# CHAPTER 5. Cottonseed Oil Biodiesel

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# 5.1 Cottonseed Background and Overview

## *5.1.1 Introduction*

The cotton plant (genus *Gossypium*) is a member of the Malvaceae, or mallow, family. In its native form, cotton grows as a perennial, but it is cultivated as an annual crop in the United States. There are dozens of cotton species native to both the Eastern and Western hemispheres and the use of cotton fibers can be traced back thousands of years in present-day Peru and Egypt. Fibers grow from and are attached to the seeds, which are contained within a capsule called a boll that forms after the cotton plant flowers. As the plant matures, the bolls open to expose the fibers and seeds (Figure 5.1). While propagation of the cotton plant is driven by demand for fiber to make cloth, the seeds of the cotton plant are also valuable as a food source. Oil extracted from the seeds is used for human consumption and the residual meal is fed to livestock. In recent years, uncrushed cottonseed also has been provided directly to cattle as feed. The typical ratio of seed to fiber (lint) is 3 to 2 by weight (Wakelyn, 2002). In order for either to have value, the lint and seeds must be separated from one another. This separation process, known as ginning, was greatly facilitated by the invention of the modern cotton gin (short for cotton engine) near the end of the 18$^{th}$ century.


**Figure 5.1.** The unopened boll of *Gossypium hirsutum* L is shown on left and an opened boll with exposed lint appears on the right. LaForest, 2008.

Currently, two species of cotton are grown commercially in the US; these are *Gossypium hirsutum*, referred to as upland cotton, and *Gossypium barbadense*, or Pima cotton. Upland cotton dominates US cultivation, characterizing 96.6% of all production in 2008 (NASS, 2009a). More than a third of this is grown in the state of Texas. Pima cotton is characterized by fibers (staples) that are longer than upland cotton and thus may be referred to as extra-long staple (ELS) cotton. Pima cotton commands a higher price as it results in a smoother, more durable cloth. The variety grown in the US was developed only 20 years ago, but because it is more valuable, ELS is becoming the dominant species in areas where it is more costly to grow cotton (i.e. where irrigation is absolutely necessary) such as in California and Arizona.

Cotton production is reported in terms of number of bales, which are highly compressed blocks of lint. A standard US bale weighs 480 pounds (218 kg), determined after the harvested cotton (also called "seed cotton") has been ginned and is ready for delivery to textile mills. Consequently, seed mass is not reflected in reported cotton production, nor are the very short fibers that stay affixed to the seeds through the ginning process referred to as "linters" (Figure 5.2). Each bale when bound is approximately 54 by 20 by 33 inches (1.4 x 0.5 x 0.8 meters) (NCCA, 2009). The term "running bale" is used in the ginning process. It is a working quantity of cotton estimated to weigh approximately that of a standard bale.

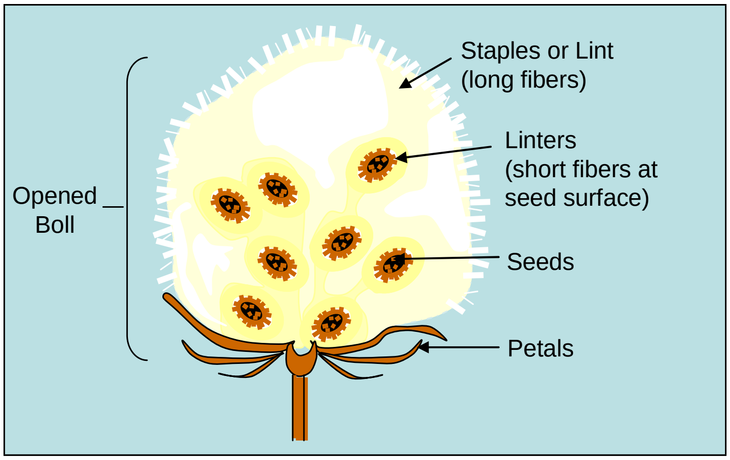


**Figure 5.2.** A diagram of an open cotton boll shows the various constituents and their relative positions.

The US Department of Agriculture (USDA) reports cottonseed production as an estimate rather than direct measurements; the values are based on 3-year average lint-seed mass ratios. These ratios are not published in annual reports such as the Crop Production Summary (NASS, 1999 - 2009), but they can be back-calculated using the data that are included in the summaries. For example, cottonseed production in 2006 was 7.35 x $10^6$ tons (6.67 x $10^6$ kilograms). Cotton (lint) production in the same states for which cottonseed is reported was 21.6 x $10^6$ bales or 5.18 x $10^6$ tons (21.6 x $10^6$ bales * 480 lbs/bale * 2000 lbs/ton) (NASS, 2009a). From this it can be concluded that the average lint-seed ratio is 0.705. As the aim of the current work is to focus on cottonseed rather than cotton lint, the inverse of the lint-seed ratio, or seed-lint mass ratio, will be used instead. Based on seed and lint production numbers for 2006, the seed-lint mass ratio was 1.42. A similar calculation for 2007 results in a value of 1.43.

Cotton is grown as an annual crop in the southern US, almost exclusively at latitudes of 37 degrees north or less. It requires a long, sunny growing season, is not frost tolerant, and prefers well-drained, loose soils. The USDA lists a total of 17 states where cotton is currently cultivated. However, only nine states account for 90% of the production; these are, in decreasing order of amount produced: Texas, Arkansas, Georgia, California, Mississippi, North Carolina, Missouri, Louisiana, and Tennessee. Roughly 40% of all US cotton is produced in Texas, where it is grown mostly at the southern end of the High Plains on the Llano Estacado (Spanish for palisaded plains) and southeastward onto the Cap Rock Escarpment and northern edge of the Edwards Plateau. More than three-quarters of Texas acreage is located within 100 miles of the city of Lubbock (Smith and Anciso, 2005) where water for irrigation is drawn from the Ogallala Aquifer.

### *5.1.2 Historical Trends*

The amount of land from which cotton is harvested has stayed relatively constant since 1980 (Figure 5.3). A notable exception has occurred in the last few years. During this time period, an extreme drought and hot weather has caused many farmers to forego harvesting. Cotton producers in Texas abandoned a third (1.60 x $10^6$ acres) of the 5.00 million acres (2.0 x $10^6$ ha ) planted in 2008 (NASS, 2009a). Along the Gulf Coast, where irrigation is not used, 90 to 95% of cotton crops were abandoned in 2009 (Ford, 2009).

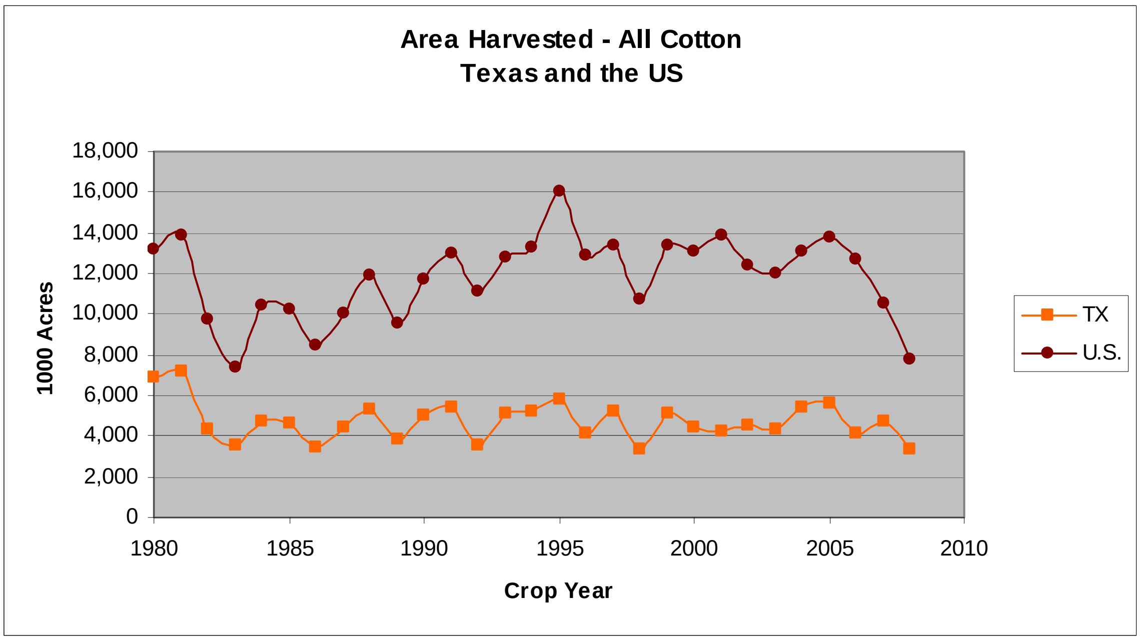


**Figure 5.3**. The area harvested for cotton in the United States has remained relatively constant over the past approximately thirty years (based on data from ERS, 2008).

While the amount of land under cultivation has remained relatively unchanged, cotton lint production has increased over the past 27 years (Figure 5.4), with the again notable exception of the last two years. This increase is due largely to increases in yield, as measured in pounds of lint per acre (Figure 5.5). The major cotton producing states have all experienced an increase in yield of approximately 60% during this time period. The increase in lint yield, in part, has occurred due to a decrease in seed-lint ratios (Figure 5.6). Although no documented explanation for this trend was found in the literature, it seems likely that cotton farmers are preferentially growing varieties that have higher proportions of lint in order to maximize profits. During the 2007/08 season, for example, the average US price for cottonseed was \$162/ton, while the price for cotton lint was \$0.613/lb or \$1226/ton, making cotton lint 7.6 times more valuable than seed (NASS, 2009b). The yield of cottonseed in tons per acre has, however, increased slightly since 1980 (approximately 20% nationwide) (Figure 5.7). This is presumably because overall yields (raw cotton per acre) have increased at a faster rate than the seed-lint ratios have declined.

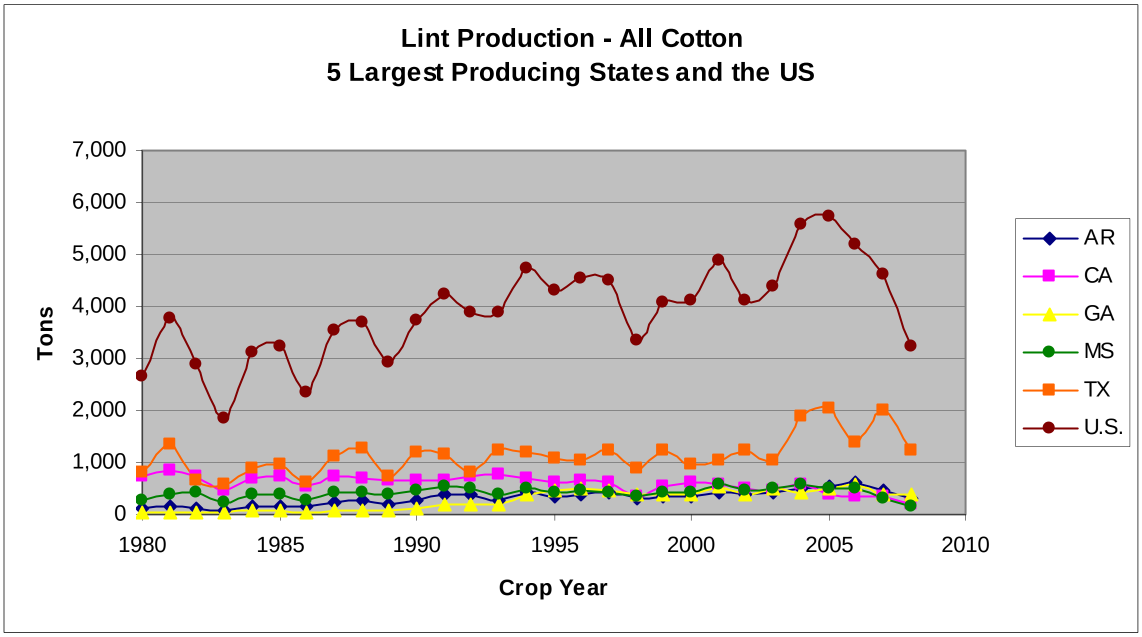


**Figure 5.4**. In general, cotton production in the United States has increased over the past approximately thirty years (based on data from ERS, 2008).

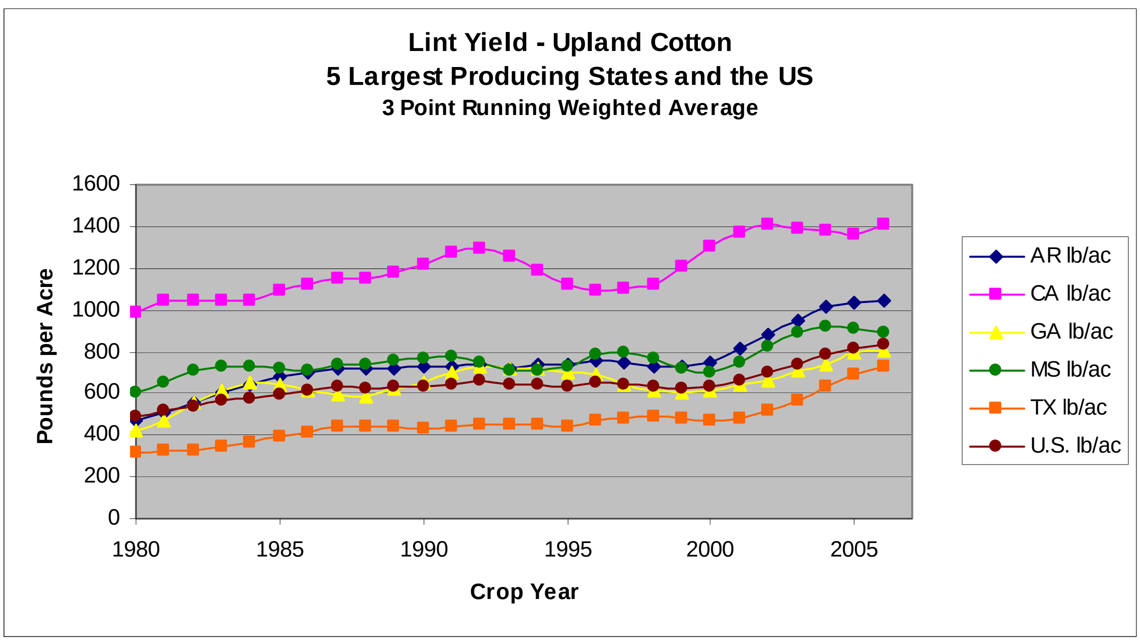


**Figure 5.5**. Cotton lint yield has increased almost 60% in all of the five top producing states over the past three decades (based on data from ERS, 2008).

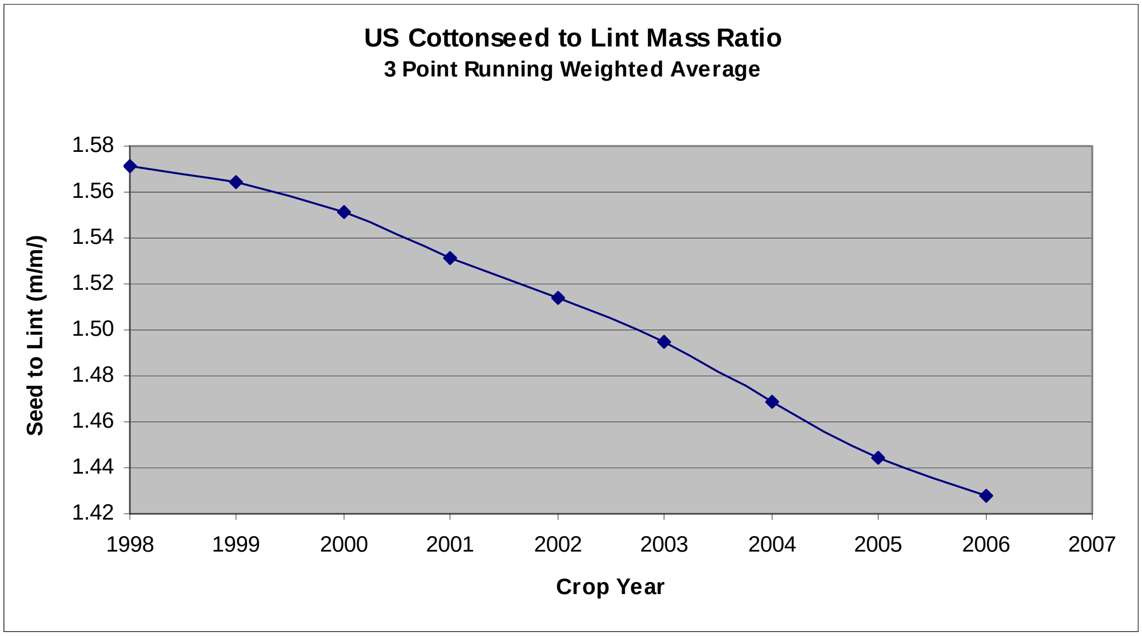


**Figure 5.6**. The cottonseed to lint mass ratio has decreased 10% over the past 10 years (based on data from NASS, 1999 - 2009).

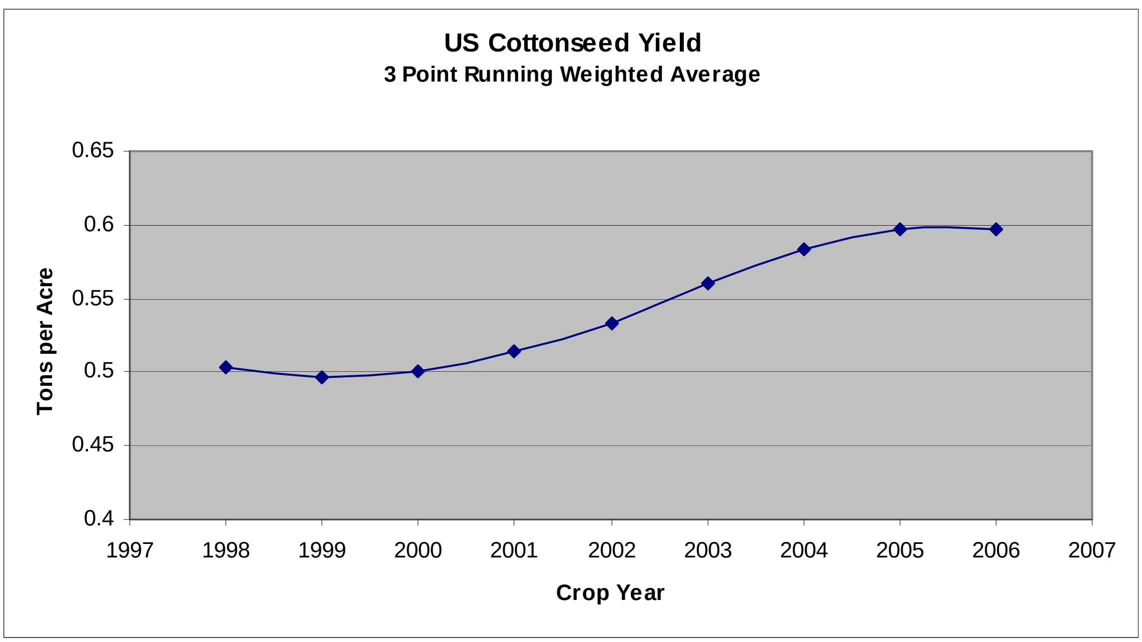


**Figure 5.7**. US cottonseed yield has increased by approximately 20% over the past three decades (based on data from NASS, 1999 - 2009).

# 5.2 Cottonseed Oil Supply

## *5.2.1 Current Supply*

The US produced 4.4 x $10^6$ tons (4.0 x $10^6$ Mg) of cottonseed in 2008; this is nearly half the 8.2 x $10^6$ tons (7.4 x $10^6$ Mg) annual production in 2004 and 2005 (Figure 5.8). If weather conditions improve or irrigation is increased, it is conceivable that production could again rise to 2004/2005 levels in the near future.

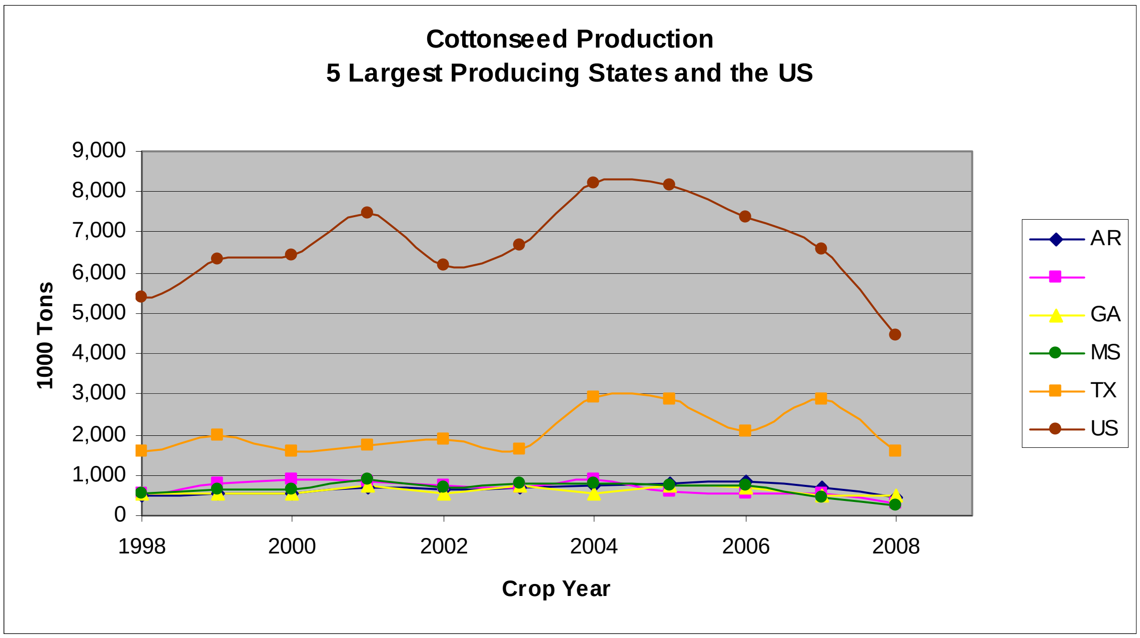


**Figure 5.8**. Maximum cottonseed production in the last 10 years occurred in 2004; the minimum was in 2008 (based on data from NASS, 1999-2009).

Since 1980, the proportion of seed being crushed to produce oil and meal has dropped from 91% to less than 40% (Figure 5.9). Seed is instead being used directly as cattle feed (Ash and Dohlman, 2008). While this may be due to the "unique protein, energy and fiber content of whole cottonseed" (Blasi and Drouillard, 2002), it is likely that it is also the result of decreased demand for cottonseed oil in the food industry as a response to various health concerns. Note that one of these concerns, the presence of a naturally occurring toxin called gossypol, is also a potential problem for cattle when whole seed is consumed rather than meal (Santos, et al, 2005; Villaseñor, et al 2008). If cottonseed oil were to be used as a feedstock for biodiesel, it is expected that meal would be readily substituted for whole grain as livestock fodder and that it would not have a large impact on food-grade vegetable oil supplies. Based on data from Ash and Dohlman (2008, Appendix Table 31) during the 2006/07 season, US net consumption of all edible fats and oils was 30.1 x $10^9$ pounds, of which only 708 x $10^6$ (2%) was from cottonseed. Relative global consumption is similar. Diversion of cottonseed oil from food to fuel is, therefore, not expected to have a significant impact on cottonseed oil used for human consumption.

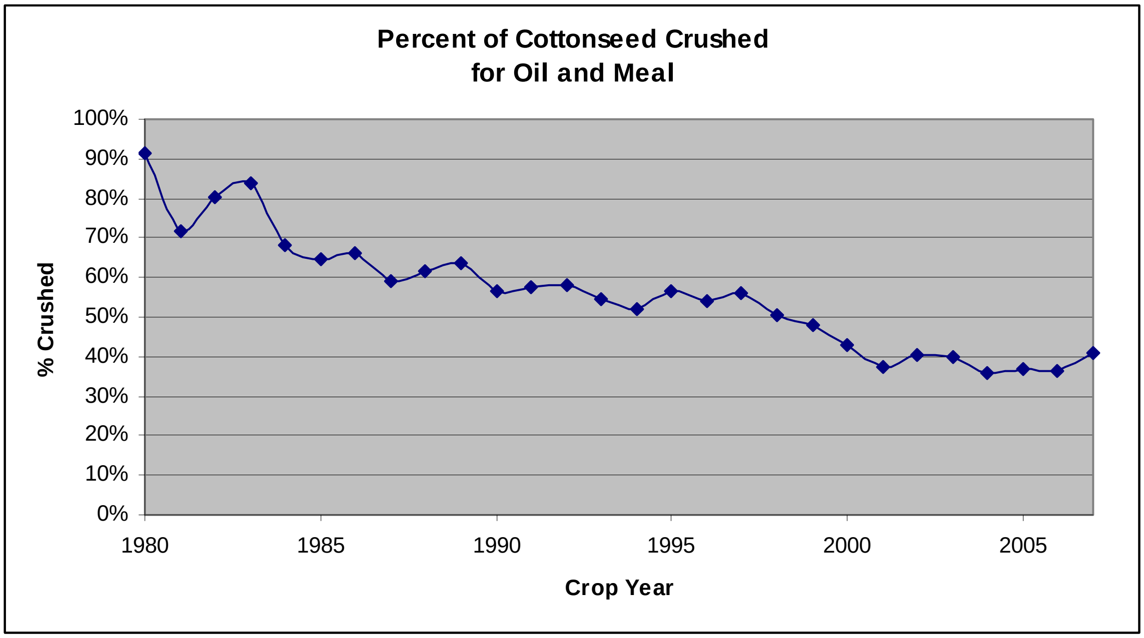


**Figure 5.9**. The percentage of cottonseed crushed for oil and meal has decreased from approximately 90% to less than 40% since 1980 (based on data from Ash and Dohlman, 2008).

Based on data from the US Department of Agriculture (Ash and Dohlman, 2008), the average amount of oil produced from cottonseed was 16.0% between production years 1980/81 and 2006/07 with annual values ranging from 14.5% to 17.7%. Similarly, the amount of meal ranged from 41.8% to 50.3%, with a mean of 45.7%. The remaining mass typically consists of about 27% hulls, 8% linters (short fibers approximately 0.33 mm long), and 3 to 4% trash (e.g., stems) (Wakelyn, 2002). Assuming 8.2 x $10^6$ tons (7.4 x $10^6$ Mg) annual production of cottonseed (the maximum during the last 10 years) containing 16% oil, a supply of 1.3 x $10^6$ tons (1.2 x $10^6$ Mg) of cottonseed oil per year could be generated under current practices. At a density of 7.5 lb/gal (NCPA, 2002), this equates to 350 x $10^6$ gallons (1.3 x $10^9$ liters) of seed oil per year. The maximum yield during the past 10 years was 1256 lbs of cottonseed per acre (1408 kg/ha) in 2007. From this, it is estimated that the maximum production potential on a per area basis is 20 gallons per acre per year (187 liters per hectare-yr) under current practices.

The US produced 683 x $10^6$ gallons (2.6 x $10^9$ liters) of biodiesel in 2008 and 320 x $10^6$ gallons (1.2 x $10^9$ liters) were consumed; the difference is accounted for as net exports (EIA, 2009). Assuming a 1:1 conversion rate of cottonseed oil to biodiesel and the maximum amount of cottonseed oil produced in the last decade, the 350 x $10^6$ gallons (1.3 x $10^9$ liters) of cottonseed biodiesel that could be produced per year is equal to 109% of current consumption and 51% of current production. The energy content of fatty acid methyl ester (FAME) biodiesel expressed as lower heating value (LHV) is equal to 119,550 Btu LHV/gallon (33.32 MJ/liter); that of petroleum diesel is 128,450 Btu LHV/gallon (35.8 MJ/liter) (ANL, 2009). This means that for every gallon of petroleum diesel, 1.07 gallons of biodiesel is required to produce the same amount of heat. Thus, 350 x $10^6$ gallons (1.3 x $10^9$ liters) of cottonseed biodiesel could displace 325.7 x $10^6$ gallons (1.2 x $10^9$ liters) of petroleum diesel. This is equal to 0.74% of the petroleum diesel consumed by the US transportation sector in 2008 (EIA, 2009).

## 5.2.2 Potential to Increase Supply

Three alternatives are considered for increasing production of cottonseed in the US. These are to increase the total amount of land used to raise cotton, to increase seed-lint ratios in order to obtain a greater seed yield (mass per unit area), and/or to increase the proportion of cotton land that is irrigated.

### 5.2.2.1 Increase in Irrigation and Seed-Lint Ratios

The lint yields for cotton by state (Table 5.1) indicate that California is currently almost twice as productive, on a per area basis, as Texas and historically has been as much as three times so (Figure 5.5). One significant difference between the two regions is that 100% of California cotton is irrigated, while only 35% of the Texas land harvested for cotton in 2007 was irrigated (USDA, 2009). The relationship between irrigation and yield is well known by agronomists and is a function of the amount and timing of water application as well as the ability to grow irrigated plants closer together. However, farmers must make a tradeoff between increased incomes from higher yields and. the cost of irrigation (see for example, Grismer, 2001).

**Table 5.1.** Data for US cotton producing states for 2007 in order of decreasing mass produced. States with highest lint yields (mass per land area) are shaded green

| | Abbreviation | Bales[1] | Harvested Area[1] | Lint Yield | Irrigated Area[1] | % Irrigated Land | % US production | Seed-Lint Ratio[2] |
|---|---|---|---|---|---|---|---|---|
| | | 480 lbs | Acres | lbs/acre | Acres[1] | | | |
| United States | US | 18,898,128 | 10,493,238 | 864 | 4,035,610 | 38.5% | | 1.43 |
| 91% of all US Production | | | | | | | | |
| Texas | TX | 8,147,970 | 4,674,229 | 837 | 1,626,181 | 34.8% | 43.1% | 1.44 |
| Arkansas | AR | 1,902,073 | 854,410 | 1,069 | 687,334 | 80.4% | 10.1% | 1.47 |
| Georgia | GA | 1,628,260 | 996,427 | 784 | 309,442 | 31.1% | 8.6% | 1.22 |
| California | CA | 1,418,751 | 471,378 | 1,445 | 471,378 | 100.0% | 7.5% | 1.58 |
| Mississippi | MS | 1,289,270 | 656,051 | 943 | 295,396 | 45.0% | 6.8% | 1.48 |
| North Carolina | NC | 785,557 | 526,060 | 717 | 10,756 | 2.0% | 4.2% | 1.30 |
| Missouri | MO | 723,043 | 377,960 | 918 | 198,446 | 52.5% | 3.8% | 1.51 |
| Louisiana | LA | 698,557 | 333,804 | 1,005 | 87,442 | 26.2% | 3.7% | 1.36 |
| Tennessee | TN | 581,236 | 504,057 | 553 | 11,386 | 2.3% | 3.1% | 1.41 |
| 9% of all US Production | | | | | | | | |
| Arizona | AZ | 513,758 | 171,300 | 1,440 | 171,300 | 100.0% | 2.7% | 1.47 |
| Alabama | AL | 407,598 | 382,566 | 511 | 22,484 | 5.9% | 2.2% | 1.51 |
| Oklahoma | OK | 279,871 | 164,273 | 818 | 67,687 | 41.2% | 1.5% | 1.58 |
| South Carolina | SC | 159,213 | 158,296 | 483 | 14,259 | 9.0% | 0.8% | 1.24 |
| Florida | FL | 109,206 | 80,053 | 655 | 9,145 | 11.4% | 0.6% | 1.18 |
| Virginia | VA | 101,745 | 59,243 | 824 | 348 | 0.6% | 0.5% | 1.30 |
| New Mexico | NM | 97,206 | 42,207 | 1,105 | 42,207 | 100.0% | 0.5% | 1.44 |
| Kansas | KS | 54,814 | 40,924 | 643 | 10,419 | 25.5% | 0.3% | 1.46 |

[1] 2007 Census of Agriculture (USDA, 2009)

[2] based on data from Crop Production 2008 Summary (NASS, 2009a)

The values for lint yield and percent irrigated land given in Table 5.1 are determined as follows based on data presented in the 2007 Census of Agriculture (USDA, 2009).

$$yield_{lint,\,s} = \frac{q_{bale,\,s} * m_{bale}}{A_{harvested,\,s}} \tag{5.1}$$

where

$yield_{lint,\,s}$ is the yield of cotton lint in state s, as pounds per acre

$q_{bale,\,s}$ is the quantity of bales produced in state s,

$m_{bale}$ is the mass of a bale (480 pounds), and

$A_{harvested,\,s}$ is the area harvested in state s as measured in acres.

The fraction of harvested land that is irrigated is calculated as

$$fraction_{irr,\,s} = \frac{A_{irr,\,s}}{A_{harvested,\,s}} \tag{5.2}$$

where

$fraction_{irr,\,s}$ is the fraction of cotton acreage irrigated in state s,

$A_{irr,\,s}$ is the quantity of bales produced in state s, and

$A_{harvested,\,s}$ is the area harvested in state s as measured in acres

Seed -lint ratios are calculated from NASS state-level data as

$$\text{seed-lint ratio} = \frac{\text{seed production (1000 tons)}}{\text{lint production (1000 bales)}} * \frac{\text{2000 lbs / ton}}{\text{480 lbs / bale}} \tag{5.3}$$

The 2007 Census of Agriculture also reports data at the county level for the number of acres of harvested cotton, the number of cotton acres that are irrigated, and the total number of bales produced. Tables containing this information are not included in the main census report but are available online (USDA, 2009). These data were gathered for all 17 cotton producing states. Lint yields and fraction of land irrigated were calculated for each county, as was done for the states (equations 5.1 and 5.2, replacing variables with subscript s for state with subscript k for county).

When county-level data are plotted to show cotton lint yield (lbs/acre) as a function of the fraction of cotton acreage that is irrigated, it appears that the use of irrigation in areas that currently rely entirely on rainfall could result in a doubling of lint yields (Figure 5.10). Cotton acreage that receives no irrigation produces just over 600 lbs/acre (673 kg/ha), while the yield in counties where all cotton is irrigated averages approximately 1200 lbs/acre (1345 kg/ha).

Assuming relatively constant seed-lint ratios, this also suggests that irrigation is a possible means for similarly increasing cottonseed production by roughly 100% in non-irrigated areas.

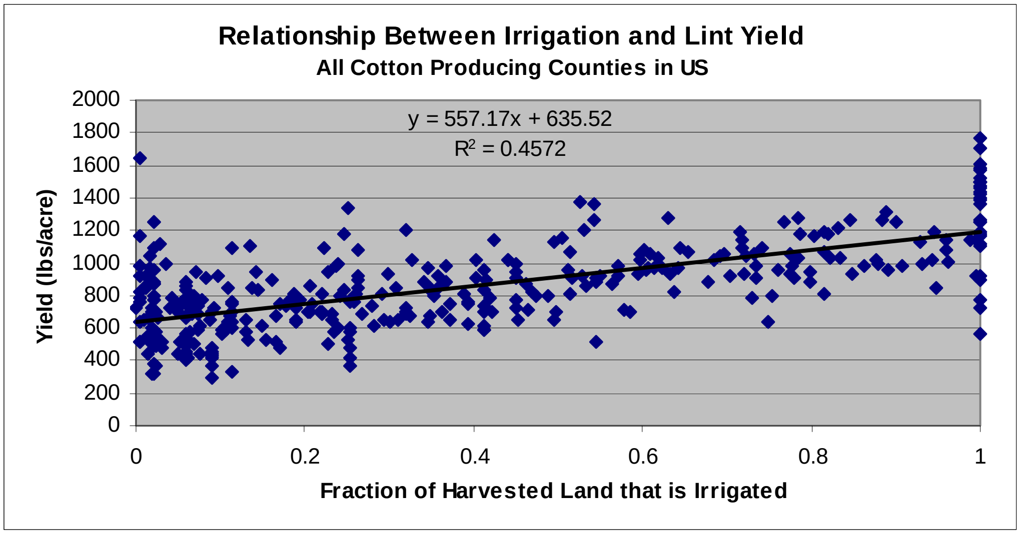


**Figure 5.10**. A linear regression performed on a plot of lint yield vs. the fraction of irrigated land for all counties that produce cotton suggests that there is reasonably strong correlation between the two and a potential to double cotton yield with irrigation (based on data from USDA, 2009, Volume 1, Chapter 2: County Level Data, Table 26)

County-level data for cottonseed production are not included in the US Census of Agriculture. However, The National Agricultural Statistics Service does publish cottonseed production (total tons) and acres harvested for cotton at the state level (NASS, 2009a), which can be used to determine cottonseed yield in tons per acre. When these yields are plotted and compared with state-level cotton irrigation area fractions from census data (Figure 5.11), a rough correlation between cottonseed yield and fraction of land irrigated is also indicated, although this tendency appears stronger for western states than for those east of the Mississippi.

As a means of exploring possible mechanisms for increasing cottonseed production, the empirically derived relationship, determined in the linear regression shown in Figure 5.10, is used to estimate yield increases in response to irrigation. Note that the purpose of this exercise is to approximate the magnitude of such an effect rather than to perform a rigorous analysis or make specific projections. In addition, the evaluation is intended to understand what the effect of increasing irrigation might have, and should not necessarily be interpreted as a recommendation to do so.

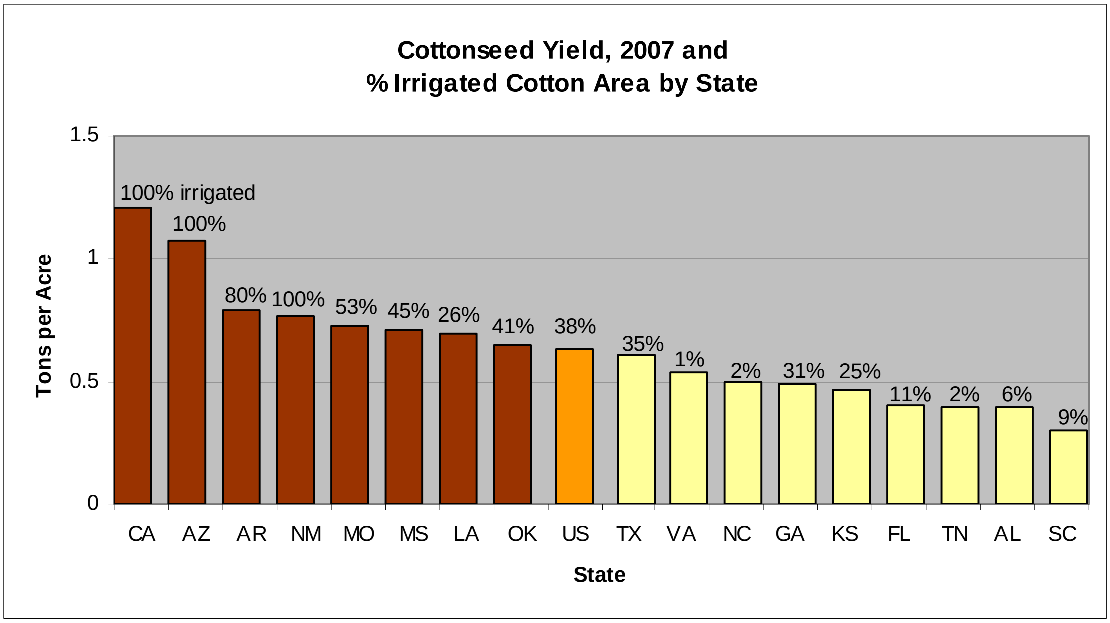


**Figure 5.11.** A rough correlation between cottonseed yield and fraction of land irrigated at the state level is observed, especially for states west of the Mississippi (based on irrigation data from USDA, 2009 and yield data from NASS, 2009a).

Predicted cotton lint yield, under conditions where all cotton land is irrigated, is determined using 2007 county-level census data for each of the nine top producing states (accounting for 90% of US production) inserted into the following expression

$$yield_{lint,\, irr,\, k} = 557 * (1 - fraction_{irr,\, 2007,\, k}) + yield_{lint,\, 2007,\, k} \quad (5.4)$$

where

$yield_{lint,\, irr,\, k}$ is predicted cotton lint yield (lbs/acre) in county k with 100% irrigation,

$fraction_{irr,\, 2007,\, k}$ is the fraction of cotton acreage irrigated in 2007 in county k, and

$yield_{lint,\, 2007,\, k}$ is the pounds per acre of cotton lint produced in county k in 2007.

557 is the constant determined in the linear regression of lint yield vs. irrigation fraction.

The resulting predicted yields for each county are weighted by the percentage of cotton produced in 2007 relative to the state as a whole The weighted values are then totaled to give a state yield as:

$$yield_{lint,\, irr,\, s,} = \sum_{k} [(fraction_{lint,\, 2007,\, k}) * yield_{lint,\, irr,\, k}] \quad (5.5)$$

where:

$yield_{lint,\, irr,\, s}$ is predicted cotton lint yield (lbs/acre) in state s with 100% irrigation,

$fraction_{lint,\, 2007,\, k}$ is the mass fraction of cotton lint produced in 2007 in county k, and

$yield_{lint,\, irr,\, k}$ is mass of cotton lint (lbs/acre) predicted for county k with 100% irrigation.

Results of these calculations are illustrated in Figure 5.12 for the US as a whole and for the 17 cotton producing states. Overall, this exercise suggests that maximizing the amount of irrigated cotton acreage has the potential to increase national production of cotton lint by approximately 67%. However, since cottonseed rather than cotton lint is the commodity of interest, the next step is to determine how an increase in lint production might affect seed production. It is worth noting that in 2007, California had both the highest lint yield and the highest seed-to-lint ratio (Table 5.1); therefore, at least at this juncture, it does not appear that there is a conflict in attempting to optimize for both.

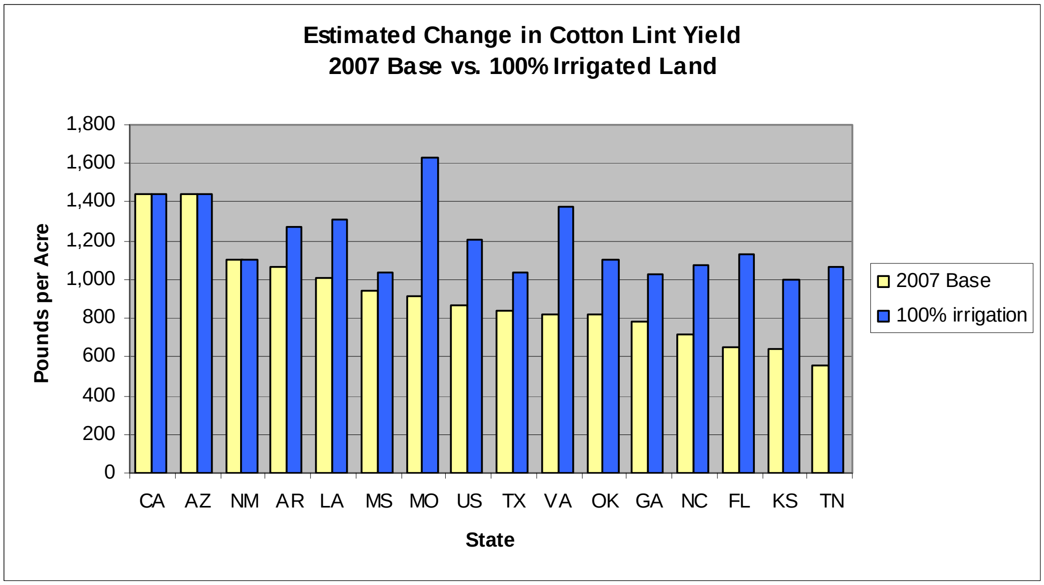


**Figure 5.12.** An estimation of potential cotton lint yield increase suggests that US yield could be increased by 67% under a 100% irrigation scenario (from 864 lbs/acre to 1207 lbs/acre).

The potential to increase cottonseed production as the result of 100% irrigation is assessed using two different assumptions for the seed-lint mass ratio. In the first scenario, 2007 state-level seed-lint values (Table 5.1) are assumed. In the second scenario, the seed-lint ratio is set to 1.6 for all states. This was the average US value for 1998 and the 10-year maximum for 1998 to 2007. In both scenarios, county-level lint yield is set to $yield_{lint, irr, k}$, as determined above (5.5) for states for 100% irrigated fields.

The results of these scenario analyses (Figure 5.13, Table 5.2) indicate that irrigation could produce 38% more cottonseed with the biggest total gains ($1 \times 10^6$ tons per year) occurring in Texas. Improving the seed-lint ratio to an average of 1.6 in combination with 100% irrigation is estimated to increase total US production by $3.5 \times 10^6$ tons (55%) over the 2007 base year. The average yield (mode) under these circumstances would be 0.95 tons of cottonseed per acre (2.1 Mg/ha) (Figure 5.14).

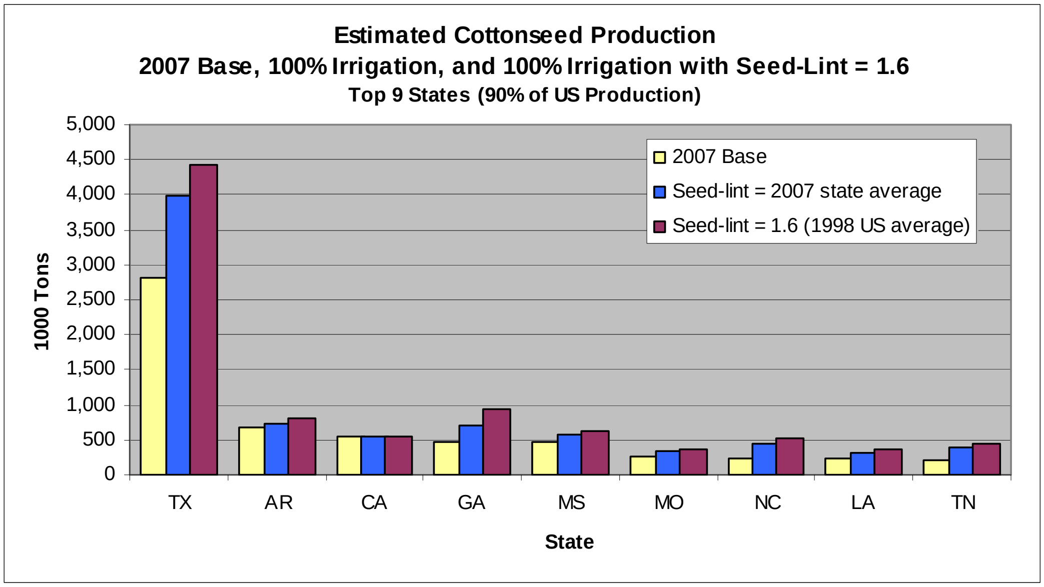


**Figure 5.13.** Practicing 100% irrigation and reverting to a seed-lint ratio of 1.6 (US mean in 1998) results in a predicted 55% increase in US cottonseed production.

**Table 5.2.** Cottonseed production in 2007 and for two scenarios

| | | | 100% Irrigation | | | |
|---|---|---|---|---|---|---|
| | 2007 Base | | Seed-lint = 2007 state average | | Seed-lint = 1.6 (1998 US average) | |
| | Lint | Cottonseed | Cottonseed | | Cottonseed | |
| State | 1000 tons | 1000 tons | 1000 tons | % Increase | 1000 tons | % increase |
| TX | 1,956 | 2,810 | 3,983 | 42% | 4,435 | 58% |
| AR | 456 | 673 | 742 | 10% | 805 | 20% |
| CA | 341 | 537 | 537 | 0% | 545 | 1% |
| GA | 391 | 478 | 708 | 48% | 927 | 94% |
| MS | 309 | 457 | 584 | 28% | 633 | 38% |
| MO | 174 | 261 | 337 | 29% | 358 | 37% |
| NC | 189 | 245 | 430 | 76% | 530 | 116% |
| LA | 168 | 228 | 318 | 40% | 375 | 65% |
| TN | 139 | 200 | 396 | 98% | 442 | 120% |
| AZ | 123 | 181 | 181 | 0% | 197 | 9% |
| AL | 98 | 148 | 299 | 102% | 317 | 114% |
| OK | 67 | 106 | 144 | 35% | 145 | 37% |
| SC | 38 | 47 | 95 | 102% | 124 | 161% |
| NM | 23 | 34 | 34 | 0% | 37 | 11% |
| VA | 24 | 32 | 53 | 67% | 65 | 106% |
| FL | 26 | 31 | 53 | 72% | 72 | 133% |
| KS | 13 | 19 | 30 | 55% | 33 | 71% |
| Total | 4,536 | 6,486 | 8,924 | 38% | 10,039 | 55% |

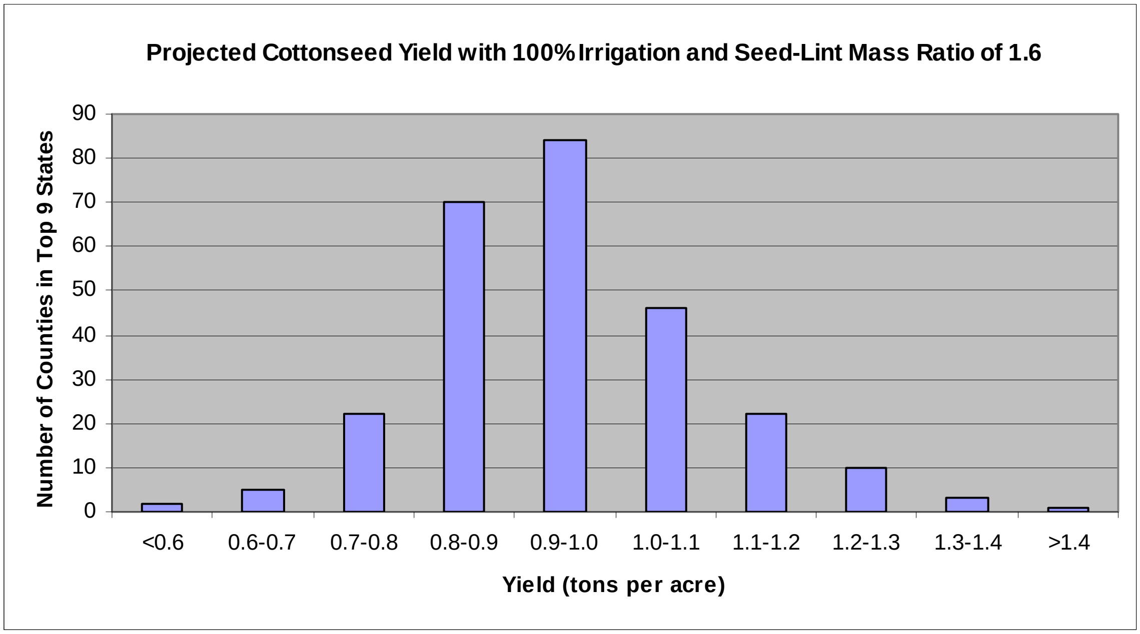


**Figure 5.14.** Practicing 100% irrigation and targeting a seed-lint ratio of 1.6 results in a predicted mode of 0.95 tons of cottonseed per acre.

### 5.2.2.2 Increase in Cotton Cropland

Perhaps the most obvious option for increasing total cottonseed production would be to increase the land area used to grow cotton. Two land use cases are explored. In the first case, it is assumed that the best areas for growing cotton are in counties where it is currently being produced. The scenario examines conversion of all existing cropland in these counties to cotton. The displaced crops would be grown on land that is currently not being cultivated and would thus result in land use change for areas currently designated grass- or forestland. Cases that include 100% irrigation and increased seed-lint ratios are considered within this scenario. The second scenario is an extreme that assumes the demand for cottonseed becomes so great that virtually every available acre located south of latitude 37ºN is converted to cotton land. In this instance, only an increased seed-lint ratio is considered, as irrigating this extent of land would be even more unlikely than complete land conversion. The purpose of this exercise is to estimate only the potential for cottonseed oil production, thus land use changes are accounted for without regard to the environmental consequences of such actions. In particular, the intent of second scenario is to determine a theoretical physical maximum.

#### *5.2.2.2.1 Scenario: Conversion of Existing Cropland to Cotton*

The US Census of Agriculture reports the amount of total cropland, harvested cropland, area of cropland harvested for cotton, and area planted in cotton that is irrigated (USDA, 2009, county-level statistics). This scenario considers the impact on cottonseed supply if all cropland in US counties currently growing any cotton were to grow nothing except cotton. In counties where cotton is grown, the percentage of total cropland that is harvested equals approximately 75%. Consequently, in this analysis, it is assumed that the total amount of land harvested for cotton is equal to 75% of all cropland; this is applied across all counties uniformly. Four sets of cultivation factors, based on different irrigation levels and seed-lint ratios, are examined. Each set of parameters is applied to both the cropland conversion scenario and to the base case (2007 land use data). The assumptions for each case are described in Table 5.3.

**Table 5.3**. Parameters used in scenario analysis where existing cropland is converted to cotton

| | | Irrigation Rate | |
|---|---|---|---|
| | | Percent of Cotton Land Irrigated in 2007 [1] | 100% of Harvested Area |
| Seed-Lint Ratio | 2007 value for each state (US average = 1.43) [2] | A1, B1 | A3, B3 |
| | 1998 US average = 1.6 [3] | A2, B2 | A4, B4 |
| | A1, A2, A3, A4 | Area Harvested = 2007 Harvested Cotton Land [1] | |
| | B1, B2, B3, B4 | Area Harvested = 75% of 2007 Total Cropland (including cotton) [1] | |

[1] USDA, 2009, county-level data

[2] State averages, calculated from data in NASS, 2009a

[3] US average, calculated from data in NASS, 2000

The prefix A or B in each of the cases refers to the land use assumed. The prefix "A" indicates the base case, where the amount of cotton equals that for 2007. The cases labeled with the prefix "B" represent those where all current cropland within the county has been converted to cotton. Cases A1 and B1, assume that the seed-lint mass ratio for each county is the average for each state in 2007; as a point of reference, the US average for 2007 was 1.43. They also both assume the same irrigation rates at the county level as reported for 2007 (in B1 the total amount of land that is irrigated scales with the increased area harvested). Cases A2 and B2 assume 2007 irrigation rates but use a seed-lint ratio of 1.6 (the mean US value in 1998). Irrigation rates are increased to 100% in Cases A3 and B3, but seed-lint ratios are kept at 2007 levels. Both 100% irrigation and the increased seed-lint ratio of 1.6 are assumed in Cases A4 and B4.

Total seed production is calculated at the county level and summed for each of the 17 cotton producing states. A US total is then determined by summing the values for each of the states. The expression used to estimate seed production for is given for scenario 1A and is similarly applied for the other cases.

$$production_{seed,\ \mathrm{A1,\ s}} = \sum_{\mathrm{k}} [(seed\text{-}lint_{\mathrm{A1,\ s}}) * yield_{lint,\ \mathrm{A1,\ k}} * area_{harvested,\ \mathrm{k}}] \qquad (5.6)$$

where:

$production_{seed,\ \mathrm{A1,\ s}}$ is predicted cottonseed production (tons/year) in state s with conditions set by Scenario A1.

$seed\text{-}lint_{\mathrm{A1,\ s}}$ is the mass fraction of cottonseed to lint produced according to conditions set by Scenario A1.

$yield_{lint,\ \mathrm{A1,\ k}}$ is the yield of cotton lint (tons/acre) predicted for county k with conditions set by Scenario A1 and calculated using 5.5.

$area_{harvested,\ \mathrm{k}}$ is the area of cotton harvested (acres) according to the 2007 census

In order to protect individual farm information, census data from counties where there are only one or two farms is not reported. A final “county” called “Remainder” is thus included in the sum for each state to avoid totals of less than 100%, where the $area_{harvested,\,k}$ for “Remainder” is obtained by subtracting the total land reported for individual counties from the state total. Yields and irrigation rates (used to estimate yields in two of the scenarios) are based the state average.

The results of this analysis at the national level are presented in Table 5.4. Assuming a volumetric one-to-one equivalency of cottonseed oil to diesel and 100% utilization of cottonseed as a fuel feedstock, the maximum amount of diesel that cottonseed oil could displace in the base case (i.e., land use and cultivation factors for 2007) equals less than one percent of the 2008 US 44 billion gallons per year consumption of diesel fuel in the transportation sector (EIA, 2009). In the most extreme case, where all cropland in existing locations is planted in cotton, seed-lint ratios are increased, and all harvested land is irrigated, the maximum amount of diesel displacement is estimated to be 4%. This would entail conversion of nearly 47 x $10^6$ acres (19 x $10^6$ ha) of forest or grassland to cropland to accommodate displaced crops and require a 10-fold increase in irrigation.

**Table 5.4**. Increasing cottonseed oil production by conversion of existing cropland to cotton

| Cultivation Factors | Scenario | Land in Cotton [1] | Irrigated Land [2] | Irrigation Increase | Land Use Change | Production | | |
|---|---|---|---|---|---|---|---|---|
| | | -- 1000 Acres -- | | | | Cottonseed 1000 tons | Cottonseed Oil 1000 gallons [3] | volume % of 2008 diesel [4] |
| 2007 Land Use | | | | | | | | |
| Base | A1 | 13,991 | 4,036 | 0 | 0 | 6,486 | 276,744 | 0.63% |
| Seed-lint = 1.6 | A2 | 13,991 | 4,036 | 0 | 0 | 7,257 | 309,627 | 0.71% |
| 100% irrigation | A3 | 13,991 | 10,493 | 6,458 | 0 | 8,924 | 380,758 | 0.87% |
| 100% irrigation, seed-lint = 1.6 | A4 | 13,991 | 10,493 | 6,458 | 0 | 10,039 | 428,331 | 0.98% |
| All cropland in cotton producing counties to cotton with ILUC to compensate for displaced crops | | | | | | | | |
| Base | B1 | 60,899 | 22,206 | 0 | 46,908 | 29,781 | 1,270,645 | 2.90% |
| Seed-lint = 1.6 | B2 | 60,899 | 22,206 | 0 | 46,908 | 32,948 | 1,405,798 | 3.21% |
| 100% irrigation | B3 | 60,899 | 45,674 | 41,639 | 46,908 | 39,101 | 1,668,318 | 3.81% |
| 100% irrigation, seed-lint = 1.6 | B4 | 60,899 | 45,674 | 41,639 | 46,908 | 43,406 | 1,851,982 | 4.23% |

[1] Land in cotton based on data from USDA, 2009.
2007 Land Use = harvested cotton land / 0.75;
cropland to cotton = total cropland in cotton producing counties

[2] Irrigated land (based on data from USDA, 2009):
A1 and A2= reported acres in 2007;
A2 and B2 = calculated percentage in 2007 applied to harvested land;
A3, and A4 = 100% of harvested cotton land
B3, and B4 = 0.75% of total cropland

[3] Assumes 16 wt% oil in seeds and 7.5 pounds per gallon of oil (National Cottonseed Products Association, 2002)

[4] 2,855 thousand bbls of diesel consumed per day by transportation sector = 44 billion gallons in 2008 (EIA 2009)

##### *5.2.2.2.2 Scenario: Conversion of All Available Land South of 37ºN to Cotton*

The final scenario considered is extremely improbable, but is undertaken in an attempt to define a physical maximum to cottonseed oil production in the US. The 37th parallel is a distinct demarcation for cotton cultivation in the US. All 13 states that lie completely south of 37° N produce cotton. Cotton production in Virginia, Missouri, and Kansas is limited to the very southern portions of these states in counties that account for approximately 10% of the total land area. Cotton is also grown in the southern half of California. Using data from the Natural Resources Conservation Service (NRCS, 2007), the maximum amount of land that in the most extreme case could be used to grow cotton in the US is estimated as the total of all 1) current cotton land, 2) Conservation Reserve Program (CRP) land, 3) rangeland, 4) pastureland, 5) other rural land, and 6) forestland in these states or portions of these states. Although much of this land actually is not and never would be available to grow cotton it is, at least for this exercise, regarded as land on which cotton conceivably could be grown, given strong enough market forces and/or policy. Land that is considered completely unavailable includes developed land, cropland used for products other than cotton, water areas, and federal land.

The maximum amount of "available" new cotton land is thus estimated to be 457 x $10^6$ acres (185 x $10^6$ ha). If only 75% is harvested in any given year, only 343 x $10^6$ acres (139 x $10^6$ ha) are productive (Table 5.5). Irrigating this land would be completely impractical so lint yield on all new land is assumed to be the current average of non-irrigated land or 636 pounds per acre (713 kg/ha) (Figure 5.10). The seed-lint ratio on new land is assumed to be optimized at 1.6. This equates to additional cottonseed production of (343 x $10^6$ new acres) * 636 lb lint/acre * 1 ton/2000 lb * 1.6 ton seed/ 1 ton lint) or 174.5 x $10^6$ tons. Cottonseed production in 2007 was 6.49 x $10^6$ tons (Table 5.2) for a total of 181 x $10^6$ tons (existing plus new production). At 16% oil, 7.5 lbs/gallon (National Cottonseed Products Association, 2002), and a one-to-one conversion rate of cottonseed oil to biodiesel this is equal to 7.7 x $10^9$ gallons of biodiesel. If petroleum diesel has 1.07 times the energy content (LHV) of FAME, this cottonseed biodiesel could displace 16.4% of the 44 x $10^9$ gallons of petroleum diesel consumed in the US transportation sector in 2008 (EIA, 2009), but would require conversion of nearly two thirds (457 out of 715 x $10^6$ acres) of all land south of the 37th parallel to cotton growing land.

**Table 5.5**. Land use and calculation of maximum available land for growing cotton in the US, assuming a northern extreme of 37 degrees N latitude (based on 2003 data from NRCS, 2007 and USDA, 2009)

| | "Available" Land | | | | | | | | Unavailable Land | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| State | Cotton Land | CRP | Pasture-land | Range-land | Other Rural Land | Forest Land | Maximum New Cotton Land | Maximum New Harvested Cotton Area | Non-Cotton Cropland | Developed, Federal, and Water Areas | Total Surface Area |
| | -- 1000 Acres -- | | | | | | | | | | |
| AL | 510 | 459 | 3,401 | 73 | 449 | 21,530 | 25,912 | 19,434 | 1,999 | 5,003 | 33,424 |
| AZ | 228 | 0 | 82 | 32,255 | 3,029 | 4,141 | 39,507 | 29,630 | 706 | 32,524 | 72,964 |
| AR | 1,139 | 146 | 5,322 | 38 | 393 | 15,008 | 20,907 | 15,680 | 6,383 | 5,608 | 34,037 |
| CA [1] | 629 | 67 | 594 | 8,879 | 2,312 | 6,952 | 18,804 | 14,103 | 4,106 | 27,217 | 50,755 |
| FL | 107 | 78 | 3,619 | 2,697 | 2,807 | 12,733 | 21,934 | 16,451 | 2,766 | 12,726 | 37,534 |
| GA | 1,329 | 294 | 2,798 | 0 | 854 | 21,893 | 25,839 | 19,379 | 2,823 | 7,750 | 37,741 |
| KS [2] | 55 | 261 | 240 | 1,584 | 73 | 155 | 2,313 | 1,734 | 2,592 | 307 | 5,266 |
| LA | 445 | 201 | 2,249 | 284 | 2,940 | 13,338 | 19,011 | 14,258 | 4,990 | 6,931 | 31,377 |
| MS | 875 | 791 | 3,224 | 0 | 427 | 16,755 | 21,196 | 15,897 | 4,101 | 4,355 | 30,527 |
| MO [2] | 504 | 146 | 1,067 | 9 | 69 | 1,255 | 2,546 | 1,910 | 864 | 548 | 4,461 |
| NM | 56 | 583 | 232 | 39,956 | 2,059 | 5,478 | 48,308 | 36,231 | 1,492 | 27,967 | 77,823 |
| NC | 701 | 88 | 1,832 | 0 | 873 | 15,456 | 18,249 | 13,687 | 4,811 | 9,947 | 33,709 |
| OK | 219 | 1,003 | 8,458 | 14,129 | 451 | 7,368 | 31,409 | 23,557 | 8,752 | 4,358 | 44,738 |
| SC | 211 | 181 | 1,093 | 0 | 831 | 11,161 | 13,267 | 9,950 | 2,157 | 4,305 | 19,939 |
| TN | 672 | 233 | 4,757 | 0 | 572 | 11,959 | 17,520 | 13,140 | 4,078 | 4,703 | 26,974 |
| TX | 6,232 | 3,993 | 15,836 | 96,109 | 2,286 | 10,613 | 128,838 | 96,629 | 19,330 | 16,651 | 171,052 |
| VA [2] | 79 | 4 | 290 | 0 | 58 | 1,318 | 1,671 | 1,253 | 207 | 752 | 2,709 |
| Total | 13,991 | 8,527 | 55,096 | 196,011 | 20,483 | 177,112 | 457,230 | 342,922 | 72,157 | 171,652 | 715,030 |

[1] All land areas in California scaled to 50% to represent land south of 37°N

[2] All land areas in Kansas (KS), Missouri (MO), and Virginia (VA) scaled to 10% to represent land south of 37°N

Based this analysis, cottonseed oil has little potential as a major contributor to the supply of biodiesel feedstocks and should be viewed only as a possible means for supplementing other sources. Under these circumstances, the fate of the cottonseed oil co-products must also be taken into consideration. These include cotton lint, cottonseed meal, and linters. For every kilogram of cottonseed oil produced, there will be nearly 4 times as much lint, nearly three times as much meal, and half again as much short cotton lint (linters) (Table 5.6).

**Table 5.6**. Mass ratios of cottonseed oil byproducts (based on data from Wakelyn, 2002)

| | per kg of seed | per kg of oil |
|---|---|---|
| lint | 0.63 | 3.91 |
| oil | 0.16 | 1.00 |
| meal | 0.46 | 2.88 |
| hulls | 0.27 | 1.69 |
| linters | 0.08 | 0.50 |
| trash | 0.03 | 0.19 |

The amount of cotton lint that would be produced under the extreme circumstances described above (i.e., 7.7 x $10^9$ gallons of cottonseed biodiesel) is estimated to be 109 x $10^6$ tons (99 x $10^6$ Mg). The global production of cotton lint in the 2008/2009 season was only 23 x $10^6$ Mg (FAS, 2009), thus this would represent a more than four-fold increase in the world cotton supply. Furthermore, the cottonseed meal produced as a by-product would represent a significant increase in the supply of animal feed with unknown consequences.

## 5.3 Cottonseed Oil Biodiesel, Life Cycle Assessment

The life cycle assessment approach taken is that of an attributional rather than consequential LCA and evaluates the typical practices in the United States in the year 2007 (approximately). A description of life cycle assessment, and in particular, its application to transportation fuels is addressed in Chapter 1 of this report. A simplified process flow, illustrating the overall life cycle of biodiesel produced from a cottonseed oil feedstock is presented in Figure 5.15.

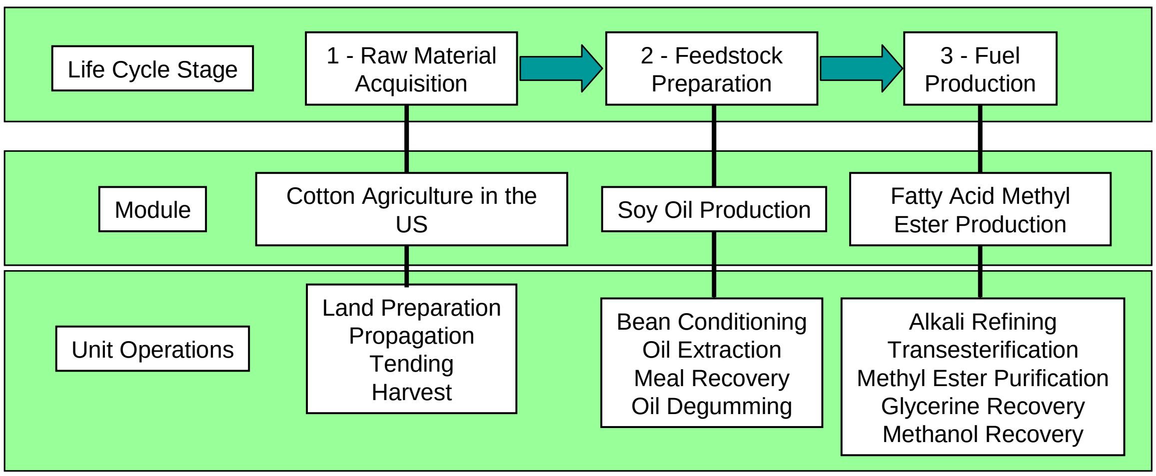


**Figure 5.15.** Biodiesel as FAME (fatty acid methyl ester) produced from cottonseed oil can be characterized by three life cycle stages each potentially separated by a transportation event.

### *5.3.1 Cottonseed Oil Biodiesel, LC Stage 1, Raw Material Acquisition: Land Preparation, Propagation, Nurturing, and Harvest*

#### 5.3.1.1 General

##### *5.3.1.1.1 System Boundaries*

The first life cycle stage in the production of biodiesel from cottonseed is the acquisition of cottonseed through conventional agricultural systems in the US. This entails preparation of the land for planting, planting of seed, tending the cotton plants, and harvest of the "fruit" or boll, which consists of both seeds and lint. Separation of the seeds from the lint through the ginning process is covered in the next stage of the life cycle. Because the greatest amount of data is available for 2007, to the extent possible, that is the reference year for this analysis. The system includes consumption of raw materials, energy, land, and water, as well as emissions to air. Emissions to land and water are addressed only to the extent that they contribute to greenhouse gas emissions. Upstream energies associated with production of agricultural chemicals and fertilizers are included, but development of infrastructure and manufacture of farm equipment are not (Figure 5.16). The downstream system boundaries are terminated with the harvesting of the crop, thus transport and storage activities from and off the cropland are included in life cycle stage (stage 2). This decision is driven primarily by the change in reference flow from a unit area of land in life cycle stage one to a unit mass of cottonseed in life cycle stage two and the recognition that activities for transportation and storage are better modeled in units of mass.

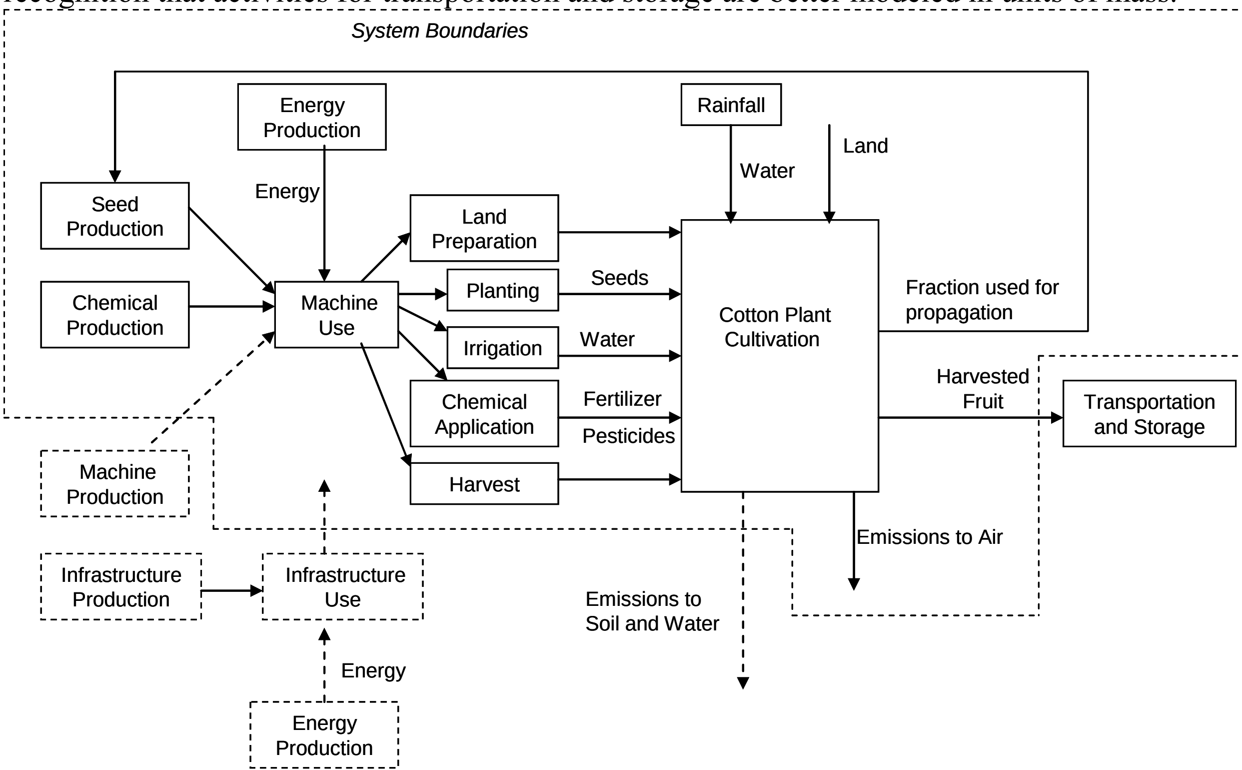


**Figure 5.16**. The above shows a simplified process flow and system boundaries for cottonseed oil biodiesel life cycle stage 1 (raw material acquisition), which includes land preparation, propagation, tending, and harvest.

### *5.3.1.1.2 Units*

The basis for this portion of the life cycle is one hectare of harvested land in one year (1 ha-yr). Most US agricultural data are reported in English units, therefore, both metric and English units will be used in the tracking of flows. Although it is more common to use the harvested product as the reference flow, this value can vary significantly because of ranges in crop yields. In addition, the material and energy flows associated with this life cycle stage are much more tightly coupled to the amount of land acted upon than they are to the mass of plant matter removed. A final transformation to mass of seed cotton produced per area of land per year (kg/hectare-yr) is performed at the end of stage one, along with the embodied inventories, for input into the second stage of the life cycle, where the basis is one kilogram (1 kg) of cottonseed with variances noted as a function of harvest yield. One standard US bale of cotton lint weighs 480 pounds (lb), or 218 kilograms (kg), and an average seed-lint ratio is 1.42. Thus, 1 bale of cotton is assumed to produce 682 lb (309 kg) of seed and the total mass seed cotton is 1162 lb (527 kg) per bale.

#### *5.3.1.1.3 Resources*

Growing cotton requires, as do all agricultural products, sunlight, land (soil), water, and nutrients. Sunlight is limited by climate and location of the field (degrees latitude). The amount of land that must be committed (actively managed) in order to produce a hectare of cotton is greater than the final harvested area. There are crop failures and land must be left uncultivated periodically in order to maintain soil health and productivity. In addition, some fraction of land must be used to grow cottonseed that will be used to start crops in the following season. The amount of land suitable for growing cotton is limited by climate, terrain, and competing demands from both within and external to the agricultural sector. While rain is an important source of water, more than a third (38%) of the cotton grown in the US was irrigated in 2007 (USDA, 2009). Nutrients naturally available in the soil are insufficient for commercially viable yields, thus these must also be supplied. Equipment, buildings, and energy in the form of electricity and liquid fuel are required to manage these resources.

### 5.3.1.2 Unit Operations and Activities

The unit operations involved in the growing of cotton plants include: land preparation and management, planting of seeds, tending (including application of fertilizer and pesticides, irrigation, and secondary tillage), harvesting, and any transportation and storage that occurs on the farm.

The specific list of activities that are performed within these unit operations and their descriptions, for the purpose of this analysis, are taken from cost and return documents supplied by state agricultural extension services. These documents, also referred to as enterprise budgets, are developed by agricultural economists, as planning aids for cotton farmers. The extension services base these budgets on information gathered through farm surveys. Therefore, they represent actual practices within the state. In the current analysis, the final activities considered and the flows associated with them are based on the detailed information provided by the ten states that account for 93% of the land harvested for cotton in the US in 2007. Based on the 2007 Census of Agriculture (USDA, 2009), these are, in decreasing order, Texas (44.6%), Georgia (9.5%), Arkansas (8.1%), Mississippi (6.3%), North Carolina (5.0%), Tennessee (4.8%), California (4.4%), Alabama (3.6%), Missouri (3.6%), and Louisiana (3.2%).

Multiple budgets are supplied for each state. For the ten states under consideration, a total of nearly 100 cotton planning budgets are provided for 2008 (or from the available budgets, the year closest to 2008). The budgets for a given year are based on surveys conducted in the previous year, thus 2008 budgets are taken to be representative of 2007 activities. The budgets vary according to one or more of the following: the location within the state, the type of tillage used, whether or not the seed is genetically modified to be resistant to herbicides and/or certain insects and the type of modification, and the irrigation technology used (including none). In some cases, particularly for Texas, activities are out-sourced and other than cost, there is little detailed information regarding the operations. Under these circumstances, activity data from other budgets with similar cultivation systems may be used as a surrogate.

The budgets supplied for Tennessee, Missouri, and Alabama apply to all of the cotton land within the state. For all other states, budgets are grouped according to the geographic region to which they apply. The total land area included by each of these regions was determined by comparing the geographic description of the region to county maps (Census Finder, 2009). In the case of Texas, a list of specific counties to which each district applies is provided by the agricultural extension service (TAES, 2009). (Note that the district naming and numbering convention used by the Texas Agricultural Extension Service does not match that used by the USDA).

In terms of total harvested cotton land, some of the regions within an individual state are relatively small, especially when considered at a national scale. Arizona, the eleventh-ranked state in 2007 accounted for only 1.6% of the US cotton land harvested. It and the other six states that individually contain less than 1.6% of US cotton land are excluded from the analysis. Likewise, any designated district or region within the top 10 states estimated to contain less than 1.6% of US cotton land was eliminated, along with the associated budgets. This reduced the total number of budgets to be considered to just over 80, while still representing 90% of the total land harvested for cotton.

Several other steps were taken to assemble an appropriate set of budgets for consideration. Data from the Agricultural Resource Management Survey (ARMS) (ERS, 2009a) were used as sources of state-level activity data with regard to tillage practices and use of genetically modified seed. The area of irrigated land within each region was determined from county-level data in the 2007 census (USDA, 2009). Proportional use of different types of irrigation systems (drip, gravity, or sprinkler) was determined from Farm and Ranch Irrigation Surveys (USDA, 2004; 2010). Based on these sources of information, the estimated percent of US cotton land affected by each individual budget was then determined. As necessary, a small number of budgets representing relatively small land areas were eliminated in order to not exceed state-level activity data. In cases where the only difference between budgets was the specific variety of genetically modified seed (modified for the same resistant characteristics), a single budget was taken to be representative of all. Four budgets were eliminated because available information suggested that these were not common practices. Most of the states combine irrigation activities within one or more individual budgets. The exceptions to this are Louisiana and Mississippi, which provide separate “add-on” budgets for irrigation.

A list of all budgets in regions of the US that constitute more than 1.6% of the US land harvested for cotton in 2007 is given in Table 5.7. In general, the names of the budgets used by the extension service are retained, although in some cases they are shortened in the interest of brevity. Explanations of the terms used in the budget names are provided in the text immediately following the table.

**Table 5.7**. Available budgets for geographic regions that constitute more than 1.6% of the US land harvested for cotton in 2007. Percent of US refers to area of harvested cotton land. (Explanations of terms used in the budget names are given in the report body.)

| State/Region | % of US | Budget | | References |
|---|---|---|---|---|
| | | Name | % of US | |
| Texas (TX), District 2, South Plains | 24.75% | Dry, RRFlex | 12.96% | TAES, 2007; TAES, 2009 |
| | | Pivot, BGIIFlex | 11.79% | |
| | | Drip, BGIIFlex | See Note [1] | |
| Texas (TX), District 6, Far West, non St. Lawrence | 3.13% | Dry, Conventional Seed | 2.35% | |
| | | Furrow, Trans Pecos Seed | 0.78% | |
| Texas (TX), District 6, Far West, St. Lawrence | 1.15% | St. Lawrence | See Note [2] | |
| Texas (TX), District 11, Coastal Bend | 3.81% | Dry, GMO Seed & Conventional Till | 3.81% | |
| | | Dry, Conventional Seed & Till | See Note [3] | |
| Texas (TX), District 3, Rolling Plains | 3.44% | Dry, 2X1 planting pattern | 2.67% | |
| | | Sprinkler | 0.77% | |
| | | Dry, Solid 40 in rows | See Note [4] | |
| Texas (TX), District 7, West Central | 3.42% | Dry, follow wheat, GMO Seed | 3.14% | |
| | | Drip, follow corn, GMO Seed | 0.28% | |
| Texas (TX), District 1, Panhandle | 1.65% | Dry, GMO Seed & Conventional Till | 0.82% | |
| | | Center Pivot, RR Seed & Till | 0.83% | |
| | | Dry, Conventional Seed & Till | See Note [3] | |
| Georgia (GA), Southern and Eastern | 9.44% | Irrigated, Conventional Tillage | 2.33% | Shurley and Ziehl, 2007 |
| | | Irrigated, Strip Tillage | 2.15% | |
| | | Non-Irrigated, Conventional Tillage | 1.77% | |
| | | Non-Irrigated, Strip Tillage | 3.19% | |
| Arkansas (AR), Northern | 5.40% | AG-1182 Non-irrigated, 8 Row, RR Flex | 1.37% | UAR, 2009 |
| | | AG-1183 through AG-1186 Center Pivot | See Note [5] | |
| | | AG-1189 Furrow, 12 Row, BG/RR [6] | 3.20% | |
| | | AG-1190 through AG-1193, Furrow, GMO seed | See Note [6] | |
| | | AG-1187 Center Pivot, 12 Row, No-Till, BG/RR [7] | 0.83% | |
| | | AG-1188 Center Pivot, 12 Row, No-Till, BGII/RRFlex | See Note [7] | |
| Arkansas (AR), Southern | 2.72% | AG-1172 Non-irrigated, 8 Row, RR Flex | 0.22% | |
| | | AG-1173 Center Pivot, 8 Row, Conventional Till, RR Flex [8] | 0.35% | |
| | | AG-1174 and AG-1175, Center Pivot [8] | See Note [8] | |
| | | AG-1176 Furrow, 8 Row, Conventional Till, BG/RR [9] | 2.15% | |
| | | AG-1177 through AG-1180, Furrow, GMO seed [9] | See Note [9] | |
| | | AG-1181 Furrow, 12 Row, No-Till, BGII/RRFlex [10] | See Note [10] | |
| Mississippi (MS), Delta area | 4.98% | 8R-38”, solid, BtRR [11] | 3.23% | MSU, 2008 |
| | | 8R-38”, solid, BGII/Flex [11] | See Note [11] | |
| | | 8R-38”, solid, no-till, BtRR | 0.75% | |
| | | 8R-38”, 2x1 full-skip, BtRR variety [12] | 0.00% | |
| | | 8R-38”, solid, RR | 0.20% | |
| | | 12R-38”, solid, BtRR [13] | See Note [13] | |
| | | 12R-38” solid, BGII/ Flex [13] | 0.81% | |
| | | 12R-38”, solid, no-till, BtRR | 0.19% | |
| | | Pipe irrigation, 47% of each | 2.34% total | |
| | | Center Pivot irrigation, 22% of each | 1.11% total | |

**Table 5.7 (cont).**

| | | | | |
|---|---|---|---|---|
| North Carolina (NC), Non-Tidewater area | 3.76% | Conventional Tillage | 1.08% | NCSU, 2009 |
| | | Strip Tillage | 2.68% | |
| Tennessee (TN) | 4.80% | Roundup Ready - Conventional Tillage [14] | 0.34% | McKinley and Gerloff, 2009; UTN, 2008 |
| | | Roundup Ready Flex - Conventional Tillage [14] | See Note [14] | |
| | | BGRR - Conventional Tillage [14] | See Note [14] | |
| | | BGII RR Flex - Conventional Tillage | 4.13% | |
| | | Roundup Ready - No Tillage [14] | See Note [14] | |
| | | Roundup Ready Flex - No Tillage | 0.53% | |
| | | BGRR - No Tillage [15] | 3.89% | |
| | | BGII RR Flex - No Tillage [15] | See Note [15] | |
| California (CA), San Joaquin Valley | 4.41% | Upland cotton, 40 in rows [16] | 1.89% | UCD, 2003a; UCD, 2003b; UCD, 2003c; NASS, 2009a |
| | | Pima Cotton | 2.52% | |
| | | GMO | 0.26% | |
| Alabama (AL) | 3.65% | GMO seed, non-irrigated | 2.70% | Auburn, 2009 |
| | | Conventional Seed | 0.73% | |
| | | Irrigated | 0.21% | |
| Missouri (MO) | 3.60% | Dry, BGII/RR Flex | 1.71% | UMO, 2009 |
| | | Center Pivot, BGII/RR Flex | 1.89% | |
| Louisiana (LA), Northeastern Region | 2.49% | Sandy Soil, 8-row Equipment, Conventional seed | 0.30% | Paxton, 2008; LDAF, 2008 |
| | | Sandy Soil, 8-row Equipment, Solid Planted, BG/RR | 1.57% | |
| | | Clay Soil, 8-row Equipment, RR | 0.10% | |
| | | Sandy Soil, 12-row Equipment, Solid Planted, BG/RR | 0.44% | |
| | | Silty Soil, 8-row Equipment, Solid Planted, BG/RR | 0.09% | |
| | | Pipe irrigation, 27% of each | 0.67% total | |
| | | Center Pivot irrigation, 4% of each | 0.09% total | |

[1] Only 2% of TX acres use drip irrigation (USDA, 2004)
[2] St. Lawrence limited to 3 counties (TCP, 2007), with a cotton area less than state of AZ (USDA, 2009)
[3] Fraction of conventional seed (ERS, 2009a) is accounted for in other districts
[4] Assume solid 40 in rows is not common in dryland
[5] Fraction of center pivot irrigation is accounted for in no-till budget
[6] Take AG-1189 as representative of all GMO, stale seedbed, furrow irrigated land in northern AR
[7] Take AG-1187 as representative of all irrigated no-till and all center pivot irrigated land in northern AR
[8] Take as representative of all center pivot irrigated land in southern AR
[9] Take AG-1176 as representative of all GMO, stale seedbed, furrow irrigated land in southern AR
[10] Fraction of no-till is accounted for in other region
[11] Take BtRR as representative of 8R-38”, solid, conservation tillage, GMO seed
[12] Seeding rates too high for this to be common (ERS, 2009a)
[13] Take BGII/ Flex as representative of 12R-38” solid, conservation tillage, GMO seed
[14] Take Roundup Ready - Conventional Tillage as representative of all RR seed
[15] Take BGRR - No Tillage as representative of all BtRR no-till
[16] 30 inch rows are not common
ALL: 2007 harvested and irrigated area by county (USDA, 2009); county locations (Census Finder, 2009); 2007 tillage practices and GMO seed use (ERS, 2009a); 2003 irrigation type (USDA, 2004)

Terms used to name the cotton budgets given in Table 5.7 are described below, grouped by general practice category.

##### 5.3.1.2.1 Irrigation Practices

Dry or dryland cotton refers to that produced on non-irrigated land. Non-irrigated cotton, especially west of the Mississippi, is commonly grown using what is called a 2x1 planting pattern (skipping every third row when planting). The resulting decreased plant density reduces overall water demand and protects the cotton from drought-induced stress. “Furrow” and “pipe” are forms of gravity feed irrigation, and are the most frequently used methods in the Lower Mississippi River Valley. “Pivot,” or “center pivot,” is a type of sprinkler irrigation typically employed in the Texas plains. “Drip” irrigation uses localized ground-level application of water and is relatively uncommon in cotton agriculture. The percent by different irrigation type is available in the Farm and Ranch Irrigation Surveys (USDA, 2004; 2010).

##### 5.3.1.2.2 Row Size

Standard row spacing for cotton is 36 to 40 inches. Equipment for US cotton cultivation is typically sized to work in either 8-row or 12-row sections, although 4- and 6-row implements are used for certain operations. In general, a 12-row implement is pulled by a more powerful tractor than the equivalent 8-row implement (e.g., 225 horsepower (HP) rather than 190 HP); and because they are able to cover 50% more area per pass, 12-row implements perform tasks more quickly and overall fuel consumption is slightly lower, despite more demanding engines. The larger swath covered by 12-row equipment also means, however, that a larger volume of soil is being managed at any one time. Consequently, it may be necessary to use smaller, 8-row equipment in heavier soils, such as those found in the flood plains along the banks of the Mississippi River in northwestern Mississippi, northeastern Louisiana, and southern Arkansas. (Note that this region, referred to as the Mississippi Delta should not be confused with the Mississippi River Delta; the latter is located several hundred miles to the south, where the river empties into the Gulf of Mexico). Unless otherwise stated, row sizes are assumed to be on 38 (± 2) inch (approximately 1 meter) centers. The size of equipment used (number of rows covered) is included in all budgets that provide detailed activity data and is often used to differentiate between budgets. In cases where information for both 8- and 12-row equipment is given for the Mississippi Delta region, it is assumed, for this analysis, that 80% of the land area is managed using an 8-row system.

##### 5.3.1.2.3 Seed Variety

Most cotton seed sold within the past five years is genetically modified to be resistant to the herbicide glyphosate; glyphosate is sold under the Monsanto brand name Roundup. This permits the farmer to control weeds by spraying herbicide after cotton plants have sprouted (post-emergence) without damaging the crop. The seeds for this variety of plant are referred to as Roundup Ready (RR); RR Flex seeds are similar, but draw upon a slightly different herbicide program. In addition to herbicide resistance, cotton can be genetically modified to produce a toxin that is poisonous to the larvae of butterflies and moths (caterpillars), as well as beetles. This trait is desirable because certain of these pests are capable of destroying an entire cotton crop. The toxin is naturally produced by the bacteria *Bacillus thuringiensis*, thus the generic name “Bt cotton” is used to describe this variety. Monsanto markets Bt cotton as Bollgard (BG or BGII) in reference to its ability to protect the cotton boll. Most genetically modified (GMO) seed is both insect and herbicide resistant and is referred to as BtRR, BG/RR, BGII/RR Flex, etc. In this analysis, if only GMO seed is specified by the budget, it is assumed to be BG/RR.

The first Bt cotton was planted in 1997. The USDA Agricultural Resource Management Survey (ERS, 2009a) reports that in 2007, 65.6% of the crop was Bt cotton and 89.7% was herbicide resistant. In spite of this, however, more than one-third (38.5%) of cotton crop area continues to be mechanically cultivated for weed control and 64.5% of all acres are treated with insecticide. While the use of Roundup Ready cotton has become relatively accepted, there are a number of concerns with the cultivation of Bt cotton including the development of resistant insects, especially the pink bollworm in western states (EPA, 2006).

##### *5.3.1.2.4 Tillage System*

Until the late 1990’s, virtually all cotton in the US was produced using what is referred to as conventional (or intensive) tillage; however, this approach results in exposed soil that is then subject to erosion by water and wind. It also increases the amount of particulate matter, nitrogen, and carbon that is released to the environment. Alternative practices include no-till, strip-till, ridge-till, or mulch till practices. No-till, by definition, leaves a minimum of 30% plant residue on the surface of the field. Ridge-till and strip-till are generally categorized as “reduced tillage;” in order to fall into this classification, 15 to 30% residue must remain. These approaches are possible due to improvements in planting equipment and in particular to the development of genetically modified herbicide resistant cotton varieties. The term “conservation” tillage may be used to describe practices that, in general, reduce the amount of tilling (number of passes) that are made, but do not necessarily leave less area undisturbed or greater amounts of residue on the surface. In cotton farming, one such approach, called “stale seedbed” planting, entails performing deep tillage of soils in the fall, after harvest, with no subsequent tilling in the spring (i.e., immediately before planting). Mulch till refers to the practice of maximizing retention of crop residue on the soil surface without stating precise limits about the percentage that remains. As such, it is a broad term that can be, in principle, applied to a number of tillage systems including no till, strip till, or conventional till using either a disc or chisel plow; however, a no-till system typically can be assumed. Mulch till is sometimes used to describe the practice of seeding through a chemically killed or suppressed cover crop (Lal, 1995).

Conventional tillage dominates US cotton land preparation in regions not subject to erosion (Wakelyn, 2002). According to the Agricultural Resource Management Survey (ARMS), 83% of US cotton land was managed through conventional tillage systems in 2002, decreasing to 68% in 2007 (ERS, 2009a). Budgets supplied by the state extension agencies (also based on actual practices) suggest that conventional till systems were more common in 2007 than is indicated by ARMS data. This analysis assumes 80%, primarily driven by the very low number of no-till budgets available for the state of Texas. In addition, budgets labeled “stale seedbed” and “conservation tillage” are included in the conventional tillage total, as there is no statement as to the percent residue left. In general, no-till and strip-till methods are most common in the Mississippi Valley and southeastern US, while conventional tillage is typical in western states. Although operating costs are slightly lower for reduced tillage and no-tillage systems, they generally require either new equipment or equipment modification, thus investment costs can be a barrier to converting from a conventional to low-tillage program. In addition, these systems tend to be highly dependent upon the use of herbicides, which can off-set some of the savings realized with decreased fuel use in low-till practice. Residues tend to keep the soil cooler longer in the spring, making it a less desirable practice in areas with a shorter growing season. Another problem with the no-till approach is management of insect pests, which can require complete soil turn-over and elimination of cotton plant host material (Mitchell, 2006). A recent study (Nelson et al., 2009) concluded that reduced-till practices for cotton appear to be used most often in regions where overall resource demand for growing cotton is high (particularly fuel consumption), thus this approach may be driven as much by economics as agricultural ecology. The decision of whether or not to use a no-till system is often determined by soil type, as cotton seedlings need fine soil in order to emerge successfully (Wakelyn, 2002).

##### *5.3.1.2.5 Budgets Selected for Use in the Analysis*

A second cut of available budgets was made by eliminating all of those that are estimated to represent practices that occur on less than 1% of US cotton land, as given in Table 5.7. This reduced the total number of budgets to be considered to 25, while still representing 80% of the land area. Care was taken to minimize distortions in the distribution of seed type used, percent area irrigated, and tillage systems. Land that is managed as “no-till” and seed that is genetically modified to be herbicide resistant but not insect resistant are both underrepresented by three to four percent. The fraction irrigated is virtually identical. The final set of budgets used to define the activities considered and the flows associated with them are a composite of the remaining budgets, summarized in Table 5.8.

**Table 5.8**. State agricultural extension service enterprise budgets used in this analysis. Percent of US cotton land area is reapportioned between budgets such that total is 100%.

| State/Region | Budget | | | % this analysis | |
|---|---|---|---|---|---|
| | ID | Name | % of US | Materials | Equipment |
| TX, District 2, South Plains | A | Dry, RRFlex | 12.96% | 16.17% | 17.55% |
| | B | Pivot, BGIIFlex | 11.79% | 14.71% | 15.96% |
| TX, District 6, Far West | C | Dry, Conventional Seed | 2.35% | 2.93% | 3.18% |
| TX, District 11, Coastal Bend | D | Dry, GMO Seed & Conventional Till | 3.81% | 4.75% | 5.16% |
| TX, District 3, Rolling Plains | E | Dry, 2X1 planting pattern | 2.67% | 3.33% | 3.62% |
| TX, District 7, West Central | F | Dry, follow wheat, GMO Seed | 3.14% | 3.92% | 4.24% |
| GA, Southern and Eastern | G | Irrigated, Conventional Tillage | 2.33% | 2.91% | 3.15% |
| | H | Irrigated, Strip Tillage | 2.15% | 2.68% | 2.92% |
| | I | Non-Irrigated, Conventional Tillage | 1.77% | 2.21% | 2.39% |
| | J | Non-Irrigated, Strip Tillage | 3.19% | 3.98% | 4.32% |
| AR, Northern | K | AG-1182 Non-irrigated, 8 Row, RR Flex | 1.37% | 1.71% | 1.85% |
| | L | AG-1189 Furrow, 12 Row, BG/RR | 3.20% | 3.99% | 4.33% |
| AR, Southern | M | AG-1176 Furrow, 8 Row, Conv Till, BG/RR | 2.15% | 2.68% | 2.91% |
| MS, Delta area | N | 8R-38", solid, BtRR, non-irrigated | 1.71% | 2.13% | 2.31% |
| | O | 8R-38", solid, BtRR, pipe irrigated | 1.52% | 1.90% | 2.06% |
| NC, Non-Tidewater area | P | Conventional Tillage | 1.08% | 1.35% | 1.47% |
| | Q | Strip Tillage | 2.68% | 3.34% | 3.63% |
| TN, all | R | BGII RR Flex - Conventional Tillage | 4.13% | 5.15% | 5.59% |
| | S | BGRR - No Tillage | 3.89% | 4.85% | 5.27% |
| CA, San Joaquin Valley | T | Upland cotton, 40 inch rows | 1.89% | 2.36% | 2.56% |
| | U | Pima Cotton | 2.52% | 3.14% | 3.41% |
| AL, all [1] | V | GMO seed, non-irrigated | 2.70% | 3.37% | 0% |
| MO, all [1] | W | Dry, BGII/RR Flex | 1.71% | 2.13% | 0% |
| | X | Center Pivot, BGII/RR Flex | 1.89% | 2.36% | 0% |
| LA, Northeast | Y | Sandy Soil, 8-row, Solid Planted, BG/RR | 1.57% | 1.96% | 2.12% |

[1] Alabama and Missouri budgets do not contain specific equipment activity data

### *5.3.1.2.1 Land Preparation and Management*

#### *5.3.1.2.1.1 General Description:*

There are three primary tasks in preparing land to grow cotton: 1) removing old plant material, 2) eliminating weeds and insects, and 3) mechanical manipulation of the soil. The essential goal is to prepare the soil for optimum seed germination and seedling emergence. Mechanical tillage is used to improve soil texture, which facilitates the mobility of nutrients and water. Other objectives include protection of the plant, by killing, removing, and/or burying pests; and management of water flow and soil temperature, through the formation of rows and ridges in the soil. In most cases, the process is completed over a period of several months, beginning immediately after the preceding crop is harvested and continuing until the subsequent one is planted. The activities vary depending upon the soil type, tillage system used, and regionally specific threats of insect damage.

While cotton is grown as an annual, it is actually a perennial plant. The first step in land preparation when growing cotton, therefore, is to destroy the previous crop. This is especially important in areas where freezing temperatures are relatively uncommon. Any remaining live plant material may compete with the subsequent crop, but more importantly, a complete kill of any remaining portion of the cotton plant is required in order to prevent overwintering of pests that feed on live plant material. Removal of the cotton host is particularly critical in western states where the pink bollworm is a problem. On virtually all US cotton land, regardless of location or tillage system, a stalk shredder is used to eliminate above-ground vegetation. In many states, including Texas where most cotton is grown, stalk destruction is required by law (IPM, 2009). Complete removal of below-ground vegetation may be accomplished using a stalk- or root-puller; this is most commonly employed in areas where potential insect damage is of particular concern. In most regions, destruction of below-ground matter and remaining above-ground plant material is achieved either through mechanical tillage (chopping up the plant material and incorporating it into the soil) and/or application of herbicides. Use of a rotary disc harrow has been shown to produce a complete kill of remaining plants (Mitchell, 2006).

The term “tillage” is a generic one and encompasses all seedbed preparation activities that optimize soil and environmental conditions for seed germination, seedling establishment, and crop growth. It includes mechanical manipulation of the soil, application of herbicides, and use of fallow crops and crop residues (Lal, 1995). Primary tillage applies to activities during the land preparation unit operation (i.e., before planting). When used without qualification, the term “tillage” is taken to refer to primary, mechanical tillage. In conventional tillage, soil is cut and/or turned using implements such as a chisel (knife blades), disc (large rotating blades), or harrow (a set of smaller implements, such as discs or tines, run in parallel to one another). Deep tillage, until the late 1990’s, was often accomplished using a moldboard plough. By some estimates (West and Marland, 2002), this single piece of equipment was responsible for more than one-third of the fuel consumption and associated emissions when used in the cultivation of cotton. None of the state extension budgets (which are primarily from 2008 and 2009 and therefore reflect practices in 2007 and 2008) include this piece of equipment.

Cotton is particularly sensitive to deficiencies in nitrogen (N), potassium (K), sulfur (S), and boron (B). Most fertilizer is added during the land preparation unit operation, although a second application, particularly of nitrogen, is often required during the growth stage of the plant. Irrigated cotton requires 20 to 25% more nitrogen (Crozier, 2009) than non-irrigated crops. This not only supports the increase in plant growth resulting from added nutrients, but also replaces nitrogen lost through leaching. The presence of additional water increases the leaching rate and available nitrogen is subsequently transported away from the root zone as water drains from the site. In some locations, limestone ($CaCO_3$) may be added to the soil as a source of calcium and as a means to reduce acidity. Crozier (2009) notes that dolomite ($CaMg(CO_3)_2$), rather than limestone, should be used on soils that are deficient in magnesium, but application of this material is not mentioned in any of the budgets studied.

##### *5.3.1.2.1.2 Activities*

The number of activities required in preparing land for growing cotton varies significantly depending upon regional differences, seed type used, and tillage method. For a no-till system in Tennessee, the only activities employed are chopping stalks after harvest and applying herbicide before planting the next crop (McKinley and Gerloff, 2009). California cotton, in contrast, is grown primarily with conventional seed and conventional tillage. There, after cotton is harvested, the stalks are first chopped and then incorporated, along with other plant residue, into the soil with two passes of a disc. Tillage with a disc is repeated prior to planting. Every three years, the ground is ripped or subsoiled in two passes, 2 to 3 feet deep, in order to reduce compaction in the soil that can affect root penetration and water infiltration. In all years, the ground is disced twice before planting to break up large clods. This is followed by two passes with a finish or offset disc with herbicide applied in between the last two passes. The second pass with the disc incorporates the herbicide into the soil and smoothes the surface. A tractor implement known as a lister is used to form beds and complete the process (UCD, 2003a; 2003b).

Fertilizers and soil amendments are often applied in what is known as a custom operation, in which the farmer pays an outside service to perform a particular activity. In these cases, the amount of fertilizer or amendment is itemized separately so that only the flows associated with use of the equipment need to be accounted for separately. A surrogate is created using a typical piece of equipment that might be used to apply these substances.

Herbicides are typically applied by spray, either on the ground or from the air. Aerial applications are always a custom operation. The budgets provide total cost data but no information with respect to the amount of fuel that is combusted by the aircraft or time required to complete each operation. The maximum amount of fuel used by aircraft is during climbout. Based on data from the Federal Aviation Administration Emissions and Dispersion Modeling System a typical consumption rate for air tractors (crop dusters) is 0.075 kg per second. In working mode, it is assumed that fuel consumption is between 30% and 50% of the maximum, or 0.03 kg/sec (0.01 gallon per second) (ERG, 2009). A typical working speed for these aircraft is assumed to be about 170 km/hr. Thus it would take only a few seconds for an aircraft with a 10 meter wing span to cover one acre, even accounting for turns and overlap. The fuel and chemical holding capacity of these craft is adequate to cover 1500 hectares for most applications. The total amount of fuel for landing and takeoff (LTO) is estimated to be 21 gallons (based on EPA, 1992, Table 5A); thus, even for a small, 100-acre application, only an additional 0.21 gallons per acre would be consumed. Based on these estimations, fuel consumption and associated emissions for application of chemicals by air are not considered in this analysis. However, it should be noted that most general aircraft used leaded fuel (EPA, 2008), which may be a concern in some areas.

The budgets listed in Table 5.8 were used to create sets of activities associated with land preparation under different circumstances. These sets are presented in Table 5.9. Rather than naming specific pieces of equipment, the general function of the implements and/or objective of the activity is described. The interested reader is directed to the state budgets for a complete list and size of all tractor implements used as well as the specific order in which the different activities are performed. Note that these can vary significantly between the different budgets. References for each budget are given in Table 5.7. The documentation that accompanies the budgets for Mississippi, provided by Mississippi State University Extension Service, is an especially useful resource; it contains the most complete listing of equipment along with detailed characteristics and can be used as a general guide in many other states (MSU, 2008).

**Table 5.9**. Equipment and activities used in the land preparation unit operation for cotton as characterized by major regions and management systems used in the US. Percent of US cotton land area is reapportioned between budgets with equipment activity data such that total is 100%.

| Budget ID | % of US | Unit | HP | Activity | hrs/ acre | acre/ yr | gal/ hr | gal/ ac=yr | liters/ ha-yr |
|---|---|---|---|---|---|---|---|---|---|
| A, B | 33.51% | Tractor | 125 | cut stalks | 0.069 | 1 | 6.69 | 0.5 | 4.3 |
| | | Tractor | 125 | chisel plow | 0.099 | 1 | 6.69 | 0.7 | 6.2 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | Sprayer | 200 | apply herbicide [1] | 0.011 | 1 | 10.29 | 0.1 | 1.1 |
| | | Tractor | 100 | weed/cultivate | 0.077 | 1 | 5.40 | 0.4 | 3.9 |
| | | Tractor | 100 | till and form beds | 0.114 | 1 | 5.40 | 0.6 | 5.8 |
| | | TOTAL | | | | | | 3.0 | 28.4 |
| C | 3.18% | Tractor | 150 | shred stalks | 0.082 | 1 | 7.72 | 0.6 | 5.9 |
| | | Tractor | 190 | chisel plow | 0.076 | 1 | 9.77 | 0.7 | 6.9 |
| | | Tractor | 150 | harrow | 0.073 | 1 | 7.72 | 0.6 | 5.3 |
| | | Tractor | 190 | cultivate | 0.046 | 1 | 9.77 | 0.4 | 4.2 |
| | | Tractor | 170 | list beds | 0.060 | 1 | 8.75 | 0.5 | 4.9 |
| | | Tractor | 190 | cultivate | 0.077 | 1 | 9.77 | 0.8 | 7.0 |
| | | TOTAL | | | | | | 3.7 | 34.3 |
| D | 5.16% | Tractor | 150 | shred stalks | 0.083 | 1 | 7.72 | 0.6 | 6.0 |
| | | Tractor | 225 | form beds | 0.040 | 2 | 11.58 | 0.9 | 8.7 |
| | | Tractor | 225 | apply fertilizer | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | Sprayer | 200 | apply herbicide | 0.020 | 1 | 10.29 | 0.2 | 1.9 |
| | | TOTAL | | | | | | 2.5 | 23.7 |
| E | 3.62% | Tractor | 125 | shred stalks | 0.209 | 1 | 6.69 | 1.4 | 13.1 |
| | | Tractor | 125 | disc | 0.105 | 2 | 6.69 | 1.4 | 13.1 |
| | | Tractor | 125 | chisel plow | 0.091 | 1 | 6.69 | 0.6 | 5.7 |
| | | Tractor | 125 | spray herbicide | 0.088 | 1 | 6.69 | 0.6 | 5.5 |
| | | Tractor | 125 | form beds | 0.114 | 1 | 6.69 | 0.8 | 7.1 |
| | | TOTAL | | | | | | 4.8 | 44.6 |
| F | 4.24% | Sprayer | 200 | apply herbicide | 0.011 | 3 | 10.29 | 0.3 | 3.2 |
| | | TOTAL | | | | | | 0.3 | 3.2 |
| G, I | 5.54% | Tractor | 210 | mow, shred stalks | 0.125 | 1.2 | 11.58 | 1.7 | 16.2 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.33 | 11.58 | 0.3 | 2.4 |
| | | Tractor | 210 | disc | 0.054 | 2 | 11.58 | 1.3 | 11.7 |
| | | Tractor | 210 | disc and incorporate herbicide | 0.063 | 2 | 11.58 | 1.5 | 13.6 |
| | | Tractor | 210 | rip and bed | 0.133 | 1.5 | 11.58 | 2.3 | 21.6 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | TOTAL | | | | | | 7.8 | 72.7 |
| H, J | 7.24% | Tractor | 210 | mow, shred stalks | 0.125 | 1.2 | 11.58 | 1.7 | 16.2 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.33 | 11.58 | 0.3 | 2.4 |
| | | Tractor | 150 | apply herbicide | 0.025 | 5 | 7.72 | 1.0 | 9.0 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | TOTAL | | | | | | 3.7 | 34.8 |

**Table 5.9 (cont)**

| Budget ID | % of US | Unit | HP | Activity | hrs/ acre | acre/ yr | gal/ hr | gal/ ac-yr | liters/ ha-yr |
|---|---|---|---|---|---|---|---|---|---|
| K | 1.85% | Tractor | 190 | chop stalks | 0.100 | 1 | 9.77 | 1.0 | 9.1 |
| | | Tractor | 190 | till and form beds | 0.160 | 1 | 9.77 | 1.6 | 14.6 |
| | | Sprayer | 110 | apply herbicide | 0.017 | 2 | 5.66 | 0.2 | 1.8 |
| | | Tractor | 190 | disc | 0.074 | 1 | 9.77 | 0.7 | 6.8 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | Tractor | 190 | condition beds | 0.059 | 1 | 9.77 | 0.6 | 5.4 |
| | | TOTAL | | | | | | 4.8 | 44.9 |
| L | 4.33% | Tractor | 225 | chop stalks | 0.100 | 1 | 11.58 | 1.2 | 10.8 |
| | | Tractor | 225 | till and form beds | 0.107 | 1 | 11.58 | 1.2 | 11.6 |
| | | Sprayer | 200 | apply herbicide | 0.011 | 2 | 10.29 | 0.2 | 2.1 |
| | | Tractor | 225 | disc | 0.049 | 1 | 11.58 | 0.6 | 5.3 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | Tractor | 225 | condition beds | 0.040 | 1 | 11.58 | 0.5 | 4.3 |
| | | TOTAL | | | | | | 4.4 | 41.3 |
| M | 2.91% | Tractor | 190 | chop stalks | 0.100 | 1 | 9.77 | 1.0 | 9.1 |
| | | Tractor | 190 | chisel plow | 0.076 | 1 | 9.77 | 0.7 | 6.9 |
| | | Tractor | 190 | heavy disc | 0.075 | 1 | 9.77 | 0.7 | 6.9 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | Tractor | 190 | cultivate | 0.046 | 1 | 9.77 | 0.4 | 4.2 |
| | | Tractor | 190 | form beds | 0.074 | 1 | 9.77 | 0.7 | 6.8 |
| | | Tractor | 190 | condition beds | 0.059 | 1 | 9.77 | 0.6 | 5.4 |
| | | TOTAL | | | | | | 5.0 | 46.4 |
| N | 2.31% | Tractor | 190 | shred stalks | 0.117 | 1 | 9.77 | 1.1 | 10.7 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.5 | 11.58 | 0.4 | 3.6 |
| | | Tractor | 190 | till | 0.080 | 1 | 9.77 | 0.8 | 7.3 |
| | | Tractor | 190 | form beds | 0.074 | 0.5 | 9.77 | 0.4 | 3.4 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | Tractor | 190 | apply fertilizer | 0.077 | 1 | 9.77 | 0.8 | 7.0 |
| | | Tractor | 190 | condition beds | 0.059 | 1 | 9.77 | 0.6 | 5.4 |
| | | TOTAL | | | | | | 4.8 | 44.5 |
| O | 2.06% | Tractor | 190 | shred stalks | 0.117 | 1 | 9.77 | 1.1 | 10.7 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.5 | 11.58 | 0.4 | 3.6 |
| | | Tractor | 190 | level ground | 0.151 | 0.25 | 9.77 | 0.4 | 3.4 |
| | | Tractor | 130 | form ditches | 0.020 | 0.5 | 6.69 | 0.1 | 0.6 |
| | | Tractor | 190 | till | 0.080 | 1 | 9.77 | 0.8 | 7.3 |
| | | Tractor | 190 | form beds | 0.074 | 0.75 | 9.77 | 0.5 | 5.1 |
| | | Tractor | 190 | condition beds | 0.059 | 1 | 9.77 | 0.6 | 5.4 |
| | | Tractor | 190 | apply fertilizer | 0.077 | 1 | 9.77 | 0.8 | 7.0 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | TOTAL | | | | | | 5.4 | 50.3 |

**Table 5.9 (cont)**

| Budget ID | % of US | Unit | HP | Activity | hrs/ acre | acre/ yr | gal/ hr | gal/ ac-yr | liters/ ha-yr |
|---|---|---|---|---|---|---|---|---|---|
| P | 1.47% | Tractor | 190 | shred stalks [2] | 0.117 | 1 | 9.77 | 1.1 | 10.7 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.333 | 11.58 | 0.3 | 2.4 |
| | | Tractor [3] | 190 | disc harrow | 0.140 | 2 | 9.77 | 2.7 | 25.6 |
| | | Tractor [3] | 190 | subsoil and form beds | 0.100 | 1 | 9.77 | 1.0 | 9.1 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | TOTAL | | | | | | 5.9 | 54.9 |
| Q | 3.63% | Tractor | 190 | shred stalks [2] | 0.117 | 1 | 9.77 | 1.1 | 10.7 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.333 | 11.58 | 0.3 | 2.4 |
| | | Tractor | 225 | apply fertilizer [1] | 0.066 | 1 | 11.58 | 0.8 | 7.1 |
| | | TOTAL | | | | | | 2.2 | 20.2 |
| R | 5.59% | Tractor | 215 | chop stalks | 0.100 | 1 | 11.58 | 1.2 | 10.8 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.5 | 11.58 | 0.4 | 3.6 |
| | | Tractor | 215 | chisel plow | 0.100 | 1 | 11.58 | 1.2 | 10.8 |
| | | Tractor | 215 | disc | 0.060 | 2 | 11.58 | 1.4 | 13.0 |
| | | Tractor | 215 | cultivate | 0.080 | 1 | 11.58 | 0.9 | 8.7 |
| | | Tractor | 215 | apply fertilizer | 0.070 | 1 | 11.58 | 0.8 | 7.6 |
| | | TOTAL | | | | | | 5.8 | 54.5 |
| S | 5.27% | Tractor | 215 | chop stalks | 0.100 | 1 | 11.58 | 1.2 | 10.8 |
| | | Tractor | 225 | apply lime [1] | 0.066 | 0.5 | 11.58 | 0.4 | 3.6 |
| | | Sprayer | 200 | apply herbicide | 0.011 | 1 | 10.29 | 0.1 | 1.1 |
| | | TOTAL | | | | | | 1.7 | 15.5 |
| T, U | 5.97% | Tractor [3] | 150 | chop stalks | 0.130 | 1 | 7.72 | 1.0 | 9.4 |
| | | Tractor [3] | 150 | disc residue | 0.240 | 2 | 7.72 | 3.7 | 34.7 |
| | | Tractor [3] | 230 | rip | 0.270 | 0.33 | 11.58 | 1.0 | 9.7 |
| | | Tractor [3] | 230 | primary disc | 0.250 | 2 | 11.58 | 5.8 | 54.2 |
| | | Tractor [3] | 230 | apply herbicide | 0.200 | 1 | 11.58 | 2.3 | 21.7 |
| | | Tractor [3] | 230 | disc and incorporate herbicide | 0.140 | 1 | 11.58 | 1.6 | 15.2 |
| | | Tractor [3] | 150 | list beds | 0.070 | 1 | 7.72 | 0.5 | 5.1 |
| | | Tractor [3] | 150 | form ditches | 0.060 | 1 | 7.72 | 0.5 | 4.3 |
| | | Tractor [3] | 150 | close ditches | 0.060 | 1 | 7.72 | 0.5 | 4.3 |
| | | Tractor [3] | 230 | pre-plant cultivate | 0.100 | 1 | 11.58 | 1.2 | 10.8 |
| | | TOTAL | | | | | | 18.1 | 169.2 |
| Y | 2.12% | Tractor | 130 | shred stalks | 0.117 | 1 | 6.69 | 0.8 | 7.3 |
| | | Tractor | 225 | till | 0.080 | 1 | 11.58 | 0.9 | 8.7 |
| | | Tractor | 170 | apply herbicide | 0.042 | 1 | 8.75 | 0.4 | 3.4 |
| | | Tractor | 190 | form beds | 0.074 | 0.5 | 9.77 | 0.4 | 3.4 |
| | | Tractor | 190 | condition beds | 0.078 | 1 | 9.77 | 0.8 | 7.1 |
| | | Tractor | 190 | apply fertilizer | 0.077 | 1 | 9.77 | 0.8 | 7.0 |
| | | Tractor | 130 | form ditches | 0.020 | 1 | 6.69 | 0.1 | 1.3 |
| | | TOTAL | | | | | | 4.1 | 38.2 |

[1] Listed as a custom operation, estimated from other budgets

[2] Not listed in budget, but assume it is done; taken to be same as MS

[3] HP of tractor not listed, estimated from other information in budget

#### *5.3.1.2.1.3 Direct Material and Energy Flows*

The direct material and energy flows associated with the land preparation and management unit operation include land, diesel fuel to power field equipment, as shown in Table 5.9, soil amendments, nutrients, herbicides, and emissions to air.

##### 5.3.1.2.1.3.1 Fuel Use

Diesel fuel use is summarized and weighted according to relative land area affected (percent of US cotton land harvested), as presented in Table 5.10. The representative US value is taken to be 42.47 liters per hectare with a minimum of 3.18 liters/ha and a maximum of 169.24 liters/ha. The minimum is associated with non-irrigated, no-till, GMO cotton grown in rotation with wheat in West Central Texas; the maximum field equipment fuel use occurs for a conventional system in California.

**Table 5.10**. Summary of field equipment diesel fuel use in the land preparation unit operation

| Budget ID | Budget | % of US | Regional Value | | US Weighted Value | |
|---|---|---|---|---|---|---|
| | | | gal/ ac | liters/ ha | gal/ ac-yr | liters/ ha-yr |
| A, B | TX D02, South Plains, Dry, RRFlex and Pivot, BGII Flex | 33.51% | 3.03 | 28.37 | 1.02 | 9.51 |
| C | TX D06, Far West, Dry, Conventional Seed | 3.18% | 3.67 | 34.29 | 0.12 | 1.09 |
| D | TX D11, Coastal Bend, Dry, GMO Seed & Conv Till | 5.16% | 2.54 | 23.73 | 0.13 | 1.22 |
| E | TX D03, Rolling Plains | 3.62% | 4.76 | 44.56 | 0.17 | 1.61 |
| F | TX D07, West Central, Dry, follow wheat, GMO Seed | 4.24% | 0.34 | 3.18 | 0.01 | 0.13 |
| G, I | GA, Conventional Tillage | 5.54% | 7.77 | 72.71 | 0.43 | 4.03 |
| H, J | GA Strip Tillage | 7.24% | 3.72 | 34.78 | 0.27 | 2.52 |
| K | AR North, AG-1182, Non-irrigated, 8 Row, RR Flex | 1.85% | 4.80 | 44.86 | 0.09 | 0.83 |
| L | AR North, AG-1189 Furrow, 12 Row, BG/RR | 4.33% | 4.42 | 41.33 | 0.19 | 1.79 |
| M | AR South, AG-1176, Furrow, 8 Row, Conv Till, BG/RR | 2.91% | 4.97 | 46.45 | 0.14 | 1.35 |
| N | MS Delta area, 8R-38", solid, BtRR, non-irrigated | 2.31% | 4.76 | 44.54 | 0.11 | 1.03 |
| O | MS Delta area, 8R-38", solid, BtRR, pipe irrigated | 2.06% | 5.38 | 50.30 | 0.11 | 1.04 |
| P | NC Non-Tidewater, Conventional Tillage | 1.47% | 5.87 | 54.95 | 0.09 | 0.81 |
| Q | NC Non-Tidewater, Strip Tillage | 3.63% | 2.16 | 20.22 | 0.08 | 0.73 |
| R | TN, BGII RR Flex - Conventional Tillage | 5.59% | 5.82 | 54.48 | 0.33 | 3.05 |
| S | TN, BGRR - No Tillage | 5.27% | 1.65 | 15.47 | 0.09 | 0.82 |
| T, U | CA, Upland and Pima | 5.97% | 18.09 | 169.24 | 1.08 | 10.10 |
| Y | LA Northeastern | 2.12% | 4.09 | 38.22 | 0.09 | 0.81 |
| US Cotton, Land Preparation, fuel consumption | | min | Min | 0.34 | 3.18 | |
| | | max | Max | 18.09 | 169.24 | |
| | | US representative value | | | 4.54 | 42.47 |

Re-grouping the activities listed in Table 5.9 and summing fuel use across the general categories of stalk destruction, mechanical tillage, fertilizer application, and herbicide application, it can be seen that mechanical tillage accounts for more than half (56%) of the diesel fuel consumption in this unit operation (24.3 liters/ha). Stalk destruction, which is practiced in all non-rotation crops, regardless of tillage system, uses 19% of the fuel (8.3 liters/ha). Pre-plant applications of fertilizer and herbicides account for 16% and 9% respectively (Figure 5.17).

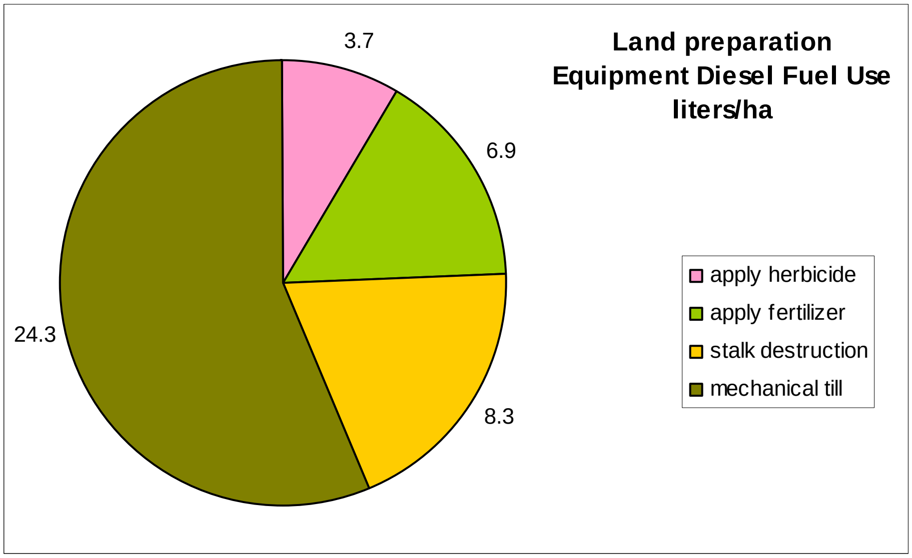


**Figure 5.17**. The majority of diesel fuel use (56%) in the land preparation unit operation is for mechanical tillage.

<u>5.3.1.2.1.3.2 Fertilizer and Soil Amendments</u>

Limestone is added to soils in some locations in order to reduce acidity (increase the pH). According to the state budgets, this is always done as a custom operation and application typically consists of applying one short ton per acre every two to three years. Use of this soil amendment is independent of agricultural management system. The range in application rates is from zero to 1,121 kilograms per hectare-year (0.5 tons/acre-year). Application rates by state and region are given in Table 5.11. The representative US application rate is taken to be 364 kilograms per hectare-year (kg/ha-yr).

**Table 5.11**. Lime applications on US cotton land

| State/ Region | Budget ID | % of US | tons/yr | weighted value | |
|---|---|---|---|---|---|
| | | | | lb/acre-yr | kg/ha-yr |
| GA, Southern and Eastern | G, H, I, J | 11.8% | 0.33 | 77.71 | 87.11 |
| MS, Delta area | N, O | 4.0% | 0.5 | 40.29 | 45.17 |
| NC, Non-Tidewater area | P, Q | 4.7% | 0.33 | 30.95 | 34.70 |
| TN, all | R, S | 10.0% | 0.5 | 100.04 | 112.13 |
| AL, all | U | 3.1% | 0.33 | 20.75 | 23.25 |
| MO, all | V & W | 5.5% | 0.5 | 55.01 | 61.66 |
| US Representative Value | | | | 324.75 | 364.01 |

The amount and types of fertilizer used varies by region. Application typically occurs during the land preparation unit operation, although nitrogen in the form of urea may be added during the tending unit operation. In general, the amount of nitrogen added after the plants have begun to mature should be minimized, as this can result in an undesirable amount of vegetative growth relative to cotton bolls. Increased vegetation (i.e., leaves) not only reduces yield, but can increase the food supply for pests. In some areas nitrogen is not applied at all. Boron and sulfur are the only two micronutrients applied.

A list of budgets and corresponding use of fertilizer during the land preparation unit operation is presented in Table 5.12. The timing of solid fertilizer application is not noted in the North Carolina and Georgia budgets, but is assumed to occur prior to planting using a custom operation. The Georgia budgets account for supplemental application of nitrogen (after planting) in equipment activity, but nitrogen per acre-year is reported as a single sum (i.e., the amount of nitrogen applied at different times is not broken out). For this analysis, it is assumed that 10 lbs of nitrogen is applied as a side dressing during the tending unit operation on Georgia cotton fields and the remainder is applied preplant. The budget for the mulch till crop in Texas (budget F) calls for application during the planting unit operation. As no other budget includes fertilization during the planting process and the amounts are small, this material is included with the land preparation unit operation.

The US representative values for each of the three macronutrients are 66.1 kilograms per hectare-year (59.0 pounds per acre-year) of nitrogen, 34.2 kg/ha-yr (30.5 lb/ac-yr) of phosphorus (as $P_2O_5$), and 42.4 kg/ha-yr (37.8 lb/ac-yr) of potassium (as $K_2O$). Micronutrients are applied at a rate of 1.7 kg/ha-yr (1.5 lb/ac-yr) of sulfur (S) and 0.4 kg/ha-yr (0.4 lb/ac-yr) of boron (B).

**Table 5.12.** Fertilizer application rates during land preparation for US cotton

| Nutrient | lb/ ac-yr | kg/ ha-yr | Budget IDs | % of US | Weighted Value | |
|---|---|---|---|---|---|---|
| | | | | | lbs/ acre-yr | kg/ ha-yr |
| Nitrogen (N) | 18.7 | 21.0 | F | 3.9% | 0.7 | 0.8 |
| | 30 | 33.6 | A | 16.2% | 4.8 | 5.4 |
| | 57 | 63.9 | E | 3.3% | 1.9 | 2.1 |
| | 60 | 67.3 | I, J | 6.2% | 3.7 | 4.2 |
| | 80 | 89.7 | G, H, P, Q, W, X | 14.8% | 11.8 | 13.2 |
| | 90 | 100.9 | V, Y | 5.3% | 4.8 | 5.4 |
| | 100 | 112.1 | B, D | 19.5% | 19.5 | 21.8 |
| UAN (urea and ammonium nitrate, as N) | 64 | 71.7 | N, O | 4.0% | 2.6 | 2.9 |
| Urea (as N) | 60 | 67.3 | O | 1.9% | 1.1 | 1.3 |
| | 80 | 89.7 | R, S | 10.0% | 8.0 | 9.0 |
| US representative (N) value | | | | | 59.0 | 66.1 |
| Phosphorous (P2O5) | 18.7 | 21.0 | F | 3.9% | 0.7 | 0.8 |
| | 20 | 22.4 | A | 16.2% | 3.2 | 3.6 |
| | 25 | 28.0 | B | 14.7% | 3.7 | 4.1 |
| | 30 | 33.6 | W | 2.1% | 0.6 | 0.7 |
| | 33.3 | 37.4 | D | 4.8% | 1.6 | 1.8 |
| | 40 | 44.8 | K, L, M, P, Q, X | 15.4% | 6.2 | 6.9 |
| | 50 | 56.0 | I, J | 6.2% | 3.1 | 3.5 |
| | 60 | 67.3 | G, H, R, S, V | 19.0% | 11.4 | 12.8 |
| US representative ($P_2O_5$) value | | | | | 30.5 | 34.2 |
| Potassium (K2O) | 8.3 | 9.3 | D | 4.8% | 0.4 | 0.4 |
| | 30 | 33.6 | W | 2.1% | 0.6 | 0.7 |
| | 35 | 39.2 | X | 2.4% | 0.8 | 0.9 |
| | 60 | 67.3 | V | 3.4% | 2.0 | 2.3 |
| | 80 | 89.7 | I, J, P, Q | 10.9% | 8.7 | 9.8 |
| | 90 | 100.9 | G, H, K, L, M, N, O, R, S | 28.0% | 25.2 | 28.2 |
| US representative ($K_2O$) value | | | | | 37.8 | 42.4 |
| Sulfur (S) | 5.5 | 6.2 | F | 3.9% | 0.2 | 0.2 |
| | 10 | 11.2 | K, L, M, P, Q | 13.1% | 1.3 | 1.5 |
| US representative (S) value | | | | | 1.5 | 1.7 |
| Boron (B) | 0.5 | 0.6 | R, S | 10.0% | 0.1 | 0.1 |
| | 1 | 1.1 | K, L, M, V, W, X | 16.2% | 0.2 | 0.2 |
| | 3 | 3.4 | P, Q | 4.7% | 0.1 | 0.2 |
| US representative (B) value | | | | | 0.4 | 0.4 |

NOTES

Budgets that report N fertilizer without stating a form are assumed to be using anhydrous ammonia

AR and AL budgets give proportions of nutrients; units are assumed to equal to pounds which gives masses similar to other budgets

GA and NC budgets do not specify application timing; all fertilizer in NC and all except 10 lb of N in GA is assumed to be applied preplant

### 5.3.1.2.1.3.3 Herbicides

Herbicide types and application rates during land preparation are given in Table 5.13. Unfortunately, many of the budgets assume a custom operation for the application of herbicides and provide only cost information. This applies to all of the Texas panhandle budgets, including District 02, which accounts for one-fourth of the US cotton land. Herbicides applied in Georgia were acquired through personal communication (Shurley, 2010). In each case where detailed activity data are absent, budgets most similar in terms of seed-type used, tillage system, location, and total cost were selected as surrogates and are noted at the end of Table 5.13.

**Table 5.13**. Herbicide application rates during land preparation for US cotton.

| Trade Name | Common Chemical Name | Active Ingredient (a.i.) | Product Use Rate | | Active Ingredient Use Rate | | Budget IDs | % of US cotton land | Weighted Mean | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | lb/gal | gal/ acre | liters/ ha | lbs/ acre | kg/ ha | | | lbs/ acre-yr | kg/ ha-yr |
| 2,4-D Amine | 2,4-D amine | 3.8 | 0.16 | 1.5 | 0.6 | 0.7 | F | 3.92% | 0.099 | 0.110 |
| | | | 0.30 | 2.8 | 1.1 | 1.3 | Q | 3.34% | | |
| | | | 0.50 | 4.7 | 1.9 | 2.1 | Y | 1.96% | | |
| Clarity | dicamba | 4 | 0.06 | 0.6 | 0.3 | 0.3 | A, B, K, L, N, O, S | 45.45% | 0.114 | 0.127 |
| unspecified | diuron | 4 | 0.25 | 2.3 | 1.0 | 1.1 | H, J | 6.66% | 0.067 | 0.075 |
| Reflex 2LC | fomesafen | 2 | 0.13 | 1.2 | 0.3 | 0.3 | A, B, K, L | 36.57% | 0.091 | 0.102 |
| Glyphosate Plus (3 lb/gal a.e.) | glyphosate | 4 | 0.25 | 2.3 | 1.0 | 1.1 | A, B, K, L, N, O | 40.60% | 0.874 | 0.980 |
| unspecified | | 5 | 0.19 | 1.8 | 0.9 | 1.1 | D | 4.75% | | |
| | | | 0.13 | 1.2 | 0.6 | 0.7 | E | 3.33% | | |
| | | | 0.25 | 2.3 | 1.3 | 1.4 | H, J, P, Q, V | 14.72% | | |
| | | | 0.75 | 7.0 | 3.8 | 4.2 | F | 3.92% | | |
| Roundup Power Max | | 5.5 | 0.20 | 1.9 | 1.1 | 1.2 | S | 4.85% | | |
| Roundup Weather Max | | | 0.17 | 1.6 | 0.9 | 1.1 | Y | 1.96% | | |
| Prowl | pendimethalin | 3.3 | 0.25 | 2.3 | 0.0 | 0.0 | G, I | 5.11% | 0.033 | 0.037 |
| | | | 0.30 | 2.8 | 1.0 | 1.1 | V | 3.37% | | |
| Treflan HFP | trifluralin | 4 | 0.19 | 1.8 | 0.8 | 0.8 | T, U | 5.50% | 0.041 | 0.046 |
| Staple | pyrithiobac | | | | 0.024 | 0.027 | T, U | 5.50% | 0.001 | 0.001 |
| Caparol | prometryn | 4 | 0.38 | 3.5 | 1.5 | 1.7 | T, U | 5.50% | 0.083 | 0.092 |

NOTES

Texas District 02 assumes custom operations and provides no information regarding amount and type of herbicide applied; Arkansas data are assumed

NC strip tillage (budget P) lumps all herbicide use together; assume approximately 1/3 is preplant

GA budgets do not give amount and type of herbicide applied. Data obtained through personal communication

AL (budget U) does not provide information regarding amount and type of herbicide applied; NC conventional till is assumed

Active ingredient contents from MWSC, 2009

5.3.1.2.1.3.4 Emissions to Air

Criteria Air Pollutants

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. Criteria air pollutants that result from the burning of diesel fuel in the equipment listed in Table 5.9 are calculated based on the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004; EPA, 2005). The only two powered pieces of ground equipment are tractors and sprayers, both of which are taken to have life expectancies of 8 years (MSU, 2008). The majority of the equipment is assumed to be at or near the median age; thus in 2007 most of the equipment is assumed to be model years 2002 to 2005, and the profile is estimated to be 30% Tier 1, 60% Tier 2, and 10% Tier 3 technology. Sulfur content of the diesel is assumed to be 0.05 wt%, as would be expected for agricultural equipment in 2007. The resulting emissions in grams per liter of fuel burned and grams per hectare-year are given in Table 5.14.

**Table 5.14**. Emissions in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the land preparation unit operation (based on emission factors from the NONROAD model (EPA, 2004; 2005) and equipment data from sources listed in Table 5.7; fuel use is weighted by the percent of US harvested land affected by that equipment type.

| Equipment | Unit Power (HP) | Wtd Fuel Use liters/ ha-yr | Emissions g/liter | | | | | Emissions g/ha-yr | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | VOC | CO | $NO_X$ | PM | $SO_2$ | VOC | CO | $NO_X$ | PM | $SO_2$ |
| Sprayer | 110 | 0.0 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 0.1 | 0.2 | 1 | 0.0 | 0.0 |
| | 200 | 0.7 | 1.71 | 6.18 | 21.4 | 0.97 | 0.83 | 1.3 | 4.6 | 16 | 0.7 | 0.6 |
| Tractor plus implements | 100 | 3.2 | 2.19 | 18.60 | 22.8 | 1.73 | 0.88 | 7.1 | 60.1 | 74 | 5.6 | 2.9 |
| | 125 | 5.1 | 1.79 | 6.89 | 20.9 | 1.28 | 0.80 | 9.2 | 35.4 | 107 | 6.6 | 4.1 |
| | 130 | 0.2 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 0.4 | 1.4 | 4 | 0.3 | 0.2 |
| | 150 | 4.8 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 8.9 | 34.2 | 104 | 6.3 | 4.0 |
| | 170 | 0.2 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 0.4 | 1.6 | 5 | 0.3 | 0.2 |
| | 190 | 5.4 | 1.71 | 6.19 | 21.4 | 0.97 | 0.83 | 9.2 | 33.4 | 115 | 5.2 | 4.5 |
| | 210 | 4.7 | 1.59 | 5.77 | 19.9 | 0.91 | 0.78 | 7.5 | 27.0 | 93 | 4.2 | 3.6 |
| | 215 | 3.4 | 1.63 | 5.91 | 20.4 | 0.93 | 0.80 | 5.6 | 20.2 | 70 | 3.2 | 2.7 |
| | 225 | 8.0 | 1.71 | 6.18 | 21.4 | 0.97 | 0.83 | 13.7 | 49.4 | 171 | 7.8 | 6.7 |
| | 230 | 6.7 | 1.75 | 6.32 | 21.8 | 0.99 | 0.85 | 11.6 | 42.1 | 145 | 6.6 | 5.7 |
| TOTAL | | 42.5 | 21.5 | 90.7 | 257.0 | 14.1 | 9.9 | 74.8 | 309.6 | 905 | 46.8 | 35.1 |

Greenhouse Gas Emissions

Greenhouse gas emissions from burning of diesel fuel are estimated using IPCC emission factors (IPCC, 2006a). The default carbon dioxide ($CO_2$) emission rate for agricultural diesel operations is 74.1 kilograms (kg) of $CO_2$ per gigajoule (GJ) of fuel burned. If diesel is assumed to have a lower heating value (LHV) energy content of 0.0358 GJ/liter (ANL, 2009), this is equivalent to 2.65 kg $CO_2$ per liter of diesel burned. Similarly, the IPCC default value for methane ($CH_4$) is 4.15 kilograms per terajoule (TJ) and the default value for $N_2O$ is 28.6 kg/TJ. These equate to emissions of 0.149 and 1.02 grams of $CH_4$ and $N_2O$ respectively per liter of diesel combusted.

Applying these values to the total fuel consumed (42.5 liters per hectare), the operation of diesel powered equipment during the land preparation unit operation results in per hectare emissions of 113 kg of $CO_2$, 0.0063 kg of $CH_4$, and 0.043 kg of $N_2O$.

The application of limestone contributes to $CO_2$ emissions. IPCC guidelines (IPCC, 2006b) give an emission factor of 0.12 for limestone. This is multiplied by the mass of limestone used (364 kg/ha, Table 5.11) and by 44/12 to convert carbon to $CO_2$ for a total emission rate of

$$0.12 \ * \ 364 \text{ kg/ha} \ * \ 44/12 \ = $$

$$160 \text{ kilograms } CO_2 \text{ / hectare} \qquad (5.7)$$

Both direct and indirect greenhouse gas emissions are also released as a consequence of using fertilizers during the land preparation unit operation; (indirect emissions are discussed in section 5.3.1.3.4.2 of this report). The application of nitrogen contributes to emissions of nitrous oxide ($N_2O$). The rate at which this occurs is based on IPCC guidelines (IPCC, 2006b, Equation 11.1).

The rate of direct $N_2O$ emissions from nitrogen fertilizer can be expressed as

$$N_2O_{fert} = N_{fert,N} \ * \ EF_{N\,fert} \ * \ N_2O_{mw} \ /(2 \ *N_{aw}) \qquad (5.8)$$

where

$N_2O_{fert}$ is the mass of annual nitrous oxide emissions per unit area due to fertilization

$N_{fert,N}$ is the mass of nitrogen fertilizer, as nitrogen, applied annually per unit area

$EF_{N\,fert}$ is the emission factor for added nitrogen, taken to be 0.01 per IPCC guidelines, (IPCCb, Table 11.1).

$N_2O_{mw} \ /(2 \ *N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Representative nitrogen fertilization rates for US cotton during land preparation are taken to be 66.1 kg/ha-yr (Table 5.12). Thus direct $N_2O$ emissions for nitrogen fertilization of cotton crops during this unit operation are calculated as

$$66.1 \text{ kg /ha-yr} \ * \ 0.01 \ * \ 44/28 \ = $$

$$1.04 \text{ kilograms } N_2O \text{ / hectare-year} \qquad (5.9)$$

The specific use of urea as a nitrogen fertilizer produces emissions of $CO_2$ as well as $N_2O$. In the presence of water, urea $CO(NH_2)_2$ reacts to form ammonium ($NH_4^+$), hydroxyl ion ($OH^-$), and bicarbonate ($HCO_3^-$). The bicarbonate ion then reacts further to form $CO_2$ and water. In the development of inventories, in which flows in and out of the atmosphere are categorized by sector, the manufacturing of urea is credited with the removal of $CO_2$ from the atmosphere. This same $CO_2$ is released from the urea upon use. For the purposes of this study, which includes upstream inputs to fertilizers and other chemicals applied to cotton crops, a $CO_2$ emission credit is given to urea production and thus emissions of $CO_2$ upon use of the fertilizer must be taken into account. Another approach (not taken here) would be to assume that net $CO_2$ emissions are zero. IPCC guidelines call for assuming that all of the carbon in the urea is oxidized to $CO_2$ and released as emissions to air. There are two nitrogen atoms for every carbon atom in urea, thus the mass fraction of carbon relative to nitrogen applied as urea is ratio of the atomic masses (12/2*14), which is equal to 0.429. The amount of $CO_2$ formed per atom of carbon is expressed as (12+2*16)/12, which is equal to 3.67. The mean US application of urea on cotton crops during the land preparation unit operation is 10.2 kg/ha-yr (Table 5.12). Additional urea is applied in the form of UAN, a mixture of urea and ammonium nitrate at US representative rates of 2.89 kg/ha-yr (Table 5.12). Material Data Safety Sheets (MSDS) for UAN 32 (32% nitrogen) indicate that a typical urea content is 33 to 36 wt%; 35% is assumed in this analysis.

The resulting $CO_2$ emissions are thus calculated as

$$(10.2 + 35\% * 2.89) \text{ kg / ha-yr} * 12 / (2 * 14) * (12 + 2*16) / 12 =$$

$$17.69 \text{ kilograms } CO_2 \text{ / hectare-year} \tag{5.10}$$

<u>5.3.1.2.1.3.5 Land Use and Summary</u>

The area of land planted to cotton is always greater than the area harvested. Taking a 10 year average (1999 through 2008) for all states, 89% of land that is planted is harvested (NASS, 1999-2009). The total area affected by land preparation for the purpose of producing cotton lint is therefore estimated to be 112% of the land area harvested. In addition, a certain percentage of cotton must be grown in order to provide seed for propagation. It is presumed that this is not accounted for in reports of area harvested for cotton lint. An additional 5% burden is applied to all unit operations within life cycle stage one, raw material acquisition (i.e., cotton agriculture) to account for this activity. The basis for this estimate is the price of seed per acre relative to the average cost per acre (as reported in the state budgets) to produce cotton lint under conditions of relatively high yield. The direct material and energy flows associated with the land preparation unit operation are thus multiplied by a factor of 1.12 to account for crop failure and 0.05 to account for seed cultivation, or a total of 1.17. A summary of the land preparation material and energy flows is given in Table 5.15.

**Table 5.15**. Direct material and energy flows for land preparation of US cotton cropland

| Resource | | Calculation | Value | Units |
|---|---|---|---|---|
| Land | | 1.17 hectares / 1 hectare-year | 1.17 | 1/yr |
| Diesel | | | | |
| | Volume | 1.17 / year * 42.5 liters / hectare | 50 | l/ha-yr |
| | Mass [1] | 49.7 liters / hectare-year * 0.837 kilograms / liter | 42 | kg/ha-yr |
| | Energy [1] | 49.7 liters / hectare-year * 35.8 megajoules / liter | 1,779 | MJ/ha-yr |
| Major Nutrients | | | | |
| | Nitrogen (N) | 1.17 / year * 66.1 kilograms / hectare | 77 | kg/ha-yr |
| | Phosphorous ($P_2O5$) | 1.17 / year * 34,2 kilograms / hectare | 40 | kg/ha-yr |
| | Potassium ($K_2O$) | 1.17 / year * 42.4 kilograms / hectare | 50 | kg/ha-yr |
| Micronutrients and Other | | | | |
| | Sulfur (S) | 1.17 / year * 1.7 kilograms / hectare | 2.0 | kg/ha-yr |
| | Boron (B) | 1.17 / year * 0.4 kilograms / hectare | 0.5 | kg/ha-yr |
| | Limestone ($CaCO_3$) | 1.17 / year * 364.0 kilograms / hectare | 426 | kg/ha-yr |
| Herbicides | | | | |
| | 2,4-D amine | 1.17 / year * 0.11 kilograms / hectare | 0.129 | kg/ha-yr |
| | dicamba | 1.17 / year * 0.13 kilograms / hectare | 0.149 | kg/ha-yr |
| | diuron | 1.17 / year * 0.17 kilograms / hectare | 0.087 | kg/ha-yr |
| | fomesafen | 1.17 / year * 0.10 kilograms / hectare | 0.120 | kg/ha-yr |
| | glyphosate | 1.17 / year * 0.98 kilograms / hectare | 1.146 | kg/ha-yr |
| | pendimethalin | 1.17 / year * 0.037 kilograms / hectare | 0.044 | kg/ha-yr |
| | trifluralin | 1.17 / year * 0.046 kilograms / hectare | 0.054 | kg/ha-yr |
| | pyrithiobac | 1.17 / year * 0.0015 kilograms / hectare | 0.002 | kg/ha-yr |
| | prometryn | 1.17 / year * 0.092 kilograms / hectare | 0.108 | kg/ha-yr |
| Criteria Air Pollutants and Precursors | | | | |
| | VOC | 1.17 / year * 0.075 kilograms / hectare | 0.09 | kg/ha-yr |
| | CO | 1.17 / year * 0.31 kilograms / hectare | 0.36 | kg/ha-yr |
| | $NO_X$ | 1.17 / year * 0.90 kilograms / hectare | 1.06 | kg/ha-yr |
| | PM | 1.17 / year * 0.047 kilograms / hectare | 0.05 | kg/ha-yr |
| | $SO_2$ | 1.17 / year * 0.035 kilograms / hectare | 0.04 | kg/ha-yr |
| Greenhouse Gases | | | | |
| | $CO_2$ | 1.17 / year * (113 + 160 + 18) kilograms / hectare | 340 | kg/ha-yr |
| | $CH_4$ | 1.17 / year * 0.0064 kilograms / hectare | 0.008 | kg/ha-yr |
| | $N_2O$ | 1.17 / year * (0.044 + 1.04) kilograms / hectare | 1.267 | kg/ha-yr |

[1] Energy content and density of liquid fuels, default inputs to GREET (ANL, 2009)

#### *5.3.1.2.2 Seeding and Planting:*

##### *5.3.1.2.2.1 General Description*

Cotton in the US is planted by mechanical means in rows that are typically spaced 36 to 40 inches (1 meter) apart. Formation of narrow, thirty-inch (0.8 meter) rows, is a practice that increases plant density and presumably yield; however, it is relatively uncommon and is not considered in this analysis. In conservation tillage systems, beds may be formed at the same time as seeds are planted.

Conventional cotton seeds are typically measured by weight, while genetically modified ones are counted in multiples of one thousand ($10^3$). Depending upon the variety, there may be 2000 to 6000 seeds per pound. A typical seeding rate is 10 to 15 pounds per acre (11 to 16 kg/ha). Seeds are often treated with fungicides and/or insecticides in order to protect newly emerged seedlings. This may be done by placing the substance in the bed with the seed (in-furrow) or alternatively, the seeds may be treated prior to planting as a custom service. In the case of the latter only the cost, rather than the amount and composition of the chemicals, is included in the budgets. The fungicide application rate in these instances is estimated by assuming a cost of $2.40 per pound for a generic fungicide (MSU, 2008). Similarly, the amount of insecticide applied is estimated by assuming a cost of $3.00 per pound (Shurley and Ziehl, 2007).

#### *5.3.1.2.2.2 Activities*

The primary activity associated with the planting unit operation is placing seeds in the ground to a depth of approximately one-half inch (1.25 cm) and covering them. This is accomplished using a tractor implement, referred to simply as a "planter," which is comprised of three main elements: a seed opener, a seed tube connected to a hopper filled with seed, and a scraper or press wheel that covers the seed with soil. The seed opener creates a furrow or trench in the soil into which the seed is dropped and consists of a disc (single or double), a shank (hoe), or a slot (runner). Guides are used to control the depth of the furrow. In no-till systems, a cutting disc (coulter) may be placed in front of the seed opener in order to cut through the residue lying on top of the soil (Buchholz et al, 1993). At times, it may be necessary to repeat the planting operation over a portion of the land to fill in where seed has failed to germinate. This is accounted for in only two budgets. It is unknown whether these are more accurate reflections of the intensity of the activity or whether there are inherent differences that increase the likelihood that multiple passes will be required.

Herbicides and fertilizers may be applied and incorporated during the planting operation; however the state extension service budgets do not always provide enough information to determine whether these should be allocated to the planting or to the tending unit operation. For the purpose of this analysis, all fertilizers applied during planting are accounted for within the land preparation unit operation. All herbicides that may be applied during planting are included in the tending rather than the planting unit operation.

The budgets listed in Table 5.8 were used to create sets of activities associated with land preparation under different circumstances. These sets are presented in Table 5.16.

**Table 5.16**. Equipment and activities used in the planting unit operation for cotton, as characterized by major regions and management systems used in the US. Budget descriptions are given in Table 5.8; references are listed in Table 5.7. Percent of US cotton land area is reapportioned between budgets containing equipment activity data such that total is 100%.

| | | | | | | | Regional Value | | US Weighted Value | |
|---|---|---|---|---|---|---|---|---|---|---|
| Budget ID | % of US | Tractor HP | Activity | hrs/ acre | acre-pass / yr | gal/ hr | gal/ ac | liters/ ha | gal/ ac-yr | liters/ ha-yr |
| A | 17.55% | 75 | plant seeds | 0.152 | 1 | 3.86 | 0.59 | 5.49 | 0.10 | 0.96 |
| B | 15.96% | 75 | plant seeds | 0.152 | 1.25 | 3.86 | 0.73 | 6.86 | 0.12 | 1.09 |
| C | 3.18% | 170 | plant seeds | 0.07 | 1.25 | 8.75 | 0.77 | 7.16 | 0.02 | 0.23 |
| D | 5.16% | 225 | plant seeds | 0.05 | 1 | 11.58 | 0.58 | 5.42 | 0.03 | 0.28 |
| E | 3.62% | 125 | plant seeds | 0.086 | 1 | 6.69 | 0.58 | 5.38 | 0.02 | 0.19 |
| F | 4.24% | 150 | plant seeds | 0.074 | 1 | 7.72 | 0.57 | 5.34 | 0.02 | 0.23 |
| G, I | 5.54% | 165 | plant seeds; apply in-furrow insecticide | 0.087 | 1 | 8.75 | 0.76 | 7.12 | 0.04 | 0.39 |
| H, J | 7.24% | 210 | rip, strip, plant; apply in-furrow insecticide | 0.118 | 1 | 11.58 | 1.37 | 12.78 | 0.10 | 0.93 |
| K, M | 4.76% | 190 | plant pre-treated seeds | 0.074 | 1 | 9.77 | 0.72 | 6.76 | 0.03 | 0.32 |
| L | 4.33% | 225 | plant pre-treated seeds | 0.049 | 1 | 11.58 | 0.57 | 5.31 | 0.02 | 0.23 |
| N, O | 4.37% | 190 | plant seeds | 0.08 | 1 | 9.77 | 0.78 | 7.31 | 0.03 | 0.32 |
| P [1] | 1.47% | 170 | plant seeds | 0.09 | 1 | 8.75 | 0.79 | 7.37 | 0.01 | 0.11 |
| Q [1] | 3.63% | 170 | rip, strip, till, plant with markers | 0.12 | 1 | 8.75 | 1.05 | 9.82 | 0.04 | 0.36 |
| R, S | 10.86% | 215 | plant pre-treated seeds | 0.06 | 1 | 11.58 | 0.69 | 6.50 | 0.08 | 0.71 |
| T, U [1] | 5.97% | 150 | plant | 0.12 | 1 | 7.72 | 0.93 | 8.67 | 0.06 | 0.52 |
| Y | 2.12% | 170 | plant | 0.08 | 1 | 8.75 | 0.70 | 6.55 | 0.01 | 0.14 |
| US Cotton, Planting, fuel consumption | | | | | | min | 0.57 | 5.31 | | |
| | | | | | | max | 1.37 | 12.78 | | |
| | | | | | | US representative value | | | 0.75 | 7.00 |

[1] HP of tractor not listed, estimated from other information in budget

### *5.3.1.2.2.3 Direct Material and Energy Flows*

The direct material and energy flows associated with the planting unit operation include diesel fuel to power field equipment, as shown in Table 5.12, fungicides and insecticides, and emissions to air.

Diesel fuel use is summarized and weighted according to relative land area affected (percent of US cotton land harvested) as presented in Table 5.16. The representative US value is taken to be 7.00 liters per hectare with a minimum of 5.31 liters/ha and a maximum of 12.78 liters/ha,

There is very little information regarding the types and amounts of fungicide and insecticide used at planting. Cost information is used where amounts are not specified. The fungicide application rate is estimated by assuming a cost of $2.40 per pound (MSU, 2008); insecticide use assumes a cost of $3.00 per pound (Shurley and Ziehl, 2007). A summary of insecticide and fungicide use associated with the planting unit operation is given in Table 5.17.

**Table 5.17**. Insecticide and fungicide application on US cotton land during planting

| State/ Region | Budget ID | % of US | State / Region | | | | weighted value | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Insecticide | | Fungicide | | Insecticide | | Fungicide | |
| | | | lb/acre-yr | kg/ha-yr | lb/acre-yr | kg/ha-yr | lb/acre-yr | kg/ha-yr | lb/acre-yr | kg/ha-yr |
| Georgia, all | G, H, I, J | 11.77% | 3.5 | 3.9 | | | 0.41 | 0.46 | | |
| Arkansas, all | K, L, M | 8.38% | 3.0 | 3.3 | 3.0 | 3.4 | 0.25 | 0.28 | 0.25 | 0.29 |
| Mississippi, all | N, O | 4.37% | | | 8.3 | 9.3 | | | 0.34 | 0.38 |
| Tennessee, all | R, S | 10.01% | 3.5 | 3.9 | 2.9 | 3.3 | 0.35 | 0.39 | 0.29 | 0.33 |
| US representative value | | | | | | | 1.01 | 1.13 | 0.88 | 0.99 |

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. Criteria air pollutants that result from the burning of diesel fuel in the equipment listed in Table 5.16 are calculated based on the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004; EPA, 2005). The only powered pieces of equipment are tractors taken to have life expectancies of 8 years (MSU, 2008). The majority of the equipment is assumed to be at or near the median age; thus in 2007 most of the equipment is assumed to be model years 2002 to 2005, and the profile is estimated to be 30% Tier 1, 60% Tier 2, and 10% Tier 3 technology. Sulfur content of the diesel is assumed to be 0.05 wt%, as would be expected for agricultural equipment in 2007. The resulting emissions in grams per liter of fuel burned and grams per hectare-year are given in Table 5.18.

**Table 5.18**. Emissions in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the planting unit operation (based on emission factors from the NONROAD model (EPA, 2004; 2005) and equipment data from sources listed in Table 5.7; fuel use is weighted by the percent of US harvested land affected by that equipment type.

| Equipment | Unit Power (HP) | Wtd Fuel Use liters/ ha-yr | Emissions g/liter | | | | | Emissions g/ha | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | VOC | CO | $NO_X$ | PM | $SO_2$ | VOC | CO | $NO_X$ | PM | $SO_2$ |
| Tractor plus implements | 75 | 2.1 | 2.39 | 19.52 | 24.4 | 2.00 | 0.93 | 4.9 | 40.2 | 50 | 4.1 | 1.9 |
| | 125 | 0.2 | 1.79 | 6.89 | 20.9 | 1.28 | 0.80 | 0.3 | 1.3 | 4 | 0.2 | 0.2 |
| | 150 | 0.7 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 1.4 | 5.3 | 16 | 1.0 | 0.6 |
| | 165 | 0.4 | 1.81 | 6.96 | 21.1 | 1.29 | 0.81 | 0.7 | 2.7 | 8 | 0.5 | 0.3 |
| | 170 | 0.8 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 1.5 | 6.0 | 18 | 1.1 | 0.7 |
| | 190 | 0.6 | 1.87 | 7.17 | 21.8 | 1.33 | 0.83 | 1.2 | 4.6 | 14 | 0.9 | 0.5 |
| | 210 | 0.9 | 1.59 | 5.77 | 19.9 | 0.91 | 0.78 | 1.5 | 5.3 | 18 | 0.8 | 0.7 |
| | 215 | 0.7 | 1.63 | 5.91 | 20.4 | 0.93 | 0.80 | 1.2 | 4.2 | 14 | 0.7 | 0.6 |
| | 225 | 0.5 | 1.71 | 6.18 | 21.4 | 0.97 | 0.83 | 0.9 | 3.1 | 11 | 0.5 | 0.4 |
| TOTAL | | 7.0 | 16.5 | 72.7 | 193.4 | 11.4 | 7.4 | 13.6 | 72.8 | 155 | 9.8 | 5.9 |

Greenhouse gas emissions from burning of diesel fuel are estimated using IPCC emission factors (IPCC, 2006a). The default carbon dioxide ($CO_2$) emission rate for agricultural diesel operations is 74.1 kilograms (kg) of $CO_2$ per gigajoule (GJ) of fuel burned. If diesel is assumed to have a lower heating value (LHV) energy content of 0.0358 GJ/liter (ANL, 2009), this is equivalent to

2.65 kg $CO_2$ per liter of diesel burned. Similarly, the IPCC default value for methane ($CH_4$) is 4.15 kilograms per terajoule (TJ) and the default value for $N_2O$ is 28.6 kg/TJ. These equate to emissions of 0.149 and 1.02 grams of $CH_4$ and $N_2O$ respectively per liter of diesel combusted. Applying these values to the total fuel consumed (7.0 liters per hectare), the operation of diesel powered equipment during the land preparation unit operation results in per hectare emissions of 18.6 kg of $CO_2$, 0.0010 kg of $CH_4$, and 0.0072 kg of $N_2O$.

The area of land planted to cotton is always greater than the area harvested. Taking a 10 year average (1999 through 2008) for all states, 89% of land that is planted is harvested (NASS, 1999-2009). The total area affected by land preparation for the purpose of producing cotton lint is therefore estimated to be 112% of the land area harvested. In addition, a certain percentage of cotton must be grown in order to provide seed for propagation. It is presumed that this is not accounted for in reports of area harvested for cotton lint. An additional 5% burden is applied to all unit operations within life cycle stage one, raw material acquisition (i.e., cotton agriculture) to account for this activity. The basis for this estimate is the price of seed per acre relative to the average cost per acre (as reported in the state budgets) to produce cotton lint under conditions of relatively high yield. The direct material and energy flows associated with the land preparation unit operation are thus multiplied by a factor of 1.12 to account for crop failure and 0.05 to account for seed cultivation, or a total of 1.17. A summary of the planting material and energy flows is given in Table 5.19.

**Table 5.19**. Direct material and energy flows for planting of US cotton cropland

| Resource | | Calculation | Value | Units |
|---|---|---|---|---|
| Land | | 1.17 hectares / 1 hectare-year | 1.17 | 1/yr |
| Diesel | | | | |
| | Volume | 1.17 / year * 7.0 liters / hectare | 8 | l/ha-yr |
| | Mass [1] | 8.2 liters / hectare-year * 0.837 kilograms / liter | 7 | kg/ha-yr |
| | Energy [1] | 8.2 liters / hectare-year * 35.8 megajoules / liter | 293 | MJ/ha-yr |
| Pesticides | | | | |
| | Insecticide | 1.17 / year * 1.1 kilograms / hectare | 1.33 | kg/ha-yr |
| | Fungicide | 1.17 / year * 1.0 kilograms / hectare | 1.16 | kg/ha-yr |
| Criteria Air Pollutants and Precursors | | | | |
| | VOC | 1.17 / year * 0.014 kilograms / hectare | 0.02 | kg/ha-yr |
| | CO | 1.17 / year * 0.073 kilograms / hectare | 0.09 | kg/ha-yr |
| | $NO_X$ | 1.17 / year * 0.15 kilograms / hectare | 0.18 | kg/ha-yr |
| | PM | 1.17 / year * 0.0098 kilograms / hectare | 0.01 | kg/ha-yr |
| | $SO_2$ | 1.17 / year * 0.0059 kilograms / hectare | 0.01 | kg/ha-yr |
| Greenhouse Gases | | | | |
| | $CO_2$ | 1.17 / year * 18.6 kilograms / hectare | 22 | kg/ha-yr |
| | $CH_4$ | 1.17 / year * 0.0010 kilograms / hectare | 0.001 | kg/ha-yr |
| | $N_2O$ | 1.17 / year * 0.0072 kilograms / hectare | 0.008 | kg/ha-yr |

[1] Energy content and density of liquid fuels, default inputs to GREET (ANL, 2009)

#### *5.3.1.2.3 Tending*

##### *5.3.1.2.3.1 General Description*

The primary functions of the tending unit operation are to control pests (insects and weeds), to add nutrients to the soil, and to control the water supply. This is done through secondary tillage (cultivation, or mechanical manipulation of soil and plants), chemical applications on both the ground and in the air, and irrigation. Mechanical tillage is used most often in conventional systems (seed and tillage) and/or in areas characterized by lighter soils. Chemical growth regulators may be used in some instances to ensure that the proportion of cotton bolls to green vegetative growth is high. This is particularly important where the amounts of available water and/or nitrogen are relatively high, whether naturally occurring or introduced as part of the agricultural practice. As growth regulating chemicals are often applied concurrently with defoliants shortly before harvest, this activity is accounted for in the harvest unit operation rather than with tending.

The 2008 Farm and Ranch Irrigation Survey reports that 9% of the irrigated cotton acres were subjected to chemigation (water plus pesticides) and that 23% (by land area) used irrigation water containing commercial fertilizer (USDA, 2010). The only budgets that reflect these practices are those from California, where all fertilizer is assumed to be applied through irrigation. It is therefore assumed, for this analysis, that the total amount of pesticides and fertilizer delivered in this manner is small. The reason for the discrepancy is unknown and is a source of uncertainty.

##### *5.3.1.2.3.2 Activities*

The primary activities that occur during the tending unit operation are the application of pesticides and irrigation water. Fertilizers are, in some instances, added either through side dressings or via irrigation water. Mechanical cultivation to control weeds may be employed, especially in conjunction with conventional seed and/or tillage systems. Spray applications often include a combination of chemicals (insecticides ± herbicides ± growth regulators). Therefore, in accounting for equipment use, spray activities are all noted as pesticide applications. Growth regulators are also applied along with defoliants and other “harvest aids.” In the interest of simplification, growth regulating chemicals are included in the harvest unit operation. A small amount of surfactant or crop (seed) oil is used in some applications, but it is not accounted for in this analysis.

State budgets provide some information regarding the amount of fuel and water used for irrigation, but it tends to be incomplete. Consequently, for this particular activity, data from the 2008 Farm and Ranch Irrigation Survey (USDA, 2010) are used to estimate total volume of water and energy requirements for US cotton. In accounting for irrigation energy and water use, all cotton states and regions are considered rather than just those represented in Table 5.8. A detailed explanation of how the irrigation survey data are used is provided in section 5.3.1.2.3.3.1 of this report.

A significant portion of pesticides, especially insecticides, are applied using custom services. These applications take place both on land and from the air. State budgets typically report only the total cost per acre application (including insecticide) for land-based custom operations. In these instances, a 200 HP (horse power) 600-825 gallon, 80 foot boom sprayer is assumed, with equipment characteristics taken from the appendices provided by the Mississippi State University budgets (MSU, 2008). The estimated cost per acre of operating this equipment is subtracted from the total and a typical insecticide is assumed based on the remaining cost input; the per unit cost of many insecticides is included in the Mississippi State University appendices (MSU, 2008). In the case of aerial applications, the specific insecticides and their application rates are given in the state budgets. The amount of fuel used in aerial applications is estimated to be very small relative to other activities (see discussion in section 5.3.1.2.1.2 of this report) and is therefore not accounted for in this analysis.

The budgets listed in Table 5.8 were used to create sets of activities associated with the tending unit operation, excluding irrigation. These sets are presented in Table 5.20. Rather than naming specific pieces of equipment, the general function of the implements and/or objective of the activity is described. The interested reader is directed to the state budgets for a complete list and size of all tractor implements used, as well as the specific order in which the different activities are performed. Note that these can vary significantly between the different budgets. References for each budget are given in Table 5.7.

**Table 5.20**. Equipment and activities used in the tending unit operation for cotton as characterized by major regions and management systems used in the US. Percent of US cotton land area is reapportioned between budgets with equipment activity data such that total is 100%.

| Budget ID | % of US | Unit | HP | Activity | hrs/ acre | acre-pass / yr | gal/ hr | gal/ ac-yr | liters/ ha-yr |
|---|---|---|---|---|---|---|---|---|---|
| A | 17.55% | Tractor | 75 | rotary hoe | 0.077 | 2 | 3.86 | 0.59 | 5.56 |
| | | Sand fighter [2] | 40 | condition beds | 0.057 | 2 | 2.57 | 0.29 | 2.74 |
| | | Tractor | 75 | cultivate | 0.118 | 3 | 3.86 | 1.37 | 12.78 |
| | | Sprayer | 200 | apply pesticide [1] | 0.013 | 0.5 | 10.29 | 0.07 | 0.63 |
| | | Tractor | 100 | disc | 0.138 | 0.15 | 5.4 | 0.11 | 1.05 |
| | | TOTAL | | | | | | 2.43 | 22.75 |
| B | 15.96% | Sand fighter [2] | 40 | condition beds | 0.057 | 2 | 2.57 | 0.29 | 2.74 |
| | | Tractor | 75 | rotary hoe | 0.077 | 1 | 3.86 | 0.30 | 2.78 |
| | | Sprayer | 200 | apply pesticide [1] | 0.013 | 1 | 10.29 | 0.13 | 1.25 |
| | | Tractor | 75 | cultivate | 0.118 | 2 | 3.86 | 0.91 | 8.52 |
| | | Sprayer | 200 | apply pesticide [1] | 0.013 | 1 | 10.29 | 0.13 | 1.25 |
| | | Tractor | 100 | disc | 0.138 | 0.2 | 5.4 | 0.15 | 1.39 |
| | | TOTAL | | | | | | 1.92 | 17.94 |
| C | 3.18% | Tractor | 150 | condition beds | 0.060 | 1 | 7.72 | 0.46 | 4.33 |
| | | Tractor | 170 | cultivate | 0.077 | 2 | 8.75 | 1.35 | 12.60 |
| | | Tractor | 170 | apply pesticide | 0.042 | 0.25 | 8.75 | 0.09 | 0.86 |
| | | TOTAL | | | | | | 1.90 | 17.80 |
| D | 5.16% | Sprayer | 200 | apply pesticide | 0.020 | 6 | 10.29 | 1.23 | 11.55 |
| | | Tractor | 225 | apply pesticide | 0.050 | 1 | 11.58 | 0.58 | 5.42 |
| | | TOTAL | | | | | | 1.81 | 16.97 |
| E | 3.62% | Sprayer | 200 | apply pesticide [1] | 0.013 | 1 | 10.29 | 0.13 | 1.25 |
| | | Tractor | 125 | apply pesticide | 0.088 | 2 | 6.69 | 1.18 | 11.01 |
| | | Tractor | 125 | cultivate | 0.109 | 2 | 6.69 | 1.46 | 13.64 |
| | | TOTAL | | | | | | 2.77 | 25.91 |
| F | 4.24% | Sprayer | 200 | apply pesticide | 0.011 | 2 | 10.29 | 0.23 | 2.12 |
| | | TOTAL | | | | | | 0.23 | 2.12 |
| G, H, J | 10.39% | Tractor | 150 | apply pesticide | 0.025 | 5 | 7.72 | 0.97 | 9.03 |
| | | Tractor | 150 | apply pesticide | 0.025 | 20 | 7.72 | 3.86 | 36.11 |
| | | Tractor | 165 | apply pesticide | 0.083 | 1.5 | 8.75 | 1.09 | 10.19 |
| | | Tractor | 165 | apply fertilizer | 0.083 | 1.5 | 8.75 | 1.09 | 10.19 |
| | | TOTAL | | | | | | 7.00 | 65.51 |
| I | 2.39% | Tractor | 150 | apply pesticide | 0.025 | 5 | 7.72 | 0.97 | 9.03 |
| | | Tractor | 150 | apply pesticide | 0.025 | 15 | 7.72 | 2.90 | 27.08 |
| | | Tractor | 165 | apply pesticide | 0.083 | 1.5 | 8.75 | 1.09 | 10.19 |
| | | Tractor | 165 | apply fertilizer | 0.083 | 1.5 | 8.75 | 1.09 | 10.19 |
| | | TOTAL | | | | | | 6.04 | 56.49 |
| K | 1.85% | Tractor | 190 | apply fertilizer | 0.042 | 1 | 9.77 | 0.41 | 3.84 |
| | | Sprayer | 110 | apply pesticide | 0.017 | 3 | 5.4 | 0.28 | 2.58 |
| | | Tractor | 170 | apply pesticide | 0.066 | 1 | 8.75 | 0.58 | 5.40 |
| | | TOTAL | | | | | | 1.26 | 11.82 |

**Table 5.20 (cont)**.

| Budget ID | % of US | Unit | HP | Activity | hrs/ acre | acre-pass / yr | gal/ hr | gal/ ac-yr | liters/ ha-yr |
|---|---|---|---|---|---|---|---|---|---|
| L | 4.33% | Tractor | 190 | apply fertilizer | 0.042 | 2 | 9.77 | 0.82 | 7.68 |
| | | Sprayer | 200 | apply pesticide | 0.011 | 2 | 10.29 | 0.23 | 2.12 |
| | | Tractor | 225 | cultivate and apply | 0.057 | 1 | 11.58 | 0.66 | 6.17 |
| | | Tractor | 190 | apply pesticide | 0.044 | 1 | 9.77 | 0.43 | 4.02 |
| | | TOTAL | | | | | | 2.14 | 19.99 |
| M | 2.91% | Tractor | 190 | apply fertilizer | 0.042 | 2 | 9.77 | 0.82 | 7.68 |
| | | Sprayer | 110 | apply pesticide | 0.017 | 2 | 5.4 | 0.18 | 1.72 |
| | | Tractor | 170 | cultivate and apply | 0.086 | 1 | 8.75 | 0.75 | 7.04 |
| | | Tractor | 170 | apply pesticide | 0.066 | 1 | 8.75 | 0.58 | 5.40 |
| | | TOTAL | | | | | | 2.33 | 21.83 |
| N | 2.31% | Sprayer | 200 | apply pesticide | 0.017 | 2 | 10.29 | 0.35 | 3.27 |
| | | Tractor | 190 | apply fertilizer | 0.077 | 1 | 9.77 | 0.75 | 7.04 |
| | | Tractor | 190 | apply pesticide | 0.066 | 1 | 9.77 | 0.64 | 6.03 |
| | | TOTAL | | | | | | 1.75 | 16.34 |
| O | 2.06% | Sprayer | 200 | apply pesticide | 0.017 | 3 | 10.29 | 0.52 | 4.91 |
| | | Tractor | 190 | apply fertilizer | 0.077 | 1 | 9.77 | 0.75 | 7.04 |
| | | Tractor | 190 | apply pesticide | 0.066 | 1 | 9.77 | 0.64 | 6.03 |
| | | Pipe spool [2] | 50 | roll out pipe | 0.042 | 1 | 2.06 | 0.09 | 0.80 |
| | | Pipe spool [2] | 50 | roll up pipe | 0.062 | 1 | 2.02 | 0.13 | 1.18 |
| | | TOTAL | | | | | | 2.13 | 19.95 |
| P | 1.47% | Sprayer | 110 | apply pesticide | 0.040 | 7 | 5.4 | 1.51 | 14.14 |
| | | Tractor [2] | 190 | cultivate | 0.100 | 2 | 9.77 | 1.95 | 18.28 |
| | | TOTAL | | | | | | 3.47 | 32.42 |
| Q | 3.63% | Sprayer | 110 | apply pesticide | 0.040 | 7 | 5.4 | 1.51 | 14.14 |
| | | Tractor [2] | 170 | apply pesticide | 0.080 | 1 | 8.75 | 0.70 | 6.55 |
| | | TOTAL | | | | | | 2.21 | 20.69 |
| R | 5.59% | Sprayer | 200 | apply pesticide | 0.012 | 7 | 10.29 | 0.84 | 7.86 |
| | | TOTAL | | | | | | 0.84 | 7.86 |
| S | 5.27% | Sprayer | 200 | apply pesticide | 0.012 | 7 | 10.29 | 0.84 | 7.86 |
| | | Tractor | 215 | apply fertilizer | 0.070 | 1 | 11.58 | 0.81 | 7.58 |
| | | TOTAL | | | | | | 1.65 | 15.44 |
| T, U | 5.97% | Tractor [2] | 150 | cultivate | 0.080 | 1 | 7.72 | 0.62 | 5.78 |
| | | Tractor [2] | 150 | cultivate | 0.310 | 3 | 7.72 | 7.18 | 67.16 |
| | | Tractor [2] | 150 | apply fertilizer | 0.140 | 1 | 7.72 | 1.08 | 10.11 |
| | | Sprayer | 105 | apply pesticide | 0.200 | 1 | 5.4 | 1.08 | 10.10 |
| | | Sprayer | 105 | apply pesticide | 0.200 | 1 | 5.4 | 1.08 | 10.10 |
| | | TOTAL | | | | | | 11.04 | 103.25 |
| Y | 2.12% | Tractor [2] | 170 | apply pesticide | 0.066 | 3 | 8.75 | 1.73 | 16.21 |
| | | Sprayer | 200 | apply pesticide | 0.017 | 1.5 | 10.29 | 0.26 | 2.45 |
| | | Tractor [2] | 170 | | 0.042 | 1 | 8.75 | 0.37 | 3.44 |
| | | TOTAL | | | | | | 2.36 | 22.10 |

[1] Listed as a custom operation, estimated from other budgets

[2] Some equipment characteristics determined indirectly, based on other information in budget

#### *5.3.1.2.3.3 Direct Material and Energy Flows*

The direct material and energy flows associated with the tending unit operation include land, diesel fuel to power field equipment, as shown in Table 5.20, water and energy for irrigation, nutrients, herbicides, growth regulators, insecticides, and emissions to air.

##### 5.3.1.2.3.3.1 Fuel Use

Diesel fuel use is summarized and weighted according to relative land area affected (percent of US cotton land harvested), as presented in Table 5.21. The representative US value is taken to be 29.10 liters per hectare with a minimum of 2.12 liters/ha and a maximum of 103.25 liters/ha, The minimum is associated with non-irrigated, no-till, GMO cotton grown in rotation with wheat in West Central Texas; the maximum field equipment fuel use occurs for a conventional system in California.

**Table 5.21**. Summary of field equipment diesel fuel use in the tending unit operation

| Budget ID | Budget | % of US | Regional Value | | US Weighted Value | |
|---|---|---|---|---|---|---|
| | | | gal/ ac | liters/ ha | gal/ ac-yr | liters/ ha-yr |
| A | TX D02, South Plains, Dry, RRFlex | 17.55% | 2.43 | 22.75 | 0.43 | 3.99 |
| B | TX D02, South Plains, Pivot, BGII Flex | 15.96% | 1.92 | 17.94 | 0.31 | 2.86 |
| C | TX D06, Far West, Dry, Conventional Seed | 3.18% | 1.90 | 17.80 | 0.06 | 0.57 |
| D | TX D11, Coastal Bend, Dry, GMO Seed & Conventional Till | 5.16% | 1.81 | 16.97 | 0.09 | 0.88 |
| E | TX D03, Rolling Plains | 3.62% | 2.77 | 25.91 | 0.10 | 0.94 |
| F | TX D07, West Central, Dry, follow wheat, GMO Seed | 4.24% | 0.23 | 2.12 | 0.01 | 0.09 |
| G, H, J | GA Strip Tillage and Irrigated Conventional Tillage | 10.39% | 7.00 | 65.51 | 0.73 | 6.81 |
| I | GA Non-irrigated Conventional Tillage | 2.39% | 6.04 | 56.49 | 0.14 | 1.35 |
| K | AR North, AG-1182, Non-irrigated, 8 Row, RR Flex | 1.85% | 1.26 | 11.82 | 0.02 | 0.22 |
| L | AR North, AG-1189 Furrow, 12 Row, BG/RR | 4.33% | 2.14 | 19.99 | 0.09 | 0.87 |
| M | AR South, AG-1176, Furrow, 8 Row, Conventional Till, BG/RR | 2.91% | 2.33 | 21.83 | 0.07 | 0.64 |
| N | MS Delta area, 8R-38", solid, BtRR, non-irrigated | 2.31% | 1.75 | 16.34 | 0.04 | 0.38 |
| O | MS Delta area, 8R-38", solid, BtRR, pipe irrigated | 2.06% | 2.13 | 19.95 | 0.04 | 0.41 |
| P | NC Non-Tidewater, Conventional Tillage | 1.47% | 3.47 | 32.42 | 0.05 | 0.48 |
| Q | NC Non-Tidewater, Strip Tillage | 3.63% | 2.21 | 20.69 | 0.08 | 0.75 |
| R | TN, BGII RR Flex - Conventional Tillage | 5.59% | 0.84 | 7.86 | 0.05 | 0.44 |
| S | TN, BGRR - No Tillage | 5.27% | 1.65 | 15.44 | 0.09 | 0.81 |
| T, U | CA, Upland and Pima | 5.97% | 11.04 | 103.25 | 0.66 | 6.16 |
| Y | LA Northeastern | 2.12% | 2.36 | 22.10 | 0.05 | 0.47 |
| US Cotton, Tending, field equipment, fuel consumption | | min | 0.23 | 2.12 | | |
| | | max | 11.04 | 103.25 | | |
| | | US representative value | | | 3.11 | 29.10 |

In addition to diesel fuel, a number of state budgets include use of one or more pickup trucks on the farm, with per acre consumption of gasoline ranging from one to three gallons per acre. Budget A, which represents the largest single land area, assumes 2 gallons of gasoline per acre, or 18.7 liters per hectare, for pickup truck operation. As this is the mid-point value, as well as characteristic of a major budget, this value is taken to be representative of all US land planted in cotton.

5.3.1.2.3.3.2 Water and Energy for Irrigation

More than a third of the land harvested for cotton in 2007 was irrigated (USDA, 2009). Most of the water is drawn from underground sources using electric, diesel or natural gas powered pumps (USDA, 2010). Cost and return documents for just four states (Texas, Arkansas, Mississippi, and Louisiana) provide information and data regarding the energy source used for pumping, the amount of energy required for irrigation, and the amount of water applied as measured in acre-inches or acre-feet. (An acre-foot is the volume of water that would cover an acre to the depth of one foot and is equal to 325,851 gallons (1,233,480 liters) of water). Within the state of Texas, data is supplied only for the western districts where irrigation is most common. In all cases, data for only one energy type is supplied.

The Farm and Ranch Irrigation Survey (USDA, 2010) was used to obtain the average amount of water applied to cotton crops on irrigated land in 2008. There is generally good agreement between the values in the survey and those given by the state budgets. The data in the USDA irrigation survey are converted to acre-inches and combined with the percent of harvested cotton land irrigated in 2007 (USDA, 2009) to obtain a weighted US average for all harvested cotton land (irrigated and non-irrigated). This value, 6.32 acre-inches per acre-year, is equivalent to 1.6 x $10^6$ liters per hectare-year (Table 5.22).

Water consumption is taken to be equivalent to crop evapotranspiration ($ET_C$), which is roughly equal to precipitation during the growing season plus irrigation water applied. Comprehensive evapotranspiration data for cotton in all regions of the US were not available; therefore estimates were made based on county-level precipitation data (WorldClimate, 2008), county-level data for harvested area irrigated (USDA, 2009), and state-level data for predominant irrigation technology and average amount of water applied to cotton (USDA, 2010). Gravity irrigation was assumed to be 70% efficient and sprinkler irrigation was assumed to be 80% efficient. Only the top 10 states, which account for 93% of the harvested area in the US, are considered and the fractional area is reapportioned to sum to 1.0. A summary of the estimated values is presented in Table 5.23.

**Table 5.22**. Water used for irrigation in the production of US cotton in 2008

| State | % of US Harvested Land [1] | % Harvested Cotton Land Irrigated [1] | State Average, Irrigated Cotton (acre-in applied) [2] | US Weighted, All Harvested Cotton Land | |
|---|---|---|---|---|---|
| | | | | ac-in/ac-yr | liters/ha-yr |
| Alabama | 3.6% | 5.9% | 7.2 | 0.02 | 3,934 |
| Arizona | 1.6% | 100.0% | 57.6 | 0.94 | 238,838 |
| Arkansas | 8.1% | 80.4% | 9.6 | 0.63 | 159,631 |
| California | 4.5% | 100.0% | 37.2 | 1.67 | 424,459 |
| Florida | 0.8% | 11.4% | 7.2 | 0.01 | 1,591 |
| Georgia | 9.5% | 31.1% | 9.6 | 0.28 | 72,011 |
| Kansas | 0.4% | 25.5% | 8.4 | 0.01 | 2,122 |
| Louisiana | 3.2% | 26.2% | 7.2 | 0.06 | 15,242 |
| Mississippi | 6.3% | 45.0% | 8.4 | 0.24 | 60,028 |
| Missouri | 3.6% | 52.5% | 9.6 | 0.18 | 46,111 |
| New Mexico | 0.4% | 100.0% | 27.6 | 0.11 | 28,198 |
| North Carolina | 5.0% | 2.0% | 6 | 0.01 | 1,528 |
| Oklahoma | 1.6% | 41.2% | 15.6 | 0.10 | 25,557 |
| South Carolina | 1.5% | 9.0% | 9.6 | 0.01 | 3,311 |
| Tennessee | 4.8% | 2.3% | 7.2 | 0.01 | 2,021 |
| Texas | 44.5% | 34.8% | 13.2 | 2.05 | 519,741 |
| Virginia | 0.6% | 0.6% | 3.6 | 0.00 | 31 |
| US Average | | | | 6.32 | 1,604,352 |

[1] 2007 Census of Agriculture (USDA, 2009)

[2] Farm and Ranch Irrigation Survey (USDA, 2010)

**Table 5.23**. Water consumption based on estimated values of crop evapotranspiration ($ET_C$)

| State | Wt% (top 10 states) [1] | % area irrigated [1] | $ET_C$ Irrigated Cotton | | $ET_C$ Dryland Cotton | | US Weighted Value | |
|---|---|---|---|---|---|---|---|---|
| | | | ac-in/ac-yr | liters/ha-yr | ac-in/ac-yr | liters/ha-yr | ac-in/ac-yr | liters/ha-yr |
| AL | 3.9% | 5.9% | 29.8 | 7,576,510 | 26.1 | 6,636,823 | 1.0 | 261,856 |
| AR | 8.7% | 80.4% | 30.4 | 7,717,800 | insufficient data [2] | | 2.7 | 674,461 |
| CA | 4.8% | 100.0% | 37.3 | 9,478,881 | na | | 1.8 | 457,008 |
| GA | 10.2% | 31.1% | 29.9 | 7,605,666 | 23.0 | 5,833,622 | 2.6 | 650,625 |
| LA | 3.4% | 26.2% | 24.8 | 6,306,510 | 18.4 | 4,667,244 | 0.7 | 174,010 |
| MS | 6.7% | 45.0% | 29.6 | 7,521,100 | 24.7 | 6,278,763 | 1.8 | 458,852 |
| MO | 3.9% | 52.5% | 29.3 | 7,435,740 | insufficient data [2] | | 1.1 | 287,453 |
| NC | 5.4% | 2.0% | 25.5 | 6,483,292 | 21.6 | 5,490,110 | 1.2 | 296,495 |
| TN | 5.2% | 2.3% | 28.7 | 7,282,420 | 24.1 | 6,127,084 | 1.2 | 317,232 |
| TX | 47.8% | 34.8% | 21.3 | 5,410,804 | 17.7 | 4,492,380 | 9.1 | 2,300,508 |
| TOTAL | 100.0% | | | | | | 23.1 | 5,878,499 |

[1] Based on area harvested (USDA, 2009)

[2] Insufficient data to estimate $ET_C$ of dryland cotton; $ET_C$ for irrigated cotton applied to 100% of area

The amount of energy required to pump and distribute irrigation water for cotton was estimated by back-calculating from state-level cost data for all crops as reported in the Farm and Ranch

Irrigation Survey (USDA, 2010). The survey differentiates between acres irrigated using five possible fossil fuel energy sources: diesel, electric, natural gas, LPG (liquefied petroleum gas, propane and butane), and gasoline/gasohol. Solar and other renewable sources of energy are also listed, but these supply power to pumps servicing only 0.05% of all irrigated land in the US. The data cover all irrigated farmland at the state level, but it is assumed that the distribution of energy sources is representative of cotton irrigation within the state. Weighting each state-level energy source distribution by the proportion of US irrigated cotton land within each state, indicates that 54% of US cotton land is supplied with water using electricity-powered pumps, 30% using diesel-powered pumps, 14% using natural gas-powered pumps (virtually all in Texas) and 2% using LPG-powered pumps (half in Missouri). Gasoline and gasohol pumps account for only 0.2%.

The values associated with the top three energy sources, (electric, diesel, and natural gas) were reapportioned to create a total equal to 100%, for the purposes of this analysis. The average cost per acre to irrigate using each of these energy sources was determined by dividing the total cost by total number of acres irrigated. For each state, the average cost per acre was divided by the average acre-inches applied (to all crops) in order to obtain the average cost per acre-inch of water supplied for diesel, natural gas, and electric pumping systems. Prices of \$0.10 per kilowatt-hour (kWh), \$2.50 per gallon of diesel, and \$10 per thousand cubic feet of natural gas were assumed and used to estimate the energy input required per acre-inch of water applied via each of the energy sources.

The calculation used to estimate the average diesel fuel used to irrigate any type of crop within a given state in terms of volume of fuel per volume of water applied (e.g., gallons of diesel per acre-inch of water) is calculated as

$$(V_{diesel} / V_{water})_{all\ crops,\ \mathrm{S}} =$$

$$(cost_{diesel\ irr} / A_{diesel\ irr})_{\mathrm{TOT,\ S}} * V_{diesel} / cost_{diesel} * (V_{water} / A_{irr})_{all\ crops,\ \mathrm{S}} \tag{5.11}$$

where:

$(V_{diesel} / V_{water})_{all\ crops,\ \mathrm{S}}$ = is the volume of fuel consumed per volume of water applied (e.g., gallons of diesel per acre-inch) for any irrigated crop in state S

$(cost_{diesel\ irr} / A_{diesel\ irr})_{\mathrm{TOT,\ S}}$ is the total amount spent on diesel fuel for irrigation within state S, divided by the total land area irrigated using diesel fuel in state S.

$V_{diesel} / cost_{diesel}$ is the reciprocal of the per unit volume cost of diesel (e.g., dollars per gallon)

$(V_{water} / A_{irr})_{all\ crops,\ \mathrm{S}}$ is the average volume of irrigation water supplied per area irrigated for all crops within state S.

The amounts of electricity and natural gas required per acre-in for each state were similarly calculated. These values were multiplied by the average number of acre-inches applied to cotton, at the state-level, to give the average energy input for irrigating cotton in terms of kWh, gallons of diesel, or cubic feet of natural gas per irrigated acre. Each value was weighted by the usage fraction represented by each energy source within the state and the fraction of all US harvested cotton land (both irrigated and non-irrigated) represented by the irrigated cotton land within the state. Summing over all states, results in the estimated volume of fuel consumed for irrigation per land area harvested for cotton in the US.

The calculations used to estimate the gallons of diesel for irrigation per harvested area of cotton are:

$$(V / \mathrm{A})_{diesel\ irr,\ cotton,\ \mathrm{US}} = \sum_{\mathrm{S}} \Big[ (V_{diesel} / V_{water})_{all\ crops,\ \mathrm{S}} * fraction_{diesel\ irr,\ \mathrm{S}} * (V_{water} / A_{irr})_{cotton,\ \mathrm{S}} * fraction_{US\ cotton\ area,\ \mathrm{S}} \Big] \qquad (5.12)$$

where:

$(V / \mathrm{A})_{diesel\ irr,\ cotton,\ \mathrm{US}}$ = the amount of diesel consumed for irrigation per unit area of land harvested for cotton in the US

$V_{diesel} / V_{water})_{all\ crops,\ \mathrm{S}}$ = is the volume of fuel consumed per volume of water applied (e.g., gallons of diesel per acre-inch) for any irrigated crop in state S

$fraction_{diesel\ irr,\ \mathrm{S}}$ is the fraction of irrigated land in state S irrigated using diesel fuel

$(V_{water} / A_{irr})_{cotton,\ \mathrm{S}}$ is the average volume of irrigation water supplied per area irrigated for cotton within state S.

$fraction_{US\ cotton\ area,\ \mathrm{S}}$ is the fraction of US harvested cotton land existing in state S

Electricity use in terms of kWh per unit area and natural gas use in terms of cubic feet per unit area are estimated in the same manner.

The only situation where this approach was not applied was where the state-level budgets provided enough information to allow for a direct determination of irrigation energy consumption per acre by fuel type. These include all three energy sources for Texas and diesel consumption for Arkansas, Mississippi, and Louisiana.

Results for electricity, diesel, and natural gas inputs to irrigation for all cotton producing states are given in Table 5. 24. Based on this estimation method, energy consumption for irrigation of US cotton can be characterized as requiring 314 kWh of electricity plus 24.9 liters of diesel, plus 16 cubic meters of natural gas per harvested hectare. Expressed in English units this is equivalent to 127 kWh/acre, 2.7 gallons of diesel, and 570 cubic feet of natural gas.

**Table 5.24**. Irrigation energy, by source and amount, used in tending US cotton.

| State | Cotton, US Wtd | Irrigation Energy Fraction, All Crops [1] | | | at $0.10/ kWh | at $2.50/ gal | at $0.01/ ft$^3$ | Irrigation Energy / Harvested Cotton Land, US Wtd | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Electricity Consumption | | Diesel Consumption | | Natural Gas | |
| | ac-in/ ac-yr | electric fraction | diesel fraction | NG fraction | kWh/ ac-in | gal/ ac-in | ft$^3$/ acre-in | kWh/ acre-yr | kWh/ ha-yr | gal/ acre-yr | liters/ ha-yr | ft$^3$/ acre-yr | m$^3$/ ha-yr |
| Alabama | 0.02 | 0.34 | 0.66 | 0.00 | 49.63 | 3.91 | -- | 0.26 | 0.65 | 0.04 | 0.37 | -- | -- |
| Arizona | 0.94 | 0.85 | 0.10 | 0.05 | 15.84 | 0.36 | 300 | 12.67 | 31.31 | 0.03 | 0.32 | 13.25 | 0.38 |
| Arkansas [2] | 0.63 | 0.32 | 0.65 | 0.02 | 9.20 | 1.40 | 105 | 1.88 | 4.64 | 0.57 | 5.36 | 1.51 | 0.04 |
| California | 1.67 | 0.80 | 0.17 | 0.03 | 21.50 | 1.01 | 209 | 28.92 | 71.46 | 0.29 | 2.69 | 8.83 | 0.25 |
| Florida | 0.01 | 0.24 | 0.76 | 0.00 | 24.04 | 1.08 | -- | 0.04 | 0.09 | 0.01 | 0.05 | -- | -- |
| Georgia | 0.28 | 0.60 | 0.39 | 0.00 | 34.68 | 3.20 | 1,135 | 5.94 | 14.68 | 0.36 | 3.32 | 1.09 | 0.03 |
| Kansas | 0.01 | 0.26 | 0.18 | 0.56 | 30.98 | 2.25 | 653 | 0.07 | 0.17 | 0.00 | 0.03 | 3.06 | 0.09 |
| Louisiana [2] | 0.06 | 0.24 | 0.74 | 0.02 | 19.71 | 0.99 | 333 | 0.29 | 0.71 | 0.04 | 0.41 | 0.35 | 0.01 |
| Mississippi [2] | 0.24 | 0.29 | 0.70 | 0.01 | 14.26 | 2.27 | 134 | 0.97 | 2.41 | 0.38 | 3.53 | 0.22 | 0.01 |
| Missouri | 0.18 | 0.43 | 0.57 | 0.00 | 14.80 | 1.06 | 138 | 1.14 | 2.83 | 0.11 | 1.03 | 0.11 | 0.00 |
| New Mexico | 0.11 | 0.85 | 0.04 | 0.11 | 28.11 | 1.27 | 300 | 2.65 | 6.55 | 0.01 | 0.06 | 3.61 | 0.10 |
| North Carolina | 0.01 | 0.32 | 0.68 | 0.00 | 53.45 | 2.79 | -- | 0.10 | 0.25 | 0.01 | 0.11 | -- | -- |
| Oklahoma | 0.10 | 0.28 | 0.20 | 0.52 | 24.98 | 1.78 | 701 | 0.70 | 1.72 | 0.04 | 0.34 | 36.70 | 1.04 |
| South Carolina | 0.01 | 0.83 | 0.17 | 0.00 | 31.94 | 2.41 | -- | 0.35 | 0.86 | 0.01 | 0.05 | -- | -- |
| Tennessee | 0.01 | 0.30 | 0.70 | 0.00 | 23.88 | 1.87 | -- | 0.06 | 0.14 | 0.01 | 0.10 | -- | -- |
| Texas 3 | 2.05 | 0.62 | 0.08 | 0.30 | 55.86 | 4.53 | 825 | 70.94 | 175.29 | 0.76 | 7.11 | 502.06 | 14.22 |
| Virginia | 0.00 | 0.27 | 0.73 | 0.00 | 29.37 | 3.14 | -- | 0.00 | 0.00 | 0.00 | 0.00 | -- | -- |
| US Average | 6.32 | | | | | | | 126.98 | 313.77 | 2.66 | 24.87 | 570.80 | 16.16 |

[1] Based on USDA, 2010 with LPG and gasoline/gasohol fuel sources set to zero

[2] Arkansas, Mississippi, and Louisiana diesel use rates determined from budgets, weighted by fraction of sprinkler and gravity systems as reported in USDA, 2010

[3] Texas use rates determined from budgets: natural gas from District 01, diesel from District 02, electricity from District 06

### 5.3.1.2.3.3.3 Nutrients

Most additions of fertilizer are made during the land preparation unit operation. However, in California, where 100% of cotton is irrigated, all fertilizer (nitrogen plus potassium) is distributed through the irrigation system during the tending unit operation. Arkansas cotton growers apply all nitrogen fertilizer as a side dressing (i.e., adjacent to the plants) during tending. The Georgia budget calls for a side dressing of nitrogen after planting, but does not specify the amount; only total nitrogen is reported (Shurley, 2010). For the purposes of this analysis, the amount added during tending is assumed to be 10 pounds of nitrogen in the form of urea. The US representative values for fertilizer application during the tending unit operation are taken to be 19.5 kg/ha (17.4 lb/ac) of nitrogen and 0.1 kg/ha of potassium as $K_2O$ (Table 5.25).

**Table 5.25**. Fertilizer application rates during the tending unit operation for US cotton

| Fertilizer | lb/ ac-yr | kg/ ha-yr | Budget IDs | % of US | Weighted Value lbs/ ac-yr | Weighted Value kg/ ha-yr |
|---|---|---|---|---|---|---|
| Nitrogen (N) | 1.3 | 1.5 | T | 2.4% | 0.0 | 0.0 |
| UAN (urea and ammonium nitrate, as N) | 180 | 201.8 | T, U | 5.5% | 9.9 | 11.1 |
| Urea, as Nitrogen (N) | 10 | 11.2 | G, H, I, J | 12.8% | 1.3 | 1.4 |
| | 80 | 89.7 | K | 2.7% | 2.1 | 2.4 |
| | 100 | 112.1 | L, M | 4.0% | 4.0 | 4.5 |
| US representative (N) value | | | | | 17.4 | 19.5 |
| Potassium ($K_2O$) | 4.6 | 5.2 | T | 2.4% | 0.1 | 0.1 |
| US representative ($K_2O$) value | | | | | 0.1 | 0.1 |

## 5.3.1.2.3.3.4 Herbicides

Herbicides are used extensively on US grown cotton. Because most of the plants are genetically modified to withstand glyphosate, this substance is dominant and constitutes approximately two-thirds of the total (mass of active ingredient (a.i.)). A summary of herbicides used is presented in Table 5.26.

**Table 5.26**. Herbicide application rates during the tending unit operation for US cotton

| Trade Name | Common Chemical Name | Active Ingredient (a.i.) | Product Use Rate | | Active Ingredient Use Rate | | Budget IDs | % of US cotton land | Weighted Mean | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | lb/gal 4 | gal/ acre | liters/ ha | lbs/ acre | kg/ ha | | | lbs/ acre-yr | kg/ ha-yr |
| 2,4-D Amine | 2,4-D amine | 3.8 | 0.25 | 2.3 | 0.95 | 1.06 | D | 4.8% | 0.045 | 0.051 |
| Direx 4L | diuron | 4 | 0.13 | 1.2 | 0.50 | 0.56 | P, Q | 4.7% | 0.284 | 0.318 |
| Diuron 4L | | | 0.25 | 2.3 | 1.00 | 1.12 | G, H, I, J | 11.8% | | |
| Diuron 80DF | | na | na | | 0.38 | 0.42 | S | 4.9% | | |
| | | na | na | | 1.00 | 1.12 | K, L, M, N, O | 12.4% | | |
| Fusilade DX | fluazifop-butyl | 1 | 0.03 | 0.3 | 0.03 | 0.04 | D | 4.8% | 0.002 | 0.002 |
| | | | 0.04 | 0.4 | 0.04 | 0.04 | Y | 2.0% | | |
| Cotoran 4L | fluometuron | 4 | 0.15 | 1.4 | 0.60 | 0.67 | Y | 2.0% | 0.112 | 0.125 |
| | | | 0.25 | 2.3 | 1.00 | 1.12 | R, S | 10.0% | | |
| Reflex | fomesafen | 2 | 0.08 | 0.7 | 0.16 | 0.18 | D | 4.8% | 0.024 | 0.027 |
| | | | 0.13 | 1.2 | 0.25 | 0.28 | H, J | 6.7% | | |
| Glyphosate Plus (3 lb/gal a.e.) | glyphosate | 4 | 0.50 | 4.7 | 2.00 | 2.24 | N, O | 4.0% | 1.797 | 2.014 |
| | | | 0.75 | 7.0 | 3.00 | 3.36 | L, M, W, X | 11.2% | | |
| | | | 1.25 | 11.7 | 5.00 | 5.60 | K | 1.7% | | |
| unspecified | | 5 | 0.06 | 0.6 | 0.31 | 0.35 | E | 3.3% | | |
| | | | 0.19 | 1.7 | 0.93 | 1.04 | D | 4.8% | | |
| | | | 0.25 | 2.3 | 1.25 | 1.40 | G, H, I, J | 11.8% | | |
| | | | 0.44 | 4.1 | 2.19 | 2.45 | P | 1.3% | | |
| | | | 0.50 | 4.7 | 2.50 | 2.80 | Q | 3.3% | | |
| | | | 0.63 | 5.8 | 3.13 | 3.50 | W, X | 4.5% | | |
| | | | 1.25 | 11.7 | 6.25 | 7.01 | F | 3.9% | | |
| Roundup Power Max | | 5.5 | 0.25 | 2.3 | 1.38 | 1.54 | B, W, X | 19.2% | | |
| | | | 0.28 | 2.6 | 1.51 | 1.70 | S | 4.9% | | |
| | | | 0.75 | 7.0 | 4.13 | 4.62 | R | 5.2% | | |
| Roundup Weather Max | | | 0.43 | 4.0 | 2.36 | 2.65 | Y | 2.0% | | |
| Dual Magnum | s-metolachlor | 7.62 | 0.13 | 1.2 | 0.95 | 1.07 | K, L, M, N, O, P, R, S, Y | 25.7% | 0.245 | 0.275 |
| unspecified | MSMA | 6 | 0.31 | 2.9 | 1.88 | 2.10 | G, H, I, J | 11.8% | 0.221 | 0.247 |
| Prowl | pendimethalin | 3.3 | 0.13 | 1.2 | 0.41 | 0.5 | D 1 | 4.8% | 0.135 | 0.151 |
| | | | 0.30 | 2.8 | 0.99 | 1.1 | P, Q | 4.7% | | |
| | | | 0.31 | 2.9 | 1.03 | 1.2 | H, J | 6.7% | | |
| Suprend | prometryn | | | | 1.00 | 1.1 | L, M | 6.7% | 0.067 | 0.075 |
| Staple LX | pyrithiobac | | | | 1.9 | 2.1 | G, H, I, J | 11.8% | 0.224 | 0.251 |
| Treflan HFP | trifluralin | 4 | 0.30 | 2.8 | 1.2 | 1.4 | C | 2.9% | 0.036 | 0.040 |

NOTES

Budgets B, D, W, X: one or more herbicide not specified; cost, application rates, and similarity to other programs used to assume chemical used

GA budgets do not give amount and type of herbicide applied. Data obtained through personal communication.

Active ingredient contents from MWSC, 2009

5.3.1.2.3.3.5 Insecticides

The amount of insecticide used in growing cotton increased steadily from 1996 through 2003 from an annual rate of 1.8 kilograms of active ingredient (a.i.) per treated hectare (1.6 lb/ac-yr) to 7.8 kg a.i./ha-yr (7.0 lb/ac-yr) (ERS, 2009). During this same time period Bt cotton, was introduced. These varieties are toxic to certain insects, particularly the bollworm, which can devastate a crop. Agricultural Resource Management Survey (ARMS) data indicates that Bt cotton was quickly adopted in the first two or three years, but use then declines between 1999 and 2003. The reason for these trends are unknown; however, during this time period there were concerns about the development of resistant insects (EPA, 2006) and Monsanto introduced a second generation of Bollgard seed. It may also reflect the relative prices of insecticides and seed or a lag in acceptance of new technology. Between 2003 and 2007, Bt cotton became widely used, increasing from 10% to 66% of all cotton, while the use of pesticides dropped to 1.3 kg a.i./ha-yr (1.2 lb/ac-yr), or just slightly below the application rate at the time that Bt cotton was introduced (Figure 5.18).

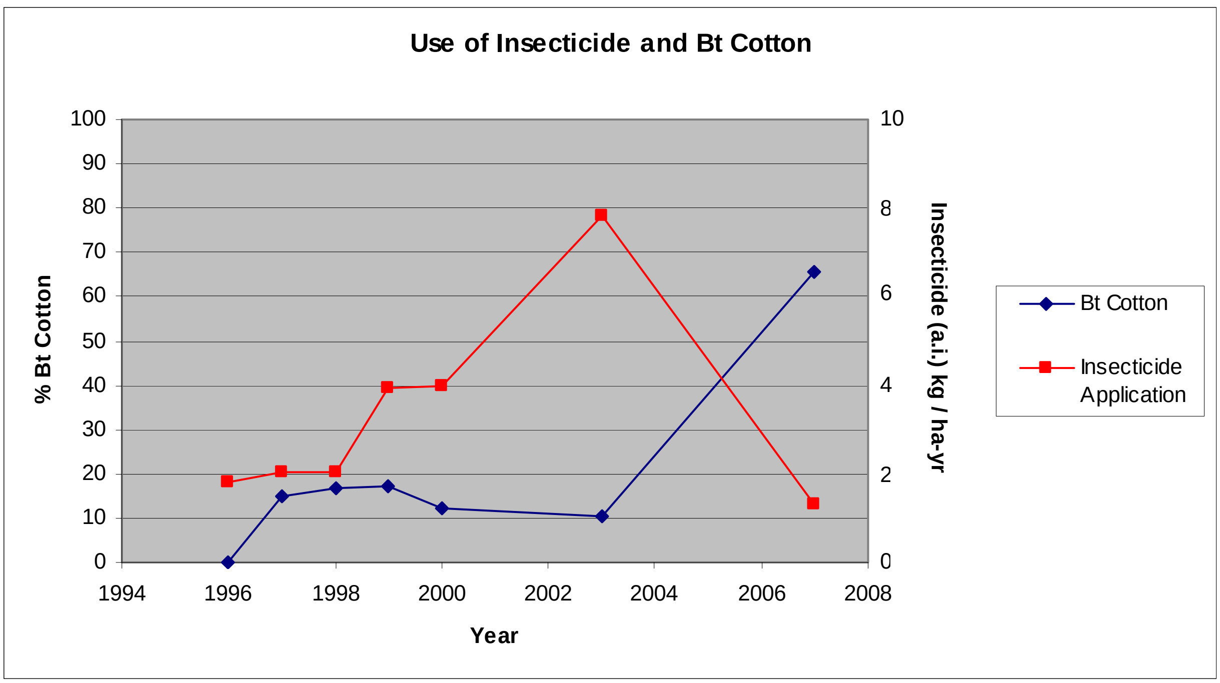


**Figure 5.18**. Use of insecticides in cotton agriculture increased steadily from 1.8 kg of active ingredient per hectare-year in 1996 to 7.8 kg/ha-yr in 2003; it then declined to 1.3 kg/ha-yr in 2007. Genetically modified (Bt) cotton was introduced during this time period, rising to 66% in 2007 (based on data from ERS, 2009).

The rate of insecticide application, as determined from state budgets, is 1.4 kg a.i./ha-yr (1.2 lb/ac-yr). This is essentially the same level of use as reported by the ARMS data for 2007 (although it should be noted that there was no attempt in this analysis to reconcile the two sources of information). A cursory examination of state budgets through 2010 (reflecting practices in 2009) indicates no major changes in insecticide use during the past 3 years. A number of budgets give only the use rate, without specifying the actual chemical used. A few budgets report only the cost per acre-application. In these cases, a variety of sources were used to identify the pesticide used. These include insecticide cost data from the Mississippi state budget (MSU, 2008), application rates from product labels, and identification of appropriate chemicals for specific pests based on the Integrated Pest Management document for Texas (IPM, 2009). A summary of insecticides used in the growing of US cotton is presented in Table 5.27.

**Table 5.27**. Insecticide application rates during the tending unit operation for US cotton

| Trade Name | Common Chemical Name | Active Ingredient | | Budget IDs [1] | % of US cotton land | Weighted Mean | |
|---|---|---|---|---|---|---|---|
| | | lbs/ acre | kg/ ha | | | lbs/ acre-yr | kg/ ha-yr |
| Zephyr | abamectin | 0.01 | 0.01 | T, U | 5.5% | 0.000 | 0.000 |
| Orthene | acephate | 0.45 | 0.50 | P, Q | 4.7% | 0.758 | 0.850 |
| | | 0.54 | 0.61 | (A, B, N, O) | 34.9% | | |
| | | 0.90 | 1.01 | (E) | 3.3% | | |
| | | 0.99 | 1.11 | Y | 2.0% | | |
| | | 1.08 | 1.21 | (R, S, W, X) | 14.5% | | |
| | | 1.10 | 1.23 | L, M | 6.7% | | |
| | | 1.10 | 1.23 | K | 1.7% | | |
| | | 1.35 | 1.51 | (R, S, W, X) | 14.5% | | |
| | | 1.37 | 1.53 | N, O | 4.0% | | |
| Temik 15G | aldicarb | 3.00 | 3.36 | Y | 2.0% | 0.270 | 0.302 |
| | | 4.50 | 5.04 | P, Q | 4.7% | | |
| Ammo 2.5 EC | cypermethrin | 0.06 | 0.07 | (D) | 4.8% | 0.005 | 0.005 |
| | | 0.08 | 0.09 | Y | 2.0% | | |
| Bidrin 8 | dicrotophos | 0.20 | 0.22 | Y | 2.0% | 0.129 | 0.145 |
| | | 0.31 | 0.35 | (S, W, X) | 9.3% | | |
| | | 0.50 | 0.56 | K, L, M, N, O, (D) | 17.2% | | |
| | | 0.20 | 0.22 | ( R) | 5.2% | | |
| Provado | imidacloprid | 0.05 | 0.05 | T, U | 5.5% | 0.007 | 0.008 |
| Trimax | | 0.05 | 0.06 | K, L, M | 8.4% | | |
| Endigo | lamda-cyhalothrin | 0.02 | 0.03 | (D) | 4.8% | 0.021 | 0.024 |
| unspecified | | 0.03 | 0.03 | (G, H, I, J) | 11.8% | | |
| Karate Z | | 0.03 | 0.04 | L, M, N, O | 10.7% | | |
| | | 0.04 | 0.05 | P, Q | 4.7% | | |
| | | 0.04 | 0.05 | (R, S, W, X) | 14.5% | | |
| Warrior | | 0.05 | 0.06 | T, U | 5.5% | | |
| Karate Z | | 0.07 | 0.07 | K | 1.7% | | |
| | | 0.07 | 0.08 | Y | 2.0% | | |
| Vydate C-LV | oxamyl | 0.05 | 0.05 | (D) | 4.8% | 0.002 | 0.003 |
| Penncap-M | parathion-methyl | 0.39 | 0.44 | Y | 2.0% | 0.008 | 0.009 |
| Tracer | spinosad | 0.03 | 0.04 | K | 1.7% | 0.001 | 0.001 |
| Endigo | thiamethoxam | 0.03 | 0.04 | (D) | 4.8% | 0.016 | 0.018 |
| Centric 40WG | | 0.05 | 0.06 | K, L, M, N, O, Y | 14.4% | | |
| | | 0.05 | 0.06 | (R, S, W, X) | 14.5% | | |
| US Representative Insecticide Use | | | | | | 1.22 | 1.36 |

[1] Name of insecticide not given for budgets in parentheses; substance designation assigned based on cost, application rate, and use description

#### 5.3.1.2.3.3.6 Emissions to Air

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. All result from the burning of fossil fuels including diesel for field equipment and irrigation pumps, gasoline for pickup trucks, and natural gas from irrigation pumps.

Criteria Air Pollutants

Criteria air pollutants that result from the burning of diesel fuel in the field equipment listed in Table 5.20 are calculated based on the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004; EPA, 2005). The two main pieces of diesel-powered ground equipment are tractors and sprayers, both of which are taken to have life expectancies of 8 years (MSU, 2008). The majority of the equipment is assumed to be at or near the median age; thus in 2007 most of the equipment is assumed to be model years 2002 to 2005, and the profile is estimated to be 30% Tier 1, 60% Tier 2, and 10% Tier 3 technology. The resulting emissions in grams per liter of fuel burned and grams per hectare-year are given in Table 5.28.

**Table 5.28**. Emissions in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the tending unit operation (based on emission factors from the NONROAD model (EPA, 2004; 2005) and equipment data from sources listed in Table 5.7; fuel use is weighted by the percent of US harvested land affected by that equipment type

| Equipment | Unit Power (HP) | Wtd Fuel Use liters/ ha-yr | Emissions g/liter | | | | | Emissions g/ha | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | VOC | CO | $NO_X$ | PM | $SO_X$ | VOC | CO | $NO_X$ | PM | $SO_X$ |
| Pipe spool | 50 | 0.0 | 4.27 | 23.62 | 32.2 | 3.72 | 1.17 | 0.2 | 1.0 | 1 | 0.2 | 0.0 |
| Sand fighter | 40 | 0.9 | 2.71 | 14.97 | 20.4 | 2.36 | 0.67 | 2.5 | 13.8 | 19 | 2.2 | 0.6 |
| Sprayer | 105 | 1.2 | 1.87 | 7.17 | 21.8 | 1.33 | 0.83 | 2.3 | 8.7 | 26 | 1.6 | 1.0 |
| | 110 | 0.8 | 1.95 | 7.51 | 22.8 | 1.39 | 0.87 | 1.6 | 6.2 | 19 | 1.1 | 0.7 |
| | 200 | 2.4 | 1.73 | 6.25 | 21.6 | 0.98 | 0.84 | 4.2 | 15.1 | 52 | 2.4 | 2.0 |
| Tractor | 75 | 5.0 | 2.39 | 19.52 | 24.4 | 2.00 | 0.83 | 12.0 | 98.0 | 123 | 10.1 | 4.2 |
| | 100 | 0.4 | 2.19 | 18.60 | 22.8 | 1.73 | 0.79 | 0.9 | 7.6 | 9 | 0.7 | 0.3 |
| | 125 | 0.9 | 1.79 | 6.89 | 20.9 | 1.28 | 0.80 | 1.6 | 6.2 | 19 | 1.1 | 0.7 |
| | 150 | 10.6 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 19.8 | 76.3 | 232 | 14.1 | 8.9 |
| | 165 | 2.6 | 1.8 | 7.0 | 21.1 | 1.3 | 0.0 | 4.7 | 18.1 | 55 | 3.4 | 0.0 |
| | 170 | 1.5 | 1.86 | 7.17 | 21.76 | 1.33 | 0.00 | 2.9 | 11.1 | 34 | 2.0 | 0.0 |
| | 190 | 1.6 | 1.71 | 6.19 | 21.37 | 0.97 | 0.00 | 2.8 | 10.2 | 35 | 1.6 | 0.0 |
| | 215 | 0.4 | 1.63 | 5.91 | 20.40 | 0.93 | 0.00 | 0.7 | 2.4 | 8 | 0.4 | 0.0 |
| | 225 | 0.5 | 1.71 | 6.18 | 21.35 | 0.97 | 0.00 | 0.9 | 3.4 | 12 | 0.5 | 0.0 |
| TOTAL | | 29.1 | | | | | | 57.0 | 277.7 | 642.8 | 41.4 | 18.5 |

Diesel and natural gas powered pumps used for irrigation (Table 5.24) also release emissions. Criteria air pollutants and their precursors are determined using EPA AP 42 guidelines for stationary gasoline and diesel engines (EPA, 1996, Table 3.3-1) and for natural gas combustion (EPA, 1998). The light-duty truck is assumed to be a model year 2000 vehicle with a fuel economy of 12 miles per gallon (slightly lower than when used on paved roads). Emissions factors are from the GREET model, for the vehicle referred to as "light-duty truck 2" (ANL, 2009). Total US emissions are presented in Table 5.29.

**Table 5.29**. Emissions of criteria pollutants and their precursors in grams per unit of fuel and grams per hectare for irrigation equipment and pickup trucks used during the tending unit operation

| Equipment | Fuel | Units | Fuel Use units/ ha-yr | Emissions g/unit of fuel | | | | | Emissions g/ha | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | VOC | CO * | $NO_X$ * | PM | $SO_2$ | VOC | CO | $NO_X$ | PM | $SO_2$ |
| Pickup truck | gasoline | liters | 18.7 | 2.61 | 27.91 | 3.27 | 0.12 | | 49 | 522 | 61 | 2 | 0 |
| Irrigation pumps | diesel | liters | 24.9 | 5.45 | 14.61 | 67.8 | 4.77 | 4.46 | 136 | 363 | 1,687 | 119 | 111 |
| | natural gas | scm | 16.2 | 0.09 | 1.35 | 1.60 | 0.12 | 0.01 | 1 | 22 | 26 | 2 | 0 |
| TOTAL US Cotton | | | | | | | | | 186 | 907 | 1,774 | 123 | 111 |

* Assume small uncontrolled boiler

## Greenhouse Gas Emissions

Greenhouse gas emissions from burning of diesel and gasoline are estimated using IPCC emission factors (IPCC, 2006a). Those for burning natural gas are from AP 42 emission factors (EPA, 1998). A summary of the factors used and the estimated emissions are presented in Table 5.30.

**Table 5.30**. Emissions of greenhouse gases in kilograms per hectare-year from fuel burned during the tending unit operation

| | | Emission Factor g/GJ [1] | | | Emission Factor g/liter | | | US Fuel Consumption | Emissions (kg/ha-yr) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Energy Content (GJ/liter) [2] | $CO_2$ | $CH_4$ | $N_2O$ | $CO_2$ | $CH_4$ | $N_2O$ | liters/ha-yr | $CO_2$ | $CH_4$ | $N_2O$ |
| Diesel | 0.0358 | 74,100 | 4.15 | 28.6 | 2,653 | 0.149 | 1.024 | 54.0 | 143 | 0.008 | 0.055 |
| Gasoline, 4-stroke | 0.0324 | 69,300 | 80 | 2 | 2,242 | 2.588 | 0.065 | 18.7 | 42 | 0.048 | 0.001 |
| | | | | | $g/m^3$ | | | $m^3$/ha-yr | | | |
| Natural Gas [3] | | | | | 1,922 | 0.037 | 0.035 | 16.2 | 31 | 0.001 | 0.001 |
| US TOTAL | | | | | | | | | 216 | 0.057 | 0.057 |

[1] IPCC, 2006a, Table 2.5 and Table 3.3.1, for agricultural use; default values expressed as kg/TJ

[2] ANL, 2009, converted from Btu/gallon

[3] Emission factors from EPA, 1998, converted from lb/$10^6$ cubic feet

Both direct and indirect greenhouse gas emissions are also released as a consequence of using fertilizers during the tending unit operation; (indirect emissions are discussed in section 5.3.1.3.4.2 of this report). The application of nitrogen contributes to emissions of nitrous oxide ($N_2O$). The rate at which this occurs is based on IPCC guidelines (IPCC, 2006b, Equation 11.1).

The rate of direct $N_2O$ emissions from nitrogen fertilizer can be expressed as

$$N_2O_{fert} = N_{fert,N} * EF_{N\,fert} * N_2O_{mw} /(2 * N_{aw}) \tag{5.8}$$

where

$N_2O_{fert}$ is the mass of annual nitrous oxide emissions per unit area due to fertilization

$N_{fert,N}$ is the mass of nitrogen fertilizer, as nitrogen, applied annually per unit area

$EF_{N\,fert}$ is the emission factor for added nitrogen, taken to be 0.01 per IPCC guidelines, (IPCCb, Table 11.1).

$N_2O_{mw} /(2 * N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Representative nitrogen fertilization rates for US cotton during tending are taken to be 19.5 kg/ha-yr (Table 5.25). Thus direct $N_2O$ emissions for nitrogen fertilization of cotton crops during this unit operation are calculated as

$$19.5 \text{ kg /ha-yr} * 0.01 * 44/28 =$$

$$0.306 \text{ kilograms } N_2O \text{ / hectare-year} \tag{5.13}$$

The specific use of urea as a nitrogen fertilizer produces emissions of $CO_2$ as well as $N_2O$, as discussed in section 5.3.1.2.1.3.4 of this report. The mean US application of urea on cotton crops during the tending unit operation is 8.3 kg/ha-yr (Table 5.25). Additional urea is applied in the form of UAN, a mixture of urea and ammonium nitrate at US representative rates of 11.1 kg/ha-yr (Table 5.25). Material Data Safety Sheets (MSDS) for UAN 32 (32% nitrogen) indicate that a typical urea content is 33 to 36 wt%; 35% is assumed in this analysis.

The resulting $CO_2$ emissions are thus calculated as

$$(8.3 + 35\% * 11.1) \text{ kg / ha-yr} * 12 / (2 * 14) * (12 + 2*16) / 12 =$$

$$19.15 \text{ kilograms } CO_2 \text{ / hectare-year} \tag{5.14}$$

5.3.1.2.3.3.7 Summary of Material and Energy Flows for Tending

The tending unit operation would affect all harvested land, but not necessarily all planted land, as fields that are failing may be abandoned. The land preparation and seeding unit operations are burdened by 117%, 5% due to seed propagation and 12% for other factors. For the tending unit operation the amount for seed propagation is retained, as it is assumed that these fields would receive more than adequate care and be irrigated. The remaining 12% burden is reduced to 5% for a total burden of 10% for tending since fields which are not harvested will not be tended as extensively as those that are harvested. Thus all material and energy flows for this unit operation are multiplied by a factor of 1.10. A summary of tending material and energy flows is given in Table 5.31.

**Table 5.31**. Direct material and energy flows for tending of US cotton cropland

| Resource | | Calculation | Value | Units |
|---|---|---|---|---|
| Land | | 1.10 hectares / 1 hectare-year | 1.1 | 1/yr |
| Diesel | | | | |
| | Volume | 1.10 / year * (24.9 + 29.1) liters / hectare | 59 | l/ha-yr |
| | Mass 1 | 59.4 liters / hectare-year * 0.837 kilograms / liter | 50 | kg/ha-yr |
| | Energy 1 | 59.4 liters / hectare-year * 35.8 megajoules / liter | 2,126 | MJ/ha-yr |
| Gasoline | | | | |
| | Volume | 1.10 / year * 18.7 liters / hectare | 21 | l/ha-yr |
| | Mass 1 | 20.6 liters / hectare-year * 0.744 kilograms / liter | 15 | kg/ha-yr |
| | Energy 1 | 20.6 liters / hectare-year * 32.4 megajoules / liter | 666 | MJ/ha-yr |
| Natural Gas | | | | |
| | Volume | 1.10 / year * 16.2 cubic meters / hectare | 17.8 | m3/ha-yr |
| | Mass 1 | 17.8 m3 / hectare-year * 0.777 kilograms / m3 | 14 | kg/ha-yr |
| | Energy 1 | 17.8 m3 / hectare-year * 36.6 megajoules / m3 | 651 | MJ/ha-yr |
| Electricity (irrigation) | | 1.10 / year * 314 kWh | 345 | kWh/ha-yr |
| | | equivalent to | 1,243 | MJ/ha-yr |
| | TOTAL Energy Consumption for Field Operations | | 1,812 | MJ/ha-yr |
| | TOTAL Energy Consumption for Irrigation | | 2,873 | MJ/ha-yr |
| Herbicides | | | | |
| | 2,4-D amine | 1.10 / year * 0.0506 kilograms / hectare | 0.06 | kg/ha-yr |
| | Diuron | 1.10 / year * 0.318 kilograms / hectare | 0.35 | kg/ha-yr |
| | fluazifop-butyl | 1.10 / year * 0.00249 kilograms / hectare | 0.00 | kg/ha-yr |
| | Fluometuron | 1.10 / year * 0.125 kilograms / hectare | 0.14 | kg/ha-yr |
| | Fomesafen | 1.10 / year * 0.0270 kilograms / hectare | 0.03 | kg/ha-yr |
| | Glyphosate | 1.10 / year * 2.01 kilograms / hectare | 2.22 | kg/ha-yr |
| | s-metolachlor | 1.10 / year * 0.275 kilograms / hectare | 0.30 | kg/ha-yr |
| | MSMA | 1.10 / year * 0.247 kilograms / hectare | 0.27 | kg/ha-yr |
| | Pendimethalin | 1.10 / year * 0.151 kilograms / hectare | 0.17 | kg/ha-yr |
| | Prometryn | 1.10 / year * 0.0748 kilograms / hectare | 0.08 | kg/ha-yr |
| | Pyrithiobac | 1.10 / year * 0.251 kilograms / hectare | 0.28 | kg/ha-yr |
| | Trifluralin | 1.10 / year * 0.0398 kilograms / hectare | 0.04 | kg/ha-yr |
| | TOTAL Herbicides | | 3.93 | kg/ha-yr |
| Insecticides | | | | |
| | Abamectin | 1.10 / year * 0.000434 kilograms / hectare | 0.00 | kg/ha-yr |
| | Acephate | 1.10 / year * 0.850 kilograms / hectare | 0.93 | kg/ha-yr |
| | Aldicarb | 1.10 / year * 0.302 kilograms / hectare | 0.33 | kg/ha-yr |
| | Cypermethrin | 1.10 / year * 0.00509 kilograms / hectare | 0.01 | kg/ha-yr |
| | Dicrotophos | 1.10 / year * 0.145 kilograms / hectare | 0.16 | kg/ha-yr |
| | Imidacloprid | 1.10 / year * 0.00778 kilograms / hectare | 0.01 | kg/ha-yr |
| | lamda-cyhalothrin | 1.10 / year * 0.0240 kilograms / hectare | 0.03 | kg/ha-yr |
| | Oxamyl | 1.10 / year * 0.00251 kilograms / hectare | 0.00 | kg/ha-yr |
| | parathion-methyl | 1.10 / year * 0.00859 kilograms / hectare | 0.01 | kg/ha-yr |
| | Spinosad | 1.10 / year * 0.000665 kilograms / hectare | 0.00 | kg/ha-yr |
| | Thiamethoxam | 1.10 / year * 0.0179 kilograms / hectare | 0.02 | kg/ha-yr |
| | TOTAL Insecticides | | 1.50 | kg/ha-yr |

1 Energy content and density of liquid fuels, default inputs to GREET (ANL, 2009)

**Table 5.31 (cont)**

| Resource | | Calculation | Value | Units |
|---|---|---|---|---|
| Major Nutrients | | | | |
| | Nitrogen (N) | 1.10 / year * 19.5 kilograms / hectare | 21.45 | kg/ha-yr |
| | Potassium (K2O) | 1.10 / year * 0.1 kilograms / hectare | 0.11 | kg/ha-yr |
| Water | | | | |
| | Withdrawn | 1.10 / year * 1.60 x 106 liters/ hectare | 1.76 | $10^6$ liters/ha-yr |
| | Consumed | 1.10 / year * 5.88 x 106 liters/ hectare | 6.47 | $10^6$ liters/ha-yr |
| | | | | |
| Criteria Air Pollutants and Precursors | | | | |
| | VOC | 1.10 / year * 0.243 kilograms / hectare | 0.27 | kg/ha-yr |
| | CO | 1.10 / year * 1.18 kilograms / hectare | 1.30 | kg/ha-yr |
| | NOX | 1.10 / year * 2.42 kilograms / hectare | 2.66 | kg/ha-yr |
| | PM | 1.10 / year * 0.164 kilograms / hectare | 0.18 | kg/ha-yr |
| | SO2 | 1.10 / year * 0.130 kilograms / hectare | 0.14 | kg/ha-yr |
| Greenhouse Gases | | | | |
| | CO2 | 1.10 / year * (216 + 19) kilograms / hectare | 259 | kg/ha-yr |
| | CH4 | 1.10 / year * 0.057 kilograms / hectare | 0.06 | kg/ha-yr |
| | N2O | 1.10 / year * (0.057 + 0.306) kilograms / hectare | 0.40 | kg/ha-yr |

#### ***5.3.1.2.4 Harvesting (separation of target material from growing medium):***

##### *5.3.1.2.4.1 General Description*

The harvest operation is characterized by two types of activities. The first involves spray application of chemicals that are targeted at the cotton plant (rather than weeds or insects) and the second is the actual removal of the seed cotton from the standing plant, followed by collection and storage. Some of the chemical applications occur in combination with pesticides. In these instances the equipment activity is covered under the tending unit operation, but the material usage is accounted for in harvesting. In order to avoid double-counting, all of the spraying equipment activities included in the harvest unit operation are ones in which the only chemicals applied are those that specifically target the cotton plants.

There are two types of chemicals applied to the cotton plant. The first, known as a plant growth regulator (PGR), is used to control plant height. PGR almost exclusively refers to the compound Mepiquat chloride, sold under the trade name Pix. It works by inhibiting cell elongation in the stems, making the cotton plant smaller and more compact. In addition, Mepiquat treatment 1) hastens maturity by speeding up the reproductive process; 2) suppresses late-season vegetative growth, which reduces plant height and insect host material, thus decreasing the need for insecticides; and 3) encourages retention of early-produced cotton bolls, thus decreasing boll rot (Edmisten, 2009a; IPM, 2009). All of these factors in combination act to increase yield and to synchronize plant readiness for harvesting. Plant growth regulators are most commonly used in areas of high rainfall and/or irrigation; its use also may be necessary under circumstances where excess nitrogen is available. The only budgets in this analysis that do not include its use are those in Texas (with the exception of the one representing the Coastal Bend region), and non-irrigated cotton in Arkansas.

The second category of chemicals which target the cotton plant are referred to as harvest aids, of which there are three types: desiccants, defoliants, and boll openers. The chemical paraquat dichloride, sold under various trade names, is a desiccant used to dry plant tissue. It acts very rapidly, killing the leaves and causing them stick to the stalk or fall to the ground. This minimizes unwanted plant material in the harvested seed cotton. Desiccants also speed up the rate at which bolls dry. Cotton must be harvested at moisture contents below 12% in order to avoid spoilage; thus desiccants may be used in areas where the growing season is relatively short in order to facilitate an earlier harvest. Use of this product is limited to northwestern Texas and California.

Defoliants are herbicides that damage leaves to the extent that they drop off the cotton plant. It is undesirable to actually kill the leaves as they will remain attached to the stem. Defoliants are used mainly in areas where picker harvesting systems are used, as this type of harvester pulls at the whole plant and can easily collect leaves as well as seed cotton. Elimination of leaves reduces trash as well as the main source of staining of the lint. It speeds up the harvesting operation not only by minimizing the total material that must be handled by the pickers, but also by promoting quicker drying of dew, which allows picking to begin earlier in the day (Edmisten, 2009b). Virtually all areas use either defoliants or desiccants, with the split generally between picker and stripper harvesting systems, respectively. (These two types of harvesting systems are explained later in this section.). One notable exception to this is where cotton is grown in immediate rotation with another crop, such as wheat.

Cotton bolls must be open and dry before they can be harvested. Under natural conditions, this will not happen simultaneously, but rather in waves, potentially requiring as many as three sequential harvests. The main function of boll openers is to control timing of the harvest, either to promote earlier readiness in areas of shorter growing season or to synchronize readiness so that only one harvest is necessary. Only the budgets from California actually account for a second harvest, but it may occur in other regions as well. Ethephon, sold under the trade name Prep, is the chemical used for boll opening. In some cases, however, a mix of defoliant and boll opener is used (e.g., Finish which contains cyclanilide plus ethephon). With the exception of parts of Texas and Louisiana, this product is used on all US cotton.

Once the cotton plant has been treated to promote optimal harvesting conditions, a self-propelled field unit, called a harvester, is used to mechanically pick the seed cotton. There are two types of harvesters, spindle pickers (also simply called “pickers”) and strippers. Stripper harvesting works best on short, compact plants. It is generally performed in regions with a relatively short growing season and where tightbolled, "stormproof" cotton varieties are grown (IPM, 2009). In the US, they are used almost exclusively in northwestern Texas. In this harvesting process, the entire cotton boll (carpels and seed cotton) is removed from the stalk and extraneous plant trash is subsequently removed either on site using a field cleaner (an air separation unit) or at the gin. There are two types of cotton stripping machines. The conventional stripper uses two 7-in diameter rollers rollers equipped with alternating bats and brushes (three of each per roller). The rollers rotate in opposite directions and simply knock the entire boll into a conveyor. These systems are very efficient, but cannot discriminate between open and unopened bolls. The finger type stripper uses multiple metal angles turned upward and angled slightly with respect to the ground to pull the bolls off the stalks.

Spindle pickers remove only the seed cotton and leave stems and bolls behind. Pickers have tapered, barbed spindles that rotate perpendicular to the ground and use a twisting motion to pick the seed cotton from the burs (seed case). As the harvester moves through field, the cotton plant is guided through the picker head until it encounters the picking bar. The seed cotton is wrapped around the spindle, pulled from the bur, removed from the spindle with a rubber doffer, and then transferred to a basket. Doffers, which consist of a stack of rubber lined pads corresponding in height to the barbs on the spindle, "grab" the cotton from the spindle and knock the seed cotton into a vacuum-assisted conveying system.

The cotton is transferred from the harvester to a boll buggy, pulled by a tractor. Using the boll buggy, the seed cotton is transported to a module builder where the cotton is layered and compressed hydraulically for storage. Each module consists of 12 to 15 bales. The modules can be left in the field until the gin is able to take them.

#### *5.3.1.2.4.2 Activities*

The number of activities required in harvesting are very similar between all locations and cultivation systems, although the intensity of the activities may vary. The budgets listed in Table 5.8 were used to create sets of activities associated with harvesting as represented by diesel equipment used in the field. These are separated into spray application of growth regulators and harvest aids (Table 5.32) and the actual harvesting of the cotton (Table 5.33). In cases where budgets list custom operations (mostly in Texas), a surrogate was used based on similar location and cultivation practices. Harvesting is the one activity in this life cycle stage that scales with yield, rather than being strictly a function of land area. Therefore, in instances where surrogates were used, activities were scaled according the projected yields given in the budgets. References for each budget are given in Table 5.7.

**Table 5.32**. Equipment associated with spraying activities in preparation for harvest as characterized by major regions and management systems used in the US. Percent of US cotton land area is reapportioned between budgets with equipment activity data such that total is 100%.

| Budget | % of US | Unit | HP | hrs/ac-pass | ac-pass/yr | gal/hr | Regional Value | | US Weighted Value | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | gal/ ac-yr | liters/ ha-yr | gal/ ac-yr | liters/ ha-yr |
| A*, C | 20.7% | Spray (Broadcast) 60' | 170 | 0.028 | 1 | 8.75 | 0.25 | 2.29 | 0.051 | 0.475 |
| B* | 16.0% | Spray (Broadcast) 60' | 170 | 0.028 | 2 | 8.75 | 0.49 | 4.58 | 0.078 | 0.732 |
| D | 5.2% | Sprayer - 76 ft boom | 200 | 0.020 | 3 | 10.29 | 0.62 | 5.78 | 0.032 | 0.298 |
| F | 4.2% | Sprayer( (600-825Gal) 90' | 200 | 0.011 | 3 | 10.29 | 0.34 | 3.18 | 0.014 | 0.135 |
| G, H, J | 10.4% | Spray (Broadcast) | 150 | 0.025 | 10 | 7.72 | 1.93 | 18.05 | 0.201 | 1.876 |
| I | 2.4% | Spray (Broadcast) | 150 | 0.025 | 5 | 7.72 | 0.97 | 9.03 | 0.023 | 0.216 |
| K | 1.9% | Sprayer (300-450Gal) 60' | 110 | 0.017 | 1 | 5.4 | 0.09 | 0.86 | 0.002 | 0.016 |
| L | 4.3% | Sprayer (600-825Gal) 90' | 200 | 0.011 | 2 | 10.29 | 0.23 | 2.12 | 0.010 | 0.092 |
| M | 2.9% | Sprayer (300-450Gal) 60' | 110 | 0.017 | 2 | 5.4 | 0.18 | 1.72 | 0.005 | 0.050 |
| P*, Q* | 5.1% | Spray (Broadcast) 60' | 170 | 0.028 | 1 | 8.75 | 0.25 | 2.29 | 0.012 | 0.117 |
| R, S | 10.9% | SP Boom Sprayer, 90' | 200 | 0.012 | 3 | 10.29 | 0.36 | 3.37 | 0.039 | 0.366 |
| T, U | 6.0% | Sprayer, over the top | 105 | 0.017 | 3 | 5.4 | 0.28 | 2.58 | 0.016 | 0.154 |
| US Representative Value | | | | | | | | | 0.484 | 4.525 |

* custom operation; C used as surrogate

**Table 5.33**. Equipment associated with actual harvesting as characterized by major regions and management systems used in the US. Percent of US cotton land area is reapportioned between budgets with equipment activity data such that total is 100%.

| Budget | % of US | Unit | HP | hrs/ac-pass | ac-pass/yr | gal/hr | Regional Value | | US Weighted Value | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | gal/ ac-yr | liters/ ha-yr | gal/ ac-yr | liters/ ha-yr |
| A*, C, E* | 24.4% | Cotton Stripper [1] | 350 | 0.145 | 1 | 18.01 | 2.61 | 24.43 | 0.64 | 5.95 |
| | | Boll Buggy | 190 | 0.246 | 0.06 | 9.77 | 0.14 | 1.35 | 0.04 | 0.33 |
| | | Module Builder | 150 | 0.246 | 0.06 | 7.72 | 0.11 | 1.07 | 0.03 | 0.26 |
| | | TOTAL | | | | | 2.87 | 26.84 | 0.70 | 6.54 |
| B* | 16.0% | Cotton Stripper [1] | 350 | 0.435 | 1 | 18.01 | 7.83 | 73.28 | 1.25 | 11.70 |
| | | Boll Buggy | 190 | 0.738 | 0.06 | 9.77 | 0.43 | 4.05 | 0.07 | 0.65 |
| | | Module Builder | 150 | 0.738 | 0.06 | 7.72 | 0.34 | 3.20 | 0.05 | 0.51 |
| | | TOTAL | | | | | 8.61 | 80.53 | 1.37 | 12.85 |
| D*, M | 8.1% | Cotton Picker (4R-38) | 255 | 0.257 | 1 | 13.12 | 3.37 | 31.54 | 0.27 | 2.55 |
| | | Boll Buggy | 170 | 0.257 | 1 | 8.75 | 2.25 | 21.03 | 0.18 | 1.70 |
| | | Module Builder | 150 | 0.257 | 1 | 7.72 | 1.98 | 18.56 | 0.16 | 1.50 |
| | | TOTAL | | | | | 7.60 | 71.13 | 0.61 | 5.74 |
| F*, K | 6.1% | Cotton Picker (4R-38) | 255 | 0.257 | 1 | 13.12 | 3.37 | 31.54 | 0.21 | 1.92 |
| | | Boll Buggy | 150 | 0.257 | 1 | 7.72 | 1.98 | 18.56 | 0.12 | 1.13 |
| | | Module Builder | 150 | 0.257 | 1 | 7.72 | 1.98 | 18.56 | 0.12 | 1.13 |
| | | TOTAL | | | | | 7.34 | 68.66 | 0.45 | 4.18 |
| G, H | 6.1% | Cotton Picker (6R-38) | 350 | 0.200 | 1 | 18.01 | 3.60 | 33.69 | 0.22 | 2.05 |
| | | Boll Buggy | 210 | 0.200 | 1 | 11.58 | 2.32 | 21.66 | 0.14 | 1.31 |
| | | Module Builder | 165 | 0.200 | 1 | 8.75 | 1.75 | 16.37 | 0.11 | 0.99 |
| | | TOTAL | | | | | 7.67 | 71.73 | 0.47 | 4.35 |
| I, J | 6.7% | Cotton Picker (6R-38) | 350 | 0.189 | 1 | 18.01 | 3.40 | 31.84 | 0.23 | 2.14 |
| | | Boll Buggy | 210 | 0.189 | 1 | 11.58 | 2.19 | 20.47 | 0.15 | 1.37 |
| | | Module Builder | 165 | 0.189 | 1 | 8.75 | 1.65 | 15.47 | 0.11 | 1.04 |
| | | TOTAL | | | | | 7.25 | 67.78 | 0.49 | 4.55 |
| L | 4.3% | Cotton Picker (6R-38) | 330 | 0.172 | 1 | 18.01 | 3.10 | 28.98 | 0.13 | 1.25 |
| | | Boll Buggy | 170 | 0.172 | 1 | 8.75 | 1.51 | 14.08 | 0.07 | 0.61 |
| | | Module Builder | 150 | 0.172 | 1 | 7.72 | 1.33 | 12.42 | 0.06 | 0.54 |
| | | TOTAL | | | | | 5.93 | 55.47 | 0.26 | 2.40 |
| N, O | 4.4% | Cotton Picker (4R-38) | 325 | 0.257 | 1 | 16.72 | 4.30 | 40.19 | 0.19 | 1.76 |
| | | Boll Buggy | 190 | 0.257 | 1 | 9.77 | 2.51 | 23.49 | 0.11 | 1.03 |
| | | Module Builder | 190 | 0.257 | 1 | 9.77 | 2.51 | 23.49 | 0.11 | 1.03 |
| | | TOTAL | | | | | 9.32 | 87.17 | 0.41 | 3.81 |
| P, Q | 5.1% | Cotton Picker (4R-38) | 325 | 0.380 | 1 | 16.72 | 6.35 | 59.43 | 0.32 | 3.03 |
| | | Boll Buggy | 190 | 0.340 | 1 | 9.77 | 3.32 | 31.07 | 0.17 | 1.58 |
| | | Module Builder | 190 | 0.110 | 1 | 9.77 | 1.07 | 10.05 | 0.05 | 0.51 |
| | | TOTAL | | | | | 10.75 | 100.56 | 0.55 | 5.13 |

**Table 5.33 (cont)**

| Budget | % of US | Unit | HP | hrs/ac -pass | ac-pass/ yr | gal/hr | Regional Value | | US Weighted Value | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | gal/ ac-yr | liters/ ha-yr | gal/ ac-yr | liters/ ha-yr |
| R, S | 10.9% | Cotton Picker SP-6R* | 330 | 0.140 | 1 | 18.01 | 2.52 | 23.59 | 0.27 | 2.56 |
| | | Boll Buggy | 215 | 0.140 | 1 | 11.58 | 1.62 | 15.16 | 0.18 | 1.65 |
| | | Module Builder | 150 | 0.140 | 1 | 7.72 | 1.08 | 10.11 | 0.12 | 1.10 |
| | | TOTAL | | | | | 5.22 | 48.86 | 0.57 | 5.31 |
| T | 2.6% | Cotton Picker (4R-38) | 325 | 0.300 | 1 | 16.72 | 5.02 | 46.92 | 0.13 | 1.20 |
| | | Module Builder | 190 | 0.300 | 1 | 9.77 | 2.93 | 27.42 | 0.08 | 0.70 |
| | | TOTAL | | | | | 7.95 | 74.34 | 0.20 | 1.90 |
| U | 3.4% | Cotton Picker (4R-38) | 325 | 0.500 | 1 | 16.72 | 8.36 | 78.20 | 0.29 | 2.67 |
| | | Module Builder | 190 | 0.500 | 1 | 9.77 | 4.89 | 45.69 | 0.17 | 1.56 |
| | | TOTAL | | | | | 13.25 | 123.89 | 0.45 | 4.22 |
| Y | 0.0212 | Cotton Picker (4R-38) | 255 | 0.257 | 1 | 13.12 | 3.37 | 31.54 | 0.07 | 0.67 |
| | | Boll Buggy | 190 | 0.257 | 1 | 9.77 | 2.51 | 23.49 | 0.05 | 0.50 |
| | | Module Builder | 190 | 0.257 | 1 | 9.77 | 2.51 | 23.49 | 0.05 | 0.50 |
| | | TOTAL | | | | | 8.39 | 78.51 | 0.18 | 1.66 |
| US Representative Value | | | | | | | | | 6.70 | 62.65 |

* Other budget used as a surrogate

[1] Fuel use back-calculated based on cost

### *5.3.1.2.4.3 Direct Material and Energy Flows*

The direct material and energy flows associated with the harvesting unit operation include land, diesel fuel to power field equipment, as shown in Tables 5.32 and 5.33, chemical applications, and emissions to air.

#### 5.3.1.2.4.3.1 Fuel Use

Diesel fuel use is summarized and weighted according to relative land area affected (percent of US cotton land harvested), as presented in Tables 5.32 and 5.33. The representative US value for spraying is taken to be 4.5 liters/ha-yr with a minimum of 0.86 liters/ha-yr and a maximum of 18 liters/ha-yr. The representative amount of diesel fuel required for harvesting is 62.7 liters per hectare-year with a minimum of 26.8 liters/ha-yr for dryland cotton grown in Texas and a maximum of 124 liters/ha-yr for pima cotton grown in California. The total for the harvesting unit operation (the sum of the two types of activities) is 67.2 liters per hectare-year.

#### 5.3.1.2.4.3.2 Chemical Applications

A complete list of chemicals used in preparation for harvest is presented in Table 5.34. A summary is given in Table 5.35. The representative amounts of each major application type are taken to be 0.044 kg/ha-yr of plant growth regulator (PGR) over slightly more than half the harvested area, 0.546 kg/ha-yr of desiccant applied to more than a third of all cotton land (in

Texas and California), 0.114 kg/ha-yr of defoliants applied almost universally, and 1.13 kg/ha-yr of boll opener applied in most regions.

**Table 5.34**. Chemicals applied directly to the cotton plant in preparation for harvest

| Common Chemical Name | Function | a.i. (lb/gal) | Trade Name | Budgets | % of US | Product Use Rate | | Active Ingredient Use Rate | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | gal/ acre | liters/ ha | lbs/ acre | kg/ ha |
| ethephon | boll opener | 6 | Finish | P, Q | 4.7% | 0.039 | 0.365 | 0.234 | 0.263 |
| | | | Prep or unspecified | C | 2.9% | 0.063 | 0.585 | 0.375 | 0.420 |
| | | | | A | 16.2% | 0.125 | 1.169 | 0.750 | 0.841 |
| | | | | N, O | 4.0% | 0.166 | 1.555 | 0.998 | 1.118 |
| | | | | G, H, I, J, R | 16.9% | 0.188 | 1.754 | 1.125 | 1.261 |
| | | | | B, K, S, T, U, V, W, X | 34.6% | 0.250 | 2.338 | 1.500 | 1.681 |
| | | | Prep and Finish | L, M | 6.7% | 0.289 | 2.704 | 1.734 | 1.944 |
| carfentrazone-ethyl | defoliant | 2 | Aim 2EC | L, M, P, Q | 11.4% | | | 0.042 | 0.047 |
| cyclanilide | defoliant | 0.75 | Finish | L, M, P, Q | 13.3% | 0.039 | 0.365 | 0.029 | 0.033 |
| diuron | defoliant | 0.5 | Ginstar | T, U | 5.5% | 0.063 | 0.585 | 0.031 | 0.035 |
| s,s,s-tributyl phosphorotrithioate | defoliant | 6 | Def 6 | L, M, P, Q, R, S | 21.4% | 0.031 | 0.292 | 0.188 | 0.210 |
| thidazuron | defoliant | 1 | Ginstar | T, U | 5.5% | 0.063 | 0.585 | 0.063 | 0.070 |
| | | 4 | Dropp SC or unspecified | D, G, H, I, J, K, L, M, P, Q, V, W, X | 37.5% | | | 0.100 | 0.112 |
| | | | | N, O | 4.0% | | | 0.125 | 0.140 |
| | | | | Y | 2.0% | | | 0.200 | 0.224 |
| tribufos | defoliant | 0.5 | unspecified | N, O | 4.0% | 0.063 | 0.585 | 0.031 | 0.035 |
| paraquat dichloride | desiccant | 4.143 | Cyclone Max or unspecified | C | 2.9% | 0.023 | 0.219 | 0.097 | 0.109 |
| | | | | A | 16.2% | 0.063 | 0.585 | 0.259 | 0.290 |
| | | | Gramoxone Max or unspecified | B, T | 17.1% | 0.125 | 1.169 | 0.518 | 0.580 |
| | | | | U | 3.1% | 0.164 | 1.532 | 0.678 | 0.760 |
| sodium chlorate | desiccant | 6 | Defol 6 | T, U | 5.5% | 1.000 | 9.354 | 6.000 | 6.725 |
| Mepiquat chloride | PGR | 0.35 | Pix or unspecified | Y | 2.0% | 0.047 | 0.438 | 0.016 | 0.018 |
| | | | | T | 2.4% | 0.063 | 0.585 | 0.022 | 0.025 |
| | | | | V | 3.4% | 0.094 | 0.877 | 0.033 | 0.037 |
| | | | | N, W | 4.3% | 0.125 | 1.169 | 0.044 | 0.049 |
| | | | | O | 1.9% | 0.138 | 1.286 | 0.048 | 0.054 |
| | | | | D, R, U | 13.0% | 0.188 | 1.754 | 0.066 | 0.074 |
| | | | | L, M | 6.7% | 0.234 | 2.192 | 0.082 | 0.092 |
| | | | | G, H, I, J, P, Q, S, X | 23.7% | 0.250 | 2.338 | 0.088 | 0.098 |

**Table 5.35**. Summary of chemicals applied in preparation for harvest

| Common Chemical Name | Function | Budgets | % of US | US Weighted Mean | |
|---|---|---|---|---|---|
| | | | | lbs/ acre | kg/ ha |
| ethephon | boll opener | all except D, E, F, Y | 86.0% | 1.009 | 1.131 |
| All boll openers | | US Representative value | | 1.009 | 1.131 |
| carfentrazone-ethyl | defoliant | L, M, P, Q | 11.4% | 0.005 | 0.005 |
| cyclanilide | defoliant | L, M, P, Q | 13.3% | 0.004 | 0.004 |
| diuron | defoliant | T, U | 5.5% | 0.002 | 0.002 |
| s,s,s-tributyl phosphorotrithioate | defoliant | L, M, P, Q, R, S | 21.4% | 0.040 | 0.045 |
| thidazuron | defoliant | all except A, B, C, E, F, R, S | 48.9% | 0.050 | 0.056 |
| tribufos | defoliant | N, O | 4.0% | 0.001 | 0.001 |
| All defoliants | | US Representative value | | 0.102 | 0.114 |
| paraquat dichloride | desiccant | C | 2.9% | 0.003 | 0.003 |
| paraquat dichloride | desiccant | A, B, C, T, U | 39.3% | 0.154 | 0.173 |
| sodium chlorate | desiccant | T, U | 5.5% | 0.330 | 0.370 |
| All desiccants | | US Representative value | | 0.487 | 0.546 |
| Mepiquat chloride | PGR | all except A, B, C, E, F, K | 57.2% | 0.039 | 0.044 |
| All PGR | | | | 0.039 | 0.044 |
| US Representative Total | | | | 1.637 | 1.835 |

## 5. 3.1.2.4.3.3 Emissions to Air

### Criteria Air Pollutants

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. Criteria air pollutants that result from the burning of diesel fuel in the equipment listed in Tables 5.32 and 5.33 are calculated based on the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004; EPA, 2005). There are three categories of powered equipment: sprayers, tractors, and harvesters. Sprayers and tractors are taken to have life expectancies of 8 years, while harvesters are assumed to last 10 years (MSU, 2008). The majority of the equipment is assumed to be at or near the median age; thus in 2007 most of the tractors and sprayers are assumed to be model years 2002 to 2005, and the most of harvesters are assumed to be model years 2001 to 2004. For all three equipment types the profile is estimated to be 30% Tier 1, 60% Tier 2, and 10% Tier 3 technology. Sulfur content of the diesel is assumed to be 0.05 wt%, as would be expected for agricultural equipment in 2007. The resulting emissions in grams per liter of fuel burned and grams per hectare-year are given in Table 5.36.

**Table 5.36**. Emissions in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the harvesting unit operation (based on emission factors from the NONROAD model (EPA, 2004; 2005) and equipment data from sources listed in Table 5.7; fuel use is weighted by the percent of US harvested land affected by that equipment type.

| Equipment | Unit Power (HP) | Wtd Fuel Use liters/ ha-yr | Emissions g/liter | | | | | Emissions g/ha | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | VOC | CO | $NO_X$ | PM | $SO_2$ | VOC | CO | $NO_X$ | PM | $SO_2$ |
| Sprayer | 105 | 0.2 | 1.87 | 7.17 | 21.8 | 1.33 | 0.83 | 1.9 | 7.2 | 22 | 1.3 | 0.8 |
| | 110 | 0.1 | 1.95 | 7.51 | 22.8 | 1.39 | 0.87 | 0.1 | 0.5 | 2 | 0.1 | 0.1 |
| | 150 | 2.1 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 3.9 | 15.0 | 46 | 2.8 | 1.7 |
| | 170 | 1.3 | 1.86 | 7.17 | 21.8 | 1.33 | 0.83 | 2.5 | 9.5 | 29 | 1.8 | 1.1 |
| | 200 | 0.9 | 1.71 | 6.18 | 21.4 | 0.97 | 0.83 | 1.5 | 5.5 | 19 | 0.9 | 0.7 |
| Tractor | 150 | 6.2 | 0.34 | 1.31 | 4.0 | 0.24 | 0.15 | 2.1 | 8.1 | 25 | 1.5 | 0.9 |
| | 165 | 2.0 | 1.81 | 6.96 | 21.1 | 1.29 | 0.81 | 3.7 | 14.1 | 43 | 2.6 | 1.6 |
| | 170 | 2.3 | 1.86 | 7.17 | 21.8 | 1.33 | 0.00 | 4.3 | 16.5 | 50 | 3.1 | 0.0 |
| | 190 | 8.4 | 1.71 | 6.19 | 21.4 | 0.97 | 0.00 | 14.3 | 51.9 | 179 | 8.1 | 0.0 |
| | 210 | 2.7 | 1.6 | 5.8 | 19.9 | 0.9 | 0.0 | 4.3 | 15.5 | 54 | 2.4 | 0.0 |
| | 215 | 1.6 | 1.63 | 5.91 | 20.40 | 0.93 | 0.00 | 2.7 | 9.7 | 34 | 1.5 | 0.0 |
| Cotton Picker | 255 | 5.1 | 1.71 | 6.18 | 21.36 | 0.97 | 0.00 | 8.8 | 31.8 | 110 | 5.0 | 0.0 |
| | 325 | 8.7 | 1.03 | 8.12 | 23.00 | 0.85 | 0.00 | 8.9 | 70.3 | 199 | 7.4 | 0.0 |
| | 330 | 3.8 | 0.97 | 7.65 | 21.68 | 0.80 | 0.00 | 3.7 | 29.2 | 83 | 3.1 | 0.0 |
| Pickers and Strippers | 350 | 21.8 | 1.03 | 8.12 | 22.99 | 0.85 | 0.00 | 22.4 | 177.1 | 502 | 18.6 | 0.0 |
| TOTAL | | 68.8 | | | | | | 41.3 | 153.5 | 500.6 | 26.1 | 7.0 |

Greenhouse Gas Emissions

Greenhouse gas emissions from burning of diesel fuel are estimated using IPCC emission factors (IPCC, 2006a). The default carbon dioxide ($CO_2$) emission rate for agricultural diesel operations is 74.1 kilograms (kg) of $CO_2$ per gigajoule (GJ) of fuel burned. If diesel is assumed to have a lower heating value (LHV) energy content of 0.0358 GJ/liter (ANL, 2009), this is equivalent to 2.65 kg $CO_2$ per liter of diesel burned. Similarly, the IPCC default value for methane ($CH_4$) is 4.15 kilograms per terajoule (TJ) and the default value for $N_2O$ is 28.6 kg/TJ. These equate to emissions of 0.149 and 1.02 grams of $CH_4$ and $N_2O$ respectively per liter of diesel combusted. Applying these values to the total fuel consumed (68.8 liters per hectare), the operation of diesel powered equipment during the land preparation unit operation results in per hectare emissions of 178 kg of $CO_2$, 0.00998 kg of $CH_4$, and 0.0687 kg of $N_2O$.

Greenhouse gas emissions also result from crop residues. As with synthetic fertilizer, a portion of the nitrogen contained within the plant matter reverts to $N_2$ with $N_2O$ formed and released as an intermediate product during the reaction sequence. Because accumulation of crop residues is concentrated immediately before and after harvest, they are accounted for in this unit operation.

The rate of direct $N_2O$ emissions due to crop residues can be expressed as

$$N_2O_{CR} = m_{CR} * fraction_{N,CR} * EF_{N,CR} * N_2O_{mw} /(2 * N_{aw}) \tag{5.15}$$

where

$N_2O_{CR}$ is the mass of annual nitrous oxide emissions per unit area due to crop residues

$m_{CR,N}$ is the mass of crop residues, supplied annually per unit area

$fraction_{N,CR}$ is the fraction of nitrogen in the crop residues.

$EF_{N,CR}$ is the emission factor for crop residue nitrogen, taken to be 0.01 (per IPCC guidelines, Table 11.1).

$N_2O_{mw} /(2 * N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Default values for cotton biomass residues and nitrogen content contained within those residues are not provided by IPCC. It is assumed that the amount of residue is independent of the tillage system (the only difference being whether the plant matter stays on the surface or is incorporated into the soil). Most studies suggest that under normal growing conditions, there is little variation in nutrient uptake or concentration of nitrogen by plant part as a function of soil type or plant variety (*c.f.*, Unruh and Silvertooth, 1996; Boquet and Breitenbeck, 2000). Consequently, residue is estimated as a fraction of harvested mass for all areas and management systems.

Below-ground biomass residue consists of the roots of the cotton plant. In a study by Gemtos and Tsiricoglou (1999), the root was found to account for 19.0% of the total dry matter of the cotton plant after hand harvest (i.e., after removal of only the seed cotton). These results are consistent with an earlier study cited by the authors, which reports a range of 14.3 to 29.1 wt% with a mean of 23.2 wt%. The present analysis assumes that the root accounts for 20% of the plant dry matter, excluding lint and seed. The nitrogen content of the root is taken to be equal to 1.2% as cited in Gemtos and Tsiricoglou (1999); this is equivalent the nitrogen content of below-ground biomass for non-N-fixing fodder as given by IPCC (IPCC, 2006b, Table 11.2).

The composition and nitrogen content of the above-ground (aerial) biomass is taken from Boquet and Breitenbeck (2000) for crops receiving either 0 kg/ha or 84 kg/ha added nitrogen. The authors consider not only standing residue, but plant litter or debris that falls from plant as it grows. While some of the standing plant matter will be removed from the field during harvest (i.e., gin trash), a portion lint and seed will also remain in the field, especially with machine harvesting. For simplicity, it will be assumed that these two factors cancel each other out. A summary of the partitioning of mass and nitrogen by plant component is presented in Table 5.37.

**Table 5.37**. Partitioning of mass and nitrogen at maturity by plant part for cotton receiving either 0 or 84 kg/ha nitrogen fertilizer (after Boquet and Breitenbeck, 2000)

| | No added nitrogen (N) fertilizer | | | | 84 kg/ha added nitrogen (N) | | | |
|---|---|---|---|---|---|---|---|---|
| Plant Component | Dry Matter kg/ha | N kg/ha | %N | % of lint (mass) | Dry Matter kg/ha | N kg/ha | %N | % of lint (mass) |
| Stem | 1217 | 7.8 | 0.64% | 135% | 2,254 | 12.4 | 0.55% | 130% |
| Branch | 419 | 2.4 | 0.57% | 46% | 978 | 7.2 | 0.74% | 57% |
| leaf blade | 477 | 9.8 | 2.05% | 53% | 776 | 19.6 | 2.53% | 45% |
| Petiole | 68 | 0.5 | 0.74% | 8% | 124 | 2 | 1.61% | 7% |
| carpel (boll pieces) | 1075 | 12.3 | 1.14% | 119% | 1,964 | 28.9 | 1.47% | 114% |
| Seed | 1117 | 36.6 | 3.28% | 124% | 2,279 | 85.1 | 3.73% | 132% |
| Lint | 902 | 2 | 0.22% | 100% | 1,728 | 4.3 | 0.25% | 100% |
| plant debris | 1090 | 26.4 | 2.42% | 121% | 2,220 | 49.9 | 2.25% | 128% |
| total aerial plant matter | 6365 | 97.8 | 1.54% | 706% | 12,323 | 209.4 | 1.70% | 713% |
| harvest index (seed cotton/total aerial plant matter) | 0.317 | | | | 0.325 | | | |
| aerial residue after harvest | 4,346 | 59.2 | 1.36% | 482% | 8,316 | 120 | 1.44% | 481% |
| root * | 1,087 | 13 | 1.20% | 120% | 2,079 | 25 | 1.20% | 120% |
| TOTAL CROP RESIDUE | 5,433 | 72 | 1.33% | 602% | 10,395 | 145 | 1.39% | 602% |

* Assume root is 20% of total (25% of aerial) containing 1.2% N (Gemtos and Tsiricoglou, 1999)

According to the work of Boquet and Breitenbeck (2000), as shown in Table 5.37, the amount of total cotton crop residue is expected to be 602% of the mass of the harvested lint, for fertilization levels between 0 and 84 kg/ha. This range encompasses most US cotton (Table 5.12). As the average is closer to 84 kg/ha, the nitrogen content is assumed to be 1.39%.

Cotton lint yield in the United States in 2007 was 969 kg/ha (NASS, 2009a); thus using the values expressed in Table 5.37, and applying equation 5.15 gives $N_2O$ emissions due to crop residues as

$$10{,}395 \text{ kg/ha-yr} \; * \; 0.0139 \; * \; 0.01 \; * \; 44/28 =$$

$$2.27 \text{ kilograms } N_2O \text{ / hectare-year} \qquad (5.16)$$

5. 3.1.2.4.3.4 Land Use and Summary

A 5% burden is applied to all unit operations within life cycle stage one, raw material acquisition (i.e., cotton agriculture) to account for seed for propagation. While the area affected by the harvest unit operation should equal the area harvested, as second harvests are sometimes required, the area for the actual harvesting activities are burdened by an additional 10%. Thus, the direct material and energy flows associated with spraying activities are multiplied by a factor of 1.05 and those associated with harvesting by a factor of 1.15. A summary of harvesting material and energy flows is given in Table 5.38.

**Table 5.38**. Direct material and energy flows for harvesting of US cotton cropland

| Resource | | Calculation | Value | Units |
|---|---|---|---|---|
| Land | | 1.10 hectares / 1 hectare-year | 1.1 | 1/yr |
| Diesel | | | | |
| | Volume | 1.15 / year * 67.18 + 1.05* 4.52) liters / hectare | 77 | l/ha-yr |
| | Mass 1 | 76.8 liters / hectare-year * 0.837 kilograms / liter | 64 | kg/ha-yr |
| | Energy 1 | 76.8 liters / hectare-year * 35.8 megajoules / liter | 2,750 | MJ/ha-yr |
| Chemical Treatments to Cotton | | | | |
| | ethephon | 1.05 / year * 1.131 kilograms / hectare | 1.187 | kg/ha-yr |
| | carfentrazone-ethyl | 1.05 / year * 0.00533 kilograms / hectare | 0.006 | kg/ha-yr |
| | cyclanilide | 1.05 / year * 0.00437 kilograms / hectare | 0.005 | kg/ha-yr |
| | diuron | 1.05 / year * 0.00193 kilograms / hectare | 0.002 | kg/ha-yr |
| | s,s,s-tributyl phosphorotrithioate | 1.05 / year * 0.0449 kilograms / hectare | 0.047 | kg/ha-yr |
| | thidazuron | 1.05 / year * 0.0559 kilograms / hectare | 0.059 | kg/ha-yr |
| | tribufos | 1.05 / year * 0.00141 kilograms / hectare | 0.001 | kg/ha-yr |
| | paraquat dichloride | 1.05 / year * 0.00319 kilograms / hectare | 0.003 | kg/ha-yr |
| | paraquat dichloride | 1.05 / year * 0.173 kilograms / hectare | 0.182 | kg/ha-yr |
| | sodium chlorate | 1.05 / year * 0.370 kilograms / hectare | 0.388 | kg/ha-yr |
| | Mepiquat chloride | 1.05 / year * 0.0442 kilograms / hectare | 0.046 | kg/ha-yr |
| Criteria Air Pollutants and Precursors | | | | |
| | VOC | 1.15 * 0.0314 + 1.05 * 0.009884 kilograms / hectare | 0.05 | kg/ha-yr |
| | CO | 1.15 * 0.116 + 1.05 * 0.0376 kilograms / hectare | 0.17 | kg/ha-yr |
| | NOX | 1.15 * 0.384 + 1.05 * 0.117 kilograms / hectare | 0.56 | kg/ha-yr |
| | PM | 1.15 * 0.0193 + 1.05 * 0.00682 kilograms / hectare | 0.03 | kg/ha-yr |
| | SO2 | 1.15 * 0.00256 + 1.05 * 0.00448 kilograms / hectare | 0.01 | kg/ha-yr |
| Greenhouse Gases | | | | |
| | CO2 | 1.15 * 166 + 1.05 * 12.0 kilograms / hectare | 203.74 | kg/ha-yr |
| | CH4 | 1.15 * 0.00931 + 1.05 * 0.000672 kilograms / hectare | 0.011 | kg/ha-yr |
| | N2O | 1.15 * 0.0642 + 1.05 * (0.00463 + 2.27) kg / hectare | 2.914 | kg/ha-yr |

#### *5.3.1.2.5 Waste management*

There are no known waste management activities for this life cycle stage.

#### *5.3.1.2.6 Summary of Direct Material and Energy Flows for Life Cycle Stage 1*

Summary tables for energy and water, emissions to air, and material application for all unit operations within the first life cycle stage, raw material acquisition, cotton agriculture in the US are presented in Tables 5.39, 5.40, and 5.41 respectively.

**Table 5.39**. Energy and water used during cotton agriculture in the US, 2007

| | Electricity | | Diesel | | Gasoline | | Natural Gas | | TOTAL | Water | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Volume | Energy | Volume | Energy | Volume | Energy | Energy | Withdrawn | Consumed |
| Unit Operation | kWh/ ha-yr | MJ/ ha-yr | liter/ ha-yr | MJ/ ha-yr | liter/ ha-yr | MJ/ ha-yr | $m^3$/ha-yr | MJ/ ha-yr | MJ/ ha-yr | $10^3$ liter/ ha-yr | $10^3$ liter/ ha-yr |
| Land Preparation | 0 | 0 | 50 | 1,779 | 0 | 0 | 0 | 0 | 1,779 | 0 | 0 |
| Planting | 0 | 0 | 8 | 293 | 0 | 0 | 0 | 0 | 293 | 0 | 0 |
| Tending (Field) | 0 | 0 | 32 | 1,146 | 21 | 666 | 0 | 0 | 1,812 | 0 | 0 |
| Tending (Irrigation) | 345 | 1,243 | 27 | 979 | 0 | 0 | 18 | 651 | 2,873 | 1,765 | 6,466 |
| Harvesting | 0 | 0 | 77 | 2,750 | 0 | 0 | 0 | 0 | 2,750 | 0 | 0 |
| TOTAL | 345 | 1,243 | 194 | 6,947 | 21 | 666 | 18 | 651 | 9,506 | 1,765 | 6,466 |

**Table 5.40**. Emissions released to the atmosphere during cotton agriculture in the US, 2007

| Unit Operation | Emissions kg/ha | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Criteria Air Pollutants and Precursors | | | | | Greenhouse Gases | | |
| | VOC | CO | $NO_X$ | PM | $SO_2$ | $CO_2$ | $CH_4$ | $N_2O$ |
| Land Preparation | 0.088 | 0.362 | 1.059 | 0.055 | 0.041 | 342 | 0.008 | 1.267 |
| Planting | 0.016 | 0.085 | 0.181 | 0.011 | 0.007 | 22 | 0.001 | 0.008 |
| Tending | 0.267 | 1.303 | 2.658 | 0.181 | 0.142 | 259 | 0.063 | 0.399 |
| Harvesting | 0.046 | 0.173 | 0.564 | 0.029 | 0.008 | 204 | 0.011 | 2.914 |
| TOTAL | 0.417 | 1.923 | 4.462 | 0.276 | 0.198 | 826 | 0.083 | 4.589 |

**Table 5.41.** Nutrients and chemicals applied during cotton agriculture in the US, 2007

| Major Nutrients | kg/ha-yr | Herbicides | kg/ha-yr | Insecticides | kg/ha-yr | PGRs and Harvest Aids | kg/ha-yr |
|---|---|---|---|---|---|---|---|
| Nitrogen (N) | 98.8 | 2,4-D amine | 0.18 | abamectin | 0.000 | carfentrazone-ethyl | 0.006 |
| Phosphorous ($P_2O_5$) | 40.0 | dicamba | 0.15 | acephate | 0.935 | cyclanilide | 0.005 |
| Potassium ($K_2O$) | 49.7 | diuron | 0.44 | aldicarb | 0.333 | diuron | 0.002 |
| | | fluazifop-butyl | 0.00 | cypermethrin | 0.006 | ethephon | 1.187 |
| Micronutrients | kg/ha-yr | fluometuron | 0.14 | dicrotophos | 0.159 | Mepiquat chloride | 0.046 |
| Sulfur (S) | 2.0 | fomesafen | 0.15 | imidacloprid | 0.009 | paraquat dichloride | 0.185 |
| Boron (B) | 0.5 | glyphosate | 3.36 | lamda-cyhalothrin | 0.026 | sodium chlorate | 0.388 |
| | | MSMA | 0.27 | oxamyl | 0.003 | thidazuron | 0.059 |
| Soil Amendments | kg/ha-yr | pendimethalin | 0.38 | parathion-methyl | 0.009 | tribufos | 0.001 |
| Limestone ($CaCO_3$) | 425.9 | prometryn | 0.19 | spinosad | 0.001 | s,s,s-tributyl phosphorotrithioate | 0.047 |
| | | pyrithiobac | 0.28 | thiamethoxam | 0.020 | | |
| Fungicide | kg/ha-yr | s-metolachlor | 0.30 | unspecified insecticide | 1.33 | | |
| unspecified fungicide | 1.16 | trifluralin | 0.10 | | | | |

#### 5.3.1.3 Environmental Metrics

Four categories of environmental metrics are considered in the study: land use, net energy, water use, and emissions to air. Land use includes a quantitative assessment of the total amount of land required to support production of the crop. Net energy is the difference between quantity of energy required to produce the product less energy generated. Water use includes both consumption and withdrawals (i.e., that lost to evaporation and that returned to the source in an altered state). Emissions to air that are considered in the analyses include carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), carbon monoxide (CO), particulate matter (PM), volatile organic compounds (VOCs), oxides of nitrogen ($NO_X$), and oxides of sulfur ($SO_X$). This section is also used to account for indirect flows and embodied inventories that occur due to activities upstream from the reference flow of cotton agriculture. In the case of the latter, only energy and emissions to air are considered.

##### *5.3.1.3.1 Land Use, Area Requirements*

The reference flow for the first life cycle stage in the production of biodiesel from cottonseed oil is one hectare of land. The amount of cottonseed that is produced on one hectare of land (yield) is primarily dependent on use of irrigation, but also a function of location in terms of degrees latitude, and probably of cultivar (although the level of detail provided by national statistics does not permit this factor to be used directly in the evaluation). Yields are highest in California and Arizona where 100% of all cotton is irrigated, where the growing season is long, and where Pima is a common variety. The lowest yielding state in terms of seeds per unit area is South Carolina. Other low yielding states include Tennessee, Alabama, and Florida.

State level seed to lint ratios, calculated from NASS, 2009a for 2007, are applied to county level data for area harvested and lint mass harvested (USDA, 2009) to determine county-level cottonseed yields.

The approximate 5$^{th}$ and 95$^{th}$ percentiles, in terms of amount of harvested land producing at a given yield, are determined to be at 0.79 and 2.45 megagrams (metric tons) of seed per hectare, respectively. The median (50$^{th}$ percentile) is equal to 1.30 Mg/ha-yr hectare and the weighted mean is 1.38 Mg/ha-yr. The yield distribution is shown graphically in Figure 5.19. Note that an anomalous tail is created by California and Arizona which are irrigated at 100% and grow significant amounts of Pima cotton. If these states are excluded, the 95$^{th}$ percentile lies at 1.90 Mg/ha-yr hectare. This relationship stated in terms of the amount of cottonseed harvested equates to a mean land use of $7.69 \times 10^{-4}$ hectares per kilogram of cottonseed harvested, with a range of $4.08 \times 10^{-4}$ to $1.27 \times 10^{-3}$ hectares of land per kilogram of cottonseed.

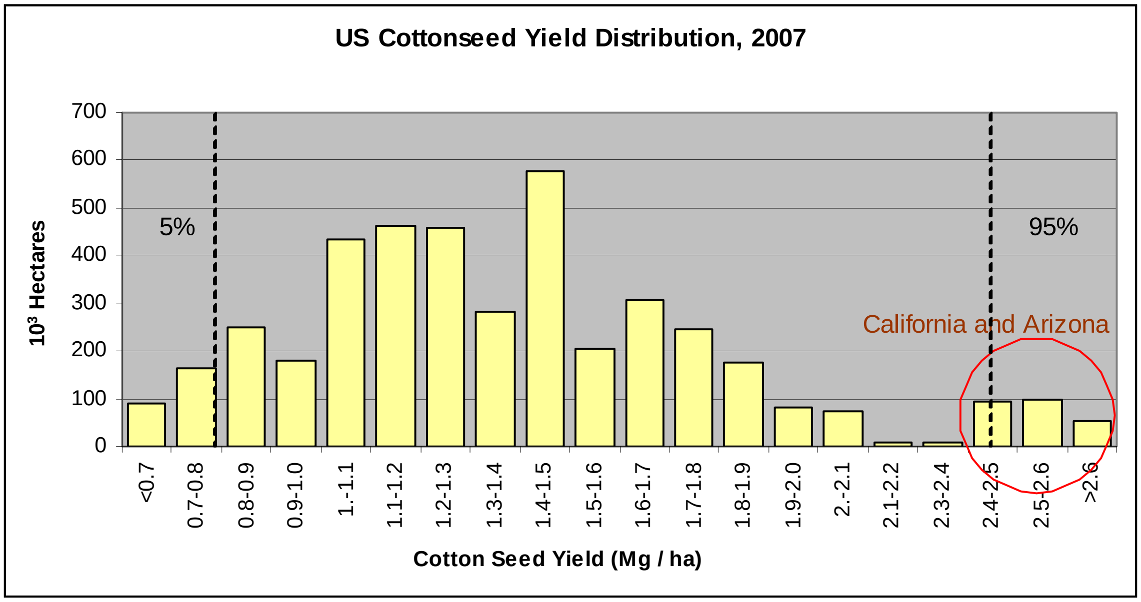


**Figure 5.19**. The median yield of cottonseed in 2007 is estimated to be 1.30 Mg/ha-yr. The $5^{th}$ percentile lies at 0.79 and the $95^{th}$ at 2.45 Mg/ha-yr. If California and Arizona are excluded, the $95^{th}$ percentile lies at 1.90 Mg/ha-yr.

#### *5.3.1.3.2 Water Use*

A total of 1.77 x $10^6$ liters per harvested hectare is withdrawn annually in the US to grow cotton. The amount consumed by the cotton plants is estimated to average 6.47 x $10^6$ liters per hectare. The water lost through drainage to surface waters contains fertilizer, pesticides, and suspended solids. Given an effective mean yield of 1.38 Mg cotton seed / hectare-year and a range of 0.79 to 2.45 Mg seed / hectare-year, this translates to a mean embodied water use of 1,358 liters of water withdrawn and 4,974 liters consumed per kilogram of cotton seed. The corresponding ranges are 720 to 2,234 liters withdrawn /kg seed and 2,639 to 8,125 liters consumed /kg seed. Just under two-thirds of consumed water is currently provided by rainfall, with the remainder supplied by irrigation.

#### *5.3.1.3.3 Net Energy*

There are no energy products produced during this stage of the life cycle, therefore, net energy is equivalent to all the direct energy inputs to cotton agriculture, plus the upstream energy required to generate the direct energy, as well as the embodied energy in the chemicals that are applied to the plants and soil. The upstream energy inputs for energy production are taken from the GREET model (ANL, 2009). The multipliers, based on the sum of the energy used to produce the feedstock plus the fuel, are applied to the energy used to grow cotton in the form of electricity and fossil fuels (Table 5.39). The inputs and calculated upstream energy requirements are shown in Table 5.42. Gasoline is taken to be 90% conventional and 10% California reformulated gasoline in order to reflect the fraction of land used to grow cotton for processing in California.

**Table 5.42.** Upstream energy required to produce electricity and fossil fuels (based on ANL, 2009)

| | MJ/ha-yr | Upstream Energy Factor | Upstream Energy MJ/ha-yr |
|---|---|---|---|
| Electricity | 1,243 | 2.565 | 3,186 |
| Diesel | 6,755 | 0.180 | 1,215 |
| Gasoline * | 666 | 0.223 | 148 |
| Natural Gas | 651 | 0.130 | 85 |
| TOTAL | 9,314 | | 4,634 |

* Gasoline is 90% conventional and 10% CARFG

The amount of energy consumed in the production of agricultural chemicals (fertilizers, soil amendments, and pesticides, and harvest aids) is significant. The GREET model (ANL, 2009) is used to determine the values associated with the manufacture and transportation of fertilizers. Upstream energies of pesticides are taken from Bhat and others (1994); transportation energy requirements are from GREET. There are no data for micronutrients. As the mass fraction is small and the specific composition is unknown, the upstream energies associated with micronutrients are not included in the analysis. Total estimated upstream energies for each of the fertilizers are presented in Table 5.43.

**Table 5.43**. Upstream energies associated with the manufacture and transportation of fertilizer and soil amendments (based on data from ANL, 2009)

| Nutrient | Use Rate | MJ/kg nutrient | | Total Upstream Energy |
|---|---|---|---|---|
| | kg/ha-yr | Feedstock + Production | Transportation | MJ/ha-yr |
| Nitrogen (N) as nitrate | 62 | 62.52 | 2.57 | 4,036 |
| Nitrogen (N) as urea | 21 | 51.16 | 2.15 | 1,129 |
| Nitrogen (N) as UAN | 16 | 58.55 | 2.42 | 950 |
| Phosphate (P2O5) | 40 | 13.05 | 0.93 | 559 |
| Potash (K2O) | 50 | 7.86 | 0.91 | 436 |
| Limestone | 426 | 7.86 | 0.16 | 3,413 |
| TOTAL | | | | 10,524 |

Energy requirements for production of pesticides are taken from a report produced by the US Department of Energy (Bhat *et al*., 1994). While the information is dated, it is the most complete available and is a key source of data in many life cycle inventory databases for the energy associated with pesticide manufacturing. A summary is presented in Table 5.44.

**Table 5.44**. Upstream energies associated with the manufacture and transportation of pesticides (based on data from Bhat *et al*., 1994)

| Pesticide | Pesticide Use | Production Energy | | Production plus Transportation [1] |
|---|---|---|---|---|
| | kg/ha-yr | MJ/kg | MJ/ha-yr | MJ/ha-yr |
| 2,4-D amine | 0.18 | 85 | 16 | 16 |
| dicamba | 0.15 | 245 | 37 | 37 |
| diuron | 0.44 | 200 | 87 | 88 |
| fluazifop-butyl | 0.00 | 518 | 1 | 1 |
| fluometuron [2] | 0.14 | 245 | 34 | 34 |
| fomesafen [2] | 0.15 | 245 | 37 | 37 |
| glyphosate | 3.36 | 454 | 1,526 | 1,529 |
| s-metolachlor | 0.30 | 276 | 83 | 84 |
| MSMA (monosodium methanearsonate) [2] | 0.27 | 245 | 67 | 67 |
| pendimethalin | 0.38 | 150 | 56 | 57 |
| prometryn | 0.19 | 200 | 38 | 38 |
| pyrithiobac [2] | 0.28 | 245 | 68 | 68 |
| trifluralin | 0.10 | 150 | 15 | 15 |
| PGRs and Harvest Aids [2] | 1.93 | 245 | 472 | 474 |
| Insecticides [3] | 2.83 | 245 | 693 | 695 |
| Fungicides [4] | 1.16 | 356 | 412 | 413 |
| TOTAL | | | 3,642 | 3,653 |

[1] Assume transportation energy is 0.919 MJ/kg

[2] Modeled as average herbicide

[3] Modeled as average insecticide

[4] Modeled as average fungicide

The annual net energy balance per hectare of cotton harvested in the US is estimated to be the sum of the following: 1,243 MJ/ha-yr from direct use of electricity plus an additional 3,186 MJ/ha-yr to produce and distribute it; 8,264 MJ/ha-yr from diesel, gasoline, and natural, plus an additional 1,448 MJ/ha-yr to produce and these fuels; 10,524 MJ/ha-yr to manufacture and distribute fertilizers; and 3,653 MJ/ha-yr to manufacture and distribute pesticides and harvest aids. This yields a total energy requirement of 28.1 GJ/ha-yr. (Figure 5.20). A total of 2872 MJ/ha-yr of direct energy, or 6, 320 MJ/ha-yr including upstream inputs (22.47% of the total) are used to irrigate slightly more than one-third of harvested cotton area. If all cotton were to be irrigated, energy due to pumping costs would likely triple to roughly 20 GJ/ha-yr. Fertilizer and pesticide consumption would be higher by an estimated 20%. Diesel fuel consumption for harvesting of the cotton would increase due to higher yields. It is therefore important to note that this is representative of all US cotton grown in 2007 and may or may not be valid for specific regions and circumstances.

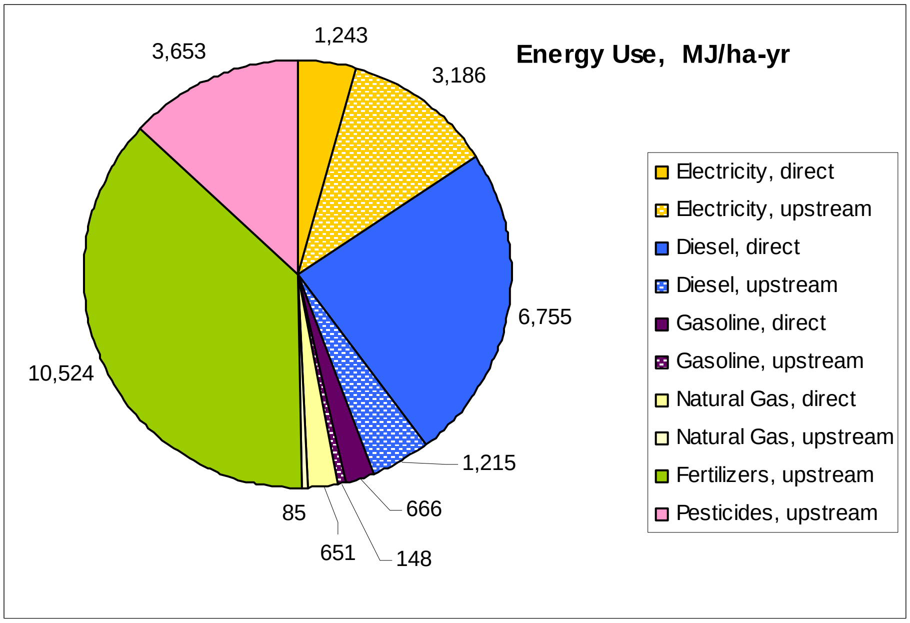


**Figure 5.20.** US cotton has a total energy requirement of 28.1 GJ/ha-yr, with roughly half due to upstream energy used in the production of fertilizers and pesticides. More than one-fifth of the total energy budget is used to irrigated one-third of harvested cotton land.

The effective mean yield for US cotton seed is 1.38 Mg / hectare-year, with a range of 0.79 to 2.45 Mg (see section 5.3.1.3.1). This translates to a mean embodied energy of 20.4 MJ/kg of harvested seed, with a range of 11.5 to 35.6 MJ per kilogram of harvested seed.

#### *5.3.1.3.4 Emissions to Air*

Emissions to air include all of the direct emissions that can be attributed to specific unit operations as well as indirect emissions of greenhouse gases due to use of nitrogen fertilizers. Production and distribution of energy, fertilizers, and pesticides also result in emissions to air (Figure 5.16).

##### *5.3.1.3.4.1 Criteria Air Pollutants*

<u>Direct Emissions</u>

Criteria pollutants and their precursors are released during the operation of agricultural equipment as a result of fuel combustion, including diesel, gasoline, and propane. Total direct emissions are summarized in Table 5.40, and are equal to 0.417 kg of VOCs per hectare-year, 1.92 kg CO/ha-yr, 4.46 kg $NO_X$/ha-yr, 0.276 kg PM/ha-yr, and 0.198 kg $SO_2$/ha-yr.

Emissions to air from diesel powered field equipment are calculated based on the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004). For HC, CO, and $NO_X$, the exhaust emission factors for a given diesel equipment type in a given model year and of a specified age are calculated as:

$$EF_{adj\ (HC,CO,NOx)} = EF_{SS} * TAF * DF$$

where:

$EF_{adj}$ is final emission factor adjusted to account for transient operation and deterioration in grams per horsepower-hour (g/hp-hr)

$EF_{SS}$ is the zero-hour, steady-state emission factor (g/hp-hr)

$TAF$ is the transient adjustment factor

$DF$ is the deterioration factor

Determination of $EF_{SS}$ and $DF$ requires that age and the technology of the equipment be known or assumed along with the horsepower of the diesel engine. In the model developed for cotton farming, most of the equipment consists of self-propelled sprayers or implements pulled by a large tractors, both of which are estimated to have a life expectancy of 8 years (MSU, 2008) giving a median model year of 2003/4 in 2007 and a median age of 4 years. The life span of picker harvesters is anticipated to be 10 years (MSU, 2008); stripper harvesters as assumed to be the same. This gives a median model year of 2002/3 in 2007 and a median age of 5 years. The technology distribution profile for this tractor is assumed using Table A1 from the EPA (2004) documentation. The equipment population profile is generated assuming that approximately 10% of the equipment is close to the maximum age, another 10% is close to the minimum age, and the remaining 80% is close to the median age. The resulting profile consists of 30% Tier 1, 60% Tier 2, and 10% Tier 3 equipment.

Upstream Emissions

Emissions of criteria air pollutants and their precursors that are released during the production and delivery of electricity, diesel, fertilizers, and pesticides used in cotton agriculture are estimated only as functions of the energy required to produce and deliver these resources. The GREET model (ANL, 2009) is used to calculate these values. . None of the pesticides used on cotton are listed in GREET. Therefore, the assumption is made that emissions resulting from the production of these substances are proportional to the energy used to manufacture them (Table 5.44). The set of emission factors used for the production of the herbicide atrazine is used as the reference. GREET assumes the same emissions per unit mass of pesticide transported, which is applied to all of the pesticides used here.

The upstream emissions of criteria air pollutants and precursors from the production of energy are listed in Table 5.45, those for nutrients and amendments are given in Table 5.46, and emissions for pesticides are presented in Table 5.47.

**Table 5.45**. Upstream criteria air pollutants and precursors from production of energy

| Energy Source | Energy Use | Total Upstream Emissions | | | | |
|---|---|---|---|---|---|---|
| | | VOC | CO | $NO_X$ | PM | $SO_2$ |
| | MJ/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr |
| Electricity | 1,243 | 0.022 | 0.064 | 0.264 | 0.338 | 0.582 |
| Diesel | 6,755 | 0.049 | 0.078 | 0.266 | 0.051 | 0.127 |
| Gasoline * | 666 | 0.017 | 0.008 | 0.028 | 0.006 | 0.014 |
| Natural Gas | 651 | 0.004 | 0.005 | 0.014 | 0.001 | 0.007 |
| TOTAL | | 0.092 | 0.156 | 0.573 | 0.397 | 0.730 |

* For 10% CARFG; 90% conventional gasoline

**Table 5.46**. Upstream criteria air pollutants and precursors from production of nutrients and amendments

| Nutrient / Amendment | Nutrient / Amendment Use | Total Upstream Emissions | | | | |
|---|---|---|---|---|---|---|
| | | VOC | CO | $NO_X$ | PM | $SO_2$ |
| | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr |
| Nitrogen (N) as nitrate | 62 | 0.475 | 0.481 | 0.631 | 0.270 | 0.260 |
| Nitrogen (N) as urea | 21 | 0.128 | 0.127 | 0.107 | 0.020 | 0.054 |
| Nitrogen (N) as UAN | 16 | 0.006 | 0.020 | 0.112 | 0.027 | 0.994 |
| Phosphate (P2O5) | 40 | 0.005 | 0.017 | 0.073 | 0.025 | 0.053 |
| Potash (K2O) | 50 | 0.004 | 0.013 | 0.041 | 0.030 | 0.047 |
| Limestone | 426 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| TOTAL | | 0.617 | 0.658 | 0.965 | 0.371 | 1.409 |

**Table 5.47.** Upstream criteria air pollutants and precursors from production of pesticides and harvest aids

| Pesticide [1] | Pesticide Use | Total Upstream Emissions | | | | |
|---|---|---|---|---|---|---|
| | | VOC | CO | $NO_X$ | PM | $SO_2$ |
| | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr |
| 2,4-D amine | 0.18 | 0.0000 | 0.0001 | 0.0004 | 0.0002 | 0.0003 |
| dicamba | 0.15 | 0.0001 | 0.0002 | 0.0007 | 0.0003 | 0.0006 |
| diuron | 0.44 | 0.0004 | 0.0013 | 0.0048 | 0.0023 | 0.0044 |
| fluazifop-butyl | 0.00 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| fluometuron | 0.14 | 0.0000 | 0.0002 | 0.0006 | 0.0003 | 0.0005 |
| fomesafen | 0.15 | 0.0001 | 0.0002 | 0.0007 | 0.0003 | 0.0006 |
| glyphosate | 3.36 | 0.0476 | 0.1777 | 0.6307 | 0.3022 | 0.5852 |
| s-metolachlor | 0.30 | 0.0002 | 0.0009 | 0.0031 | 0.0015 | 0.0029 |
| MSMA (monosodium methanearsonate) | 0.27 | 0.0002 | 0.0006 | 0.0023 | 0.0011 | 0.0021 |
| pendimethalin | 0.38 | 0.0002 | 0.0008 | 0.0027 | 0.0013 | 0.0025 |
| prometryn | 0.19 | 0.0001 | 0.0003 | 0.0009 | 0.0004 | 0.0008 |
| pyrithiobac | 0.28 | 0.0002 | 0.0007 | 0.0024 | 0.0011 | 0.0022 |
| trifluralin | 0.10 | 0.0000 | 0.0001 | 0.0002 | 0.0001 | 0.0002 |
| PGRs and Harvest Aids | 1.93 | 0.0085 | 0.0318 | 0.1137 | 0.0537 | 0.1045 |
| Insecticides | 2.83 | 0.0184 | 0.0685 | 0.2446 | 0.1154 | 0.2248 |
| Fungicides | 1.16 | 0.0044 | 0.0166 | 0.0589 | 0.0281 | 0.0545 |
| TOTAL | | 0.0804 | 0.2998 | 1.0665 | 0.5082 | 0.9861 |

[1] Modeled relative to atrazine

#### *5.3.1.3.4.2 Greenhouse Gases*

<u>Direct Emissions</u>

The direct net emissions of greenhouse gases released due to cotton farming are summarized in Table 5.40 and are equal to 826 kilograms of $CO_2$ per hectare-year, 0.083 kg $CH_4$/ha-yr, and 4.59 kg $N_2O$/ha-yr. Most of the $CO_2$ emissions are from the use of diesel equipment, although use of urea fertilizer and limestone as a soil amendment also make notable contributions. Most of the $N_2O$ emissions are the result of crop residue and use of nitrogen fertilizer..

<u>Indirect Emissions</u>

In addition to $N_2O$ emissions that are released directly from fertilized cropland, indirect emissions occur in one of two ways. In the first, N is volatilized as $NH_3$ or oxides of nitrogen ($NO_X$) and subsequently deposited either in its gaseous form or as $NH_4^+$ and $NO_3^-$ onto soil, water, or plant surfaces. The second pathway occurs when N is removed from soils by leaching or runoff before being taken up into biological systems. Nitrification and denitrification are the mechanisms by which $N_2O$ is formed, just as in direct emissions, but the reactions occur in water and soils that are peripheral to the agricultural land that was originally enriched in nitrogen (the target area).

The indirect emissions of nitrous oxide are accounted for using IPCC guidelines (IPCC, 2006b). Sources of nitrogen that contribute to indirect emissions of $N_2O$ from cotton farming include synthetic fertilizer application and crop residues left on the ground after harvesting. IPCC Equation 11.9 accounts for $N_2O$ emissions that result from atmospheric deposition of volatilized N; IPCC Equation 11.10 accounts for $N_2O$ emissions that result from leaching and runoff (IPCC, 2006b).

After eliminating factors that are equal to zero for US cotton and converting nitrogen to $N_2O$, IPCC Equation 11.9 can be written as

$$N_2O_{atm\ dep} = N_{fert,\ N} \ * \ fraction_{GASF} \ * \ EF_{atm\ dep} \ * \ N_2O_{mw} \ /(2 * N_{aw}) \qquad (5.17)$$

where

$N_2O_{atm\ dep}$ is the mass of annual nitrous oxide emissions per unit area produced from atmospheric deposition of nitrogen volatilized from cropland

$N_{fert,\ N}$ is the mass of nitrogen fertilizer, as nitrogen, applied annually per unit area

$fraction_{GASF}$ is the fraction of synthetic fertilizer that volatilizes, assumed to be 0.10 per IPCC guidelines (IPCC, 2006b, Table 11.3).

$EF_{atm\ dep}$ is the mass of annual direct nitrous oxide emission per unit area due to the application of nitrogen fertilizer; assumed to be 0.01 per IPCC guidelines (IPCC, 2006b, Table 11.3, $EF_4$).

$N_2O_{mw}$ /(2 *$N_{aw}$) is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Substituting in the rate of nitrogen fertilizer application, as nitrogen, from Table 5.41, the expression becomes

$$98.8 \text{ kg / ha-yr} \ * \ 0.10 \ * \ 0.01 \ * \ 44/28 =$$
$$0.155 \text{ kilograms } N_2O \text{ / hectare-year} \qquad (5.18)$$

Similarly, after eliminating factors that are equal to zero for US cotton and converting nitrogen to $N_2O$, IPCC Equation 11.10 (IPCC, 2006b) can be written as

$$N_2O_{leach} = (N_{fert,\ N} + N_{BM,\ N}) * fraction_{LEACH} * EF_{leach} * N_2O_{mw} /(2*N_{aw}) \qquad (5.19)$$

where

$N_2O_{leach}$ is the mass of annual nitrous oxide emissions per unit area produced from leaching and runoff of nitrogen from cropland

$N_{fert,\ N}$ is the mass of nitrogen fertilizer, as nitrogen, applied annually per unit area

$N_{BM,\ N}$ is the mass of nitrogen in biomass remaining on the ground per unit area

$fraction_{LEACH}$ is the fraction of added nitrogen that volatilizes, assumed to be 0.30 per IPCC guidelines (IPCC, 2006b, Table 11.3).

$EF_{leach}$ is the mass of annual direct nitrous oxide emission per unit area due to the leaching of nitrogen; assumed to be 0.0075 per IPCC guidelines (IPCC, 2006b, Table 11.3, $EF_5$).

$N_2O_{mw}$ /(2 *$N_{aw}$) is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

The mass of nitrogen fertilizer, as nitrogen, is 98.8 kg / ha-yr (Table 5.41). The estimated mass of nitrogen present in above-ground biomass due to crop residues is 10,395 kg/ha-yr with a nitrogen content of 1.39%, or 144.5 kg/ha-yr and the expression becomes:

$$(98.8 \text{ kg / ha-yr} + 144.5) \text{ kg / ha-yr}) * 0.30 * 0.0075 * 44/28 = 0.860 \text{ kilograms } N_2O \text{ / hectare-year} \quad (5.20)$$

The total indirect emissions of $N_2O$ are the sum of equations 5.18 and 5.20 or 1.015 kilograms $N_2O$ / hectare-year.

Upstream Emissions

Upstream greenhouse gas emissions related to the energy, fertilizers, and pesticides used directly in cotton agriculture are estimated only as functions of the energy required to produce and deliver these resources. The GREET model (ANL, 2009) is used to determine these values. None of the pesticides used on cotton are listed in GREET. Therefore, the assumption is made that emissions resulting from the production of these substances are proportional to the energy used to manufacture them (Table 5.44). The set of emission factors used for the production of the herbicide atrazine is used as the reference. GREET assumes the same emissions per unit mass of pesticide transported, which is applied to all of the pesticides used here.

The upstream emissions of greenhouse gases from the production of energy are listed in Table 5.48, those for nutrients and amendments are given in Table 5.49, and emissions for pesticides are presented in Table 5.50.

**Table 5.48**. Upstream greenhouse gas emissions from production of energy

| Energy Source | Energy Use | Total Upstream Emissions | | |
|---|---|---|---|---|
| | | CO2 | CH4 | N2O |
| | MJ/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr |
| Electricity | 1,243 | 250.8 | 0.338 | 0.003 |
| Diesel | 6,755 | 92.3 | 0.662 | 0.001 |
| Gasoline * | 666 | 10.9 | 0.067 | 0.000 |
| Natural Gas | 651 | 3.2 | 0.121 | 0.000 |
| TOTAL | | 357.2 | 1.189 | 0.005 |

* For 10% CARFG; 90% conventional gasoline

**Table 5.49.** Upstream greenhouse gas emissions from production of nutrients and soil amendments

| Nutrient / Amendment | Nutrient / Amendment Use | Total Upstream Emissions | | |
|---|---|---|---|---|
| | | CO2 | CH4 | N2O |
| | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr |
| Nitrogen (N) as nitrate | 62 | 235.9 | 0.259 | 1.220 |
| Nitrogen (N) as urea | 21 | 31.8 | 0.079 | 0.001 |
| Nitrogen (N) as UAN | 16 | 15.3 | 0.028 | 0.000 |
| Phosphate (P2O5) | 40 | 26.1 | 0.039 | 0.000 |
| Potash (K2O) | 50 | 29.5 | 0.045 | 0.000 |
| Limestone | 426 | 0.0 | 0.000 | 0.000 |
| TOTAL | | 338.5 | 0.449 | 1.222 |

**Table 5.50.** Upstream greenhouse gas emissions from production of pesticides and harvest aids

| Pesticide [1] | Pesticide Use | Total Upstream Emissions | | |
|---|---|---|---|---|
| | | $CO_2$ | $CH_4$ | $N_2O$ |
| | kg/ha-yr | kg/ha-yr | kg/ha-yr | kg/ha-yr |
| 2,4-D amine | 0.18 | 0.2 | 0.0003 | 0.0000 |
| dicamba | 0.15 | 0.4 | 0.0006 | 0.0000 |
| diuron | 0.44 | 2.9 | 0.0041 | 0.0000 |
| fluazifop-butyl | 0.00 | 0.0 | 0.0000 | 0.0000 |
| fluometuron | 0.14 | 0.3 | 0.0005 | 0.0000 |
| fomesafen | 0.15 | 0.4 | 0.0006 | 0.0000 |
| glyphosate | 3.36 | 382.6 | 0.5538 | 0.0043 |
| s-metolachlor | 0.30 | 1.9 | 0.0027 | 0.0000 |
| MSMA (monosodium methanearsonate) | 0.27 | 1.4 | 0.0020 | 0.0000 |
| pendimethalin | 0.38 | 1.6 | 0.0023 | 0.0000 |
| prometryn | 0.19 | 0.5 | 0.0008 | 0.0000 |
| pyrithiobac | 0.28 | 1.4 | 0.0020 | 0.0000 |
| trifluralin | 0.10 | 0.1 | 0.0002 | 0.0000 |
| PGRs and Harvest Aids | 1.93 | 68.0 | 0.0984 | 0.0008 |
| Insecticides | 2.83 | 146.2 | 0.2116 | 0.0016 |
| Fungicides | 1.16 | 35.6 | 0.0515 | 0.0004 |
| TOTAL | | 643.5 | 0.9314 | 0.0072 |

[1] Modeled relative to atrazine

Calculation of greenhouse gas emissions for the purpose of estimating total global warming potential requires that the each gas be scaled according to its global warming potential relative to carbon dioxide as given in the Fourth Assessment Report of the IPCC (IPCC, 2007). These factored emissions are then summed to give total greenhouse gas emissions in terms of carbon dioxide equivalents ($CO_2e$). In addition, CO and VOCs are assumed to oxidize readily to CO2. VOCs are taken to have a relatively low molecular weight and consist of 83 wt% C (e.g., pentane). The sum of the mass of greenhouse gas emissions expressed as $CO_2$ equivalents is thus calculated as:

$$GHG = \sum_{k} E_{k} * GWP_{k} + [E_{CO} * CO_{2\,mw} / CO_{mw}] + [0.83 * E_{VOC} * CO_{2\,mw} / C_{aw}] \qquad (5.21)$$

where:

$GHG$ is the sum of the mass of greenhouse gas emissions expressed as $CO_2$ equivalents

$E_k$ is the mass of emissions of GHG species k

$GWP_k$ is the global warming potential for GHG species k (IPCC, 2007)

$E_{CO}$ is the mass of CO emissions

$CO_{2\,mw} / CO_{mw}$ is the conversion factor for CO to $CO_2$, equal to 44/28

$E_{VOC}$ * is the mass of VOC emissions

$CO_{2\,mw} / C_{aw}$ is the conversion factor for C to $CO_2$, equal to 44/12

Total emissions of species contributing to the greenhouse gas inventory are given in Table 5.51 as net emissions, as well as in terms of $CO_2$ equivalents.

**Table 5.51**. Greenhouse gas emissions (net and as carbon dioxide equivalents ($CO_2$e)) in kilograms per hectare-year (kg-ha-yr) released during cotton agriculture

| | Net Emissions of GHG | | | | | Emissions of GHG in $CO_2$e | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | kg/ha-yr | | | | | kg/ha-yr | | | | | |
| Source | $CO_2$ | $CH_4$ | $N_2O$ | CO | VOC | $CO_2$ | $CH_4$ | $N_2O$ | CO | VOC | TOTAL $CO_2$e |
| GWP ($CO_2$e factor) | 1 | 25 | 298 | 1.57 | 3.04 | | | | | | |
| Direct emissions | 826 | 0.08 | 4.59 | 2 | 0.42 | 826 | 2 | 1,367 | 3 | 1 | 2,200 |
| Indirect emissions | 0 | 0 | 1.02 | 0 | 0 | 0 | 0 | 302 | 0 | 0 | 302 |
| Upstream emissions | 1,339 | 2.57 | 1.23 | 1 | 0.79 | 1,339 | 64 | 368 | 2 | 2 | 1,775 |
| TOTAL | 2,166 | 3 | 7 | 3 | 1 | 2,166 | 66 | 2,038 | 5 | 4 | 4,278 |

As can be seen in Table 5.51, roughly half (51%) of all the greenhouse gas emissions can be attributed to direct emissions that occur during farm, while another significant portion (42%) are due to upstream flows related to the production and delivery of energy, nutrients, and pesticides used in cotton farming. Only a small portion (7%) is due to indirect emissions of nitrous oxide ($N_2O$). This is shown graphically in Figure 5.21.

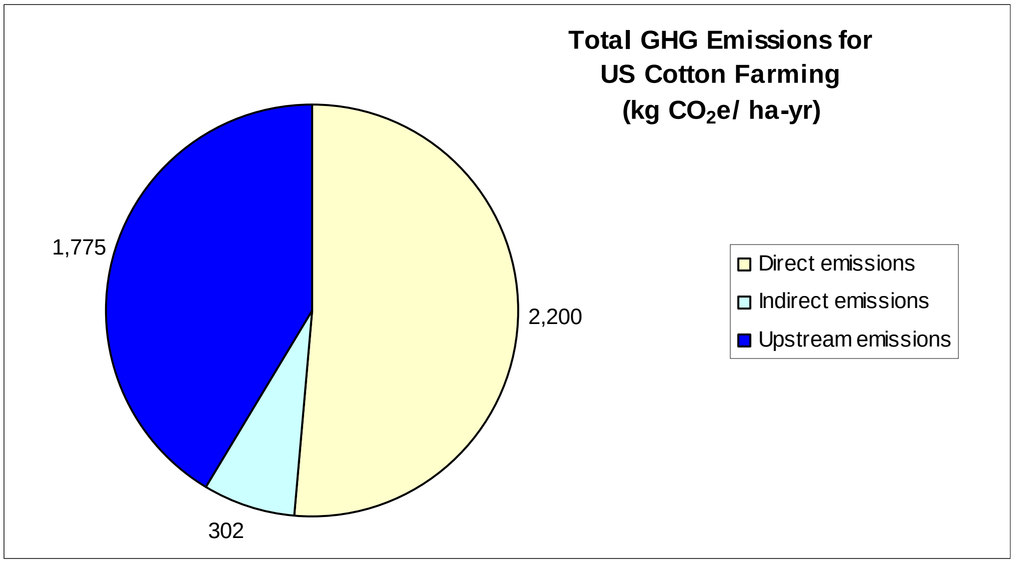


**Figure 5.21**. Roughly half (51%) of the greenhouse gas emissions associated with US cotton farming, as measured in carbon dioxide equivalents (CO2e) per hectare-year, are due to direct emissions. Those due to production and delivery of energy, nutrients, and pesticides are also significant (42%).

### 5.3.1.4 By-Products

There are no by-products associated with the growing of cotton.

## 5.4 Cottonseed Oil Biodiesel Glossary

**bale**: A compressed and bound package of cotton lint, typically weighing about 480 lb

**batt**: Matted lint cotton

**boll**: The seed pod of the cotton plant

**bt Cotton**: Cotton that has been genetically modified to release δ-endotoxins, insecticides produced naturally by the bacteria *Bacillus thuringiensis*.

**bur (or burr)**: The dried, rough casing of the boll. Often referred to as hulls after separation from the cotton

**BWEP:** Boll weevil eradication program

**carpel:** Boll segments, which when dried, form the bur

**chisel plow:** A tractor implement used for primary tillage. Shanks or teeth placed 12 to 16 inches (30 to 40 cm) apart tear at the soil. The chisel shanks may be spring mounted so that vibration causes residue to shed and to avoid damage in stony soils. Groups (gangs) of coulters or discs may be placed in front of the chisel teeth to cut stalks.

**Conservation Reserve Program**: A voluntary program managed by the US Department of Agriculture's Natural Resource Conservation Service and the Farm Service Agency whereby agricultural landowners receive annual payments in return for establishing approved conservation practices on their land. The primary purpose is to control soil erosion.

**CRP:** Conservation Reserve Program

**disc:** A tractor implement used for either primary or secondary tillage. It is capable of mixing in residue and loosening the soil surface. It is less aggressive than a chisel plow and may lead to compaction in damp soils.

**FAME**: fatty acid methyl ester

**fatty acid methyl ester:** The molecules that characterize biodiesel obtained through transesterification via a catalyzed reaction between oils containing fatty acids and methanol; often used as a synonym for biodiesel obtained through transesterification.

**fly lint (or lint fly)**: Short (less than 50 μm) cotton fibers, usually emitted from condensers and mote fan.

***Gossypium barbadense:*** A species of cotton native to South America, commonly referred to as pima or ELS (extra long staple)

***Gossypium hirsutum:*** A species of cotton native to Central America, commonly referred to as upland cotton.

**lint cotton**: Cotton fibers from which the trash and seeds have been removed.

**moldbard plow:** A tractor implement used in primary tillage. It lifts and fractures the soil and incorporates residue, fertilizer, and pesticides. Once, a common tool, it is now reserved for situations that specifically require their use (e.g. large volumes of heavy soil). Fuel consumption and soil disruption are relatively high, with the latter increasing soil erosion potential.

**no-till:** A tillage system that leaves a minimum of 30% plant residue on the surface of the soil. The primary function of the residue is to protect the surface from erosion. It also improves the texture of the soil, encourages microbial growth, contributes to soil carbon, and provides small amounts of nitrogen. Narrow seedbeds are created using a planter/drill.

**picker harvester**: A machine that removes cotton lint and seeds from open bolls with rotating spindles, leaving unopened bolls on the plant.

**PGR**: plant growth regulator

**plant growth regulator:** a chemical used to reduce vegetative growth relative to cotton boll development.

**primary tillage:** A method of preparing seedbeds prior to planting; see tillage

**rotary till:** A tractor implement used for either secondary or primary tillage in light soils. It consists of a single tool bar with non-powered rotating knives. It generally requires two passes and is not effective at mixing in residue or plant destruction.

**secondary tillage:** A method of tending seedbeds after plants have emerged. It typically includes incorporation of herbicides, fertilizers, as well as mechanical weed removal.

**seed cotton**: Raw cotton, containing lint, seed, and some waste material, as it comes from the field.

**stripper harvester**: A machine that strips all bolls — opened (mature) and unopened (immature or green) — from the plant; strippers are used on short cotton plants, grown in arid areas of Texas, Oklahoma, and New Mexico. They collect larger amounts of trash (leaves, stems, and sticks) than picker harvesters.

**tillage:** A generic term that refers to all activities that optimize soil and environmental conditions for growing crops, including mechanical manipulation of the soil, application of herbicides, and use of fallow crops and crop residues. Objectives are to improve soil texture, to form seed beds and drainage systems (rows and ridges in the soil), to minimize weeds and insects, and to incorporate chemicals and fertilizer. Most commonly used to describe mechanical methods of cutting and turning soil prior to planting (primary tillage) such as plowing and harrowing. The term cultivation may used as a synonym for secondary tillage used for mechanical weed removal.

## 5.5 Cottonseed Oil Biodiesel References

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