Summary of Life Cycle Inventory Data for Cotton

(Field to Bale – version 1.1 – 2 July 2009)

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Abbreviations Used in this Report

Bt	*Bacillus thuringiensis*
C_e	Greenhouse gas emission estimated in carbon equivalents (= CO_{2e} divided by 3.667)
CO_{2e}	Greenhouse gas emission estimated in carbon dioxide equivalents
GHG	Greenhouse gas
GJ	1 Gigajoule= 10^9 Joules = 1,000 MJ = 947,867 British Thermal Units (BTU)
Ha	1 Hectare = 10,000 square meters = 2.47 acres
LCI	Life Cycle Inventory
Mg	1 Megagram = 1,000,000 grams = 1 metric tonne = 2205 U.S. pounds
MTR	Energy embodied in Manufacturing, Transportation, and Repair of machinery
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

Introduction

This document is a summary of the publically available information and data on land, water and energy use, greenhouse gas emissions and ecosystem services for cotton production in the United States. The data are derived from U.S. government sources, United Nations documents and from publications in established, peer-reviewed scientific journals. This self-evaluation of cotton production's impact on the environment conducted by Cotton Incorporated forms the basis of a life cycle inventory (LCI) of the agricultural production of cotton, a prerequisite for conducting the more comprehensive life cycle analysis (LCA) of a cotton product.

All data sources and information used in the calculations throughout this paper are provided as Appendices A, B and C. Appendix A includes a summary of key resource impact metrics in different measurement units (English and metric), Appendix B contains additional information on the energy and GHG emissions data sources, and Appendix C provides a detailed explanation of how one set of the energy and GHG emissions estimates were derived.

Cotton Incorporated continuously reviews and works to improve cotton's environmental footprint. By its funding of agricultural research programs throughout the U.S., Cotton Incorporated assists growers in adopting technologies and practices that conserve natural resources and enhance grower efficiency. The research programs are highly valued by growers and have contributed significantly to cotton's environmental gains throughout the past 40 years. By way of example, based on the findings outlined in this summary, additional funding was directed toward the development of technologies and strategies to improve nitrogen and water use efficiencies during the cotton production. The results of these studies along with any additional data or information that we become aware of will be incorporated as revisions to this document.

Cotton Incorporated's summary of life cycle inventory data show:

Land – Cotton is very land efficient, meeting 36% of the world’s textile needs on 2.5% of agricultural land resources. Cotton is expected to meet future increases of fiber demand on fixed land resources as a result of continued yield increase (more cotton per unit of land).

Water – In the U.S., 64% of cotton is grown with naturally occurring rainfall. Most of the remaining acres receive partial or supplemental irrigation during low rainfall periods. Globally, cotton production accounts for 3% of the world’s agricultural water use, an amount proportional to cotton’s global agricultural land use of 2.5%. Cotton is a naturally drought and heat tolerant crop and provides many smallholder growers around the world with a source of income in places where few other crops can be grown.

Energy – From field to bale, cotton produces more net energy than is required for its production due to energy stored in the cottonseed.

Greenhouse Gas Emissions – Cotton has a neutral greenhouse gas (GHG) footprint when the carbon in the fiber and that stored in the soil is accounted for; when credit is given for the energy stored in the cottonseed, cotton actually captures more GHG emissions than those emitted.

Ecosystem Services - Cotton fields supply oxygen, provide habitat for wildlife and capture and store carbon. Cotton producers' are actively involved in numerous programs designed to protect ecosystems and safeguard wildlife habitat.

Land Use

According to the United Nations Food and Agricultural Organization (FAO, 2005), cotton fields represent approximately 2.5% of the world's agricultural land (Figure 1), and on this small bit of land 36% of the world's textiles are produced (Figure 2). This is possible because of cotton's consistent record of yield increase (production per area of land) throughout the last 40 years. In fact, the amount of land needed to produce 1Mg of fiber (1 Mg = 1 metric ton) is almost half of that required 20 years ago (Figure 3). Additionally, despite steep rises in demand over the last 40 years, cotton's global land requirements have essentially remained unchanged (Figure 4).

Although cotton's global land use has remained fairly stable, cotton yields and the land used for cotton production can vary depending on the region and the year. Environmental conditions, crop management practices and genetic potential contribute to this variation in yield. Figure 5 illustrates cotton yields (production per unit area of land) based on average production levels from 2005 to 2008 (Meyer et al., 2008; USDA, 2008a) for the overall world average, and then average yield levels in the U.S.

But cotton is more than just a fiber. Cottonseed, a valuable byproduct of fiber production is used in numerous food and industrial applications. For every kilogram of fiber produced, 1.5 kilograms of cottonseed are also produced (USDA, 2008a). In terms of land use it is difficult to properly value the benefits of this important byproduct because of the diversity of cottonseed uses and potential metrics used to assess their contribution (mass, biofuel potential, farm gate value, processed oil value, meal feed value, etc.). However, as illustrated in subsequent sections of this report, capturing the value of cottonseed is more straightforward when cotton production's energy use and greenhouse gas (GHG) emissions are evaluated.

Because of cotton's history of consistent technological advances in productivity (yield), cotton is expected to continue to meet demand now and in the future, despite the predicted limited availability of land.

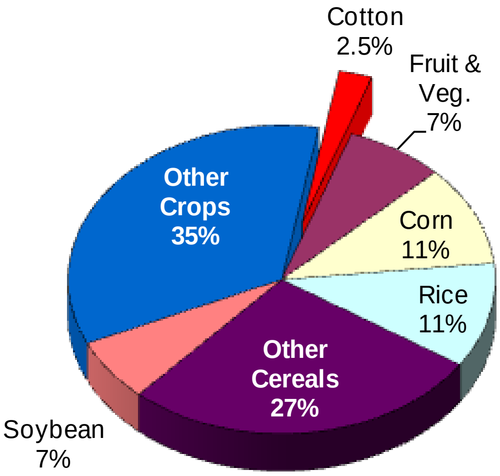

Figure 1 - Percentage of global agriculture land devoted to cotton and other crops (FAO, 2005)*

**totals more than 100% due to rounding*

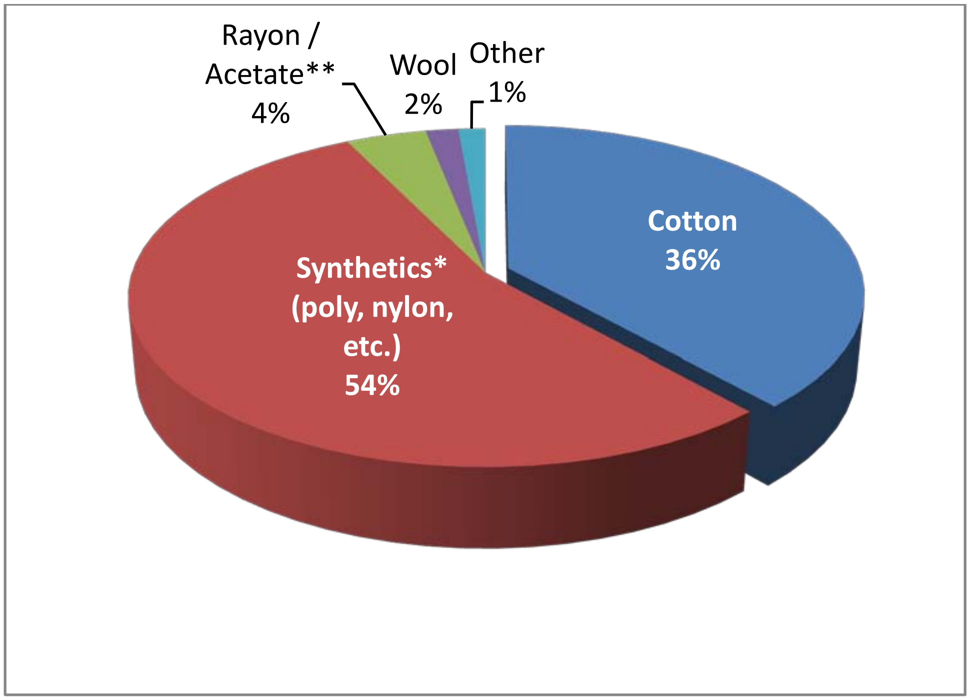

Figure 2 - World textile demand (70 million Mg total fiber use) (National Cotton Council, 2009)

*Synthetics from fossil organic compounds – polyester, nylon

**Synthetics from plant organic compounds - rayon

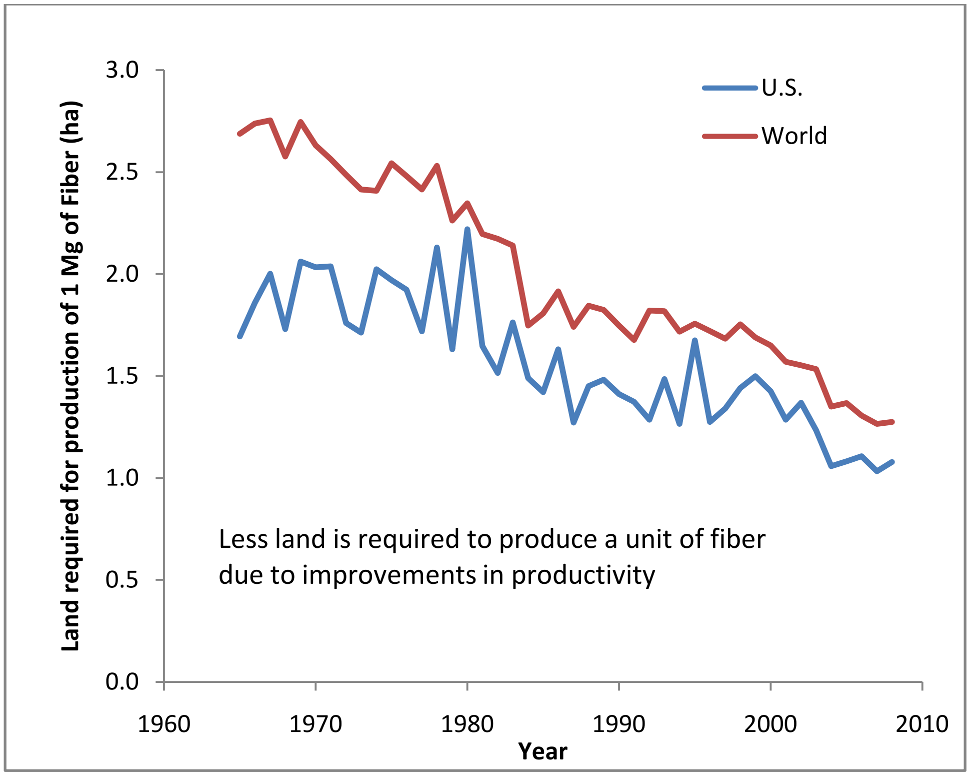

Figure 3 - Land required for the production of 1 Mg of fiber (1 Mg = 1 metric ton) (Meyer et al., 2008)

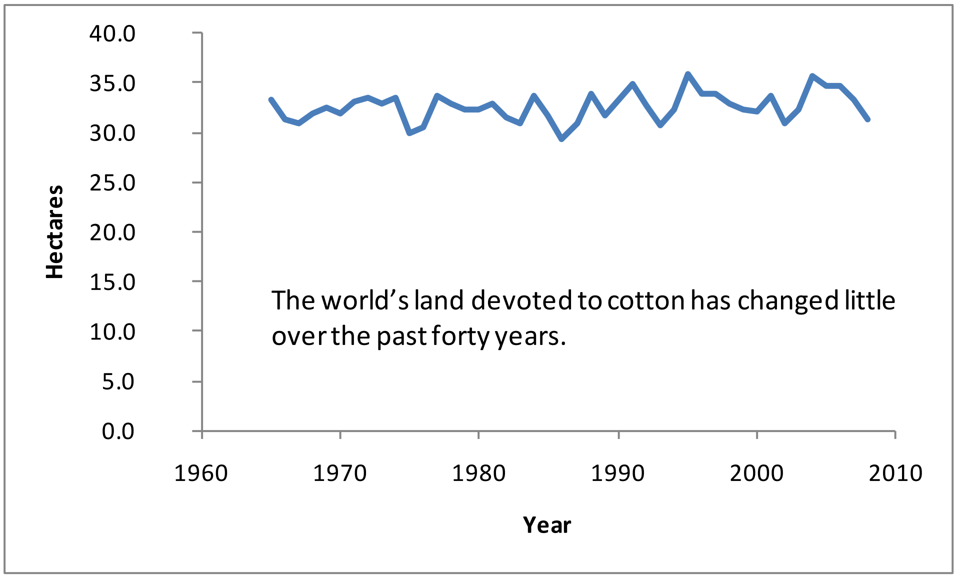

Figure 4 - Global land area devoted to cotton production (1960 – 2010) (Meyer et al., 2008)

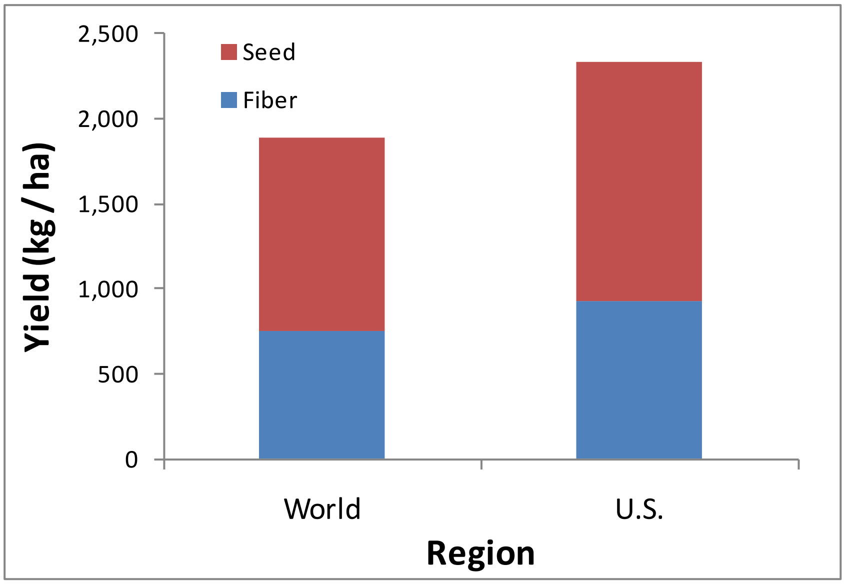

Figure 5 - Average cotton yields for the world and the U.S. from 2005 to 2008 (**Meyer et al., 2008**)

Water Use

Based on data from the United States Department of Agriculture's (USDA) Farm and Ranch Irrigation Survey (USDA, 2004), an average of 4,270 cubic meters of water per hectare (0.36 hectare-meters) were applied to irrigated cotton in the U.S. While one might imagine that irrigation levels would vary widely from year to year, the data indicates that over time the national average use of irrigation in cotton has been following a steady downward trend. The most recent USDA Agricultural Census data also indicates that in 2007 approximately 1.4 million hectares, representing only 36% of U.S. crop acres, were irrigated. Distributing U.S. irrigation water use across total US production (all lint produced non-irrigated and irrigated), **the irrigation water for the U.S. is 1800 cubic meters per Mg(1 Mg = 1 metric ton) of fiber produced or 725 cubic meters of irrigation water per Mg of fiber and seed produced.** From a global perspective, it is estimated about 50% of the world's cotton receives irrigation but the situations vary widely. In one place the crop may be completely dependent on irrigation, and in another, the crop may require only supplemental irrigation with most water coming from rainfall (Chapagain et al. 2006). Whether by rainfall or through irrigation, cotton's share of the global agricultural water footprint is 3% (Hoekstra and Chapagain, 2007), an amount proportional to cotton's global land use footprint of 2.5%. And this water produces not only fiber but valuable cottonseed as well. It is also important to note that cotton is a drought tolerant plant and can be productive in hostile environments, providing a livelihood for farmers where few other crops can be produced. For example, in West Texas, research has shown that because of cotton's lower water requirements, water use by agricultural overall would actually decrease if more of the area currently devoted to the production of other crops would be transitioned to cotton (Gowda et al., 2007).

Energy Use

There is no doubt that energy resources will be limited in the future, and optimizing cotton's energy use will continue to be an important priority. The blue bar of Figure 6 represents the average amount of energy required to produce cotton from planting through the ginning process as reported in four different studies. The green bar of Figure 6 represents the gross energy content associated with the cottonseed produced from the lint. Note that even with 60% energy conversion efficiency, the energy in the seed equals the amount of energy needed to produce the crop.

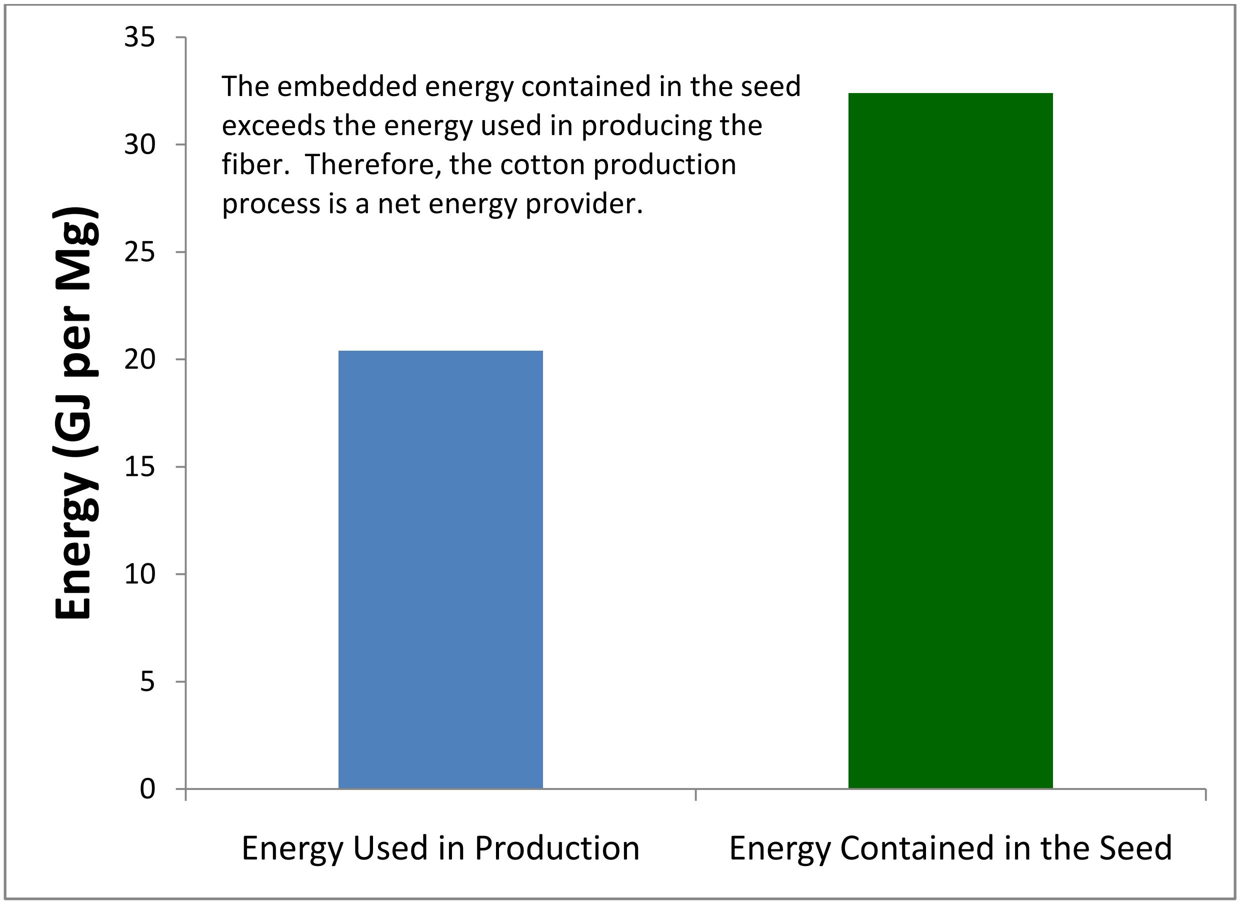

Figure 6 - Energy use estimates for U.S. cotton production and gross energy content of the seed associated with the fiber

Source: Energy required is average of four studies – see section entitled Energy Use and GHG Emission Data Sources in text below and Appendix B. Energy content in the seed based on results of samples analyzed by Minnesota Valley Testing Laboratories, Inc.

Greenhouse Gas (GHG) Emissions

Estimates of GHG emissions produced during cotton production are shown in Figure 7 (kilograms of carbon dioxide equivalents emitted per kg of cotton fiber produced). The amount of carbon stored in the fiber and soil (green bar) exceeds the total GHG emissions that occur while growing and ginning the crop (blue bar). The green bar represents the 42% carbon content of the cotton fiber plus the carbon that is stored in the soil (Causarano et al., 2006). If credit were given for the amount of biodiesel that could be produced from the cottonseed oil and the carbon emissions from petroleum diesel were replaced with biodiesel (~0.6 kilogram CO_{2e} per kilogram of fiber –see Appendix B for details), then cotton production from the field to the bale actually has higher stored GHG than portrayed in Figure 7.

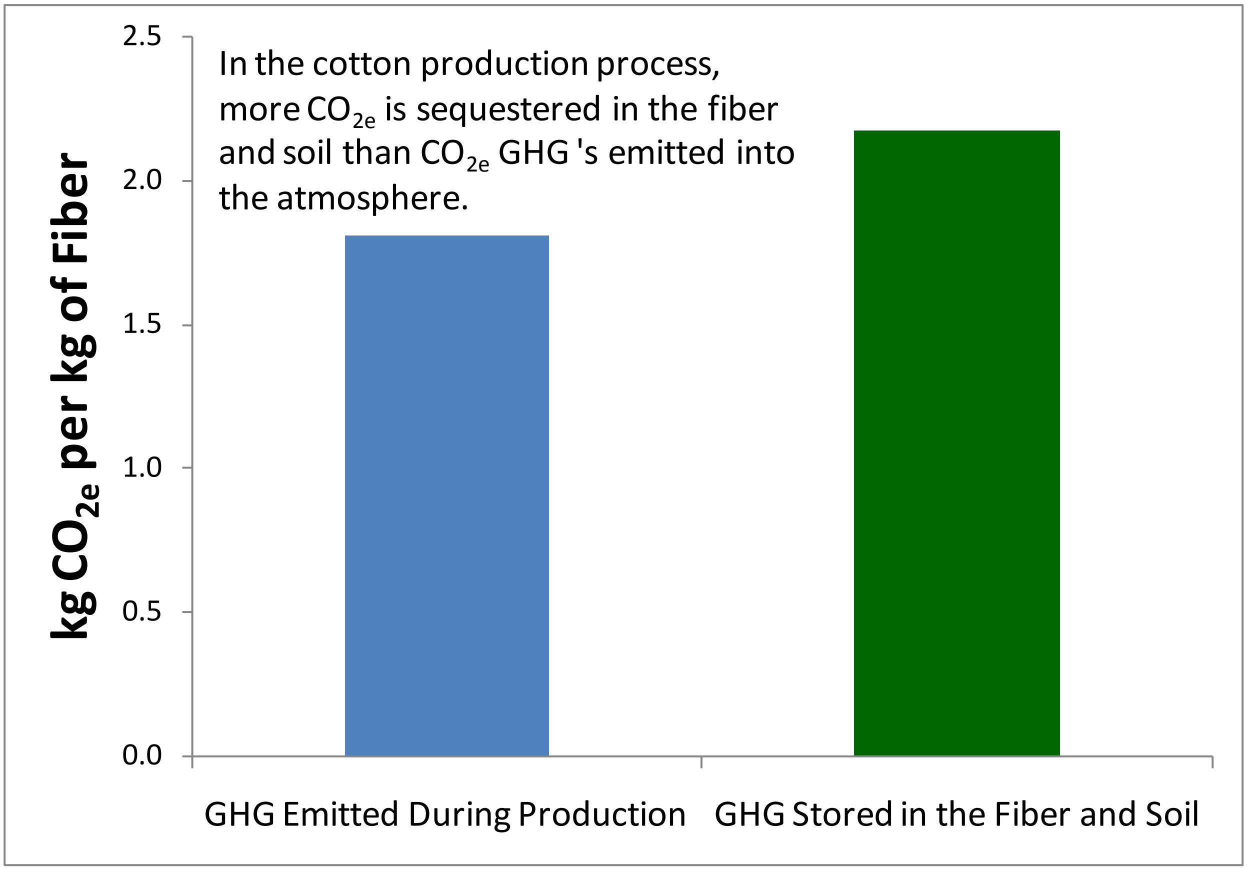

Figure 7 - Greenhouse gas emissions from U.S. cotton production, and GHG reductions due to carbon stored in the fiber and soil

Source: GHG emissions based on average of data from four studies see section entitled Energy Use and GHG Emission Data Sources in text below and Appendix B.

Energy Use and GHG Emission Data Sources

Three recently published studies and Cotton Incorporated's 2008 grower survey examines U.S. cotton's impact on energy and air resources. A study by Nelson et al. (2009) evaluated the energy use and greenhouse gas emissions of different tillage systems for different crops in the U.S., including cotton. This study is published in a peer reviewed scientific journal and was conducted without input or funding from Cotton Incorporated (it was funded largely by the U.S. Department of Energy).

A second study was released in 2009 by a collaborative group of agricultural producers, food and retail companies, conservation organizations and agribusinesses. This 35 member group called Field to Market: The Keystone Alliance for Sustainable Agriculture, developed natural resource indicators (land, water, energy use, soil loss, GHG emission) to examine U.S. agriculture's impact on the environment over the last 20 years from the production of corn, soybeans, wheat and cotton (Keystone, 2009). The development of the natural resource indicators and the study's results are based on publically available USDA data. Cotton Incorporated is a member of the Field to Market Alliance.

Cotton Incorporated funded engineers and scientists at the Center for Agricultural and Rural Sustainability at the University of Arkansas to evaluate U.S. cotton's energy and GHG footprints to help guide future research and enable U.S. cotton producers to continue making strides in reducing cotton production's impact on natural resources. Work is currently underway to prepare a manuscript of the Arkansas study for submission into a peer-reviewed scientific journal (Matlock et al., 2008; Matlock et al., 2009).

Finally, data on 2007 agricultural chemical use in cotton (USDA, 2008b) were used in combination with energy and agricultural GHG emission factors from West and Marland (2002), and Cotton Incorporated's Natural Resource Survey (Reed, et al., 2009) to develop an additional evaluation of energy use and GHG emissions using the most current available data. Details on the methods used to combine these data sources are given in Appendix C.

Average results from these four studies are used in Figures 6 and 7, and specific values from the individual studies are reported in Table B.1 of Appendix B to this report.

Ecosystem Services

Quantifying cotton's impact on ecosystem services (benefits that people obtain from ecosystems such as freshwater, timber, climate regulation, erosion control, and recreation) is a difficult metric to develop because of the numerous groups monitoring and collecting data and the myriad methodologies being utilized. Cotton Incorporated, along with many others, is evaluating several different approaches to quantify ecosystem impact. Measuring agriculture's impact on water quality is one such approach. The data source under consideration to measure impact on water quality is the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) program (Toccalino, 2007). This program regularly monitors water quality and tests for agricultural compounds in surface and ground waters. Based on USGS reports that monitor the number of nitrate and pesticides found to be above human health levels in surface and ground water, incidences of contamination of surface and ground water by fertilizers or pesticides are rare in the U.S. [see Table 2.3 of Keystone (2009)].

Thriving ecosystems are essential for the health of habitat upon which wildlife depends. U.S. cotton producers concern for ecosystems and wildlife habitat is evidenced by growers' enrollment in a number of USDA wildlife and environmental conservation programs such as the Conservation Reserve Program (CRP), the Environmental Quality Incentives Program (EQIP), Wildlife Habitat Incentives Program (WHIP), Highly Erodible Land and Wetland Conservation (HELC-WC), Conservation Security Program (CSP) or other regional and local conservation programs such as Ducks Unlimited or Delta Wildlife. According to Cotton Incorporated's Natural Resource Survey (Reed, et al.,2009), 39% of growers participate in EQUIP and 34% of growers participate in CRP. These programs make a difference as 62% of cotton producers reported an increase in wildlife in and around their cotton fields over the last 10 years (Reed et al., 2009).

Improved water quality and wildlife habitats are in large part the result of the steady decline in the number of insecticide applications and overall use of pesticides since the mid-1990's (Figure 8). In 2007, 34% of U.S. cotton acres did not require a single insecticide application (USDA, 2008b). This is due to the success of the boll weevil eradication program and an increase in the adoption of Bt cotton.

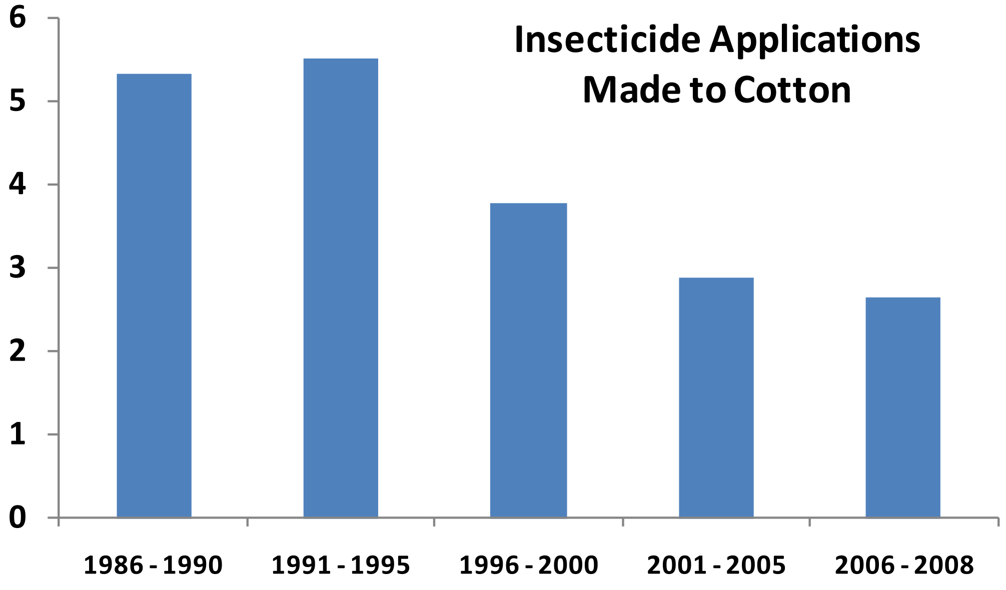

Figure 8 - Number of insecticide applications made to U.S. cotton (National Cotton Council, 2009).

There are examples where modern cotton production systems are actually restoring ecosystem services. In studies of the Beasley Lake watershed in the Mississippi delta region of the U.S., Locke et al. (2008) report: "Applying combinations of conservation practices can significantly reduce nonpoint source pollution. For example, converting row crops to reduced tillage and transgenic herbicide-resistant crops in BLW reduced suspended sediment (70% reduction), total phosphorus (41% reduction), and pesticide concentrations in lake water. Corresponding increases in Secchi visibility (97%) and chlorophyll *a* (a primary productivity indicator) likely contributed to improved fish productivity (e.g., fish weight increase comparing 1998 and 2004: *Micropterus salmoides* 87%, *Lepomis macrochirus*, 65%) during this period."

While this is only one example for the U.S., such improvements are occurring in cotton production systems around the globe as recently summarized by Naranjo (2009). For example, Naranjo (2009) reports reductions of insecticide applications in the range of 40 to 60% in China, Australia, South Africa, Argentina and Mexico due to the adoption of insect resistant cottons. Since the adoption of Bt cotton in 1997 the volume of insecticide use in China has decreased 34.5% (Brookes, 2009). And James (2008) reports that according to the Center for Chinese Agricultural Policy (CCAP), small farmers adopting Bt cotton increased yield by 9.6% and reduced insecticide use by 60% (James, 2008). Bt cotton has also had a substantial positive impact on pesticide use in India. In 1998, Indian cotton pesticides represented 30% of the total pesticide market, whereas in 2006, that number had fallen to only 18% (James, 2008). Similarly, cotton insecticides represented 42% of the total Indian insecticide market in 1998 compared to 28% in 2006 (James, 2008). Further, in the five years from 2001-2006 (years of highest rate of Bt cotton adoption), pesticide sales in India decreased by 22% (James, 2008).

Globally, the 23% reduction in insecticide use attributed to the use of Bt cotton is greater than that recorded for any other Bt crop (Brookes, 2008). Importantly, of the associated increase in environmental benefits from Bt adoption, over half occurred in developing countries (Brookes, 2008). Despite these gains, there are situations where crop protection products must be used. When pesticides are used, regulations established by the USDA, U.S. Environmental Protection Agency (USEPA) and U.S. Food and Drug Administration (FDA) ensure that they are used in a manner that minimizes environmental impact. The USEPA requires an extremely cautious approach to use of plant protection products. For regulatory approval, every product and its use undergoes rigorous testing to assure safety to humans, animals, and the environment. In fact, in 2007 the USEPA completed its 10 year review of pesticides as mandated by Congress' Food Quality Protection Act. The law required a re-review of every plant protection product and imposed additional factors to mitigate any uncertainties as to their safety. Where products failed to meet updated and stricter precautionary environmental and health standards, registration and use of such products in the U.S. was not allowed.

While developing a clear metric to measure ecological services is an ongoing challenge, current outcome based indicators support a trend of lower impact of cotton production on ecosystem services.

Ongoing improvements

The primary goal of Cotton Incorporated’s use of LCA techniques is to evaluate cotton’s environmental footprint and identify areas for improvement. As part of that process we have evaluated the relative contribution of different inputs and components of the cotton production process to identify where our largest resource use occurs. For example, Table 1 shows the total and relative amount of energy use by production activity for three different production scenarios, each representing different environments in the U.S. Details on the methodology used to make these estimates are included in Appendix C. The first column represents a non-irrigated production system that is representative of many areas of the mid-south and southeast with typical rainfall patterns. The second column represents the same geographic area where supplemental irrigation is used, while the third column represents a more irrigation intensive production system that would be representative of West Texas.

In all three production systems, particularly the first two, fertilizers represent a large portion of cotton's energy footprint, largely due to energy associated with nitrogen. While Cotton Incorporated has a long history of funding nitrogen management research, upon seeing that nitrogen use has the greatest impact on energy and GHG emissions (GHG emissions closely parallel energy), greater efforts were directed towards improving nitrogen use efficiency. Researchers are now: 1) evaluating on-the-go sensors that measure and adjust the crop's nitrogen requirement in real-time; 2) conducting nitrogen management recommendation validation trials in 10 states; 3) searching for nitrogen fixing cover crops adapted to a wide range of environments; 4) exploring traditional breeding techniques in hope of finding a cotton plant that requires less nitrogen.

A second area that will also require ongoing attention is the impact of irrigation on cotton's overall environmental footprint. Not only are water resources becoming limited in many areas of the U.S. and the world, the energy associated with pumping irrigation water can quickly dominate cotton's energy footprint. For example, the second column of Table 1 shows the divisions of energy use in an irrigated system where supplemental irrigation is applied from a shallow well. In this scenario, irrigation is a small part of cotton's energy inputs (column 2, Table 1). However, when 250 mm of irrigation water is applied from a pumping depth of 90 meters the energy requirement of irrigation increases nearly 50% relative to a non-irrigated system (12.68 Gj/Mg to 19.22 Gj/Mg). Therefore, in areas where pumping from deep wells is required, investment in renewable energies (wind or solar) could be a feasible way for producers to manage future energy costs as well as to lower their carbon emissions. Note that some cotton producers obtain irrigation water from reservoirs rather than wells. In this situation the energy partition from irrigation would be very low since drawing water from a reservoir requires less pumping than from wells. In some areas, irrigation will continue to be an important part of an efficient production system. In arid areas, the highest yields are achieved by proper irrigation ensuring a consistent level of production and maximum land use efficiency. In more humid regions, a small amount of irrigation at the right time can prevent significant yield loss and provide a stable supply of quality fiber and cottonseed from year to year.

Efforts to improve nitrogen and water use efficiency make good business sense as well. All sources of energy will be very expensive in the future and minimizing cotton’s energy footprint will increase the cotton producers' profitability.

Table 1 - Total energy requirements and percent energy requirement of major processing events for three U.S. cotton production scenarios

	Production Scenario		
	Non-irrigated	**Irrigation: 50 mm; 9 meter pumping depth**	**Irrigation: 250 mm; 90 meter pumping depth**
Total Energy Input (GJ per Mg fiber produced)	*12.7*	*13.8*	*19.2*
Yield (Mg per ha)	0.8	1.1	1.7
Source:	**Percent of Total Energy Usage**		
Planting Seed Production	3%	2%	1%
Tillage	10%	8%	4%
Fertilizers*	**48%**	**50%**	35%
Crop Protection Products*	18%	17%	11%
Harvest	10%	7%	3%
Ginning	12%	13%	9%
Irrigation	0%	3%	**37%**
Total	**100%**	**100%**	**100%**

* Includes energy embedded in the compounds, and energy required to apply to the field.

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Appendix A. Summary of units of measure and U.S. cotton data sources

One of the challenges in evaluating LCI data is that it has not always been reported in a common format. Table A.1. is a summary of the key metrics used throughout the main report using the reference data below and provides a comparison of values for different units of measure.

Table A.1. Summary of metrics used for U.S. cotton land, energy, GHG, and water use calculations

Land	Units:	kg/ha	lb/acre	ha/kg	ha/Mg*
	Fiber:	933	833	0.0011	1.072
	Seed:	1,403	1,250	0.0007	0.713
	Fiber + Seed:	2,336	2,083	0.0004	0.428

Water	Units	cubic meters per Mg	L / kg	lb/acre-in	gal/lb
	Irrigation and fiber produced	1811	1811	125	217
	Irrigation and (fiber + seed produced)	725	725	313	87

Energy	Units (per mass of fiber produced):	GJ/Mg	BTU/lb	MJ/kg	MJ/lb
	To produce fiber:	**20.4**	**8,767**	**20.4**	**9.2**
	Stored in seed:	**32.4**	**13,924**	**32.4**	**14.7**

Air	Units (per mass of fiber produced)	kg CO_{2e}/kg	lb CO_{2e} / lb	kg C_e/kg	kg CO_{2e}/lb
	GHG Emissions:	**1.8**	**1.8**	**0.49**	**3.97**
	Stored in lint & soil:	**2.2**	**2.2**	**0.59**	**4.78**

A summary of the references for Table A.1.:

- **Land** – Fiber data from Meyer et al. (2008); Seed data from USDA (2008a).
- **Energy** – Mean of the data reported in: Keystone (2008); Matlock et al. (2008); Nelson et al. (2009); West and Marland (2002) and Reed et al. (2009)
- **GHG** – Mean GHG emissions from averages reported in: Keystone (2008); Matlock et al. (2009); Nelson et al. (2009); West and Marland (2002) coefficients combined with Reed, et al. (2009)
- **Water -** USDA (2004).

Additional details on assumptions needed to summarize these data are provided in Appendix B.

Appendix B. Data sources used to derive energy use and GHG emissions estimates for U.S. cotton production

Values for energy use and GHG emissions during U.S. cotton production were derived by averaging data from four individual studies. The studies and data are listed in Table B.1. below and are the basis for Figures 6 and 7 in the main report.

Table B.1. References used to estimate the energy and greenhouse gas emissions associated with the production of one Mg of cotton fiber in the U.S.

Study	**Energy (GJ/Mg)**	**GHG emissions (kg CO_{2e} kg^{-1})**
Nelson et al. (2009)	19.4	1.3
Matlock et al. (2008; 2009)	26.6	2.2
Keystone (2009)	15.6	1.5
Appendix C*	20.0	2.2
Average	**20.4**	**1.8**

**Applying coefficients from West and Marland (2002) to data from the USDA (2008b) and Cotton Incorporated's 2008 Natural Resource Survey (Reed, et al., 2009). See Appendix C for details. Other details specific to each study are noted in the text below.*

None of the studies listed in Table B.1 included the energy use or greenhouse gas emissions from transport of cotton to the gin or the ginning process itself. Therefore, data on U.S. ginning energy use from Valco et al. (2009) were used to add an additional energy use of 1.8 GJ per Mg of fiber and 0.2 kg of CO_{2e} per kg of fiber to all of the studies estimates to accurately portray the total footprint to a bale ready for delivery to a textile mill (Table B.1 includes these additions). More detail on how these values were derived is provided in Appendix C.

The **Nelson et al. (2009)** data used was reported in their Table 1 for the 2004 crop year. As data were reported on a per hectare basis, the average U.S. fiber yield of 944 kg per hectare in 2004 (Meyer et al., 2008) was used to convert to a units of GHG and energy use per unit of fiber produced.

Matlock et al. (2008) reported energy required per unit of seed and fiber produced. A 40% lint percentage was used to convert to energy per unit of fiber. This corresponds to 1.5 units of seed per unit of lint produced. The 1.5 value was computed by calculating the ratio of total U.S. seed production as reported by the USDA (2008a) to total fiber produced as reported in Meyer et al. (2008) for the 2004 to 2008 crop years and using the average ratio calculated for that time period.

Soil carbon data used for Figure 7: Causarano et al. (2006) provided an average amount of carbon stored in the soil in no-tillage cotton fields from numerous published studies in the southeastern U.S. as 0.67 Mg C per ha per year (2.6 CO_{2e} per ha per year). Data from Cotton Incorporated's 2008 Natural Resource survey indicate that about one-third of cotton producers are using no-till, so the value used was divided by 3 (=0.63 CO_{2e} per ha per year).

Carbon off-sets due to cottonseed: The estimates of GHG emissions for cotton production include emissions associated with the production of both the fiber and the cottonseed since no additional production steps are required to obtain cottonseed; during the production of a kg of fiber, 1.5 kg of cottonseed is produced. Cottonseed has an oil content of 14% and is highly valued as a feed ingredient. Therefore, it is reasonable to claim a credit for the energy embodied in cottonseed. One approach to take in estimating the credit is to calculate the amount of biodiesel that could be produced from the oil in the seed, and then calculate the amount of CO_{2e} that would be eliminated if that amount of petroleum-based diesel were replaced with the biodiesel. Using the previously noted production of 1.5 kg of seed for every kg of fiber produced, and 14% oil content in the seed, approximately 0.24 liters of cottonseed-derived biodiesel could be produced for every kg of fiber produced (1.5 kg x 0.14 = 0.21 kg of oil x 1.14 liter of oil per kg oil = 0.24 liters of fuel). This has the impact of preventing the emission of 0.64 kg of $C0_{2e}$ due to petroleum diesel savings [using the diesel CO_{2e} emission factor at point of combustion from West and Marland (2002) and an assumed diesel energy content of 0.0387 GJ per liter]. That is, if a cotton producer used biodiesel from his cottonseed, his GHG emissions would be reduced by 0.64 kg of $C0_{2e}$.

Appendix C. Methods used to derive energy use and GHG emissions estimates for U.S. cotton production

West and Marland (2002) provided an extensive list of energy use and greenhouse gas emission factors for agricultural operations in the U.S. These factors were used in combination with USDA reported information and data from the Cotton Incorporated's Natural Resource Survey (Reed, et al., 2009) of U.S. cotton producers, conducted by OrgWide Services on behalf of the U.S. cotton industry in 2008 to provide a current estimate of U.S. cotton's energy and GHG footprint. The following narrative describes estimates of energy and GHG emissions in sequential order of cotton production (from planting the seed through harvest and ginning). The resulting energy and GHG values from the combined information are summarized in Table C.1.

Land Preparation and Planting

Data from the Natural Resource Survey indicates that on average, U.S. cotton producers conduct three tillage operations per year, and that only 46% conduct any deep tillage operations. This is also consistent with the Natural Resource Survey statistic that two-thirds of U.S. cotton producers report they are using some form of conservation tillage practices. Therefore, to characterize tillage operations, one operation was assumed to be a deep tillage operation but only at a rate of every other year. This accounts for the fact that only 46% of producers are using deep tillage, and from a case study perspective, many producers who do use deep tillage often only do so every other year. An estimate of deep tillage fuel use was taken from Raper and Bergtold (2007) as this operation was not included in West and Marland (2002). An estimate of carbon emissions was developed by using the ratio of carbon emissions to energy use for a moldboard plow of West and Marland (2002) and multiplying that ratio by the energy use associated with deep ripping [(26.75 kg C_e/ha/(1122+102MJ) = 0.0219 kg C_e / (ha MJ)]. The final two tillage operations were represented by one pass with a disk and one cultivation. The energy values used include both the diesel fuel use of the operation and the energy embodied in manufacturing, transportation and repair of the machinery associated with the operation (MTR).

West and Marland (2002) provide estimates of 33 MJ of energy and 0.65 kg of C_e emissions per kg of cotton planting seed used. An optimal planting rate of 100,000 seed per ha is typical of university

Cooperative Extension Service recommendations in the U.S. (e.g., NCSU 2009) and current cotton seed varieties tend to average 11,000 seed per kg (e.g., http://www.deltaandpine.com/dp/products/srg), resulting in a planting seed rate of 9.0 kg per ha.

Within-Season Management

In order to represent a "typical" cotton farm, the total irrigation water used for cotton was as reported in USDA (2004) and then distributed across all cotton acres, resulting in an average depth of irrigation water applied of 15 cm. An average pumping dept of 63 m at an operation pressure of 69-kPa was based on responses from Reed et al. (2009) for irrigated fields. Table C.2 provides additional details on how the total irrigation energy and GHG values were derived for Table C.1.

All chemical use rates are based on data from the USDA (2008). For pesticide use and other chemicals, an average of energy and GHG data of the herbicide, insecticide and fungicide values reported in Table 4 of West and Marland (2002) was used. An exact figure for lime use by cotton producers in the U.S. is not reported by the USDA; however, the USDA Economic Resource Service reports that only 34% of cotton acres were ever treated with lime (2003 survey data from http://www.ers.usda.gov/Data/ARMS/app/Crop.aspx) and this value was in strong agreement with the fact only 37% of producers in the Natural Resource Survey survey (Reed et al., 2009) report lime applications. In West and McBride (2005), they suggest approximately 30 Tg of lime was applied to all U.S. agricultural crops in 2001. Assuming approximately 125 million ha of U.S. crop land, this corresponds to an average annual lime use of 238 kg of lime per ha. Such a rate is reasonable – for example, assume a typical field that does require lime receives 2420 kg per ha every three years or 807 kg per ha per year. Noting 34% of cotton acres are treated with lime, a "typical" value of 274 kg per ha per year was used in this analysis. The previous values discussed did not include applications for the fertilizers and other chemicals. The Natural Resource Survey data indicate that on average, producers made a total of 6 chemical applications per year (pesticides, growth regulators and harvest aids) and values taken directly from Table 7 in West and Marland (2002) were used in the calculations shown in Table C.1.

Harvest and Ginning

Cotton harvest data were not reported by West and Marland (2002); therefore, fuel use data from Willcutt and Barnes (2008) were used to estimate harvest energy use with the MTR for harvest with a combine from Table 7 of West and Marland (2002). Transportation energy to take the cotton from the field to the gin is from Hamann et al. (2008). Ginning energy use was based on data reported in Valco et al. (2009).

Soil Nitrous Oxide Emissions

The Intergovernmental Panel on Climate Change (IPCC) assumes in their 2001 Third Assessment Report that 1% of nitrogen applied to soil is emitted as N_2O, although this amount varies significantly based on soil type, soil conditions and climate, as well as amount and timing of application. Snyder, et al. (2007) applied some of these variables to the IPCC value of 1% and determined that 1% was equivalent to 1.27 kg C_e per kg N. Based on a nitrogen use rate in cotton of 94.4 kg/ha, the total carbon equivalent emissions for nitrogen use is 119.8 kg C_e/ha, a value that represents 21% of the total GHG emissions during cotton production (Table C.1.). However, a high level of uncertainty exists as to the magnitude of N loss as N_20 (see review by Snyder et al., 2007 and Rochette and Eriksen-Hamel, 2008) and it is likely that the default IPCC factor could be less than 1% (1.27 kg C_e per kg N) for U.S. cotton production. Indeed, both USDA ERS Resource Management Survey (ARMS, see http://ers.usda.gov/Data/ARMS/app/Crop.aspx, data for the 2003 cotton season) and Natural Resource Survey data support:

- Cotton producers are very aware of the potential losses associated with nitrogen application and a majority, 73% (ERS) apply nitrogen after planting to minimize losses,
- a majority, 80% (ERS), incorporate nitrogen fertilizers into the soil to minimize losses due to nitrogen volatilization,
- Cotton producers use soil testing extensively (86% of Natural Resource Survey respondents) to determine fertilizer rates to insure the proper amount is applied.

All of these factors contribute to increased nitrogen use efficiency and would likely lower any nitrous oxide emissions that may occur during U.S. cotton production. Note that approximately the same value for nitrous oxide emissions was assumed for the GHG estimates from the Keystone (2009) and Matlock et al. (2009) studies, but not in the values reported by Nelson et al. (2009).

Relationship between per area and per mass basis

In order to translate data between a per hectare basis and per mass of fiber basis, a yield of 933 kg cotton per ha was used (2004 to 2008 average U.S. fiber yield from Meyer et al., 2008). Using this yield, the per hectare values of Table B.1 corresponds to **20 MJ of energy and 2.2 kg CO_{2e} equivalent emissions on the basis of kg of cotton fiber produced.**

Note GHG emissions values are expressed in units of C_e that in Appendix C, according to nomenclature of West and Marland (2002); however, the term carbon dioxide equivalents (CO_{2e}) was used in the main body of this report as recommended by Bowman et al. (2009), who advocates using $C0_{2e}$ to reference all GHG emissions.

Table C.1. Estimates of energy use and carbon emissions from a typical U.S. cotton field

Input	Energy Value	Energy Units	Carbon value	Carbon Units	Use Rate	Use Rate Units	Total Energy (MJ per ha)	Total C_e (kg C_e per ha)
Tillage Operations & Planting:								
Deep tillage (46%)	604	MJ/ha	13.29	kg C_e / ha	0.5	per year	302	6.6
Disk	400	MJ/ha	8.72	kg C_e / ha	1	per year	400	8.7
Cultivate	210	MJ/ha	4.57	kg C_e / ha	1	per year	210	4.6
Plant	312	MJ/ha	6.79	kg C_e / ha	1	per year	312	6.8
Planting seed	33	MJ/kg	0.65	kg C_e / kg seed	9.0	kg / ha	296	5.8
Within-season management								
Irrigation	5124	MJ/ha	175.06	kg C_e / ha	*See Table C.2*		5124	175.1
Total chemical use (excludes fertilizers)	280	MJ/kg	4.94	kg C_e / kg AI	5.72	kg AI/ha	1601	28.2
N	57	MJ/kg	0.86	kg C_e/ kg N	94.4	kg /ha	5422	80.9
P_20_5	7	MJ/kg	0.17	kg C_e / kg P_20_5	32.7	kg /ha	229	5.4
K_20	7	MJ/kg	0.12	kg C_e / kg K_20	41.1	kg /ha	282	4.9
$CaCO_3$	2	MJ/kg	0.04	kg C_e/ kg $CaCO_3$	238.0	kg/ha	407	8.5
Fertilizer application	566	MJ/ha	12.35	kg C_e / ha	1.0	per year	566	12.4
Other chemical applications	119	MJ/ha	2.54	kg C_e / ha	6.0	per year	714	15.2
Harvest and Ginning								
Harvest (pick and module)	1128	MJ/ha	24.44	kg C_e / ha	1.0	per year	1128	24.4
Transport to gin	113	MJ/ha	2.48	kg C_e / ha	1.0	per year	113	2.5
Ginning	1572	MJ/ha	47.47	kg C_e / ha	1.0	per year	1572	47.5
Soil emissions								
Nitrous Oxide	na		1.27	kg C_e / kg N	94.4	kg /ha	na	119.8
Totals							**18,679**	**557**

Table C.2. - Calculation of weighted average of irrigation energy and GHG emissions for a typical U.S. cotton farm.

Energy Source	Energy Source [1] (%)	Energy Required [2] (MJ per ha)	GHG Emission [3] (kg C per ha)
Electricity [4]	55%	4,720	236
Natural Gas	21%	6,498	94
Diesel	24%	4,850	106
Weighted Average		**5124**	**175**

[1] Based on Table 5 of West and Marland (2002)

[2] Based on energy needed to pump 15 cm of water per ha from an average dept of 61 m at an operating pressure of 69 kPa using equations 19.1 and 19.2 of Hoffman et al. (1992)

[3] Using the same ratio of kg C to GJ energy of Table 5 of West and Marland (2002)

[4] Actual energy used at pump = 449 kWh. The U.S. Deparment of Energy reports actual energy use values of 10.5 MJ per kWh for the U.S. in 2004 (http://www1.eere.energy.gov/ba/pba/intensityindicators/delivered_electricity.html)

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