbon offset paired with a high carbon price of $20 per ton is not enough of an incentive to change tillage methods within a county. Soil texture again seems to be the driving factor in capturing the benefits of sequestration. In Craighead County in Arkansas, for instance, profitability per acre is initially the same under low tillage for loamy and for clay soils at $60.30 per acre. Because clay generally can sequester more carbon than loam, introduction of an offset of $20 increases the profitability of the clay soil more (to $68.09) than the loam soil ($66.45) (Table 5). The difference is much smaller with a $1 per ton offset ($60.69 for clay and $60.61 for loam). These estimates again illustrate that a modest carbon price of $1 per ton of CE sends a weak signal to producers to alter where cotton is produced.

The data in Table 5 also can be used to estimate the inflection point at which a carbon price could hypothetically make a producer alter production. In Mississippi County, Arkansas, for instance, low-tillage is more profitable than conventional

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[7] Breakdowns of soil textures used for each county in the study are available from the authors upon request.

[8] The concept of additionality, included as a Clean Development Mechanism (CDM) defined in Article 12 of the Kyoto Protocol, provides for credits for emission reductions that are provided in addition to what would have otherwise occurred (Post et al. 2004). That is, if a producer is currently sequestering more carbon than it is emitting, it would not be rewarded for "business as usual;" it would have to lower its net carbon footprint beyond the current level to receive offset credits.

[9] Calculating payments based on additionality would require knowledge of historical crop rotations and information on net carbon footprints for the crop substitutes. Such calculations exceed the scope of this study but warrant further research.

[10] 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-till and no-till production. Thus, a profit per pound of carbon emitted could not be calculated for all states.

tillage on loam soils by an estimated $6.23 ($53.51 for low-tillage and $47.28 for conventional tillage) per acre, but low-tillage sequesters an estimated 58.51 (623.77 – 565.26) fewer pounds of carbon per acre. Therefore, a carbon offset price would have to rise to $212.96 per ton for a producer to be indifferent to production practice.[11] A lesser carbon price of $133.50 per ton would be required for clay soils in the same county to make producers indifferent to lower profitability from conventional tillage versus higher profitability (but a greater net carbon footprint) from low-tillage production, *ceteris paribus*. Given these results, if a large carbon market were to develop, it would be more likely to affect where cotton is produced (based on soil texture) than to affect the type of tillage. Under a realistic carbon price, a carbon incentive would likely fail to affect either location or production method.

Summary and Conclusions

This study set out to estimate the amount and variability of carbon-equivalent greenhouse gases emitted and the amount of carbon sequestered from cotton production on a mass per mass basis for the five counties that produce the most cotton in each of the top ten cotton-producing states. While a national carbon policy would have ramifications across crops as well as within a crop (growing locations and production practices), this study focused on cotton production in the United States and analyzed the potential effects of a federal carbon policy on growing locations and production practices. The estimates generated a suite of parameters (emissions per acre, dollars per unit of carbon emitted, and pounds of carbon sequestered per acre) that allows for comparisons of the effects of such a policy across states and within states by production practice and county. Using a cradle-to-farmgate life cycle analysis, the model estimated carbon from direct and indirect emissions, and the emissions were estimated per acre and 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 emissions from a life cycle perspective because of the energy required to produce nitrogen fertilizer and the N_2O it emits. The results of this analysis illustrated differences in emissions spatially and by inputs and production practices (tillage and irrigation).

This study also empirically highlighted the differences between a cap-and-trade policy and an offset policy. An emissions-based cap-and-trade policy could actually increase net emissions by rewarding practices and/or regions based solely on the gross level of emissions while ignoring the amount of carbon sequestered from the atmosphere during the biological life cycle of cotton. For example, Texas was estimated to have fewer emissions per acre than the national average and a *net* carbon footprint (emissions minus sequestration) that is greater than the national average. Those two factors combined suggest that a shift in acreage from a state like California, which had more emissions per acre but a smaller net carbon footprint than the national average, to Texas could increase the net emission of GHGs. Since agriculture is one of the few industries that can sequester carbon as part of the normal production process, issues of emissions versus sequestration must be given careful scrutiny when developing a policy aimed at improving environmental welfare.

From a cap-and-trade standpoint, the ratio of dollars of profit to pounds of carbon emitted per acre appears to be the factor that will drive geographical shifts in cotton production. Intuitively, one would think that areas with the greatest GHG emissions per acre would produce less cotton upon implementation of a cap-and-trade policy. However, with some cotton production methods such as center pivot irrigation (which involves high levels of fuel input) in areas like California where yields are relatively large, GHG emissions per pound of cotton are much closer to the mean of low-input, low-yield areas and production practices such as nonirrigated cotton in Alabama. Consequently, cap-and-trade will not necessarily reduce acreage in areas that require the most inputs; instead, it may reduce acreage in areas where the profit per unit of carbon released is the lowest.

From the standpoint of a carbon offset, estimates from this study show that even a high carbon price ($20 per ton of CE) will do little to change tillage methods within a county. High carbon prices would more likely affect where cotton is produced (based on soil texture). Under a moderate price expectation of $1 per ton of CE, such carbon-based incentives are unlikely to affect either where cotton

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[11] Calculated as $6.23 / $58.51 = $0.164 per pound × 2,000 pounds per ton = $212.96 per ton. Not included in this price was the cost of soil erosion or other offsetting benefits (environmental and economic) associated with no tillage.

is grown or how it is grown. When sequestration is part of a policy, soil characteristics will matter. Clay soils are expected to be more advantageous for carbon sequestration than sandy or loamy soils. While estimates of emissions by production type are relatively straightforward, estimates of sequestration will prove more problematic with a larger margin of error. Further research that reduces uncertainty as well as investigates various structures for carbon offset policies can provide useful insights to policy makers.

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