ISO-CONFORMANT LCA REPORT

Life Cycle Assessment of United States Cotton Fiber Production

COTTON INCORPORATED

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CONTENTS

TABLES

FIGURES

ABBREVIATIONS

ADP	abiotic depletion potential
AP	acidification potential
ARMS	Agricultural Resource Management Survey
AWARE	available water remaining (water scarcity LCIA method)
BOM	bill of materials
BWC	blue water consumption
BWU	blue water use
CGB	cotton gin byproducts
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CF	characterization factors
CTUe	Comparative Toxic Units equivalent (ecotoxicity)
CTUh	Comparative Toxic Units (for humans)
EF	emissions factor
EP	eutrophication potential
GHG	greenhouse gas
GWP	global warming potential
HHPA	human health particulate air
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	kilogram
kWh	kilowatt-hour
L	liter
LCA	life cycle assessment
LCA FE	LCA for Experts software from Sphera
LCI	life cycle inventory
LCIA	life cycle impact assessment
LO	land occupation
LPG	liquefied petroleum gas
m^2	square meter
m^3	cubic meter
MJ	megajoule
N_2O	nitrous oxide
NASS	National Agricultural Statistics Service
NERC	North American Electric Reliability Corporation
NRS	Natural Resource Survey
ODP	ozone depletion potential
PED	primary energy demand
PET	polyethylene terephthalate
$PM_{2.5}e$	particulate matter of 2.5 micrometer diameter or smaller equivalent
POCP	photochemical ozone creation potential
R11e	Refrigerant R11 equivalent
SO_2 e	sulfur dioxide equivalent
USDA	U.S. Department of Agriculture
USEtox	UNEP-SETAC toxicity model
USGS	U.S. Geological Survey
WSP	WSP USA Inc.

COMMON CONVERSIONS

While the functional unit of this LCA is defined as 1 kg of cotton fiber at the ginning gate, several primary data inputs are presented in U.S./imperial units. This is common practice in U.S.-based agricultural LCAs, where data is often collected in imperial units. Importantly, LCAFE defaults to the metric system in model inputs, so converting data to metric is not only beneficial but necessary when building parameterized models to ensure accuracy and reproducibility. Converting these values to metric units improves clarity and consistency.

Units of Primary Data	Conversion Factor	Units for Parameterized Model
lb	1 lb = 0.453592 kg	kg
L	1 L = 0.001 m^3	m^3
acres	1 acre = 4046.86 m^2	m^2
kWh	1 kWh = 3.6 MJ	MJ
acre inch	1 acre inch = 102.79 m^3	m^3
miles	1 miles = 1609.34 m	m

EXECUTIVE SUMMARY

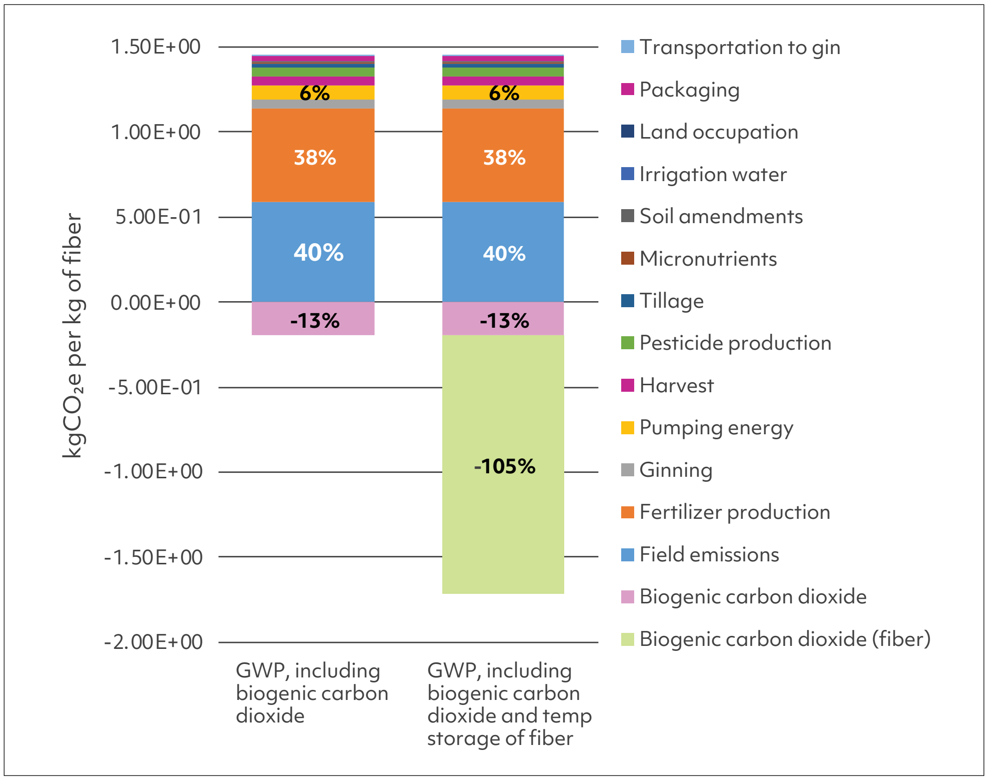
OBJECTIVE AND SCOPE

This Life Cycle Assessment (LCA) was conducted to provide an updated understanding of the cradle-to-gate environmental impacts of U.S. cotton fiber production, thereby enabling stakeholders to identify opportunities for reducing environmental footprints and aligning industry practices with global sustainability goals. This study represents the first comprehensive and rigorously conducted assessment solely focused on U.S. cotton fiber, incorporating extensive primary data collected directly from growers across major cotton-producing regions. It aims to fill existing data gaps, support continuous improvement efforts, and quantify biogenic carbon dioxide flows associated with on-farm cotton production operations.

KEY FINDINGS

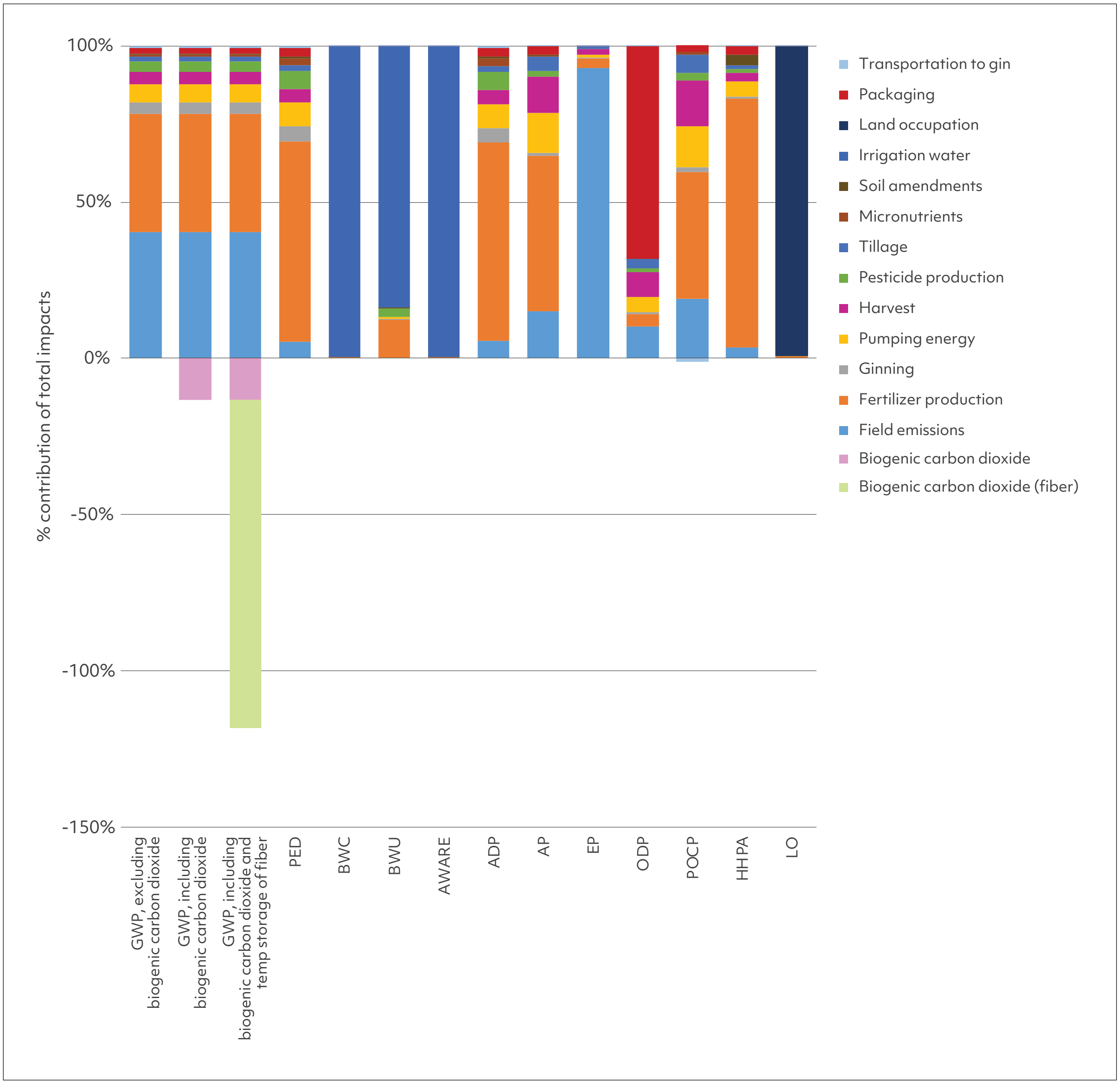
Producing 1 kg of U.S. cotton fiber generates approximately 1.45 kg of fossil CO_2 equivalent emissions. However, when considering biogenic carbon dioxide stored in both the fiber and the soil, cotton production removes approximately 1.71 kg CO_2 equivalent per kilogram of cotton fiber produced, resulting in a net cradle-to-gate footprint of -0.264 kg CO_2 equivalent per kilogram of cotton fiber (Figure ES-1). Although biogenic carbon dioxide storage may not be permanent, opportunities exist to enhance cotton circularity and thus improve storage permanence, distinguishing cotton from petroleum-derived fibers by offering a meaningful reduction in climate impacts.

FIGURE ES-1: GWP (IPCC AR6 GWP 100), including biogenic carbon dioxide, including and excluding temporary storage of fiber [kg CO_2eq per kg of cotton fiber]



Contribution analysis highlighted field emissions and fertilizer production as the primary contributors across multiple impact categories (Figure ES-2). Irrigation dominated water-related categories. These findings align closely with global cotton LCA results published in 2017.

FIGURE ES-2: Contribution analysis for U.S. cotton fiber production



SENSITIVITY AND UNCERTAINTY ANALYSIS

Sensitivity analyses demonstrated that methodological choices substantially affect LCA results. Compared to the baseline economic allocation method, mass allocation reduced impacts by 53%, biophysical allocation by 58%, and cereal unit allocation by 24%. These variations underscore that the presented results represent the most conservative, worst-case scenario concerning allocation methods. Additionally, the choice of background datasets significantly influenced results; greenhouse gas emissions increased by 34% when switching from LCA FE to ecoinvent datasets, primarily due to differences in electricity and fertilizer emission factors. This highlights the importance of transparent methodological documentation to ensure accurate interpretation and prevent inappropriate comparisons between studies.

The uncertainty analysis indicated a high statistical likelihood that baseline results typically vary +/- 5% to 20%, supporting the robustness of the overall findings despite the identified limitations.

RECOMMENDATIONS AND FUTURE DIRECTIONS

To enhance future LCA studies and the sustainability of cotton production, the following actions are recommended:

- Enhance primary data collection, particularly detailed data on nitrous oxide emissions from fertilizer application, specific fertilizer types, and precise on-farm fuel consumption.
- Promote region-specific precision agriculture practices, including optimized nutrient application, irrigation management, and regular soil testing to reduce environmental impacts and improve resource use efficiency.
- Support wider adoption of conservation agricultural practices, such as reduced or no-till farming and cover cropping, to improve soil health, enhance water retention, and reduce erosion.
- Improve irrigation efficiency by upgrading pumping systems and, over the long term, transitioning toward renewable energy sources to significantly reduce greenhouse gas emissions associated with irrigation water utilization.
- Encourage the development and use of lower impact fertilizers (green[1] and blue fertilizers[2]) to lower the environmental footprint associated with fertilizer production.

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[1] Green fertilizers are nitrogen fertilizers produced from green ammonia, where hydrogen is made using renewable-powered electrolysis, resulting in low-carbon nitrogen inputs (RMI, 2023).

[2] Blue fertilizers are nitrogen fertilizers produced from blue ammonia, where hydrogen is derived from natural gas but the resulting CO_2 emissions are captured and stored through CCS, lowering the carbon footprint relative to conventional production (Wood Group, 2021).

LIMITATIONS

The interpretation of results is subject to several limitations:

- Potential inaccuracies from grower-reported data and reliance on secondary modeling for inputs such as irrigation energy and farm fuel consumption.
- The exclusive focus on environmental impacts without evaluating social or economic dimensions limits comprehensive sustainability assessment.
- Variability in methodological approaches, particularly in allocation methods and background dataset choices, complicates direct comparisons with other LCAs.
- Plastic leakage and pollution were not assessed due to ongoing methodological development in these areas.

CONCLUSION

This study represents the most detailed and data-driven evaluation of U.S. cotton fiber production conducted thus far, incorporating extensive primary data collection and exploring a wide range of scenarios and sensitivities. Including biogenic carbon dioxide storage results in a negative cradle-to-gate carbon footprint (-0.264 kg CO_2 equivalent per kg fiber). While this storage may not be permanent, improving cotton circularity can increase benefits of temporary carbon storage. As agricultural practices and circular options for biogenic carbon dioxide capture evolve, cotton has significant potential to further reduce its environmental impact, positioning itself as an increasingly sustainable fiber that meets the growing demand for lower-impact textiles.

GOAL OF THE STUDY

1

1 GOAL OF THE STUDY

The purpose of this study was to develop a detailed U.S. average life cycle inventory (LCI) for cradle-to-gate (seed-to-bale) cotton fiber for use in LCA databases, to fill data gaps, and to conduct a life cycle assessment (LCA) to evaluate environmental impacts to help track continual improvement. Additionally, this study assessed the biogenic carbon dioxide of on-farm operations of U.S. cotton production. The study is based on the attributional LCA approach, which describes the physical reality of an existing production system by quantifying the energy and material flows to and from an existing life cycle. Cotton Incorporated commissioned WSP USA Inc. (WSP) to perform these analyses accordingto the principles of the ISO 14040 family of standards. This study has undergone critical review by an external panel of experts to ensure ISO-conformance and the highest level of credibility.

METHODOLOGY AND DATA SOURCES

The study utilized an attributional LCA approach, strictly adhering to ISO 14040 standards. Primary data were collected via the Cotton Growers Natural Resource Survey (NRS), covering 17 states within the four primary U.S. cotton production regions for the 2021/22 production year. Secondary datasets were sourced from USDA NASS, USGS, IPCC, agricultural extension services, Managed LCA Content databases (LCA FE), and peer-reviewed literature.

1.1 REASONS FOR CARRYING OUT THE STUDY

This study aims to provide an updated understanding of cradle-to-gate impacts of U.S. cotton fiber production in the 2021/22 growing season and specifically:

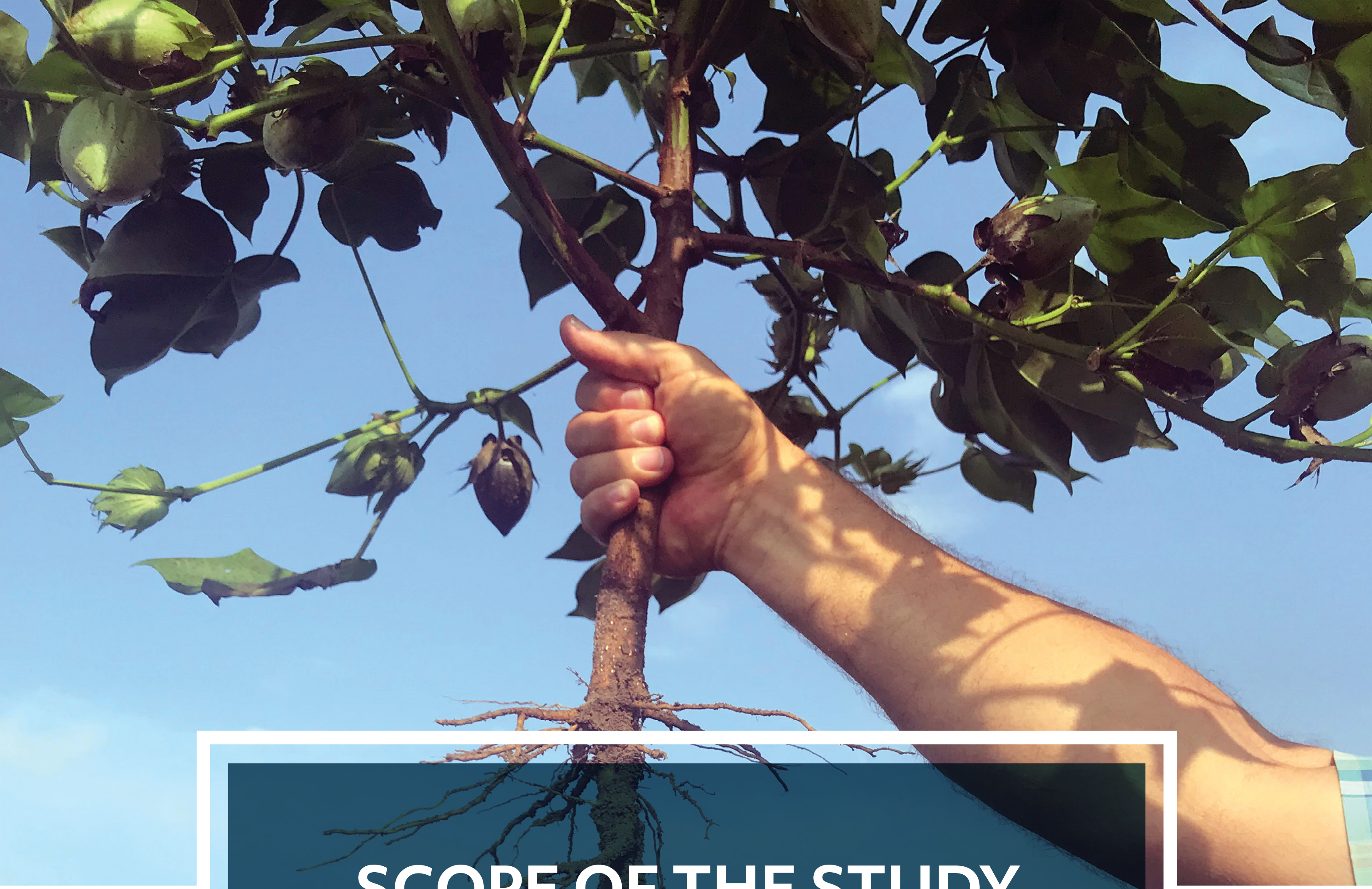
1. Update Cotton Incorporated's prior LCA work on global cotton fiber with focus on cradle-to-gate U.S. cotton production.
2. Assess the cradle-to-gate environmental impacts of U.S. cotton fiber production.
3. Understand the variability in impact results between the different allocation methods and background datasets.
4. Provide updated and accurate LCI data.
5. Track progress and measure changes from previous LCA data to establish trends.
6. Guide decisions on current research priorities and new research initiatives based on identified hotspots, sensitivities, and uncertainties from this analysis.
7. Prior to this study, Cotton Incorporated performed global LCAs on cotton fiber and cotton garments in 2010 and 2017 that included cradle-to-grave production of cotton fiber in China, India, Australia, and the U.S., manufacturing, use phase and end-of-life in other regions.

1.2 INTENDED APPLICATIONS & TARGET AUDIENCE

The study results are meant to inform internal stakeholders, such as researchers and marketers, as well as external stakeholders, including growers, importers and suppliers of cotton and cotton-derived products via the use of the updated LCI data and LCA included in this report. These results can also guide decisions on research priorities and help identify trends within U.S. cotton fiber production. The study is not suitable for comparisons to other LCA studies, as there may be differences in system boundaries, assumptions, background datasets, and impact assessment methods.

> “This study represents the most detailed and data-driven evaluation of U.S. cotton fiber production conducted thus far, incorporating extensive primary data collection and exploring a wide range of scenarios and sensitivities.”

Source: Executive Summary, Conclusion paragraph (printed p. XIV)



SCOPE OF THE STUDY

2

2 SCOPE OF THE STUDY

The following sections describe the scope of the study, including the product and function, functional unit, system boundary, and other study specific information.

2.1 Product and Function

Upland Cotton (*Gossypium hirsutum* L.) fiber (also referred to as cotton lint) is the primary fiber fraction removed from the seed during the cotton ginning process and refers to the harvested cotton after ginning without seeds and cotton gin byproducts (CGB), as shown in Figure 1: Cottonseed, cotton gin byproducts, and cotton fiber. Source Cotton Incorporated. The cotton fiber is typically spun into yarn and ultimately knitted or woven into fabrics. Cottonseed, a co-product of the cotton fiber production system, is the seed of the cotton boll, which is typically used for cottonseed oil production and whole cottonseed for cattle feed applications. Both products have important values and impacts in the U.S. cotton supply chain, however, the focus of the study is on cotton fiber. Cottonseed results are provided in Appendix A: Cottonseed LCIA Results.

FIGURE 1: Cottonseed, cotton gin byproducts, and cotton fiber. *Source Cotton Incorporated*

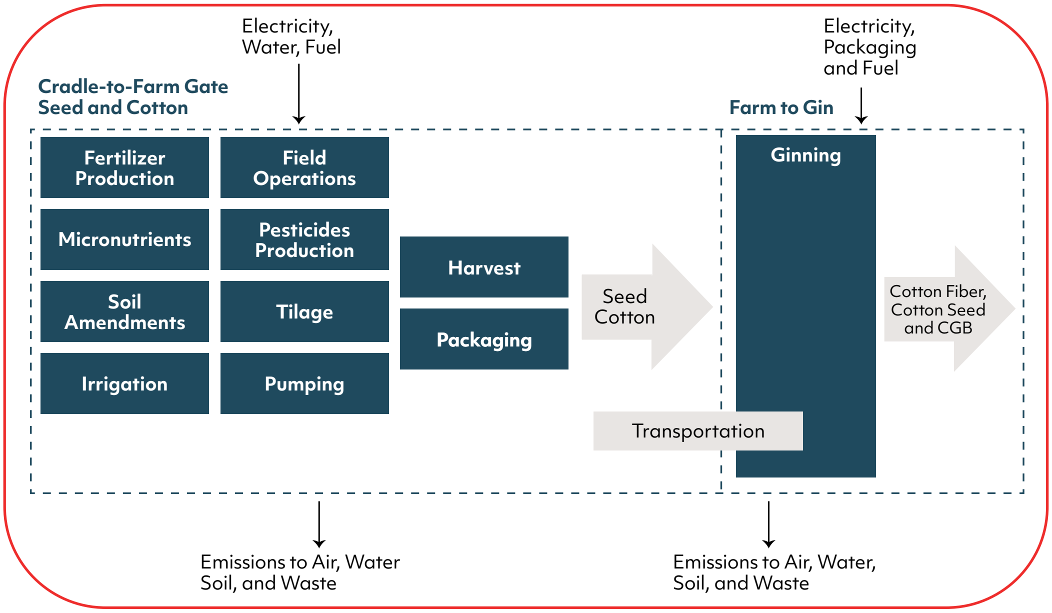
2.2 Functional Unit

The functional unit of an LCA is the "quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20). For this study, **the functional unit was defined as one kilogram of cotton fiber packaged in bales at the ginning gate at a moisture content of 6% – 7.5%** (Valco, et al., n.d.; Laws, 2005) **suitable for storage and/or shipping.**

2.3 System Boundary

The model's system boundary (Figure 2: The system boundaries of the cotton production system) is from cradle-to-gate and includes raw material extraction and refinement, material transport, and ginning.

FIGURE 2: The system boundaries of the cotton production system



The system boundary (Figure 3) for biogenic carbon dioxide calculations includes carbon uptake by cotton plants during annual growth, temporary carbon storage in plant material, animal manures, and soil, and the return of biogenic carbon dioxide to the atmosphere through decomposition of crop residues, roots, manure, and soil organic matter. In addition to these on-farm biogenic carbon dioxide flows, biogenic carbon dioxide flows throughout the cotton production supply chain are accounted for in background processes.

FIGURE 3: Biogenic Carbon Diagram

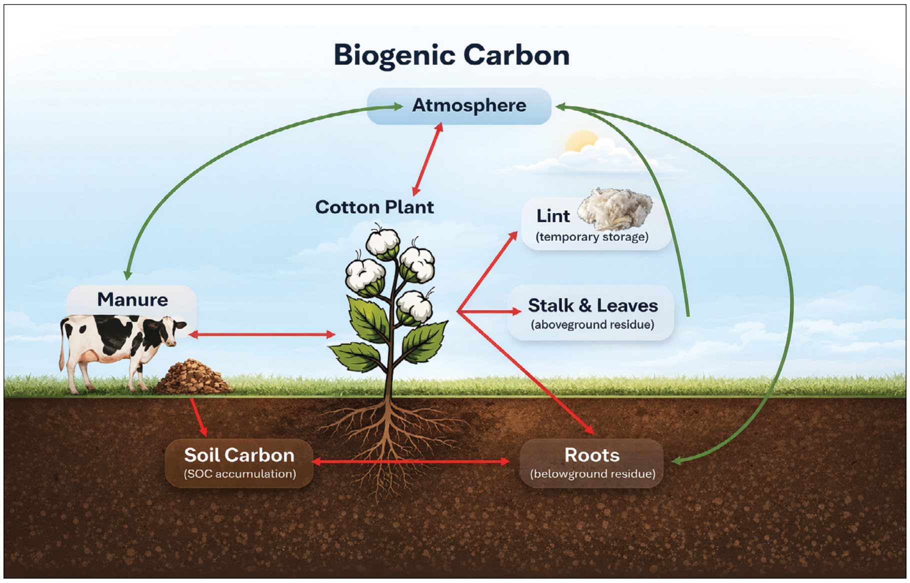


Table 1 presents the parts of the system that are included and excluded in this system's boundary and the corresponding models developed.

TABLE 1: System boundaries of the cotton system – inclusions and exclusions summary

Included in system boundary	Excluded in system boundary
▪ Irrigated vs non-irrigated yield ▪ Irrigation water applied ▪ Irrigation energy consumed ▪ Fertilizer and micro-nutrients production impacts ▪ Biogenic carbon content of manure ▪ Direct and indirect nitrous oxide emissions from crop residues and applied fertilizer ▪ Nitrogen and Phosphorus run-off ▪ Fuel consumed for tillage, fertilizer application, micro-nutrient application, field operations, and harvest ▪ Truck transport to gin ▪ Energy used at gin ▪ Packaging production impacts ▪ Pesticide production impacts	▪ Water input to gin ▪ Effects of nitrification inhibitors ▪ Fuel consumption for application of manure and associated run-off from manure ▪ Field emissions associated with lime application ▪ Embodied energy and impacts associated with building and equipment manufacturing at the farm ▪ Human activities (e.g., employee travel to and from work) ▪ R&D (i.e., the laboratory and inputs related to the development of technologies) ▪ Services (e.g., the use of purchased marketing, consultancy services and business travel)

Data for the processes related to cotton production, transportation of cotton to gin and ginning are sourced from the Cotton Growers survey, USDA and from experts at Cotton Inc. These data are primary data from the cotton growers themselves, or highly representative secondary data for US cotton growers from USDA or literature consistently used to estimate resource use. The data used for the LCA models are described in detail in section 3. The input data provided by Cotton Inc. is high quality, but data quality in a study is determined not just by input data but also by datasets used to model. There are limitations with regards to available datasets, which is why the overall data quality of the study is considered to be average. More details about the data quality can be found in section 4.7.

2.4 Temporal and Geographical Boundary

Cotton farm data was collected via the NRS survey where growers provided their 2021/22 crop year data on farm inputs and outputs. The transportation of cotton from the farm to gin is also provided for the year 2021. Ginning data was not captured in the survey; therefore, literature data was used to model energy related to the ginning process. A 100-year timeframe for GHG emissions accounting is used to assess the global warming potential of emissions. Biological carbon storage in soils is assumed to be stable over the 100-year modeling period. Temporary storage of carbon in cotton fibers was reported separately, as carbon stored in products may be released to the atmosphere on a shorter time scale.

This cradle-to-gate production process is focused within the U.S. Data collected from the NRS survey was representative of the 17 U.S. cotton-growing states. Results were generated for these 17 states using a parameterized LCA model and aggregated by region (Figure 4, Table 2).

FIGURE 4: States in each region used in this study

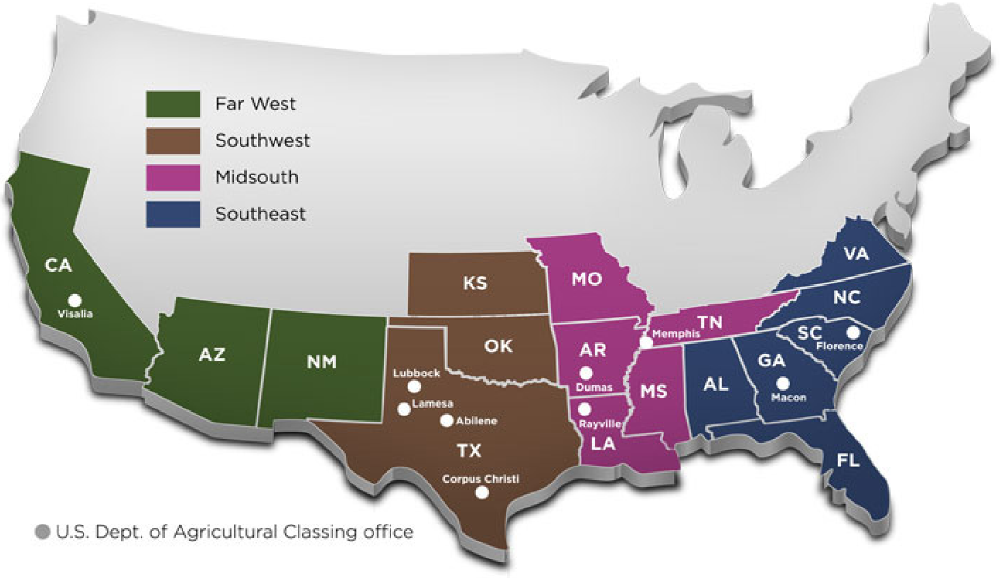


TABLE 2: States in each region used in this study

Region	States	e-Grid[3] region(s) used
Far West	Arizona, New Mexico	AZNM
	California	CAMX
Southwest	Kansas	SPNO
	Oklahoma	SPSO
	Texas	ERCT
Midsouth	Arkansas, Louisiana	SRMV
	Mississippi	SRMV, SRTV, SRSO
	Missouri	SRMW
	Tennessee	SRTV
Southeast	Alabama, Georgia,	SRSO
	Florida	FRCC
	North Carolina, South Carolina	SRVC
	Virginia	RFCW, SRVC

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[3] The e-Grid electricity data set represents the average country or region-specific electricity supply for final consumers, including electricity own consumption, transmission/distribution losses of electricity supply and electricity imports from neighboring countries. The national energy carrier mixes used for electricity production, the power plant efficiency data, shares on direct to combined heat and power generation, as well as transmission/distribution losses and own consumption values are calculated considering various information sources for the corresponding reference year.

2.5 Excluded Processes

When conducting an LCA, some aspects within the set boundaries are excluded due to statistical insignificance or irrelevancy to the goal and scope. As is customary in LCA, the following impacts were excluded from the scope and boundaries for this study:

- Human activities (e.g., employee travel to and from work);
- Research & Development activities (i.e., laboratory and other inputs related to the development of agricultural technologies such as crop protection products or planting seed varieties); and
- Services (e.g., the use of purchased marketing, consultancy services, and business travel).

In addition, infrastructure and capital goods (e.g., buildings and machines used for production) are not included due to their small contribution to the overall impact of cotton products balanced with the challenges of collecting granular and specific data on the depreciable capital involved in cotton fiber and cottonseed production. Production of infrastructure has been excluded also for background generic processes to ensure consistency between the foreground and background datasets.

2.6 Cut-off Criteria

All secondary data is considered to be internally consistent as it has been modeled according to the LCA FE modeling principles and guidelines. According to these principles, cut-off rules for each unit process require coverage of at least 95 percent mass and energy of the input and output flows and 98 percent of their environmental relevance (according to expert judgement). Where applicable, cut-off criteria would only be applied for components that contribute to 1 percent or less of total mass or energy of the system and 5 percent or less of the total environmental impacts. No cut-off criteria were applied to the primary data used in the study.

2.7 Allocation

As cotton cultivation creates both cotton fiber (the focus of this study), cottonseed, and CGB, it is a multifunctional system that needs allocation of the shared burdens. Economic allocation was used in the main Life Cycle Impact Assessment Results. Mass allocation, biophysical allocation, and cereal unit allocation were used in a sensitivity analysis, presented in Section 5.2 Sensitivity Analysis.

While ISO guidelines recommend partitioning the results based on physical properties (e.g., mass allocation), that choice does not align with the economic driver of the product system, cotton fiber production. When analyzing cotton fiber, economic allocation is the most common method used in industry. However, there is not necessarily one scientifically correct method, and the intended use of the data and LCA should, in part, drive the allocation method decision (Daystar, et al., 2024). As there is no one correct approach, all the listed methods were calculated and can be used depending on the use case of the data. When comparing the co-product treatment approaches for cotton fiber, biophysical allocation tends to yield the lowest impacts, whereas economic partitioning generally partitions more impacts to the cotton fiber, increasing the impacts in most categories (Daystar, et al., 2024). Table 3 presents the allocation approaches and associated allocation values. Further, system expansion is another approach that can be used to avoid allocation and is shown to have the lowest impacts in several impact categories. However, system expansion may introduce additional uncertainty, particularly around the most suitable substitution, marginal production, and production location (Daystar, et al., 2024).

TABLE 3: Allocation approaches applied in the study

Allocation method	Economic (baseline)	Mass	Biophysical	Cereal Unit
Description	Allocation based on the economic value	Allocation based on the mass	Allocation based on the carbon, mineral, and organic nitrogen content	Allocation based on metabolizable energy content expressed as barley equivalents
Seed allocation (%)	17%	46%	39%	20%
Fiber allocation (%)	83%	39%	35%	63%
CGB (%)	<1%	15%	26%	17%

The economic allocation factors are based on the Cascale (formerly Sustainable Apparel Coalition) publication, *Industry Aligned Life Cycle Assessment Methodology and Requirements for creating Cotton Fiber Datasets for the Higg Product Tools*, which recommends 83% fiber and 17% seed, based on a global average of the latest five years of data from ICAC Data Handbooks (2019 – 2023) for the top-producing cotton countries (Australia, Brazil, China, India, Pakistan, and United States) using weighted production volumes (Cascale, 2024). A global economic allocation factor was applied to ensure consistency with Cascale methodology and to avoid distortions that can arise from using country specific pricing. As noted in the methodology document, localized economic data may misrepresent environmental impacts due to regional price differences and policy-driven premiums (e.g., subsidies or local grower programs). Utilizing a global economic allocation factor minimizes these biases, enabling greater alignment with global sustainability tools.
It should be noted that a limitation of using economic allocation is that the relative value between seed and fiber may change, which then raises the potential for studies conducted over different time periods to have different results due to a change in cotton farming economics rather than any underlying change in environmental impact due to how cotton is grown.

CGB, although currently represents less than 1% of the economic benefit of seed cotton, can be used to create a variety of products, including (Alege, et al., 2024):

1. **Hydromulch** which is used for erosion control and weed suppression. CGB-based hydromulches have been shown to be as effective, or more effective, than conventional wood and paper hydromulches in reducing soil loss and promoting grass seed germination.
2. **Animal Feed** as a component in livestock feed rations, providing a source of fiber and fat as well as 4-8% protein (Smith, 2001).

3. **Composite boards** such as particle boards, that can be used in construction and combined with other materials to enhance specific properties such as termite resistance.
4. **Biofuel** through various thermochemical processes such as pyrolysis, torrefaction, and hydrothermal liquefaction. These processes can produce bio-oil, biochar, and syngas, which can be used as fuel or as a source for other chemicals.
5. **Compost** as a soil amendment to improve soil structure and nutrient composition.
6. **Mycelium-based biocomposites** as a substrate for growing fungi to produce mycelium-based biocomposites, which have potential uses in acoustic absorption and insulation.
7. **Biochar** is a stable, carbon-rich material produced through the pyrolysis of organic biomass, such as plant residues, wood, or agricultural waste, under low-oxygen conditions. It can be used to improve soil health, enhance carbon sequestration, and mitigate environmental impacts by storing carbon for long periods of time.

The primary challenge for these applications involves production costs and logistics (Alege, et al., 2024), but the material continues to serve as an important resource for agricultural and industrial sectors.

The mass allocation is based on the relative mass flows of cottonseed and cotton fiber during the cotton cultivation process.

The biophysical allocation is based on other physical properties, besides mass, required for physiological mechanisms involved in plant growth, such as carbon, proteins, lipids, and lignin content. This method expresses a 'construction cost' for growing the plant, thus the cost variables expressed in equation were used to calculate the biophysical partitioning coefficient (Daystar, et al., 2024).

Fiber biophysical partitioning coefficient =

$$\frac{C_{Clint}}{C_{Clint} + C_{Cseed} \ x \ Seed_{lint\ ratio}}$$

- C_{Cseed}: Total cost to produce one gram of seed biomass (grams glucose/grams dry weight)
- C_{Clint}: Total cost to produce one gram of lint biomass (grams glucose/grams dry weight)
- $\text{Seed}_{lintratio}$: Refers to the amount of seed produced per kg of lint

The cereal unit allocation is based on metabolized energy content expressed as barley and adds additional robustness to agricultural system assessments due to its physical relationship principles (Gerhard Brankatschk, 2014).

Allocation of environmental burdens to material and energy co-products throughout the upstream supply chain is embedded in the LCI data used in this study and described in the documentation of these datasets.

2.8 Impact Assessment Method

The study assesses the following impact categories, which represent common categories used in agricultural LCAs.

1. Global Warming Potential (GWP100, excluding land use change), excluding biogenic carbon dioxide
2. Global Warming Potential (GWP100, excluding land use change), including biogenic carbon dioxide[4]
3. Primary Energy Demand (PED)
4. Blue Water Use (BWU)
5. Blue Water Consumption (BWC)
6. Water Scarcity using the Available Water Remaining (AWARE) method using high characterization factor for unspecified water[5]
7. Abiotic Resource Depletion Potential (ADP)
8. Acidification Potential (AP)
9. Eutrophication Potential (EP)
10. Ozone Depletion Potential (ODP)
11. Photochemical Ozone Creation Potential (POCP)
12. Human Health Particulate Air (HHPA)
13. Land Occupation (LO)
14. Toxicity metrics (using the USEtox® method) – Human toxicity, cancer and non-cancer; Ecotoxicity

Additional information including the method and version number are found in section 4.1 Life Cycle Impact Assessment procedures and Calculation.

2.9 Type and Format of the Report

In accordance with the ISO 14040 and 14044 requirements, this document aims to report the results and conclusions of the LCA completely, accurately, transparently, and without bias. The report includes the data, methods, assumptions, and limitations in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.10 Software and Database

The LCA was performed using the LCA for Experts[6] software (formerly GaBi®), version 10.8.0.14, Schema 8007. The LCA for Experts (LCA FE) database (version 10.8.0.14) was used for secondary data. The LCA FE database was selected due to its greater number of U.S.-specific datasets compared to ecoinvent, aligning with the U.S. focus of this study. A sensitivity analysis using ecoinvent 3.9.1 as the secondary database is provided in Section 5.2.3.

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[4] Biogenic carbon refers to carbon stored by living things, including plants and animals. Biogenic carbon flows can influence the global warming potential (GWP) of agricultural products as growing crops remove carbon from the atmosphere during photosynthesis, which remains stored in plant material, such as the stalks, roots, fiber, and seeds of the cotton plant until that material decomposes or combusts. [5]

[5] The "AWARE, high characterization factor for unspecified water" quantity in LCA FE characterizes all water use of unknown location as "high". The value is calculated by sorting all 210 national AWARE values from low to high and taking the simple average of the highest third (70 countries). There is no weighting with respect to e.g. GDP or total water consumption. The list includes USA, India, China, Southern Europe, Northern Africa and the Middle East region. The quantity should be used if background data should (mainly) represent these regions. The regionalized impacts cover agriculture and energy processes only.

[6] Modeling for all systems in this study was conducted in the LCA software LCA for Experts (formerly GaBi), developed by thinkstep, now Sphera (https://sphera.com/product-sustainability-software/).

2.11 Critical review

To ensure ISO-conformance, this study has undergone a critical review per ISO 14040 and 14044 by a panel of three independent experts. The review team was chosen based on expertise in LCA and cotton agriculture. The reviewers were:

- Terrie Boguski, Harmony Environmental, LLC (panel chair)
- Allan Williams, Cotton Research and Development Corporation
- Joël Mertens, Cascale (formerly, Sustainable Apparel Coalition)

The Critical Review Statement can be found in Appendix D: Critical Review Statement. The Critical Review Report containing the comments and recommendations of the independent experts as well as the practitioner's responses is available upon request from the study commissioner in accordance with ISO/TS 14071.

2.12 Limitations of the Study

There are limitations from the data collected through the NRS survey. Human error in entry is a limitation of many large-scale surveys. Some of these errors were corrected by setting thresholds on input values for inputs like fertilizers, micronutrients, and manure application rates. In other cases, like energy inputs, separate models were used to calculate resource consumption. The following describe the limitations to this study that are driven by the assumptions made to process data and fill data gaps.

- The exact water table level depths and pump pressure were not available at each farm. A depth range and pressure range were chosen by the survey respondents.
  - The average depth range was used as the value representing the range (e.g., if the range was 10 to 20 ft, then 15 ft was used) for calculation purposes. The final water table depth descriptor was 'greater than 225 ft' in the survey, for which a depth of 275 ft was used. For participants who responded, "Don't know", a state level average water depth was calculated and assigned to these respondents. State level averages were calculated based on average water table data from the United States Geological Survey (USGS). If the state average water table depth from USGS was greater than 275 ft, then the water table depth was set to 275 ft. If the state average USGS water table depth was less than 275 ft, then the lower state average water table depth was used.
  - The average of the pressure range was used as the value representing the range (e.g., if the range was 10 to 20 psi, then 15 psi was used) for calculation purposes. The final pump pressure option for the survey respondents was 'greater than 60 psi' for which the model assumes a well pump pressure to be 70 psi for these respondents. For participants who responded, "Don't know", the average regional pressure was calculated using the data from the survey and assigned to these respondents. The average pressure for the Far West, Southwest, Midsouth, and Southeast regions were calculated to be 34 psi, 33 psi, 42 psi, and 32 psi, respectively.
  - The limitation to this approach is that the farms under consideration might have water levels depth that is lower than the assumed value and might be using pumps with lower pressure, both of which would reduce the electricity and fuel consumed for irrigation water

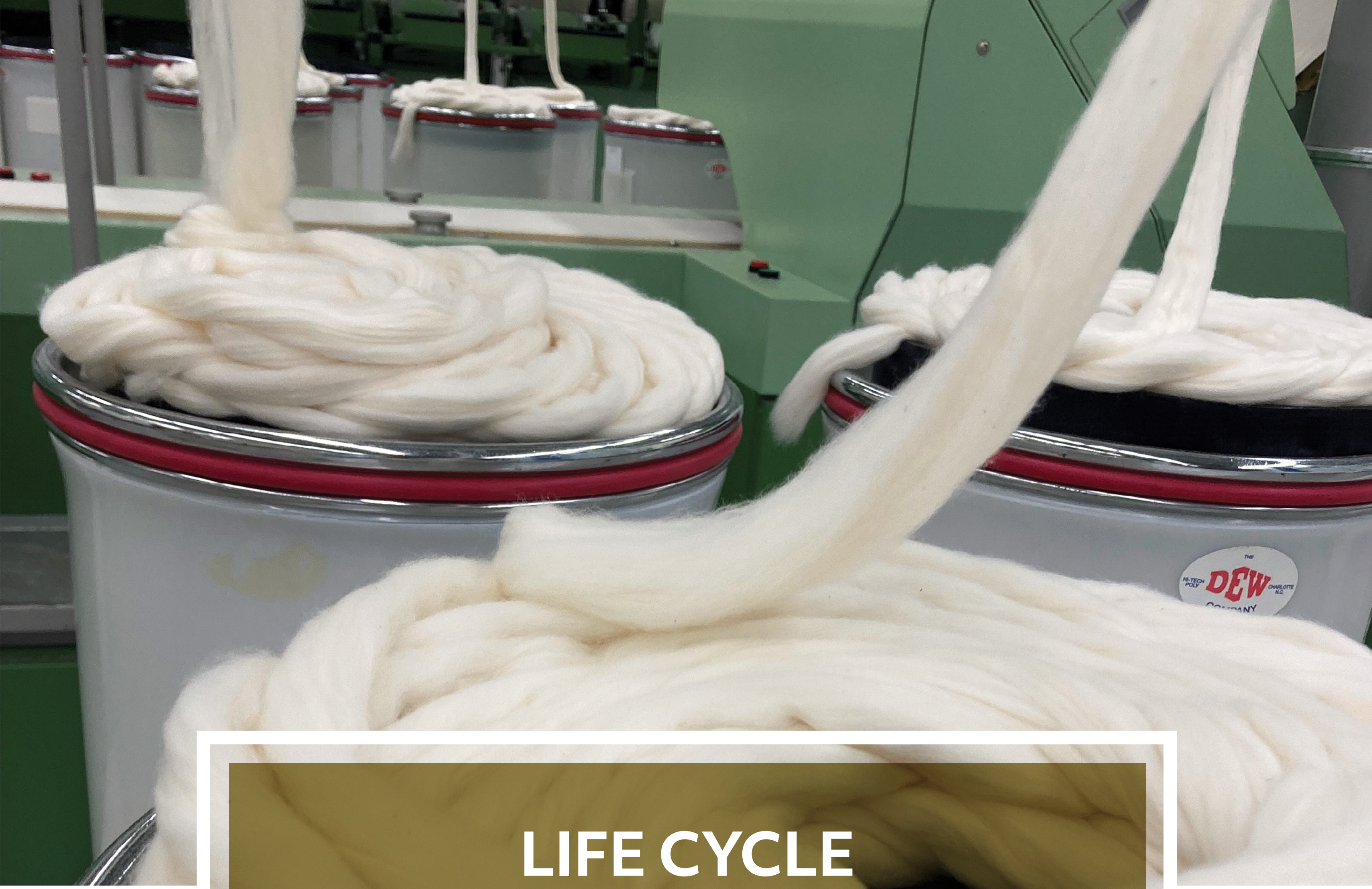
pumping. Thus, these results are conservative, as actual conditions may require less energy for irrigation than assumed in this analysis.

- Pumping energy is calculated by assuming a 95% gear head efficiency and 75% pumping plant efficiency (Hoffman, et al., 1992).
- Only wet and dry climate zones are assigned to states based on the IPCC climate zones for the U.S. Tropical dry, warm temperate dry, cool temperate dry and boral dry are all categorized as dry. All other climate zones are categorized as wet. The dry and wet categorization is used to calculate the direct and indirect flows of nitrogen from fertilizers and manure.
- The wet/dry classification for direct and indirect nitrogen emissions are not always used consistently, especially when irrigation is involved, across different cotton LCA studies. Some studies opt to use higher emission factors, conservatively (CottonConnect, 2025), which would lead to different impacts between this study and other studies.
- Nitrogen and phosphorus run-off are calculated as a set percentage of total nitrogen and total phosphorus used for all states. Nitrogen run-off is assumed to be 3.7% of total nitrogen, and phosphorus run-off is assumed to be 9.3% of total phosphorus (Daniels, et al., 2019). The limitation to this assumption is the lack of representativeness of run-off for states being modeled. Run-off levels are dependent on factors like fertilizer application rates, rainfall timing and amounts, soil type, and tillage practices. If excess fertilizer is applied, in dry climatic conditions with reduced tillage practices, runoff can approach zero, and, in wetter climates with conventional tillage practices, the values would generally be higher.
- Farm-level fuel use for farm operations like tilling, spraying, fertilizer application, and harvest were not available from the survey. Hence an average fuel use per hectare was calculated using average values for rows planted, spacing between rows, swath, travel speed, field efficiency, and fuel consumed per hour by the machinery (Hanna, 2005) (ASABE, 2011). This assumption forces similar farm operation conditions across different states, which limits the study's results to a specific set of farm management operations.
- Ginning energy is calculated using a literature source that breaks down fuel consumption by fuel type for five regions. The regions are matched to the four regions used in this study and the corresponding fuel types are used (Holt, et al., 2021). This is a limitation since ginning energy can vary by states within the region which is not accounted for by this assumption. Any water consumption impacts from ginning are also excluded from the study since ginning has very low contribution when compared to the farm operations, and due to limited data availability.
- Primary data for farms in the Far West U.S. (CA, AZ, NM) was limited due to low cotton acreage in that region during the time of data collection (2021), the region was experiencing a long-term drought that limited water supplies. Therefore, data for this region may not represent typical operating conditions.
- Primary data on the quantity and frequency of manure application was limited due to the infrequency of manure use in cotton production and the number of survey respondents reporting manure use. Similar challenges in collecting primary data on manure application for cotton production have been seen in USDA resources and datasets, including

the USDA ARMS 2007 survey used to fill data gaps in this project. For some states, national averages were used due to a lack of primary data for that region. Because manure application for cotton production is infrequent in most states and application quantities appear low, this limitation is not expected to create substantial uncertainty in the results.

- Field emissions associated with lime application were excluded. According to Section 11.3 of the IPCC Guidelines (2019), carbon dioxide emissions from liming are estimated using Tier 1 emissions factor (EF) of 0.12 kg CO_2 (limestone) and/or 0.13 kg of CO_2 (dolomite). Given that these emission factors are relatively low and the lime application rates were minimal, this exclusion is expected to have a negligible effect on overall GWP results and no impact on other impact categories (IPCC, 2019).

It is also critical to understand the limitations of certain impact categories while interpreting the results presented in Section 4 Life Cycle Impact Assessment. Toxicity results in LCAs are based on characterization factors, which describe the likelihood of harm to humans or ecosystems from the release of a chemical to the environment. These characterization factors have very low precision, with a range of 100× to 1000× for human health and 10× to 100× for freshwater ecotoxicity (Rosenbaum, et al., 2008). Low precision in characterization factors leads to high uncertainty in LCA results. This can render results unusable for comparisons, since both the product and the comparative product have a large range of potential impact. Within the USEtox tool itself, the characterization factors for many chemicals were not available, especially for the human health impact categories. Hence some chemicals may not appear to be a hot spot due to lack of data. Since many parts of the characterization factors are based on models, some models may produce incorrect values when compared to empirical figures; therefore, toxicity impacts need to be assessed with respect to known risks for chemicals that are identified to identify possible errors.



LIFE CYCLE INVENTORY ANALYSIS

3

3 LIFE CYCLE INVENTORY ANALYSIS

3.1 Cotton Life Cycle Inventory

This section outlines the inventory compiled to assess producing cotton fiber and cottonseed in the U.S. Cotton in the U.S. is grown on farms in four different regions: Far West, Southwest, Midsouth, and Southeast. The processes required for producing cotton fiber and cottonseed include on-farm operations such as tillage, irrigation (including energy for pumping), fertilization, and harvest. The harvested cotton then is transported to offsite ginning operations where electricity is consumed to separate cotton fiber from the seed and gin byproducts and to bale the cotton fiber. Additional details are provided separately to the critical review panel and Appendix C: Datasets used for Non-Elemental Flow Inputs.

3.1.1 Agricultural data collection overview

The primary data for this assessment was collected using the Cotton Growers' Natural Resource Survey (NRS) (Cotton Incorporated, 2023) developed by Cotton Incorporated and provided to WSP for this study. Specific details related to the survey and a summary of the results are detailed in the publication titled *Sustainable Cotton Farming Trends: Leveraging Natural Resource Survey Insights for U.S. Cotton Production* (Bayramova, et al., 2024). The survey was sent to cotton growers via email and by a link provided on direct mailers distributed by the United States Postal Service (USPS). The data providers were a mixture of 753 cotton growers which were regionally representative of U.S. cotton production, including all cotton growing states in the U.S., accounting for 9.2% of cotton acres grown in the U.S. The data collected from the NRS covered the 2021/22 cotton crop year. Data from this survey was aggregated by region and used in this assessment.

Additional primary and secondary data from the Intergovernmental Panel on Climate Change (IPCC) national GHG inventories (Hergoualc'h, et al., 2019), USDA National Agricultural Statistics Service, agricultural extension services, and peer-reviewed literature (Table 4) were also used.

TABLE 4: Data source overview

Data Description	Source
Yield	2021 USDA National Agricultural Statistics Service
Area harvested	2021 USDA National Agricultural Statistics Service
Irrigation water	2023 Cotton Growers' Natural Resource Survey
Irrigation energy	2023 Cotton Growers' Natural Resource Survey, 2023 United States Geological Survey Groundwater levels, Hoffman et al. (1992)

Data Description	Source
Fertilizers & micronutrients	2023 Cotton Growers' Natural Resource Survey[7]; 2021 USDA National Agricultural Statistics Service
Pesticide use	2021 USDA National Agricultural Statistics Service
Nutrient leaching & volatilization	IPCC National Greenhouse Gas Inventories
Field operations diesel	2023 Cotton Growers' Natural Resource Survey; ASABE (2011); (Hanna, 2005)
Ginning energy	Hamawand et. al., 2016; Cotton Incorporated; Holt et al., 2021
Distance to gin	2023 Cotton Growers' Natural Resource Survey

The U.S. is the third-largest cotton producing country according to 2022 global cotton production statistics (USDA, 2022). To characterize cotton production practices in the U.S. the 17 cotton growing states in the country were assigned to four regions:

1. Far West: California, Arizona, and New Mexico
2. Southwest: Texas, Oklahoma, and Kansas
3. Midsouth: Mississippi, Arkansas, Missouri, Tennessee, Louisiana
4. Southeast: Virginia, North Carolina, South Carolina, Georgia, Alabama, and Florida

The U.S. average results were calculated as a weighted average of regional results, weighted by seed cotton produced (seed cotton yield * acreage for the states in each region) (NASS, 2022), as shown in Table 5.

TABLE 5: Percent fiber in seed cotton by regional weighted production averages

Region	% fiber of seed cotton (fiber + gin byproducts + seed)
Far West	39%
Southwest	37%
Midsouth	40%
Southeast	42%

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[7] The Nitrogen Products used in the United States in 2022 report published by the International Fertilizer Association was used to determine the urea fertilizer quantity based on the elemental Nitrogen data from the 2023 Cotton Growers' Natural Resource Survey. More details are provided in provided separately to the critical review panel.

A summary of average key U.S. agricultural practices by region are provided in Table 6. Further information on agricultural practices and data can be found in the following sections.

TABLE 6: Summary of average key data collection metrics by region for the U.S.

		Region			
Measure	**Units**	**Far West**	**Southwest**	**Midsouth**	**Southeast**
Total harvested area	acre	278,300	6,108,000	1,589,000	2,297,000
Irrigation & Irrigation Energy					
Diesel use	L/acre	8.29	1.98	11.5	5.35
Irrigated area	%	97	38	51	27
Irrigated amount	Inches/acre	34.9	13.1	9.24	8.24
Irrigation energy	kWh/acre	339	98.7	46.2	46.1
Fertilizer Rates					
N	lbs/acre	124	78.5	98.6	99.6
P_2O_5	lbs/acre	57.4	25.1	88.2	88.8
K_2O	lbs/acre	38.8	33.3	54.8	53.9
Harvest and Ginning					
Fiber yield	lbs/acre	1633	694	1142	930
Distance to gin	miles	16.0	18.2	21.4	22.0
Gin electricity use	kWh/bale	74.9	51.4	30.1	33.9

Key: K_2O = potassium oxide; kWh = kilowatt-hour; L = liter; lbs = pounds; N = nitrogen; P_2O_5= phosphorus pentoxide

3.1.2 Grower practices

Cotton grower practices were characterized by using data from Cotton Incorporated's 2023 Cotton Growers' NRS. Data included farming operations such as tillage systems, number of chemical applications, cover crop implementation, and irrigation practices. The distribution of varying tillage types for each state in the four regions of interest are shown in Table 7. The tillage systems used in this analysis include conservation tillage, conventional tillage, and no-till/strip-till. Tillage types are defined as follows:

- **Conservation tillage:** Includes ridge-till, mulch-till, stale seedbed, or reduced-till. This means a system that leaves sufficient crop residue to cover the soil surface by at least 15% to 30%. This practice is shown to lead to significantly less soil erosion. Other advantages can include reduced fuel and labor requirements.

- **Conventional tillage:** Full-width tillage which disturbs all the soil surface and is performed prior to and/or during planting. Farmers generally use this practice to control weeds, mix nutrients, break compacted dirt and increase production over the short term. However, over time this method can decrease soil health.
- **No-till/Strip-till:** The soil is left undisturbed from harvest to planting except for strips up to one-third of the row width. Like conservation tillage, this practice can lead to significantly less soil erosion as well as maximizing water infiltration. Other advantages can include reduced fuel and labor requirements.

TABLE 7: Distribution of tillage types for each state in the Far West, Southwest, Midsouth, and Southeast regions

Region	State	Conservation tillage	Conventional tillage	No-till/strip-till
Far West	Arizona	33%	33%	33%
	California	40%	40%	20%
	New Mexico	29%	29%	43%
Southwest	Kansas	8%	0%	92%
	Oklahoma	14%	14%	73%
	Texas	20%	34%	46%
Midsouth	Arkansas	52%	39%	9%
	Louisiana	50%	14%	36%
	Mississippi	32%	27%	41%
	Missouri	38%	25%	38%
	Tennessee	9%	3%	84%
Southeast	Alabama	13%	24%	58%
	Florida	39%	0%	61%
	Georgia	22%	17%	60%
	North Carolina	9%	15%	76%
	South Carolina	6%	6%	88%
	Virginia	8%	8%	85%

Note: Due to rounding some row totals are more than 100%

Apart from the regular tillage operations in Table 7, deep tillage operations are also carried out. This data is aggregated at the regional level as shown in Table 8. Deep tillage is a soil modification technique that involves breaking up compacted soil layers to improve soil conditions for plant growth. The relative frequency changes between regions, which drives regional fuel consumption.

TABLE 8: Extent of usage of deep tillage and no deep tillage, along with the frequency of tilling activities

Region	No deep tillage operations were carried out	Deep tillage operations were carried out	Annual frequency of deep tillage
Far West	52%	48%	0.16
Southwest	68%	32%	0.15
Midsouth	67%	33%	0.12
Southeast	46%	54%	0.21

Other grower practices which also add to the fuel consumption at the farm include planting cover crops, spraying agrochemicals and fertilizer application. Cover crops are planted after the cotton crop has been harvested. Cover crops can help with weed control, improve soil health, improve nitrogen cycling and fix nitrogen in the soil, and can reduce nutrient leaching from the soil. Among the survey respondents, 28% of respondents plant cover crops in the Far West region, 41% of respondents plant cover crops in the Southwest region, 31% of respondents plant cover crops in the Midsouth region, and 46% of respondents plant cover crops in the Southeast region.

Spraying applications of pesticides occur during the cotton cultivation process. Spraying can be from the air or on the ground. Aerial spraying, or crop dusting, is the practice of applying pesticides from an aircraft or drone, while ground spray events happen when pesticides are applied through equipment on the ground. The data from the survey indicates the extent of use for aerial and ground spray events, as well as the frequency of spraying events per year, as shown in Table 9.

TABLE 9: Extent of usage of ground spraying and aerial spraying, along with the annual frequency of these spraying activities

Region	Percent ground spray application	Annual frequency of ground spray events	Percent aerial spray application	Annual frequency of aerial spray events
Far West	73%	3.54	27%	1.31
Southwest	82%	5.49	18%	1.25
Midsouth	75%	7.83	25%	1.73
Southeast	67%	6.72	33%	1.09

Fuel use for two fertilizer application mechanisms was obtained in the survey – injection fertilization and broadcast fertilization. Injection fertilizer application is a method of fertilizing plants by injecting a concentrated fertilizer solution directly into the soil. Broadcast fertilizer application is a method of spreading fertilizer across the soil surface to provide nutrients for plants. The extent of injection fertilizer application use in each region is calculated based on the number of respondents who reported using this method. The remaining respondents who apply fertilizer are assumed to use broadcast fertilizer application. There are two stages at which fertilizer is applied – pre-planting and in-season. Pre-planting fertilizer application is the practice of applying fertilizer to the soil before planting cotton. In-season fertilizer application is the practice of supplying nutrients to cotton during their peak growth period. The breakdown calculated from the survey data is provided in Table 10.

Table 10: Extent of use of injection fertilizer application and broadcast fertilizer application during pre-plant period and in-season period.

Region	Pre-plant Injection Fertilization	Pre-plant Broadcast Fertilization	In-season Injection Fertilization	In-season Broadcast Fertilization
Far West	20%	80%	15%	85%
Southwest	34%	66%	42%	58%
Midsouth	7%	93%	33%	67%
Southeast	10%	90%	16%	84%

3.1.3 Nutrient emissions & Leaching

The fertilizer and micronutrient application amounts were provided by the 2023 Cotton Growers' NRS, while the direct and indirect emissions of N_2O were estimated using IPCC tier 1 methods for national GHG inventories (IPCC, 2021) and indirect and direct emission equations (Hergoualc'h, et al., 2019). IPCC climate zones were used to characterize cotton-producing counties as dry or wet for the purposes of calculating direct and indirect nitrogen flows (Zhang, 2013). The effect of irrigation on dry or wet soil classifications is not available from the IPCC, therefore, it was assumed that the emissions factors from IPCC reflect use of irrigation under the wet and dry climatic conditions.

- In wet climates, soil is saturated by water for all or part of the year to the extent that biota, adapted to anaerobic conditions, particularly soil microbes and rooted plants, control the quality and quantity of the net annual greenhouse gas emissions and removals.
- Dry soil is considered every soil that is not a wet soil.

Table 11 below specifies the soil types by region and state.

TABLE 11: Soil types by region and state

Region	State	Soil Type
Far West	Arizona	Dry
	California	Dry
	New Mexico	Dry
Southwest	Kansas	Wet
	Oklahoma	Wet
	Texas	Dry
Midsouth	Arkansas	Wet
	Louisiana	Wet
	Mississippi	Wet
	Missouri	Wet
	Tennessee	Wet
Southeast	Alabama	Wet
	Florida	Wet
	Georgia	Wet
	North Carolina	Wet
	South Carolina	Wet
	Virginia	Wet

Direct nitrous oxide (N_2O) emissions quantify the increase in available nitrogen due to human-induced nitrogen additions or changes in land use or management practices. The following equation was used to calculate direct N_2O emissions:

- Direct N_2O emissions = [kg fertilizer] x [EF in kg N_2O-N per kg N in fertilizer] x [nitrogen fraction of fertilizer] x [kg N_2O per kg nitrogen]

Indirect N_2O emissions quantify the nitrogen lost to leaching and volatilization, which were calculated using the aggregated and disaggregated default values for wet and dry climates provided in the IPCC guidance and the following equation:

- Indirect N_2O (leaching & volatilization) = [kg fertilizer/ manure] x [nitrogen fraction of fertilizer/ manure] x [kg N_2O per kg nitrogen] x [nitrogen fraction volatilized] x [EF volatilized] + [kg fertilizer/ manure] x [nitrogen fraction of fertilizer/ manure] x [kg N_2O per kg nitrogen] x [nitrogen fraction leached] x [EF leach]
  - Nitrogen fraction of fertilizer/manure: proportion by weight which is elemental nitrogen in the fertilizer/ manure.
  - Nitrogen fraction for fertilizer is urea from LCA for Experts U.S. database – U.S.: Urea (agrarian) Sphera
  - Nitrogen fraction for manure is calculated based on the nitrogen content in beef manure, poultry manure and dairy manure

Both direct and indirect emissions are calculated for synthetic fertilizer and manure using the equations discussed above. The quantity of nitrogen fertilizer from the survey data is used. Manure quantities by source are calculated by combining survey manure data with USDA Agricultural Resource Management Survey (ARMS) data, which then is used to estimate on-farm manure direct and indirect emissions. In the case of crop residues, only direct emissions are calculated since there are no volatilization and leaching emissions.

3.1.4 Irrigation Energy and water data

For applied irrigation water and pumping energy, data from the 2023 Cotton Growers' NRS were used. The survey provided the irrigated acreage and amount of irrigation water applied in inches, from which total amount of irrigation water is calculated. Irrigation-related data on water table depth, pump pressure, and irrigation water applied were obtained from the survey. This calculation assumed 95% gear head efficiency and 75% pumping plant efficiency.

EQUATION 1: Equation for energy needed at pump for irrigation water derived from Hoffman et al.(1992)

$$\textit{Energy needed at pump} = 1.412 * (\textit{water table depth} * 0.3048 + \textit{pump pressure} * 0.70345) * \text{irrigation water}$$

Where depth is in feet, pressure is in PSI, irrigation is in acre-inches, and energy is MJ per acre.

The survey responses for "depth to water table" were limited to the following ranges: 0-25 ft, 26-75 ft, 76-125 ft, 126-176 ft, 176-225 ft, and greater than 225 ft. The average depth of each range was used as the reference depth for all ranges except "greater than 225 feet", for which the depth was assumed to be 275 ft. Similarly, the survey responses for well pump pressure were also limited to the following ranges: 0-5 psi, 6-10 psi, 11-15 psi, 16-20 psi, 21-30 psi, 31-40 psi, 41-50 psi, 51-60 psi, and greater than 60 psi. The average pressure for each range was used as the reference pressure for all ranges except "greater than 60 psi", for which the value was assumed to be 70 psi. The total energy was broken out for each region by the irrigation energy source fraction by region, which was obtained from the 2018 Farm and Ranch Irrigation Survey (USDA, 2019), as shown in Table 12. Engine efficiency of 30%, 91% and 23%, respectively, for diesel pumps, electric pumps and natural gas pumps, and fuel energy content of 39 MJ/L for diesel, 3.6 MJ/kWh for electricity and 34 MJ/m^3 for natural gas were used to calculate the amount of diesel, electricity and natural gas consumed.

TABLE 12: Percent of diesel, electricity and natural gas energy sources for irrigation pumps in each region

Region	Diesel	Electricity	Natural Gas
Far West	8%	90%	2%
Southwest	6%	77%	17%
Midsouth	47%	52%	1%
Southeast	30%	70%	0%

3.1.5 *On-farm Biogenic Emissions*

On-farm biogenic carbon dioxide flows were modeled separately at the county scale to supplement biogenic emissions from life cycle inventory processes in the primary model in LCA FE. Biogenic carbon dioxide flows on the farm included the uptake of atmospheric CO_2 during crop growth, return of carbon in crop residues and roots to the atmosphere during decomposition, and addition of carbon to the soil organic carbon (SOC) pool through manure application. Biomass removed from the farm system at harvest was tracked as three separate flows: cottonseed, cotton fiber, and gin byproducts.

Carbon in cotton fiber, the primary product from this system, was not modeled past the farm gate and could be considered a form of temporary (less than 100 years) carbon storage. This carbon may be released to the atmosphere at the end-of-life of the fiber during product manufacturing (e.g. cutting waste) and product end-of-life, but these emissions are outside the cradle-to-gate system boundary of this study. Recent studies show that the temporary storage of biogenic carbon dioxide in cotton apparel can have substantial climate benefits under shorter time horizons (Pires, et al., 2024). To highlight the importance of biogenic carbon dioxide flows in the product system, this study assesses GWP including biogenic carbon dioxide in two ways: including and excluding temporary storage of carbon in cotton fiber products. This assessment does not adjust the quantity of biogenic carbon storage to account for the temporary nature of cotton fiber products, which would reduce the 100-year CO_2 equivalent GHG emissions effects of temporary carbon removal from the atmosphere (1 kg of biogenic carbon dioxide stored for 10 years might be represented as 0.1 kg of carbon over 100 years, for example). Because of this limitation, the 100-year GWP including biogenic carbon dioxide results that include temporary storage from cotton fiber appear as if that storage were permanent (100+ years).

Carbon in crop residues and coproducts, including non-harvested aboveground biomass, roots, gin byproducts and cottonseed, was assumed to be at a steady state under baseline conditions. This means that annual biogenic carbon uptake by crop residues and coproducts added to the decaying organic matter pool was identical to annual biogenic CO_2 losses from decomposition. Under this assumption, soil organic carbon (SOC) was considered static under constant field management conditions.

Changes in SOC were modeled at the county scale based on changes in field management, including reduced tillage or no-till and the application of manure as fertilizer, using Tier 2 IPCC GHG accounting guidelines (Buendia et al., 2019). Field management conditions reported in the 2023 Cotton Growers' NRS were used to assess SOC accumulation or loss compared to baseline operations (conventional tillage, no manure application). Due to a low number of survey respondents reporting manure application in some states, survey data on manure application quantities (lbs/acre) and rates (% of acres) were supplemented with data from the 2007 USDA ARMS survey using regional or national average data based on the availability of data in the ARMS survey (USDA Economic Research Service, 2015). IPCC Tier 2 guidelines for soil organic carbon accounting use a matrix of tillage practices, fertilizer practices, soil type, and climate to estimate changes in SOC on a per-hectare basis. All survey responses indicating no-till, reduced tillage, and manure application were assumed to represent recent changes in field management that meet the IPCC 20-year assessment period for land cover and land management changes. In this assessment, the Tier 2 approach was applied using county-scale soil type and climate maps (Xinyu Liu, 2021), combined with estimates of the proportion of farmers using each tillage and fertilizer practice from the 2023 Cotton Growers' NRS. The county-scale soil types were developed by overlaying U.S. counties with data from IPCC default soil classes derived from the

Harmonized World Soil Data Base (Batjes, 2021). SOC accumulation estimates were checked against total biogenic carbon in crop residues and applied manure based on average carbon content values from scientific literature and agricultural extension services (Wanjura et al., 2014) (Pettygrove & Heinrich, 2010) (Wortmann & Shapiro, 2012) (Wilson, 2021). In many cases, IPCC Tier 2 methods for SOC accumulation from manure application led to a larger estimated change in SOC than was applied in manure (likely due to the relatively small quantities of manure used in cotton production). To avoid overestimating SOC accumulation from manure application, manure-related SOC accumulation was capped at 50% of the carbon content of applied manure at the county scale. This was applied for the GWP including biogenic carbon calculations but not for other impact categories.

TABLE 13: Biomass quantity and carbon content parameters used in on-farm biogenic carbon modeling

Parameter	Value	Unit	Source
Aboveground biomass (post-harvest)	5.4	kg / kg fiber yield	(Pabuayon et al., 2020)
Belowground biomass	1.8	kg / kg fiber yield	(Meshram, et al., 2021)
Carbon content of aboveground biomass (post-harvest)	48%	%	(Wanjura et al., 2014)
Carbon content of belowground biomass	48%	%	[Assumed equal to above ground biomass]
Carbon content of fiber	41.5%	%	(Xie, 2021)
Carbon content of cottonseed	53.1%	%	(Suprabhat et al., 2014)
Carbon content of manure (beef cattle)	20%	% (wet basis)	Estimated from 30% C (dry basis) and 33% moisture
Carbon content of manure (dairy cattle)	5.0%	% (wet basis)	Estimated from 34% C (dry basis) and 85% moisture
Carbon content of manure (poultry)	44%	% (wet basis)	Estimated from 64% C (dry basis) and 31% moisture

3.1.6 On-farm Energy use estimates

There are many ways energy is used in cotton production. Apart from energy for irrigation, which was discussed in Section , there are energy usages during field operations including tractors and other heavy equipment.

For tractor-based field operations, data from the 2023 Cotton Growers' NRS were combined with the American Society of Agricultural and Biological Engineers agricultural machinery management standard procedures (ASABE, 2011) and Hanna study (Hanna, 2005) to estimate fuel use for field operations. Example fuel use requirements by operation are shown in Table 14. The percentage of farmers using a given operation in a region and the number of times that operation was carried out during the season were based on data from the 2023 Cotton Growers' NRS. The summation of all operations was used to compute a fuel use rate per hectare.

Table 14: Fuel use (in liters per hectare) requirements for on-farm activities in different regions.

On-farm activity	Far West	Southwest	Midsouth	Southeast
Deep tillage	0.47	0.29	0.23	0.67
Disk	2.9	2.7	1.8	1.3
Row Clean & Cultivate	1.2	1.1	0.77	0.55
Bed	2.2	2.1	1.4	1.0
Plant	2.0	2.0	2.0	0.30
Spray (Ground Application)	3.7	6.4	8.3	6.4
Spray (Aerial Application)	0.46	0.29	0.57	0.47
Shred Stalks	5.8	5.8	5.8	5.8
Plant Cover	0.78	1.1	0.86	1.3
Broadcast Fertilizer – pre-plant	2.2	1.8	2.6	2.5
Inject Fertilizer – pre-plant	1.8	3.1	0.64	0.91
Broadcast Fertilizer – in season	2.4	1.6	1.9	2.3
Inject Fertilizer – in season	1.4	3.8	3.0	1.5
Harvest	19.3	19.3	19.3	19.3

3.1.7 Transportation and Packaging

Transportation distances between cotton fields and gins were calculated from survey responses. The responses were grouped to generate state specific averages, converted, and then multiplied by yield to create the kilogram-kilometer model input. All field-to-gin transportation was assumed to be made by truck. The complete list of distances and kilogram-kilometers, along with dataset assumptions, are shown in Table 15.

Table 15: Average transportation distances between field and gin.

Region / State	Average Distance (km)	Modeled Cargo Weight (kg)*	Transportation (kg×km)
Far West			
Arizona	28.7	1,490	42,772
California	20.3	2,244	45,508
New Mexico	44.6	1,295	57,764
Southwest			
Kansas	59.0	1,085	64,016
Oklahoma	31.5	932	29,316
Texas	26.2	821	21,500
Midsouth			
Arkansas	22.9	1,422	32,543
Louisiana	35.3	1,152	40,662
Mississippi	43.5	1,136	49,373
Missouri	33.3	1,436	47,809
Tennessee	48.8	1,181	57,598
Southeast			
Alabama	50.3	886	44,607
Florida	29.4	687	20,196
Georgia	30.7	981	30,062
North Carolina	32.3	1,091	35,272
South Carolina	44.1	1,058	46,664
Virginia	32.2	1,190	38,294

* "Cargo weight" reflects the average seed cotton yield per acre for each state, not the total mass per truck or shipment. The average distance traveled by the cargo weight is data collected from the 2023 Cotton Growers' Natural Resource Survey. The transportation impact is calculated on a per-acre as the product of cargo weight and average distance in kilogram-kilometers. Impacts are calculated using background LCI data that already account for average truck utilization and empty return trips.

LCI Dataset Assumptions	
U.S.: Diesel mix at filling station Sphera	Fuel
U.S.: Truck – Medium Heavy-duty Diesel Truck/ 22,000 lb payload - 7 Sphera <u-so>	Truck Transport Mode

Packaging consists of plastic module wrap used to wrap cotton harvested from the field as well as additional plastic wrap and metal wiring used for baling cotton prior to storage in the warehouse. Regional material data for the module wrap, bale wrap, and bale wire were provided by Cotton Incorporated.

Cotton fiber packaging involves two primary stages: regional module wrapping at the farm and bale packaging at the gin.

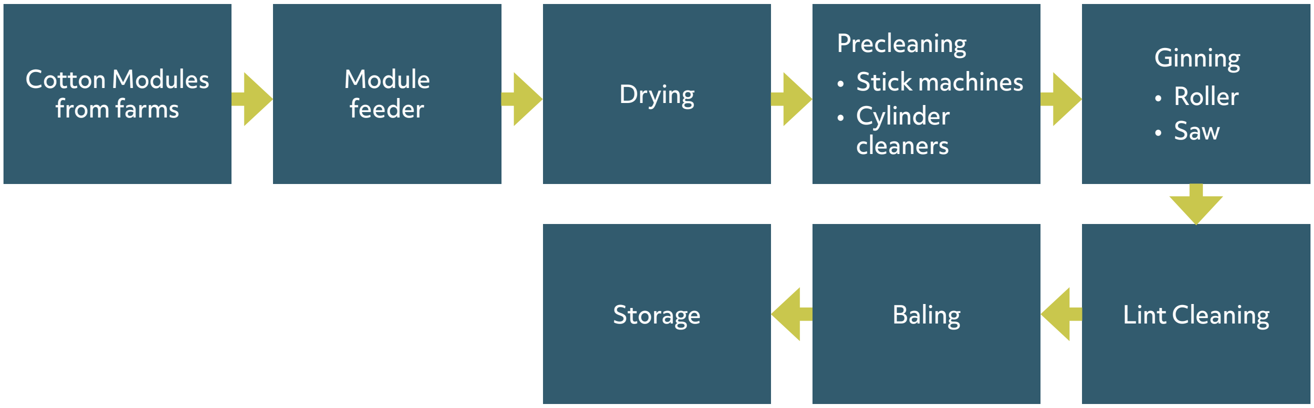
- Regional Module Wrap (Farm Level): Polyethylene terephthalate (PET) wrap is used during cotton harvest to store and protect the seed cotton harvested from the field. On average, 5.62E-05 kg of PET per kg of fiber is needed.
- Bale Packaging (Gin Level): Cotton bales are secured using plastic wrap, strapping, and metal wire. On average, each bale requires 1.15 kg of plastic wrap and strapping per bale and 0.05 kg of metal wire per bale.

3.1.8 Ginning energy estimates

Ginning is the mechanical process of separating cotton fibers from seeds. See the general process of unit operations for ginning in Figure 5, adapted from (Tumuluru, et al., 2023). Typically, when the seed cotton enters a ginning facility the first step is drying to remove excess moisture. The seed cotton is then processed through a cylinder cleaner, which uses rotating spiked cylinders to break up the seed cotton and remove foreign material such as sticks, stems, and leaves. Cotton fiber and seed is then separated by pulling the seed cotton through a series of "ginning ribs," which allow the cotton fibers to pass through due to their small size, but not the seeds. The process entails the consumption of electricity and natural gas or liquefied petroleum gas (depending on the dryer).

As natural gas and liquified petroleum gas consumption data was not readily available from that survey, the data used for natural gas and liquefied petroleum gas (LPG) were retrieved from the study conducted by Ismail et al. (2011) in six Australian cotton ginning facilities between January 2007 and December 2008. Conservatively, the higher estimates of 150.93 megajoules (MJ) natural gas per bale and 148.7 MJ liquified petroleum gas per bale were used. The higher estimates are likely appropriate for most of the U.S. conditions as the Southeastern and Midsouth growing regions have higher annual rainfall rates than Australia. Engineers from the USDA- ARS have conducted energy audits of U.S. cotton gins that have included fuel use measurements for cotton drying and humid air systems. Fuel use can vary significantly based on environmental conditions during the harvest season (Hardin & Funk, 2013). At one gin in the Midsouth and one in the Southeastern U.S., the averaged use rates were 0.174 MJ/kg and

FIGURE 5: Unit operations used for processing of seed cotton received from farms. Adapted from (Tumuluru, et al., 2023)



0.456 MJ/kg. Fuel use rates were typically under 0.791 MJ/kg and rarely went above 1.35 MJ/kg (typically under 178 MJ per 225 kg bale).

Ginning electricity consumption data are presented in Table 16. The electricity consumption data was retrieved from a survey by Holt et al. (2021) that estimates the cost of ginning cotton in 2019 for four regions, which uses USDA-specific survey results to identify trends in gin operation and how these trends have impacted ginning cost.

TABLE 16: Ginning electricity consumption per bale and state

State	kWh Electricity per Bale
Texas	51.4
Kansas	51.4
Oklahoma	51.4
California	74.9
Arizona	74.9
New Mexico	74.9
Virginia	33.9
North Carolina	33.9
South Carolina	33.9
Georgia	33.9
Alabama	33.9
Florida	33.9
Mississippi	30.1
Arkansas	30.1
Missouri	30.1
Tennessee	30.1
Louisiana	30.1

Note: A cotton bale was assumed to have an average net weight of 495 pounds.

3.2 Assumptions

This study relies on key assumptions regarding the data used, with results largely dependent on survey data that are aggregated regionally and incorporated into the model. Certain data points—such as irrigation energy use, runoff quantities, farm operations fuel consumption, and ginning energy—were not collected directly at each farm but instead estimated using methodologies from various literature sources. Additionally, there are limitations in the impact categories analyzed, particularly in toxicity results, which carry high uncertainty due to variability in characterization factors.

Additional limitations of this study include:

- A variety of fertilizers are used on farms, but available generic datasets are used to model nitrogen (N), potassium (K), and phosphorus (P) fertilizers to evaluate the embodied impacts.
- All states in the U.S. have a variety of climate zones. The states are classified as dry or wet climates based on the climate zone covering the largest area per IPCC calculations.
- Fertilizer runoff impacts include freshwater ecosystems but exclude marine eutrophication.
- Ginning natural gas and liquid petroleum gas consumption data was acquired from an Australian study, where the higher values were conservatively used in this study's assumptions and may not be exactly representative of U.S. ginning facilities, but based on available data in the U.S., the estimates appear appropriate.
- For biogenic carbon modeling, instances of reduced tillage, no-till, and manure application as fertilizer from the survey data were assumed to represent recent changes from baseline farming practices (e.g., conventional tillage, no manure application) within the 20-year period for assessment of SOC changes under IPCC Tier 2 guidelines.

LIFE CYCLE IMPACT ASSESSMENT

4

4 LIFE CYCLE IMPACT ASSESSMENT

The following sections summarize the life cycle impact assessment procedures and results.

4.1 Life Cycle Impact Assessment procedures and Calculation

The life cycle inventory was analyzed in LCA FE using the impact categories shown below. These impact categories represent common categories used in agricultural LCAs.

- GWP, excluding biogenic carbon (GWP 100 excluding land use change and excluding biogenic carbon dioxide [CO_2]) (kg CO_2 equivalent [CO_2e]) – IPCC AR6 excluding biogenic
  - Assess the emission of GHGs into the atmosphere and evaluate the contribution to GWP over a 100-year period and exclude emissions and sequestration from biological sources.
  - These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health, and material welfare.
- GWP, including biogenic carbon (GWP 100 excluding land use change and including biogenic carbon dioxide [CO_2]) (kg CO_2 equivalent [CO_2e]) – IPCC AR6 including biogenic
  - Assess the emission of GHGs into the atmosphere and evaluate the contribution to GWP over a 100-year period and include emissions, capture and storage from biological sources.
- PED (from non-renewable energy sources) (MJ) – LCA for Experts Energy Indicators, non-renewable energy
  - The low heating value (or net calorific value) approach was used to determine the primary energy from non-renewable resources and is measured in MJ.
- BWU (liters [L]) – LCA for Experts Water Indicators, BWU
  - Assess the use of freshwater resources from surface and groundwater bodies. Water use refers to the total volume of water extracted from a source.
  - The BWU results are presented in kilograms in LCA for Experts; however, since 1 kg of water is equal to 1 L of water in the metric system, results are presented in liters.
- BWC (liters [L]) – LCA for Experts Water Indicators, BWC
  - Assess the consumption of freshwater resources from surface and groundwater bodies. Water consumption refers to the quantity of water taken from a source that is not replenished.
  - The BWC results are presented in kilograms in LCA for Experts; however, since 1 kg of water is equal to 1 L of water in the metric system, results are presented in liters.

- Water Scarcity: AWARE (cubic meter [m^3] world equivalent) – high characterization factor for unspecified water
- The characterization factors are regionalized factors covering agriculture and energy processes only.
  - The "AWARE, high characterization factor for unspecified water" quantity in LCA FE characterizes all water use of unknown locations as "high". The value is calculated by sorting all 210 national AWARE values from low to high and taking the simple average of the highest third (70 countries). There is no weighting with respect to, e.g., GDP or total water consumption. The list includes USA, India, China, Southern Europe, Northern Africa and the Middle East region. The quantity should be used if background data should (mainly) represent these regions.
  - Water scarcity is defined as the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully.
  - AWARE is a water use midpoint indicator representing the relative **A**vailable **WA**ter **RE**maining per area in a watershed, after the demand of humans and aquatic ecosystems has been met expressed as cubic meter world equivalents. It assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived (WULCA, 2024).
- ADP (fossil [MJ]) – CML 2001 – August 2016
  - Assess the depletion of non-renewable resources, such as coal and natural gas, and evaluate the potential for fossil fuel resource scarcity.
- AP (kg sulfur dioxide equivalent [SO_2e]) – CML 2001 – August 2016
  - Assesses the potential acidification, based on emissions that have acidifying effects in the environment.
  - The impact is a measure of an emissions capacity to decrease water pH and is expressed as kg of SO_2e.
- EP (kg phosphate equivalent) – CML 2001 – August 2016
  - Assesses the potential impacts of excessive macronutrient flows, such as nitrogen and phosphorus run-off from fertilizer, that can lead to shifts in ecosystem compositions such as increased biomass production.
  - The impact is expressed in terms of kg phosphate equivalents.
- ODP (kg R11 equivalent) – CML 2001– August 2016, Ozone Layer Depletion Potential (ODP, steady state)
  - Assesses the air emissions that contribute to the depletion of the stratospheric ozone layer, expressed as equivalents of R11.
- POCP (kg Ethene equivalent) – CML 2001– Aug. 2016, Photochemical Ozone Creation Potential (POCP)
  - Assesses ground level smog formation, which can be harmful to both human health and ecosystems and is expressed as ethene equivalents.

- HHPA (kg particulate matter of 2.5 micrometer diameter or smaller equivalent [$PM_{2.5}$ eq.) – TRACI 2.1, Human Health Particulate Air
  - Assesses particulate matter air emissions of various diameters, expressed as 2.5 micrometer ($PM_{2.5}$) particulate matter emissions.
- LO (square meter × year equivalent) – Impact 2002+ (I02+ v2.1)
  - Assess the damage caused per area of land occupied over the duration of the occupation. Land conversion impacts are not considered since in most cases the land used has already been converted.
- Toxicity – All toxicity impacts were assessed outside of LCA FE
  - Human Health – Cancer (Comparative Toxic Units human toxicity [CTUh]) – USEtox 2.12 and factors calculated based on USEtox 2.13
    - Assess the potential harm to human health due to exposure to substances known to cause cancer
  - Human Health – Non-carcinogenic (Comparative Toxic Units human toxicity [CTUh]) – USEtox 2.12 and factors calculated based on USEtox 2.13
    - Assess the potential harm to human health due to exposure to substances that do not cause cancer, but may still have toxic effects
  - Ecotoxicity (Comparative Toxic Units ecotoxicity–) – USEtox 2.12 and factors calculated based on USEtox 2.13
    - Assess the potential toxicity of emissions to ecosystems and aquatic life and evaluate the potential harm to the environment due to the release of toxic substances

The results of the abiotic depletion, ecotoxicity, and human toxicity (cancer and non-cancer) environmental impact indicators have high uncertainty. For the toxicity impact categories, characterization factors exhibit extreme uncertainty, with ecotoxicity varying by at least 1,000% and human toxicity by 10,000% (Rosenbaum, et al., 2008). Additionally, abiotic resource depletion results should be interpreted with caution due to high uncertainty, which stems from variability in calculation methods and uncertainties in material reserve data.

This study does not use grouping or further quantitative cross-category weighting. Instead, each impact is discussed in isolation without reference to other impact categories before final conclusions and recommendations are made.

4.2 Statement of Relativity

Life Cycle Impact Assessment (LCIA) results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. No grouping of impact categories has been performed; all impacts are presented at the midpoint level. LCIA impacts presented in this report are based on midpoint characterization factors (e.g., kg CO_2e for GWP), and this study does not refer to the ultimate potential damage to human health and the environment or environmental benefits. For example, GWP and water consumption may have a negative or a positive environmental impact depending on the conditions in locations where emissions or resource consumption occur. Since this study does not present end-point results, it does not draw any conclusions about the relative impact (positive or negative) for the categories considered by the study.

4.3 Life Cycle Impact Assessment Results

The LCA for Experts software calculates life cycle impact assessment (LCIA) results by applying characterization factors from selected LCIA methodology to the life cycle inventory data.

For each impact category, the U.S. level result is the impacts per kg of cotton fiber at the U.S. scale and is generated as a weighted average of regional (Far West, Southwest, Midsouth, and Southeast) results. The following sections show results of the study for each LCIA category. The results of the model are presented per 1 kg of cotton fiber at the end of the ginning phase. Graphs are split into farm processes as described below:

- **Biogenic Carbon Dioxide (soil)**: Calculated on-farm biogenic carbon dioxide emissions from soil and crop residue.
- **Biogenic Carbon Dioxide (fiber):** Calculated biogenic carbon dioxide emissions including temporary storage from fiber.
- **Field emissions:** Impacts to air from volatilization of fertilizer and manure along with biodegradation of crop stem, leaves, and roots that release nitrogen into the atmosphere. Additionally, this includes impacts to groundwater and air from degradation of mineral and organic nitrogen and phosphorus in the soil, the impacts associated with planting (including cover crops), row cleaning, bedding, and fertilizer/pesticide application (e.g., tractor use).
- **Fertilizer production:** Embodied impacts of fertilizer production.
- **Ginning:** Impacts associated with the ginning process.
- **Pumping energy:** Impacts from operating irrigation pumps.
- **Harvest:** Impacts associated with the harvesting of the crop.
- **Pesticide production:** Impacts from pesticide production.
- **Tillage:** Impacts from fuel use for various tillage operations.
- **Micronutrients:** Embodied impacts of micronutrients (e.g., sulfur and/or boron) used or applied
- **Soil amendments:** Embodied impacts of soil amendments (e.g., lime and/or gypsum) used or applied.
- **Irrigation water:** Impacts associated with irrigation water.
- **Land occupation:** Impacts from the area of land from which the crop is grown. Also including upstream impacts.
- **Packaging:** Impacts associated with module packaging for cotton module at the farm.
- **Transportation to Gin:** Impacts associated with transportation from the farm to the gin.

The relative contribution of each in-field process to the total impact for each impact category for U.S. cotton fiber production is illustrated in Figure 6 and values listed in Table 17. The results represent U.S. averages per 1 kg of cotton fiber after ginning based on a production-weighted percentage of U.S. cotton fiber. Fertilizer Production is the main driver of impacts for primary energy demand (PED), acidification potential (AP), abiotic depletion (ADP), ozone depletion potential (ODP), smog formation (POCP) and human health particulate air (HHPA). Fertilizer field emissions are the main driver of impacts for global warming potential (GWP) and eutrophication potential (EP). Irrigation is the main driver of impacts in all the water categories – blue water consumption (BWC), blue water use (BWU), and water scarcity. Detailed discussion of each impact category is provided in the following sections.

TABLE 17: Contribution analysis, per kg of cotton fiber

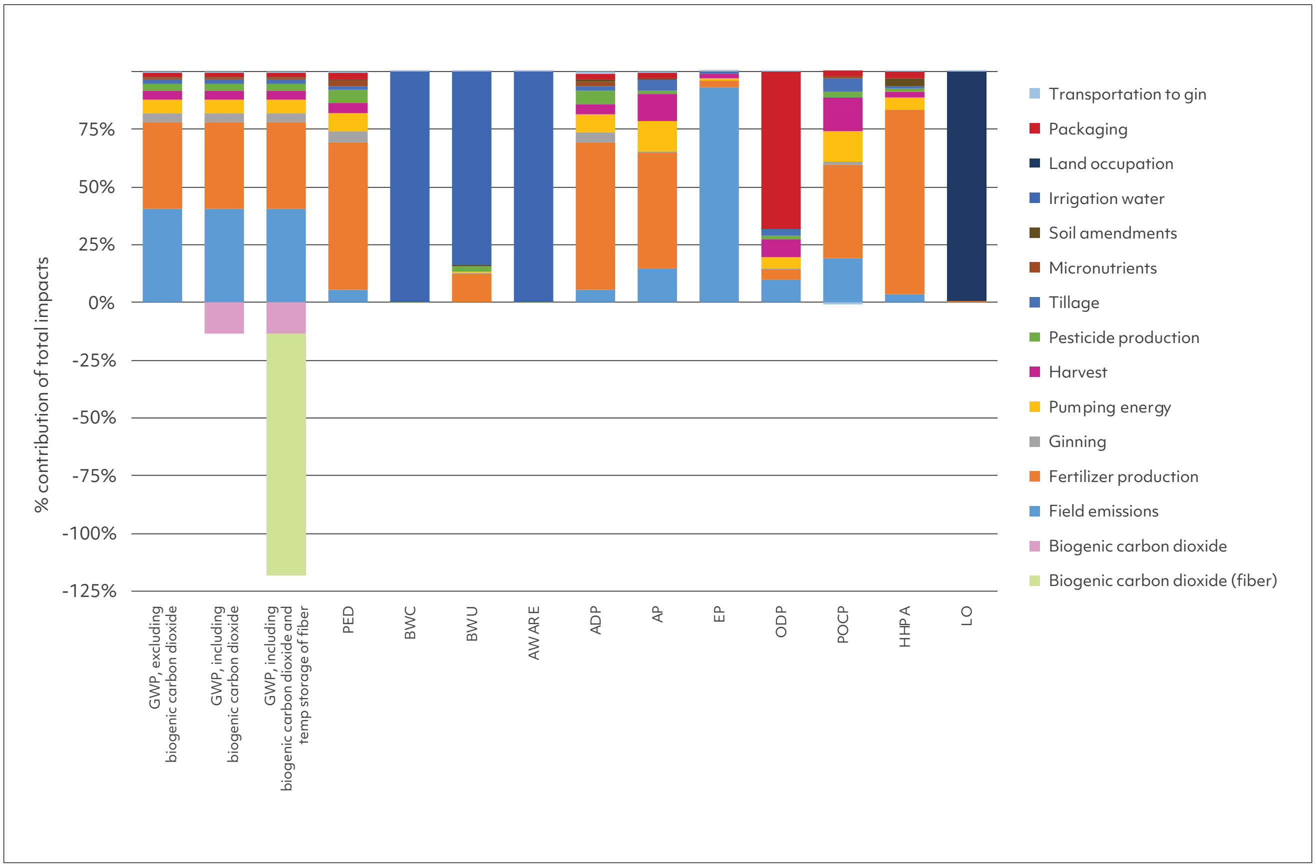
	Field emissions	Fertilizer production	Ginning	Pumping energy	Harvest	Pesticide production	Tillage	Micronutrients
GWP, excluding biogenic carbon dioxide (kg CO_2e)	5.88E-01	5.50E-01	5.23E-02	8.46E-02	5.50E-02	4.91E-02	2.22E-02	8.87E-03
GWP, including biogenic carbon dioxide (kg CO_2e)	5.88E-01	5.49E-01	5.23E-02	8.45E-02	5.50E-02	4.92E-02	2.22E-02	8.87E-03
GWP, including biogenic carbon dioxide and fiber temp storage (kg CO_2e)	5.88E-01	5.49E-01	5.23E-02	8.45E-02	5.50E-02	4.92E-02	2.22E-02	8.87E-03
PED (MJ)	9.76E-01	1.15E+01	8.38E-01	1.38E+00	7.60E-01	1.05E+00	3.06E-01	3.84E-01
BWC (L)	0.00E+00	3.96E+00	9.46E-02	9.42E-02	0.00E+00	3.83E-01	0.00E+00	1.08E-02
BWU (L)	0.00E+00	1.81E+02	8.09E+00	7.23E+00	0.00E+00	3.88E+01	0.00E+00	1.51E+00
AWARE (m^3 e)	0.00E+00	1.33E-01	3.23E-03	3.22E-03	0.00E+00	2.33E-03	0.00E+00	3.26E-04
ADP (MJ)	9.68E-01	1.07E+01	7.57E-01	1.30E+00	7.53E-01	1.01E+00	3.03E-01	3.79E-01
AP (kgSO_2e)	7.44E-04	2.48E-03	4.37E-05	6.43E-04	5.79E-04	9.01E-05	2.33E-04	9.69E-06
EP (kg PO_4^{3-}e)	6.77E-03	2.22E-04	8.41E-06	7.63E-05	1.27E-04	1.17E-05	5.10E-05	3.67E-06
ODP (kg R11e)	2.87E-12	1.16E-12	1.45E-13	1.41E-12	2.23E-12	3.37E-13	8.98E-13	7.14E-15
POCP (kg Ethene e)	7.42E-05	1.58E-04	5.61E-06	5.02E-05	5.77E-05	8.85E-06	2.32E-05	2.77E-06
HHPA (kg $PM_{2.5}$e)	1.70E-05	3.81E-04	2.09E-06	2.38E-05	1.32E-05	6.13E-06	5.32E-06	4.85E-07
LO ($m^2 \cdot$yr e)	0.00E+00	5.86E-02	2.21E-04	2.00E-04	0.00E+00	1.24E-03	0.00E+00	2.44E-05
Key	Highest impacts							Lowest Impacts

	Soil amendments	Irrigation water	Land occupation	Packaging	Transportation to ginning	Biogenic carbon dioxide (soil)	Biogenic carbon dioxide (fiber) *	Total†
GWP, excluding biogenic carbon dioxide (kg CO_2e)	7.58E-03	0.00E+00	0.00E+00	2.70E-02	8.93E-03	-	-	1.45E+00
GWP, including biogenic carbon dioxide (kg CO_2e)	7.58E-03	0.00E+00	0.00E+00	2.70E-02	8.94E-03	-1.94E-01	-	1.26E+00
GWP, including biogenic carbon dioxide and fiber temp storage (kg CO_2e)	7.58E-03	0.00E+00	0.00E+00	2.70E-02	8.94E-03	-1.94E-01	-1.52E+00	-2.64E-01
PED (MJ)	1.21E-01	0.00E+00	0.00E+00	4.93E-01	1.26E-01	-	-	1.79E+01
BWC (L)	2.21E-02	1.24E+03	0.00E+00	1.01E-01	1.72E-02	-	-	1.24E+03
BWU (L)	4.55E+00	1.24E+03	0.00E+00	2.23E+00	3.48E-01	-	-	1.48E+03
AWARE (m^3 e)	7.82E-04	4.20E+01	0.00E+00	3.40E-03	5.21E-04	-	-	4.21E+01
ADP (MJ)	1.08E-01	0.00E+00	0.00E+00	4.80E-01	1.25E-01	-	-	1.69E+01
AP (kgSO_2e)	9.37E-06	0.00E+00	0.00E+00	1.36E-04	1.36E-05	-	-	4.98E-03
EP (kg PO_4^{3-}e)	1.83E-06	0.00E+00	0.00E+00	7.73E-06	4.45E-06	-	-	7.28E-03
ODP (kg R11e)	2.06E-14	0.00E+00	0.00E+00	1.94E-11	1.29E-15	-	-	2.84E-11
POCP (kg Ethene e)	9.92E-07	0.00E+00	0.00E+00	1.12E-05	-3.98E-06	-	-	3.89E-04
HHPA (kg $PM_{2.5}$e)	1.61E-05	0.00E+00	0.00E+00	1.22E-05	8.84E-07	-	-	4.78E-04
LO (m^2·yr e)	9.06E-05	0.00E+00	9.49E+00	3.15E-05	3.36E-04	-	-	9.55E+00
Key	Highest impacts							Lowest Impacts

* Negative biogenic carbon emissions from fiber represent temporary carbon storage. Some or all of this carbon may be emitted to the atmosphere at subsequent life cycle stages (manufacturing, end-of-life, etc.).

† Due to rounding the total may be slightly different than the sum of the process contributions.

FIGURE 6: Contribution analysis for U.S. cotton fiber production

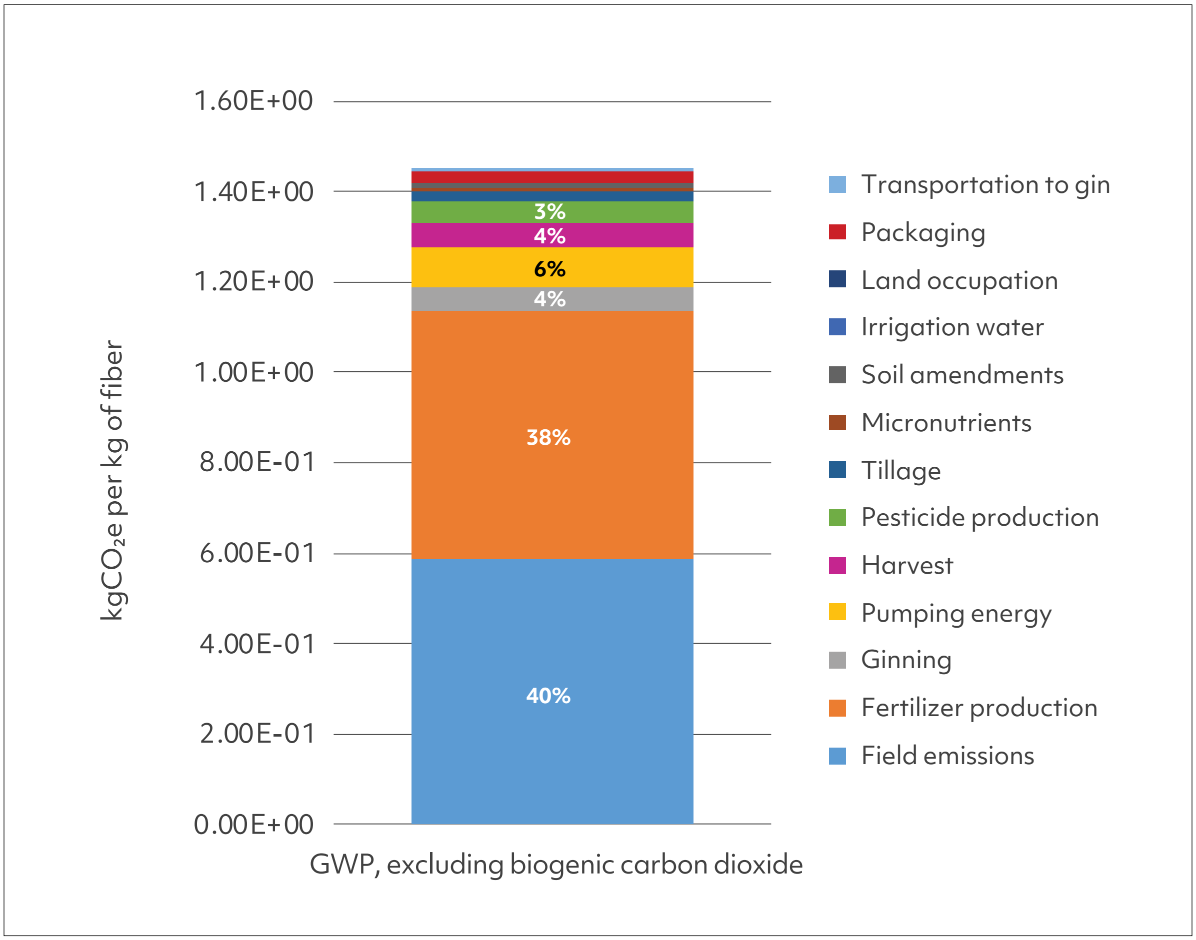


4.3.1 Global Warming Potential (Excluding Biogenic Carbon Dioxide)

The GWP, excluding biogenic carbon dioxide, per kg of cotton fiber is 1.45E+00 kg CO_2e. Field emissions (40%) are the largest drivers of impacts followed by the embodied impacts of fertilizer production (38%), as shown in Figure 7.

Direct and indirect nitrogen emissions to air from fertilizer application, as well as crop residue decomposition, lead to nitrous oxide (N_2O) emissions. N_2O has a global warming potential that is 265 times higher than carbon dioxide over a 100-year time horizon (Myhre, et al., 2013). From the calculated data, an average of 1 kg of direct and indirect N_2O is released per acre during cotton production across the four regions in the U.S. Embodied impacts from fertilizer production are also a key driver of impacts with a highlight on nitrogen fertilizer being a major contributor to GWP. Nitrogen fertilizer production uses an energy-intensive process, the Haber-Bosch method, which combines N_2 and H_2 (typically derived from natural gas) to make nitrogen fertilizer. This energy demand is supplied through fossil fuel use and electricity at manufacturing sites, with GHG emissions from the nitrogen fertilizer itself (Skowronska & Filipek, 2014; Gaidajis & Kakanis, 2021). Outside of cotton production field activities, ginning energy is the largest driver of impacts. Ginning is modeled using natural gas, LPG and electricity, which drives 4% of the GHG emissions per kg of fiber.

FIGURE 7: GWP, excluding biogenic carbon dioxide [kg CO_2 eq per kg of cotton fiber]



4.3.2 Global Warming Potential (Including Biogenic Carbon Dioxide)

The GWP, including biogenic carbon dioxide, per kg of cotton fiber is 1.26E+00 kg CO_2e as shown in Figure 8. The inclusion of biogenic carbon dioxide accounts for carbon dioxide uptake from the atmosphere by biomass (excluding the cotton fiber) during photosynthesis and release of that carbon as carbon dioxide throughout the product system. Biomass carbon emitted as methane or other greenhouse gases is accounted for here and in the GWP, excluding biogenic carbon dioxide, method. Biogenic carbon that is stored in soil due to changes in farming practices causes net negative GHG emissions from biogenic carbon dioxide flows, reducing the overall GWP of cotton products. About 0.19 kg of biogenic carbon dioxide per kg of cotton fiber is stored as soil organic carbon. The largest drivers of emissions are field emissions (40%) followed by the embodied emissions of fertilizer production (38%), like the impacts described in Section 4.2.1.

Apart from biogenic carbon in the cotton plant, which is shown in Figure 8 below, there may be sources of biogenic carbon in the upstream manufacturing of resources consumed during cotton production. In the case of diesel, the combustion dataset used assumes diesel is from a filling station. Biodiesel blends are available at some US filling stations (diesel dataset documentation indicates that the dataset has 95% coverage of all diesel production and supply and hence will include biodiesel blends) which include fuel from a biological source. Hence, these resource inputs include biogenic carbon (both biogenic methane and biogenic carbon dioxide), and the GWP of diesel inputs is different for GWP including biogenic carbon dioxide. Similarly, fertilizer, pesticide and micronutrient production can involve different sources of fuel, including biobased fuels which will involve biogenic methane and biogenic carbon dioxide which are accounted for in Sphera's Managed LCA Content databases.

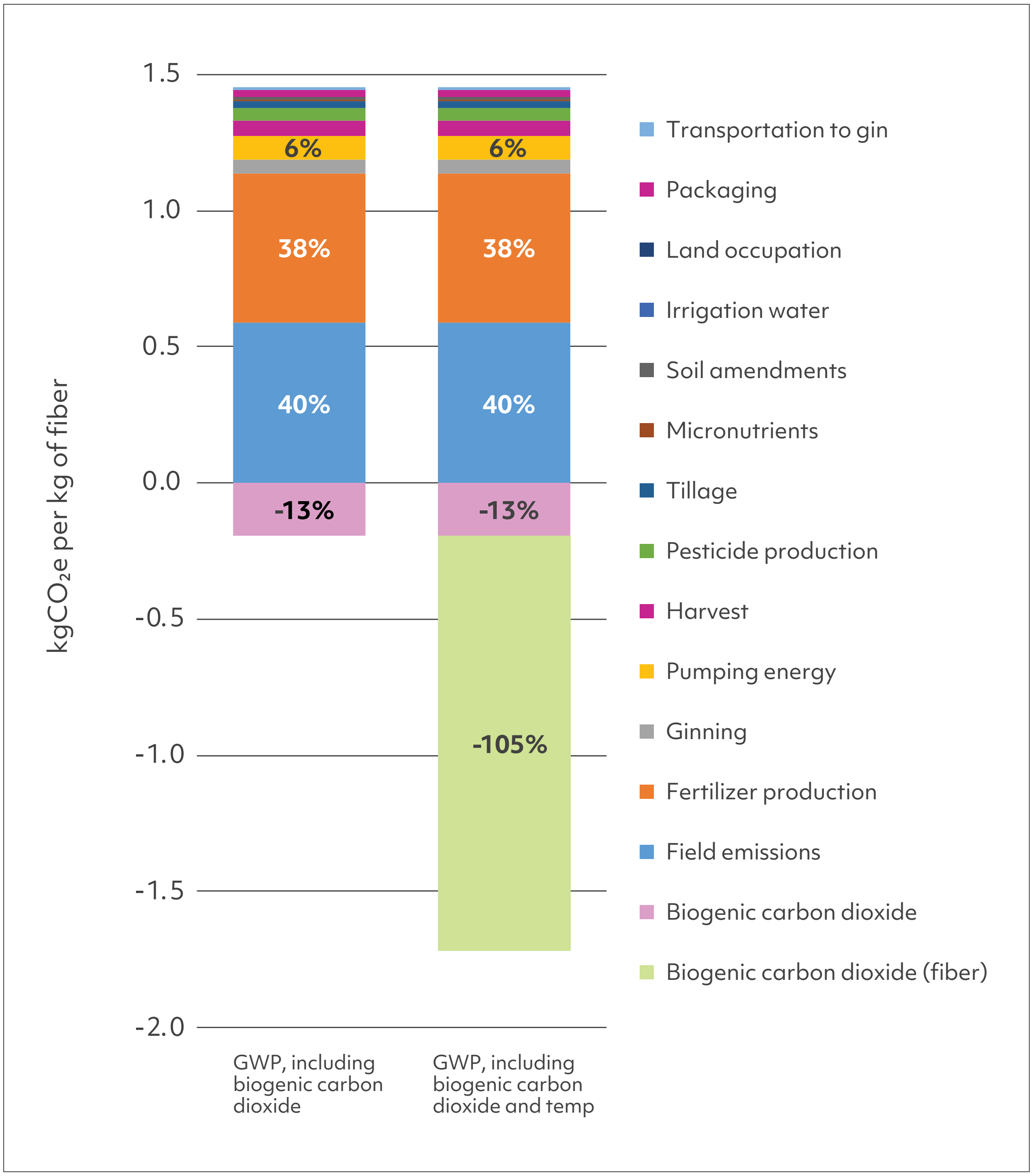
Biogenic carbon dioxide emissions can be negative, indicating removal of CO_2 from the atmosphere from biological processes. This occurs when more carbon is stored in plant material during photosynthesis than is emitted from decomposition of biomass. This study accounts for on-farm biogenic carbon flows in three ways:

1. Cotton crop biomass carbon stored in soil due changes in farming practices (i.e. reduced tillage).
2. Soil carbon storage from applied manure, when more carbon is applied than emitted as the manure decomposes.
3. Cotton crop biomass carbon is stored in harvested cotton fiber and products. This study models biogenic carbon in cotton fiber as stored up to the system boundary (the ginned bale), consistent with a cradle-to-gate scope (Figure 8). End-of-life processes are not included.

The biogenic carbon temporarily stored in cotton fiber remains contained within the ginned bale at the system boundary of this cradle-to-gate study. Because no product use or end-of-life processes for fiber occur within this boundary, no re-emissions of biogenic carbon from fiber are modeled. Therefore, the results represent temporary biogenic carbon storage with no modeled release. There is an increasing body of evidence suggesting the value of temporary biogenic carbon storage and its benefits to reducing radiative forcing (Pires, et al., 2024) (Daystar, et al., 2017) (Levasseur, et al., 2010).

Studies that model downstream product lifetimes and end-of-life pathways, such as Pires et al. (2024), show that temporary storage reduces cumulative radiative forcing by 22% at 10 years, 11% at 30 years, and 2% at 100 years relative to static LCA modeling approaches. These temporal effects arise from product lifespan and end-of-life fate, which are outside the cradle-to-gate scope of this assessment. For context, the contribution of biogenic carbon storage to the carbon footprint is reported here, though downstream emissions would depend on broader system boundaries and product use characteristics.

FIGURE 8: GWP, including biogenic carbon dioxide, including and excluding temporary storage of fiber [kg CO_2eq per kg of cotton fiber]

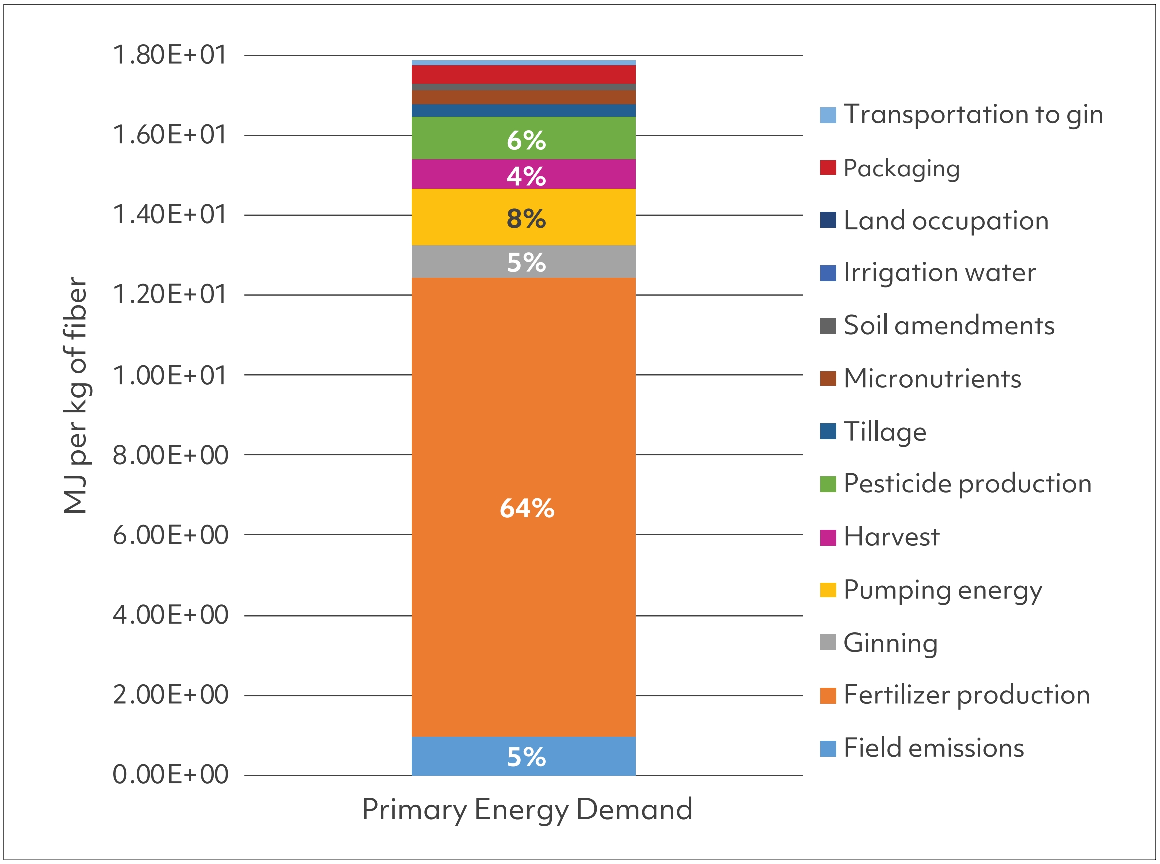


4.3.3 Primary Energy Demand (PED)

The PED for 1 kg of cotton fiber is 1.79E+01 MJ. The largest contributor to primary energy demand is embodied energy in fertilizer production (64%), as shown Figure 9. Nitrogen fertilizer production is energy intensive and consumes fossil energy during the production of ammonia and other nitrogen-based fertilizers (Skowronska & Filipek, 2014).

The primary method for producing ammonia is the Haber-Bosch process, which combines nitrogen from the air with hydrogen derived from natural gas (methane) under high pressure and temperature. This process requires significant amounts of energy, primarily from natural gas (IEA, 2024). Beyond the feedstock, additional energy is required to maintain the high temperatures and pressures needed for the Haber-Bosch process. This energy typically comes from burning fossil fuels, such as natural gas or coal. Efforts are being made to develop more sustainable methods, such as green ammonia production, which uses renewable energy sources to produce hydrogen through electrolysis (IEA, 2024). However, these technologies are still in the early stages of development and remain cost prohibitive, which limits their widespread adoption.

FIGURE 9: Primary Energy Demand from non-renewable resources (net caloric value) [MJ per kg of cotton fiber]

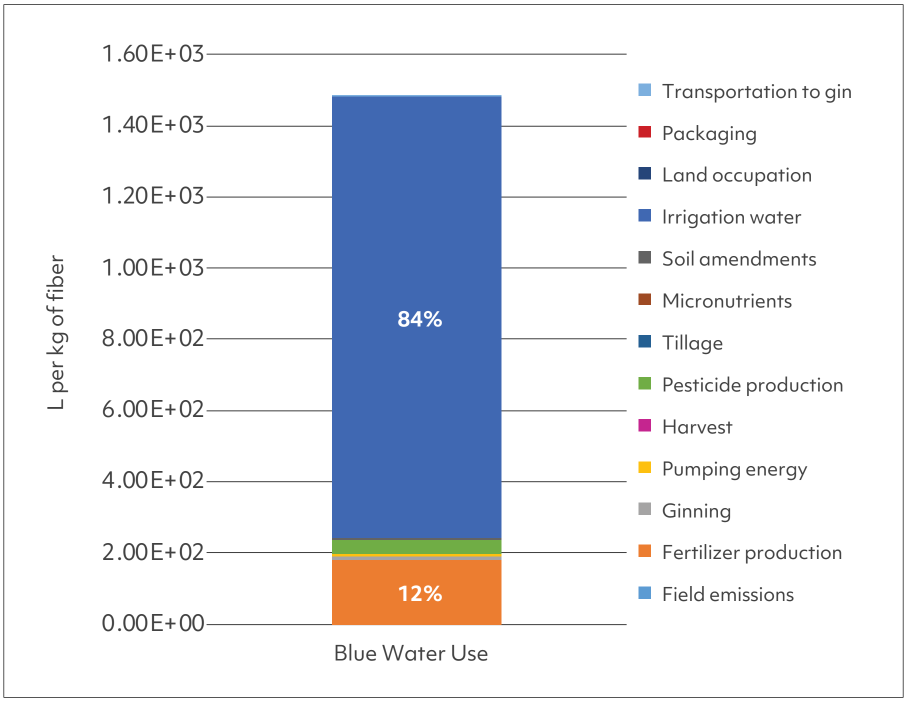


4.3.4 Blue Water Use (BWU)

BWU is 1.48E+03 L of water per kg of fiber (Figure 10). BWU is higher than BWC because BWU represents the total water withdrawn from the ecosystem. This does not account for any water returned to the ecosystem. The top two contributors to BWU are irrigation (84%) and fertilizer production (12%).

Irrigation's BWU impacts are from the withdrawals of water from the ground. Fertilizer's BWU is mostly from energy production and is used in nitrogen fertilizer production that often requires significant amount of cooling water. Water is a critical input used in nitrogen fertilizer manufacturing. Process water used to produce ammonia and urea as well as utility water used for cooling, cleaning, etc. drives the BWU impacts of nitrogen fertilizer's contribution to total BWU (Fiamelda, et al., 2020).

FIGURE 10: Blue Water Use [L per kg of cotton fiber]



4.3.5 Blue Water Consumption (BWC)

Water consumption refers to a quantity of water taken from a source that is not returned to the source. Blue Water Consumption is the removal of freshwater resources from surface and groundwater bodies (not including rain onto fields) without returning that water to the same watershed. The BWC of 1 kg of fiber is 1.24E+03 L, almost all of which is concentrated in the cotton production stage (Figure 11: Blue Water Consumption [L per kg of cotton fiber]). The water that is consumed is evaporated or incorporated into a product, in this case, seed cotton and the cotton plant. BWC also includes water abstracted from surface or groundwater which is returned to another watershed or the ocean (Hoekstra, et al., 2011). In summary, while water use or water withdrawal measures the total amount of water taken from any source, water consumption measures the net amount of water that is taken, i.e., not returned to the source.

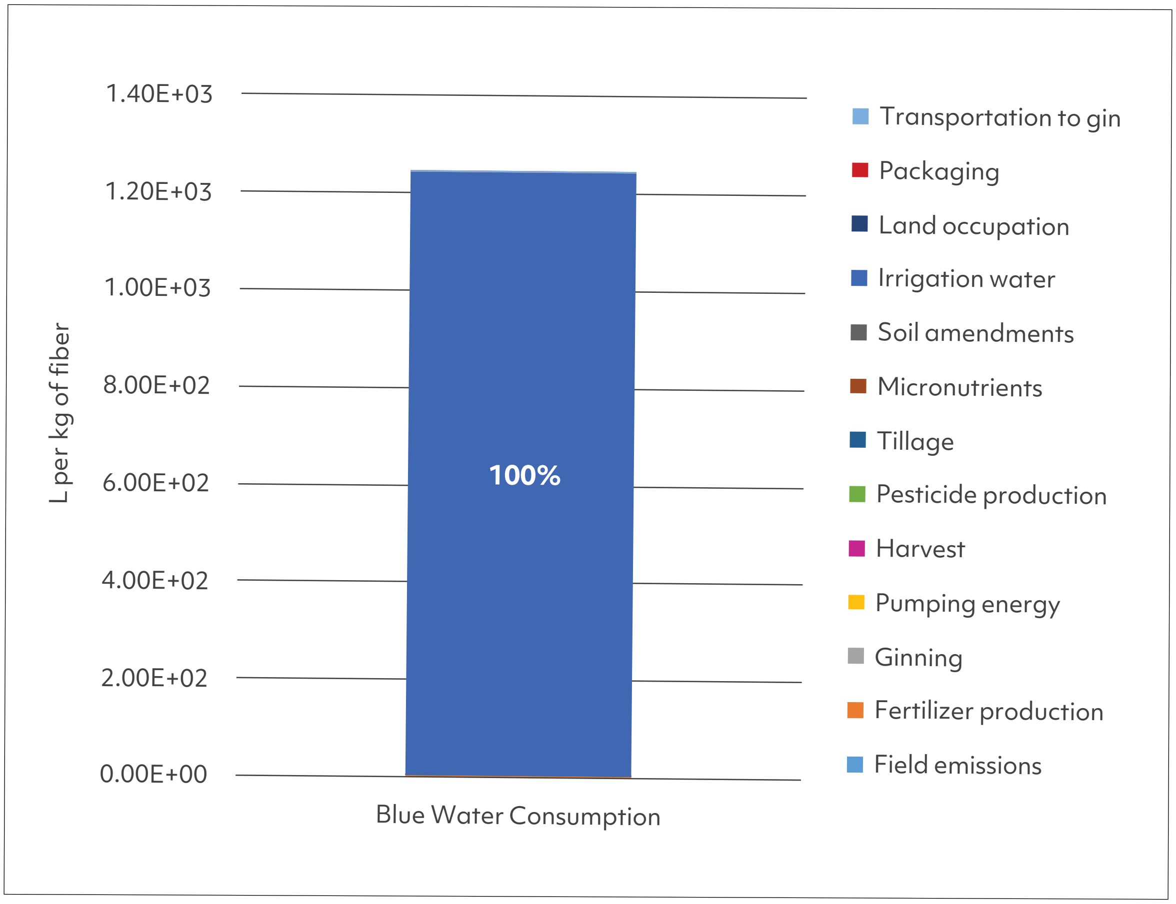
The BWC for cotton fiber is all from the irrigation water that is applied to the field. Most of this water is groundwater. Eleven inches of irrigation water per acre of cotton is needed on average (2023 Cotton Growers' NRS). There are water consumption impacts from all other stages including ginning, but that is not obvious from Figure 11: Blue Water Consumption [L per kg of cotton fiber]. This is because the contributions from all other parts of this model are less than 0.5%.

While 64% of cotton in the U.S. is grown without irrigation (Cotton Incorporated, 2025), irrigation water is still the driver of BWC results.

Citation: Cotton Incorporated (2025). Cotton & Water Production. https://cottontoday.cottoninc.com/wp-content/uploads/2026/01/Cotton-Incorporated-Water-Factsheet.pdf

Cotton water demand can be up to 0.28 inches per day during the mid-season, and, in general, irrigation results in higher yields. Studies have shown that irrigated cotton fields can produce significantly higher yields compared to non-irrigated fields. For example, in the Southeastern U.S., irrigation has been shown to nearly double cotton yields in water-limited years (Barnes & Perry, 2017). When yields increase, other impact categories, such as land use, often improve as well. This is because these impact categories are normalized by the functional unit of one kilogram of fiber. Additionally, higher yields can lead to more efficient resource use and reduced environmental footprint per unit of production.

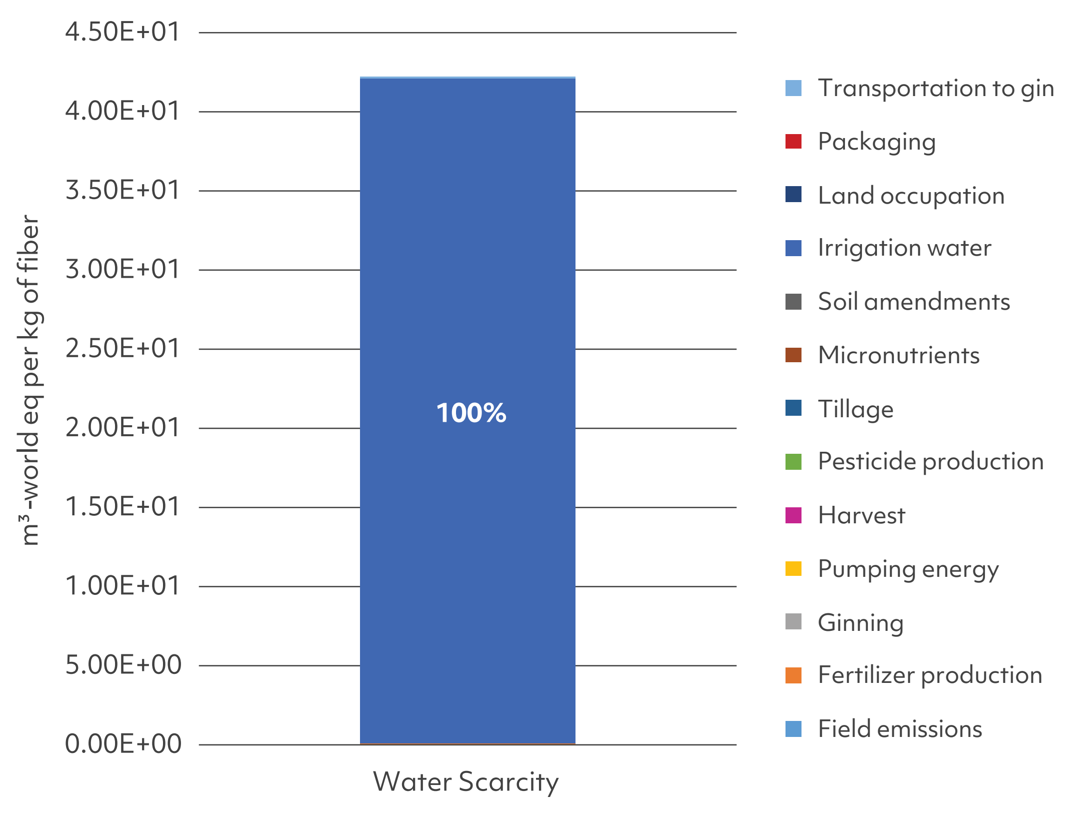
FIGURE 11: Blue Water Consumption [L per kg of cotton fiber]



4.3.6 Water Scarcity (Available Water Remaining)

The water scarcity impact of producing 1 kg of cotton fiber is estimated to be 4.21E+01 m^3-world eq., a measure representing the equivalent volume of water impacted by scarcity in global terms, with nearly 100% of these impacts occurring during the cotton production stage due to irrigation water withdrawn from groundwater aquifers (Figure 12: Water Scarcity (AWARE) [m^3 world equivalent per kg of cotton fiber]). Insights from the 2023 Cotton Growers' NRS highlight ongoing improvements in water management practices among U.S. cotton growers, which play a key role in mitigating these impacts by more efficiently utilizing groundwater resources and improving overall water conservation. For example, growers in the 2023 survey show their adoption of water monitoring technologies have been steadily increasing, with the use of flow meters and irrigation scheduling tools rising from 38% and 34% in 2015 to 52% for both practices in 2023, and soil moisture monitoring increasing from 21% to 44% in the same period (Bayramova, et al., 2024). These advancements demonstrate a clear commitment to improving water use efficiency and addressing water scarcity impacts in cotton production, providing a solid foundation for continued progress.

FIGURE 12: Water Scarcity (AWARE) [m^3 world equivalent per kg of cotton fiber]

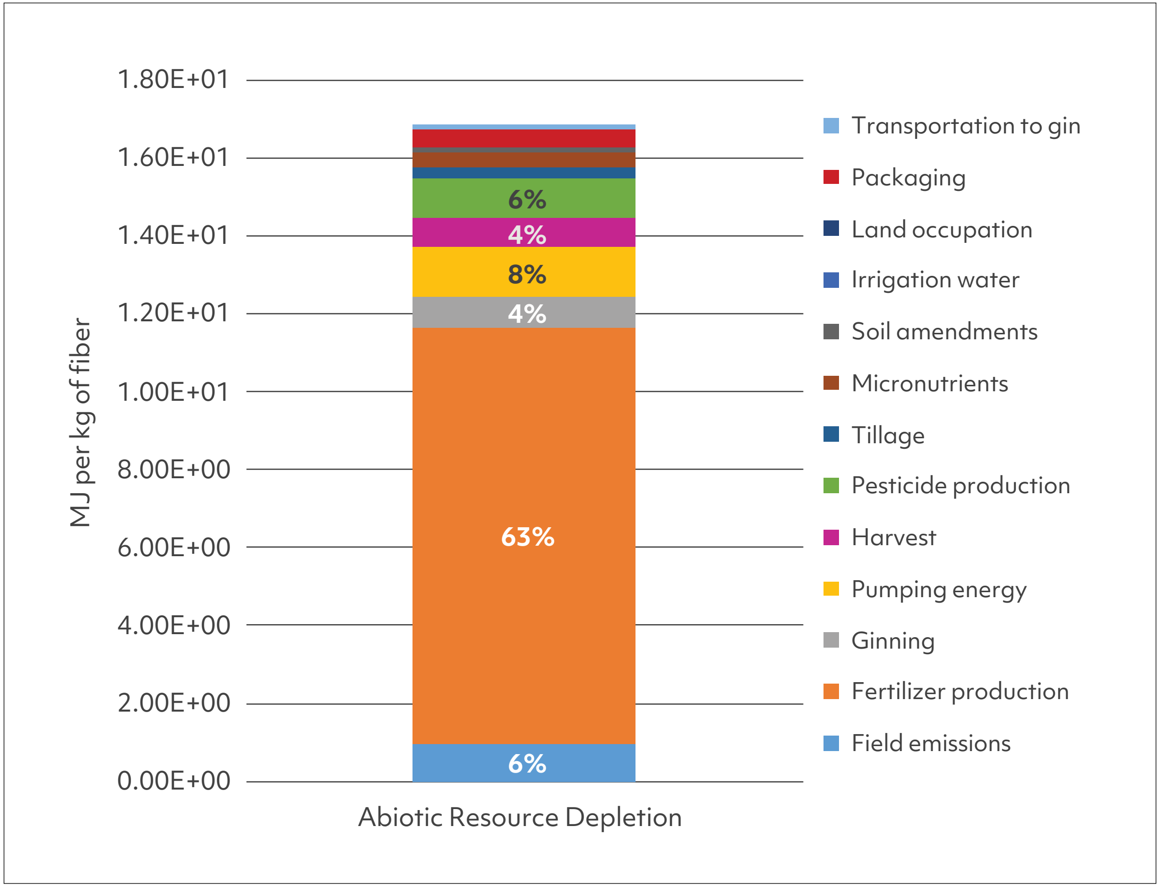


4.3.7 Abiotic Depletion Potential (ADP fossil)

The abiotic depletion potential for the weighted average of cotton production in all regions is 1.69E+01 MJ per kg of cotton fiber, with 63% of the ADP impacts driven by fertilizer production and 8% from pumping energy (Figure 13: Abiotic Resource Depletion [MJ per kg of cotton fiber]). Resources that are naturally scarce or have limited reserves tend to have a higher ADP. This is because their depletion has a more significant impact on future availability.

Electricity and fossil fuels such as natural gas and diesel are used for pumping irrigation water and electricity, natural gas and LPG are used in ginning. Across all the regional e-Grids, natural gas and hard coal drive more than 60% of the electricity production. These fossil-based electricity production technologies deplete existing reserves of fossil fuel, which adds to ADP fossil impacts. The production of nitrogen fertilizers, particularly ammonia, is highly energy-intensive and relies heavily on fossil fuels (Skowronska & Filipek, 2014).

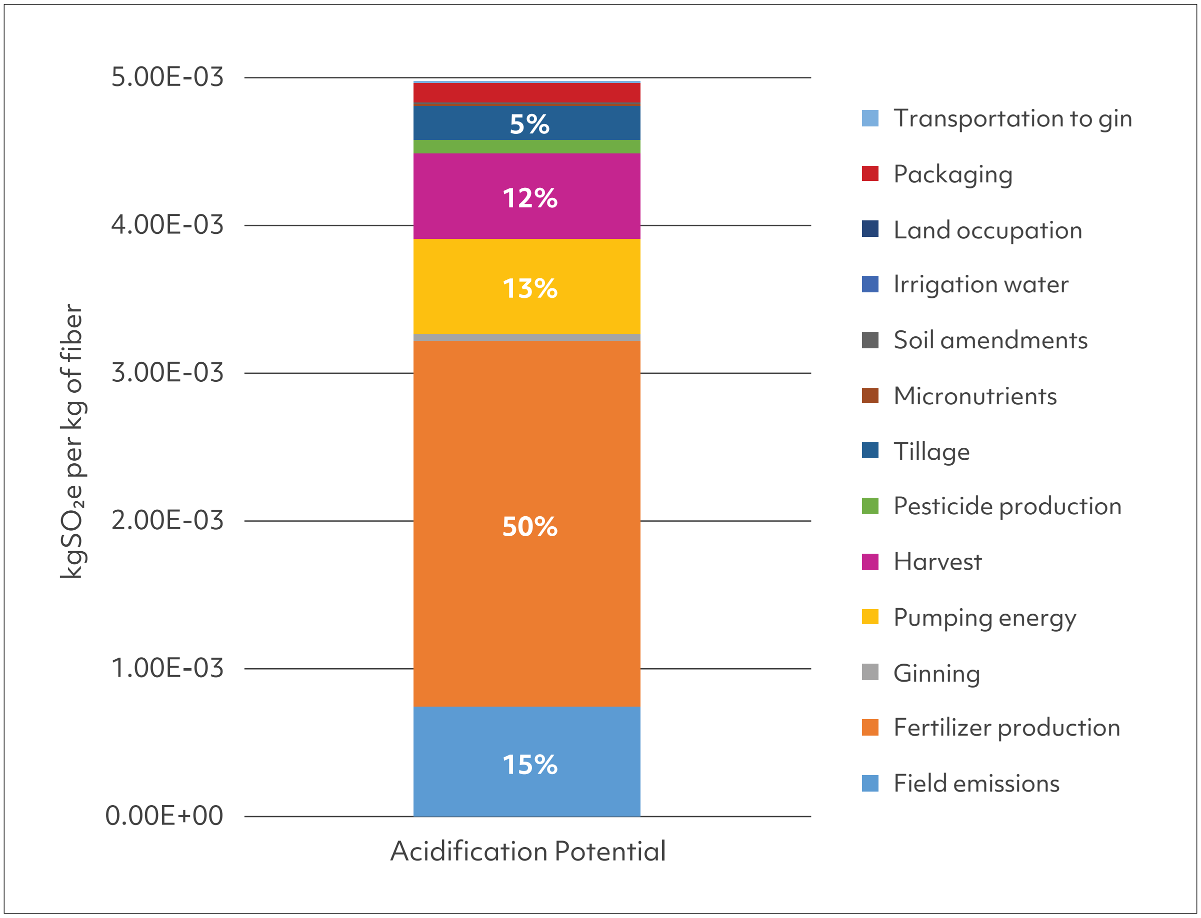
FIGURE 13: Abiotic Resource Depletion [MJ per kg of cotton fiber]



4.3.8 Acidification potential (AP)

The AP impact of 1 kg of cotton fiber is 4.98E-03 kg SO_2e, with fertilizer production emissions (50%) as the largest contributor followed by field emissions (15%), pumping energy (13%) and harvest (12%) as shown in Figure 14. Field emissions are driven by volatile emissions from fertilizer application, particularly nitrogen, which has higher AP due to the release of acidic and corrosive gases during the production, consumption and combustion of natural gas used for fertilizer production. Nitrogen fertilizer production, like ammonia, consumes high amounts of natural gas as raw material for the production anhydrous ammonia (Gaidajis & Kakanis, 2021). Natural gas production releases sulfur dioxide (Smith, et al., 2001). Natural gas and electricity are also consumed to meet the high energy demand of the production process. Combustion of fossil fuels also releases sulfur oxides (Smith, et al., 2001), which contribute to acidification potential. Diesel fuel combustion for fertilizer applications, field operations, tillage and harvest as well as fossil fuel combustion for pumping irrigation water are other drivers of acidification potential. Combustion of fossil fuel releases oxides of sulfur and nitrogen which have high propensity to form acidic compounds once released into the atmosphere.

FIGURE 14: Acidification Potential impacts [kgSO_2e per kg of cotton fiber]



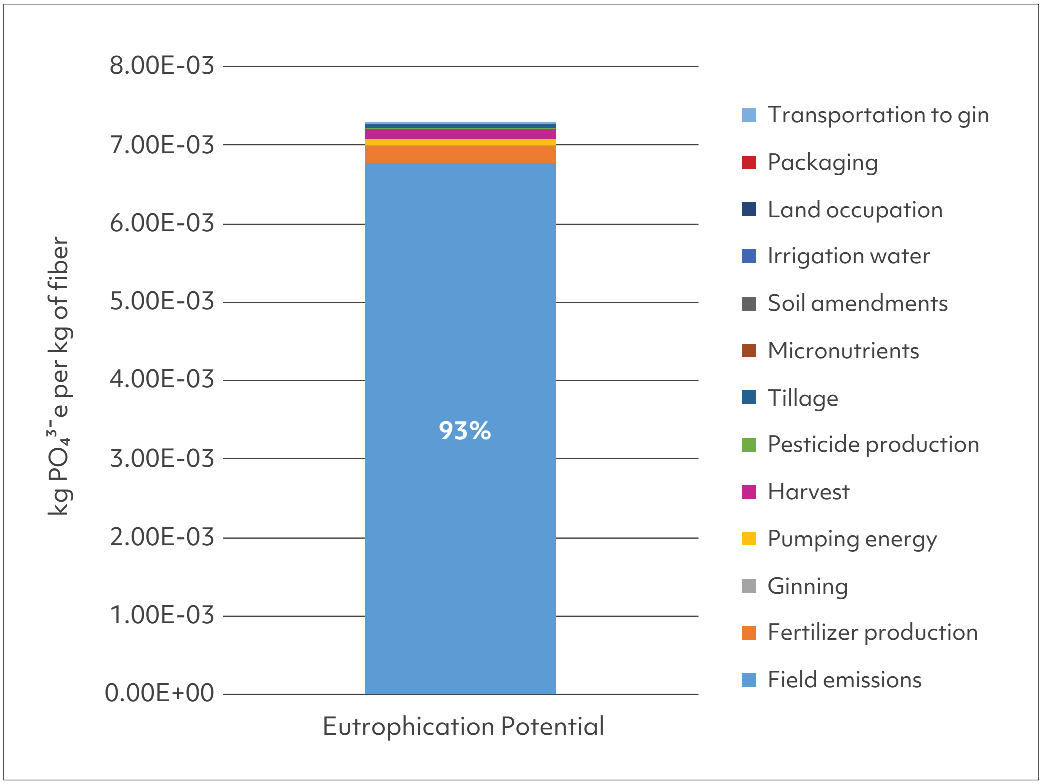
4.3.9 Eutrophication Potential (EP)

The EP of 1 kg of cotton fiber is 7.28E-03 kg PO_4^{3-}e, with 93% of the impact coming from field emissions (Figure 15: Eutrophication Potential [kg PO₄3-e per kg of cotton fiber]). Run-off drives the eutrophication impacts. Fertilizers are nutrient rich, and when applied to a field they may run off during rainfall or irrigation events, impacting freshwater ecosystems.

Exact run-off levels of nitrogen and phosphorus were not modeled for each state or region. Based on literature data, a conservative run-off rate of 3.7% and 9.3% per kg of nitrogen and phosphorus fertilizer applied were used, respectively (Daniels, et al., 2019). Hence the run-off rate is dependent on the quantity of fertilizer applied in this study. Manure, typically applied to meet nitrogen demand of the crop, is another source of run-off and eutrophication.

Eutrophication impacts from manure run-off were currently modeled as indirect nitrogen leaching using leaching factors from IPCC. Manure application was not a common practice, and the average application per acre over all producers was small. When looked at through a U.S. average, manure application was less than 1 lb/acre of cotton produced. In comparison, nitrogen applications were 100 pounds per acre on average at the national level. Since the manure application rate was <1%, the run-off from manure was excluded in this study. However, it is important to note that manure run-off can also contribute significantly to EP impacts, as manure is typically applied to meet crop nitrogen requirements, which may result in excess phosphorus (P) and potassium (K) being introduced into the freshwater ecosystems. These excess nutrients, along with others present in manure, have the potential to exacerbate eutrophication in nearby water bodies. If manure application becomes widespread in conventional cotton production or if analyzing other cotton production systems where it is more widely used, these impacts should be included in the analysis.

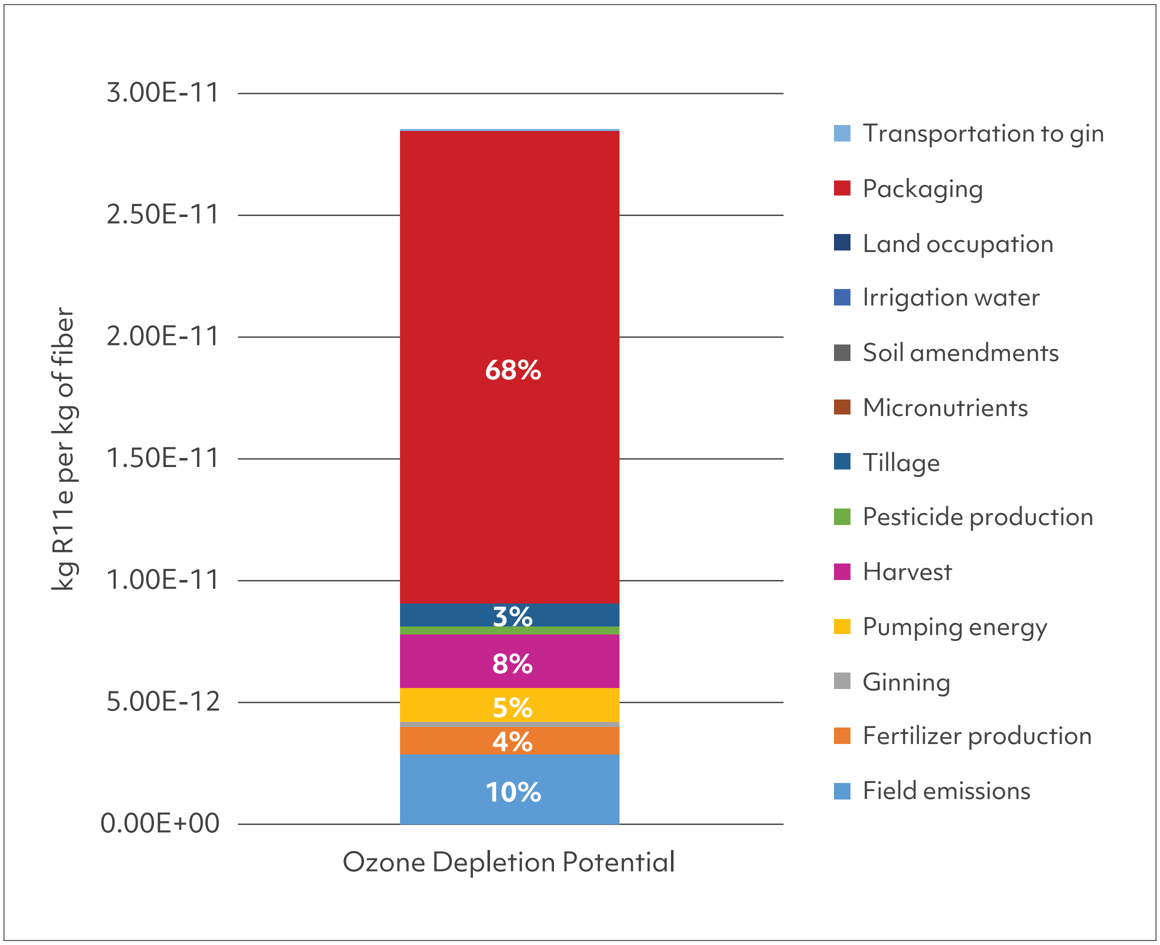
FIGURE 15: Eutrophication Potential [kg PO_4^{3-}e per kg of cotton fiber]



4.3.10 Ozone Depletion Potential (ODP)

The ODP of 1 kg of cotton fiber is 2.84E-11 kg R11e, a very low value that is not a significant environmental impact and does not contribute significantly to the environmental impacts of cotton production. The largest impact of ODP is from packaging (68%) followed by the fossil fuel use from field emissions, harvest operations, pumping energy, fertilizer production, and tillage accounting for a total of 30% of the ODP impacts (Figure 16: Ozone Depletion Potential [kg R11 eq. per kg of cotton fiber]). Combustion of fossil fuels emits N_2O and non-methane volatile organic compounds (Gillenwater, 2005), which are gases that have some ozone depleting effects.

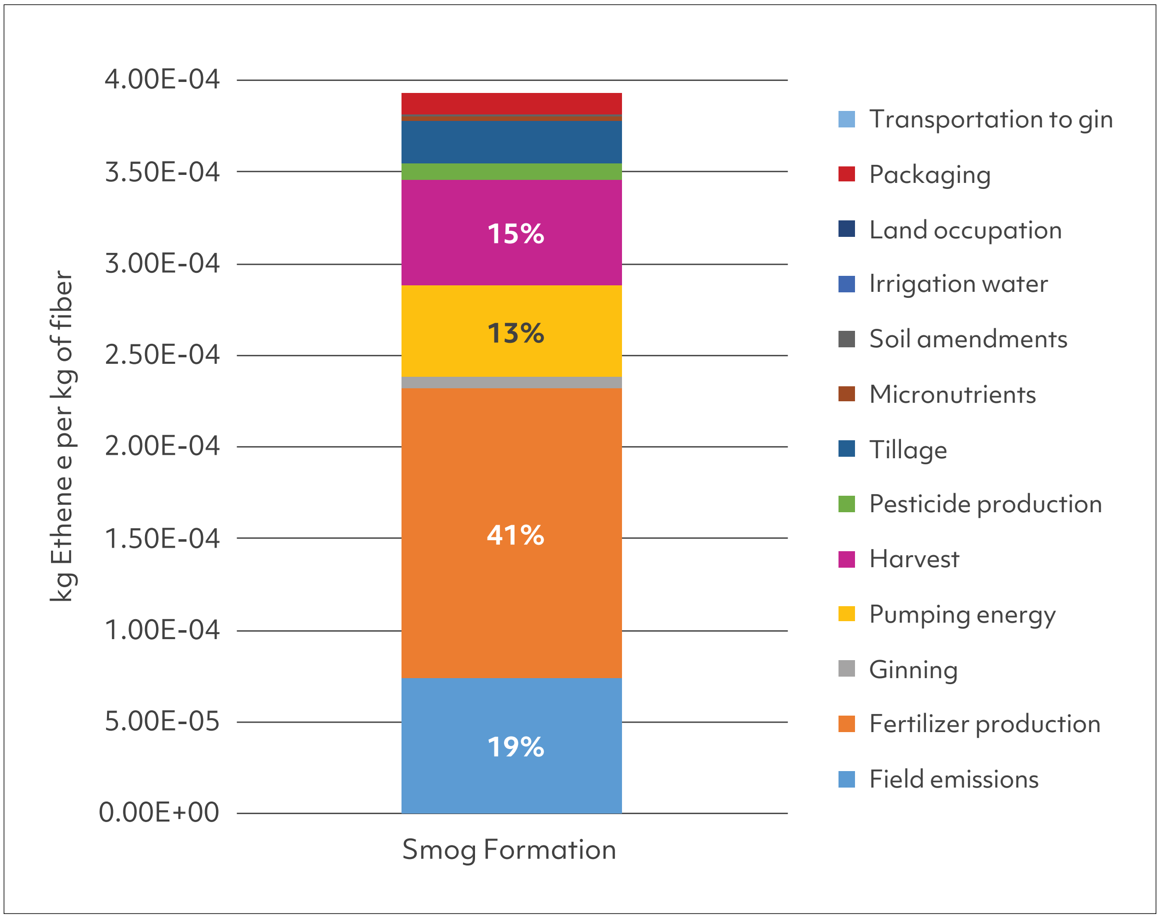
FIGURE 16: Ozone Depletion Potential [kg R11 eq. per kg of cotton fiber]



4.3.11 Smog Formation (POCP)

The smog formation impacts for 1 kg of cotton fiber is 3.89E-04 kg ethene equivalent. Smog formation is driven by fossil fuel use and combustion for field activities, harvest operations, pumping energy and fertilizer production accounting for 96% of the impacts with fertilizer production (41%) contributing the largest impact followed by field emissions (19%) shown in Figure 17: Smog Formation (POCP) [kg Ethene eq. per kg of cotton fiber]. When fossil fuels like diesel and natural gas are combusted, they release oxides of nitrogen that react with sunlight to form smog. The embodied impact of fertilizer is the second largest driver of POCP impacts. The nitrogen fertilizer production process involves combustion of fossil fuels which releases volatile organic compounds that contribute to smog formation (Hasler, et al., 2015; Laveglia, et al., 2022).

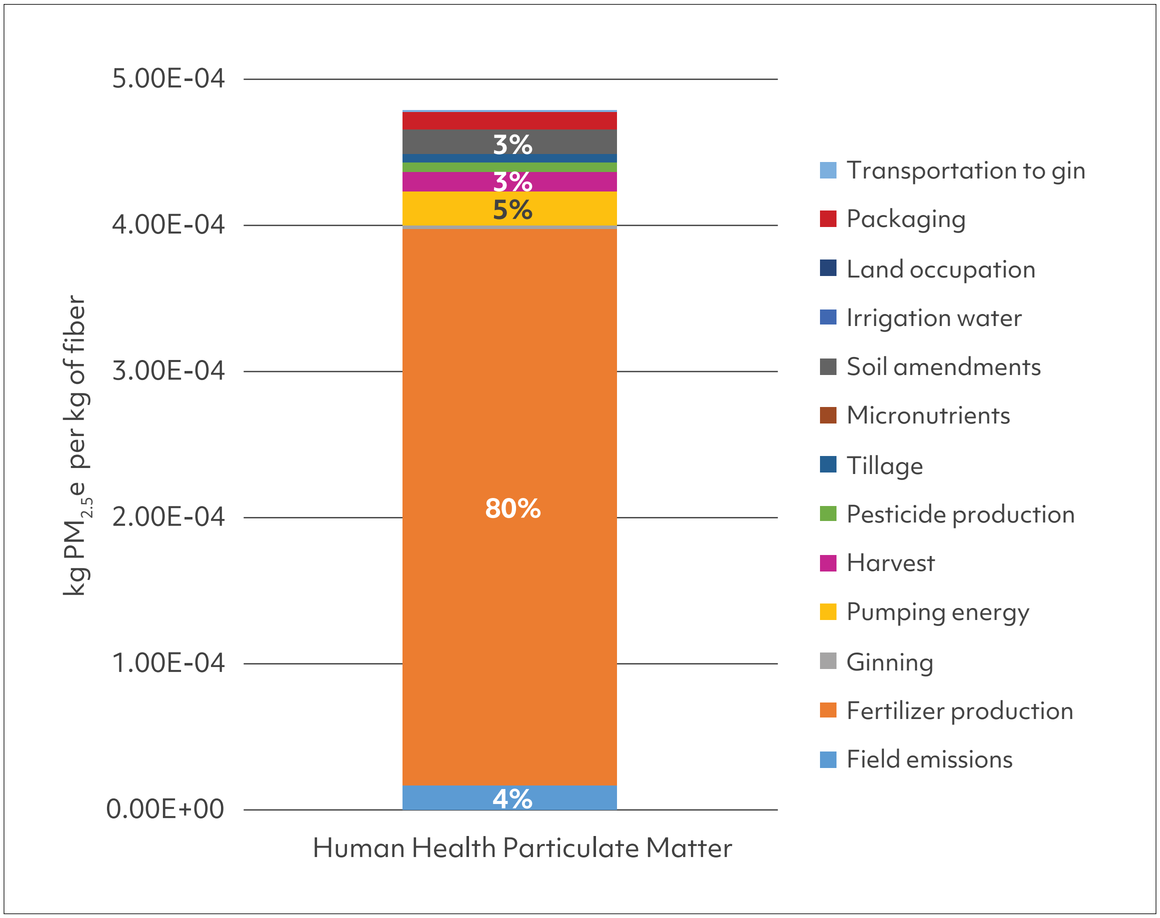
FIGURE 17: Smog Formation (POCP) [kg Ethene eq. per kg of cotton fiber]



4.3.12 Human Health Particulate Air (HHPA)

The production of 1kg of cotton fiber results in 4.78E-04 kg $PM_{2.5}$e emissions (particulate matter). Fertilizer production (80%) is the top driver of HHPA impacts (Figure 18: Human Health Particulate Air [kg $PM_{2.5}$ eq. per kg of cotton fiber]). The production of fertilizers releases particulate matter as part of the production process through the burning of fossil fuels to produce anhydrous nitrogen for nitrogen fertilizers. Burning fossil fuels contributes to the formation of particulate matter (PM) through several mechanisms like incomplete combustion, emission of pollutants, volatile organic compounds and ash/residue.

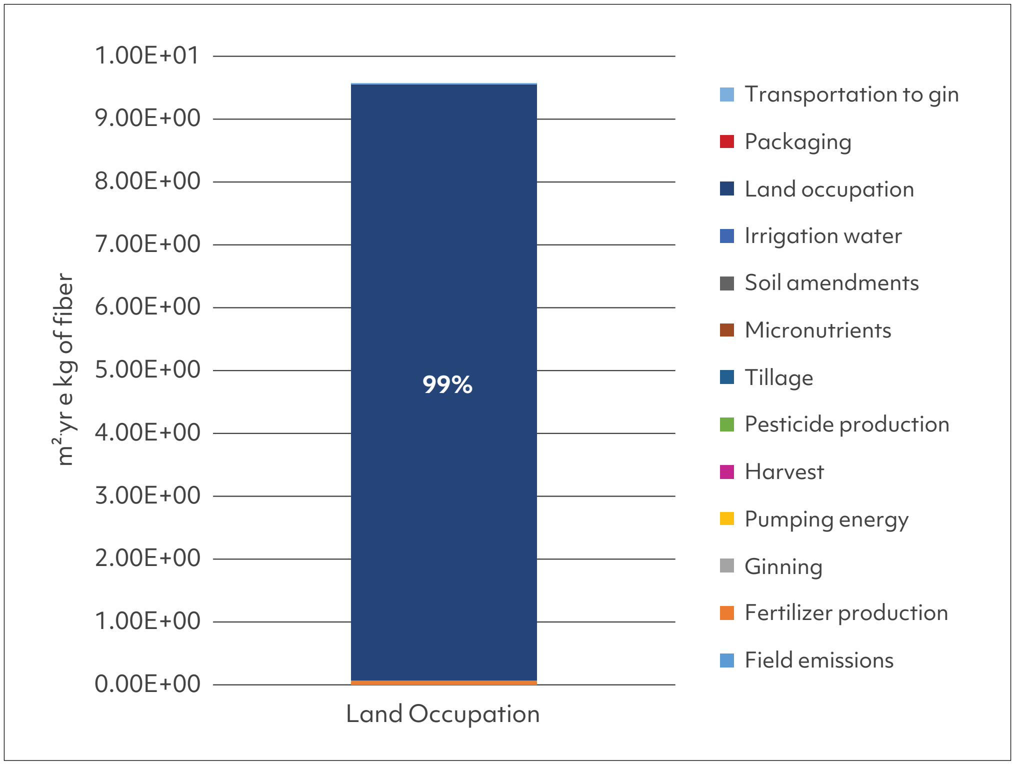
FIGURE 18: Human Health Particulate Air [kg $PM_{2.5}$ eq. per kg of cotton fiber]



4.3.13 *Land Occupation (LO)*

The land occupation impact associated with producing 1 kg of cotton fiber is 9.55E+00 square meter-years ($m^2 \cdot yr$). This represents the use of 9.5 m^2 of land over one year for cotton cultivation, including the land needed to grow the crop and support all upstream agricultural processes. Nearly all land occupation impacts (99%), stem from the field area used for cotton production itself, with negligible contributions from land used in upstream resource or energy supply chains (Figure 19: Land Occupation [m^2.yr eq per kg of cotton fiber]).

Figure 19: Land Occupation [$m^2 \cdot$yr eq per kg of cotton fiber]



4.3.14 *Toxicity Metrics*

Toxicity metrics were generated using USEtox® version 2.13. USEtox is a scientific consensus model, endorsed by the United Nations Environmental Program's (UNEP) Life Cycle Initiative, for assessing the human and ecological impacts of chemicals. Its primary output is a comprehensive database of characterization factors, which include parameters for fate, exposure, and effects (USEtox, 2024).

Human toxicity, both cancerous and non-cancerous, is reported as cases per kg of contaminant emitted. Ecotoxicity impacts, specifically freshwater aquatic ecotoxicity, are calculated as the potentially affected fraction (PAF) of aquatic species integrated over the exposed water volume and time. The impact scores for these toxicity impacts are quantified as the product of the characterization factor and the quantity of substance released.
The characterization factor is the potential toxicity impacts of a substance released to a compartment for human toxicity impacts and for ecotoxicity impacts at midpoint level. Characterization factors are calculated as a product of the fate factor, the exposure factor

and the effect factor. These factors are derived from two major aspects, one related to the environmental fate and behavior of chemicals and the other related to human and ecological effects. The fate factor evaluates the dispersion of emitted contaminants across various environments, including indoor air, urban air, agricultural soil, natural soil, freshwater, coastal marine water, and oceans. The exposure factor component converts these environmental media concentrations into estimates of freshwater ecosystem and human exposure and intake. The effect factor component translates human intake into hypothetical cases of cancer or non-cancer and converts ecosystem exposure concentrations into a measure of the potentially affected fraction of exposed species. These factors are evaluated at two spatial scales – continental and global. These scales operate across nine environmental compartments – household and occupational indoor air, urban air, rural air, agricultural soil, natural soil, freshwater and coastal marine water, and crop residues. Each chemical may interact differently with the medium in each compartment. These differences are captured by fate, exposure, and effect factors for each compartment and aggregated across both spatial scales. Characterization factors are then calculated as a product of the fate factor, the exposure factor and the effect factor are then developed based on the compartments of interest for each chemical (Fantke, et al., 2018) (USEtox v2.0 Documentation).

The typical LCA emission factors used to estimate the fate of a chemical, particularly organic pesticides, at the time of application do not account for the numerous factors that impact a compound's final resting place at the time of application, such as humidity, wind speed, percent plant and weed cover, or type of application equipment used. There is further uncertainty in the factors used to predict the fate and transport of the compound once it comes to rest. In the previous LCA in 2017 (Cotton Incorporated, 2017), comparisons were made using a typical LCA default emissions scenario of 1% emissions to air and 99% emissions to agricultural soil (which was similar to the first cotton LCA in 2010) and a specific emissions scenario for each organic chemical which was developed using agricultural models to address some of these agricultural, weather and geographic factors mentioned. The results from this analysis demonstrated that none of the organic pesticides had emissions to soil, except as a part of erosion to nearby water systems. Instead of the previous assumption of 1% to air/99% to soil, in this LCA, the emissions used were 9% to air and 1% to freshwater, based on the learnings from the specific emissions modeling and which partially aligns with the Cascale Cotton methodology (Cascale, 2024). Soil emissions are not included as it was previously shown in the 2016 LCA that soil emissions are negligible off the farm.

The precision of these characterization factors is within a factor of 100 to 1000 for human health and 10 to 100 for freshwater ecotoxicity. For example, if the toxicity impact of a chemical is 0.1, then the error puts the toxicity impact between the range 0.0001 and 100. In the case of human health factors, the variability depends on how chemicals end up in a compartment and the effect the chemical has on humans from that specific compartment. Some chemicals can cause more severe human health effects if they are inhaled versus being ingested. This variability in chemical exposure pathways from the environment to the human causes characterization factors to vary by four orders of magnitude. In the case of freshwater ecotoxicity, the pathways are more limited and hence the variability is lower, and the models show a variability of three orders of magnitude (Rosenbaum, et al., 2008).

Characterization factors (CFs) for many chemicals are available, but there were some chemicals for which custom characterization factors had to be developed. Based on USDA NASS data and the data from the California Department of Pesticide Regulation, a list of 133 chemicals that were being used across different regions were identified. Characterization factors were developed for 24 of these chemicals[8] using inputs such as molecular weight, vapor pressure, solubility, degradation rates, and adsorption coefficients (National Center for Biotechnology Information, 2023; University of Hertfordshire, 2025; USEPA, 2024) The CFs for these organic pesticides are given in Appendix B: Custom Characterization Factors for USEtox Chemicals.

There are no results given for heavy metals since the characterization factors associated with heavy metals are highly uncertain and termed "interim" and the impacts are more associated with upstream processes that the cotton grower cannot influence. Further, some inorganic substances cannot be modeled in the current version of USEtox and other dissociating substances also have "interim" CFs due to inadequate data or model uncertainty, therefore toxicity impacts for inorganic fertilizers or other chemicals were not calculated.

Additional details are provided separately to the critical review panel.

HUMAN HEALTH – CARCINOGENIC

Carcinogenic human health impacts were assessed using the USEtox tool. However, few compounds have carcinogenic characterization factors (CFs) already available, and gathering the necessary data to calculate CFs is also difficult. For the compounds in this study, the majority had no carcinogenic impact according to currently available data. Based on total impact across the U.S., fomesafen (herbicide), trifluralin (herbicide), and acephate (insecticide) are the only chemical compounds that have been estimated to have carcinogenic human health impacts and have data available. The results, in Table 18, are on the order of approximately 5 in 10 trillion to 3 in 100 billion per kg of cotton fiber. It is critical to note, especially with regard to human health impacts, the assessment depends on chances of exposure and does not consider the personal protective equipment or other requirements of application. Exposure does not imply that there will be cancer-related health implications. For example, acephate is a primary active ingredient in over-the-counter insecticides commonly used in home gardens in the U.S. and is considered acceptable by the U.S. Environmental Protection Agency for use without a special applicator license. The characterization factors used to assess carcinogenic human health impacts are understood to have an uncertainty factor of 100 to 1000 (Roos, et al., 2017). Because the CFs have high variability, the impact of each of these chemicals is not considered significantly different.

Table 18: Human health – carcinogenic impacts

Chemical name	National quantity used of chemical kg	Human Health – cancer impact Disease cases per kg of chemical	Human Health – cancer impact Disease cases per kg of cotton fiber
FOMESAFEN	1.32E+05	8.77E-07	3.02E-11
TRIFLURALIN	4.13E+05	3.38E-08	3.64E-12
ACEPHATE	3.46E+05	5.28E-09	4.76E-13

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[8] Chemicals for which custom characterization factors were developed – 2,4-D, 2-Ethylhexyl Ester, Abamectin, Acetamiprid, Afidopyropen, Bifenazate, Chlorpyrifos, Clothianidin, Cytokinin (As Kinetin), Dinotefuran, Etoxazole, Fenpyroximate, Flonicamid, Flupyradifurone, Flutriafol, Indaziflam, Indoxacarb, Mefenoxam, Methoxyfenozide, Novaluron, Pyraflufen-Ethyl, Spinetoram, Spiromesifen, Thiamethoxam.

HUMAN HEALTH – NON-CARCINOGENIC

The non-carcinogenic human health impact indicates the potential health impacts of chemicals used in cotton production that can lead to human health impacts other than cancer, such as asthma. The results do not relate to any exposure assessment or potential protective measures that may be in place during application. Like for cancer impacts, exposure does not imply that there will be health related impacts, but it does indicate that the probability of health deterioration is higher.

Across the U.S., there are seven compounds identified as potential hot spots for non-carcinogenic human health impacts (Table 19) with cases of approximately 1 in 10 billion to 7 in 10 million per kg of cotton fiber. With the large variability of the CFs, the potential impacts of each of these chemicals would not considered significantly different. The characterization factors used to assess non-carcinogenic human health impacts are understood to have an uncertainty factor of 100 to 1000 (Roos, et al., 2017).

Although tribufos appears in the USEtox database, previous investigation has shown that some of the underlying model data is incorrect. A custom CF using newer, more complete data was derived. Missing USEtox CFs for abamectin (insecticide) and chlorpyrifos (insecticide) were calculated also. Four other potential hotspots—acephate, dicrotophos (insecticide), ethephon (plant growth regulator), and a proxy for saflufenacil (herbicide)—were identified based on results from USEtox. The proxy flagged as a hotspot likely reflects the proxy selection rather than actual risk.

TABLE 19: Human health – non-carcinogenic impacts

Chemical name	National quantity used of chemical kg	Human Health – non-cancer impact Disease cases per kg of chemical	Human Health – non-cancer impact Disease cases per kg of cotton fiber
TRIBUFOS	7.55E+05	3.34E-03	6.58E-07
ABAMECTIN	4.12E+05	5.00E-03	5.36E-07
ACEPHATE	3.46E+05	1.47E-05	1.33E-09
4(1H)-Pyrimidinone, 6-methyl-2-(1-methylethyl)-	7.20E+04	1.54E-05	2.89E-10
DICROTOPHOS	3.19E+05	1.97E-06	1.63E-10
CHLORPYRIFOS	1.54E+03	3.06E-04	1.23E-10
ETHEPHON	3.34E+06	1.40E-07	1.21E-10

These chemicals are some of those used in the largest quantities or have high toxicity impacts. Although the toxicity of tribufos and abamectin each is low, when multiplied by the amount used in the U.S., the total leads to non-carcinogenic human health impacts per kg cotton fiber that produced a recognizable hotspot for cotton. Acephate results in a similar non-carcinogenic human health impact per kg of cotton fiber

ECOTOXICITY

Ecotoxicity refers to the capability of a compound or any physical agent to show the harmful effect on the environment and living organisms. On-farm cotton production may use pesticides and herbicides which naturally contribute to these impacts. Ecotoxicity impacts were assessed using the USEtox tool. Based on total impact across the U.S., **λ**-cyhalothrin (insecticide), abamectin, cypermethrin (insecticide), cyfluthrin (insecticide), bifenthrin (insecticide), fenpropathrin (insecticide), pendimethalin (herbicide), tribufos, paraquat (plant growth regulator), diuron (herbicide), trifluralin (herbicide), acetochlor (herbicide), Prometryne (herbicide), and s-metolachlor (herbicide) showed up as the hotspots for ecotoxicity impacts (Table 20). All these compounds had impacts in the range of 0.1 to 29 potentially affected fraction–cubic meter–year per kilogram of cotton fiber. Because the CFs for ecotoxicity are less uncertain than those for human toxicity, the errors range from 10-100.

Tribufos is widely used, and while its characterization factor is relatively small, the widespread use caused it to be a top contributor to ecotoxicity impacts. However, calculation of custom CFs, as was performed for tribufos as stated above, adds to the uncertainty of the result. Unlike human toxicity, it was easier to find the necessary data to construct custom characterization factors for ecotoxicity.

TABLE 20: Ecotoxicity impacts

Chemical name	National quantity used of chemical kg	Ecotoxicity impact Potentially affected fraction of species (PAF·m^3·yr) integrated over time and volume per kg of chemical	Ecotoxicity impact Potentially affected fraction of species (PAF·m^3·yr) integrated over time and volume per kg of cotton fiber
LAMBDA-CYHALOTHRIN	7.42E+04	1.44E+06	2.78E+01
ABAMECTIN	4.12E+05	2.29E+05	2.46E+01
CYFLUTHRIN	2.39E+03	5.83E+06	3.63E+00
CYPERMETHRIN	2.52E+04	5.37E+05	3.52E+00
BIFENTHRIN	1.39E+05	7.13E+04	2.58E+00
FENPROPATHRIN	5.89E+03	1.19E+06	1.83E+00
PARAQUAT	6.75E+05	1.86E+03	3.27E-01
TRIBUFOS	7.55E+05	1.61E+03	3.17E-01
PENDIMETHALIN	2.26E+05	4.79E+03	2.81E-01
DIURON	9.63E+05	1.10E+03	2.75E-01
S-METOLACHLOR	4.59E+05	1.45E+03	1.73E-01
Prometryne	6.57E+04	7.39E+03	1.26E-01
TRIFLURALIN	4.13E+05	1.09E+03	1.18E-01
ACETOCHLOR	5.80E+05	7.73E+02	1.17E-01

Cyfluthrin, **λ**-cyhalothrin, and fenpropathrin have lower chemical consumption, but the impact per kg cotton fiber is a hotspot due to the higher ecotoxicity impact per kg chemical. Abamectin and cypermethrin appear to have similar ecotoxicity impacts per kg chemical, but the CFs for cypermethrin in soil are much higher, which could be why the two have similar impacts per kg cotton even though less cypermethrin was applied. Bifenthrin, diuron, s-metolachlor, paraquat, pendimethalin, and tribufos are the most consumed chemicals, which results in similar ecotoxicity per kg cotton even though the CFs and impact per kg chemical are lower.

4.4 Description of Practitioner Value Choices

The practitioner value choices have been limited to the selected LCIA and the allocation procedures described in the relevant sections of this report. All results are presented on a midpoint basis using the methods noted in Section 4.1; normalization and weighting are not used. Other impact categories have been excluded from the results because they do not answer the questions within the objectives and scope of this report.

4.5 Identification of Relevant Findings

The study found that fertilizer production and application, irrigation, and energy use are primary contributors across multiple environmental impact categories. A summary of the environmental impacts per kg of cotton fiber is provided below:

1. **Global Warming Potential (GWP), excluding biogenic carbon dioxide:**
    - 1.45E+00 kg CO_2e, driven by field emissions (40%) and fertilizer production (38%).
2. **Global Warming Potential (GWP), including biogenic carbon dioxide:**
    - 1.26E+00 kg CO_2e, including soil organic carbon accumulation from improvements in farming practices, which is assumed to be stable over 100 years.
3. **Global Warming Potential (GWP), including biogenic carbon dioxide and fiber temporary storage:**
    - -2.64E-01 kg CO_2e, from biogenic carbon stored in soil and fiber, temporarily reducing atmospheric CO_2.
4. **Primary Energy Demand (PED):**
    - 1.79E+01 MJ, largely from energy for fertilizer production (64%).
5. **Blue Water Use (BWU):**
    - 1.48E+03 L, driven primarily by irrigation (84%) and fertilizer production (12%).
6. **Blue Water Consumption (BWC):**
    - 1.24E+03 L, almost entirely due to irrigation.
7. **Water Scarcity (AWARE):**
    - 4.21E+01 m^3 world equivalent almost entirely due to irrigation water that is withdrawn from groundwater aquifers.
8. **Abiotic Depletion Potential (ADP):**
    - 1.69E+01 MJ, driven by fertilizer production (63%) and pumping energy (8%).
9. **Acidification Potential (AP):**
    - 4.98E-03 kg SO_2e, driven by fertilizer production (50%).

10. **Eutrophication Potential (EP):**
    - 7.28E-03 kg PO_4^{3-}-e, primarily from field emissions, specifically from fertilizer runoff (93%).
11. **Ozone Depletion Potential (ODP):**
    - 2.84E-11 kg R11e, driven by packaging (68%).
12. **Smog Formation (POCP):**
    - 3.89E-04 kg ethene equivalents, driven by fertilizer production (41%) and field emissions (19%).
13. **Human Health Particulate Air (HHPA):**
    - 4.78E-04 kg $PM_{2.5}$ equivalents, driven by fertilizer production (80%).
14. **Land Occupation (LO):**
    - 9.55E+00 m^2*yr.e, with 99% of the impacts from land used for cotton cultivation.
15. **Toxicity hotspots (using the USEtox method):**
    - Carcinogenic: Fomesafen, Trifluralin, and Acephate use.
    - Non-carcinogenic: Tribufos, Abamectin, Dicrotophos, Chlorpyrifos, Ethephon, 4(1H)-Pyrimidinone, 6-methyl-2-(1-methylethyl)-and Acephate use.
    - Ecotoxicity: **λ**-Cyhalothrin, Abamectin, Cypermethrin, Cyfluthrin, Bifenthrin, Fenpropathrin, Pendimethalin, Tribufos, Paraquat, Diuron, Prometryne, Trifluralin, Acetochlor and S-metolachlor use.

4.6 Sensitivity Analysis

Sensitivity analysis is performed to understand the influence of variations in the assumptions, methods and data on the results. In other words, a sensitivity analysis allows for key parameters that have the most significant impact on the results to be identified as well as assess the robustness of the conclusions and showcase limitations that may be present.

There were two types of sensitivity analyses performed. The first is an analysis on the coproduct treatment method which can have a large impact on the result, since it changes the burdens partitioned to the products in a multi-product system (i.e., cotton lint and cottonseed). The coproduct treatment sensitivity analysis assesses the impacts across three different coproduct treatments – mass allocation, biophysical allocation and cereal unit allocation. Biophysical allocation and cereal unit allocation are discussed in further detail in Section . The second sensitivity analysis is focused on a primary driver for the results, nitrous oxide emissions. This scenario analysis assesses both the nitrous oxide from fertilizer application and crop residue emission factors. The third sensitivity analysis is focused on the background datasets themselves (LCA FE vs ecoinvent), highlighting the variations in outcomes that arise from those selections. Note these sensitivities do not include the GWP, including biogenic carbon dioxide including temporary storage of fiber.

4.6.1 Allocation

Cotton cultivation processes vary considerably across regions and over time due to multiple influencing factors. Key variables include fiber-to-seed mass ratios, fluctuations in fiber and seed market prices, and uncertainties related to upstream inventory. These variables are strongly influenced by regional and annual environmental conditions.

Daystar et al. (2024) analyzed these uncertainties, emphasizing how the choice of coproduct allocation method significantly affects the outcomes of a cotton Life Cycle Assessment (LCA). The study compared various coproduct allocation methods, discussing their advantages and disadvantages relative to different applications.

Key findings from Daystar et al. (2024) are as follows:

- Mass allocation: Allocates most impacts to cottonseed due to its greater mass relative to fiber.
- Biophysical allocation: Also assigns most impacts to seed since seed development requires more energy than fiber formation, a crucial factor in biophysical allocation.
- Cereal unit allocation: Results in lower impacts per kilogram of fiber compared to mass and economic allocation but higher impacts than biophysical allocation.
- Economic allocation: Assigns the highest impacts per kilogram of fiber because of fiber's higher economic value.

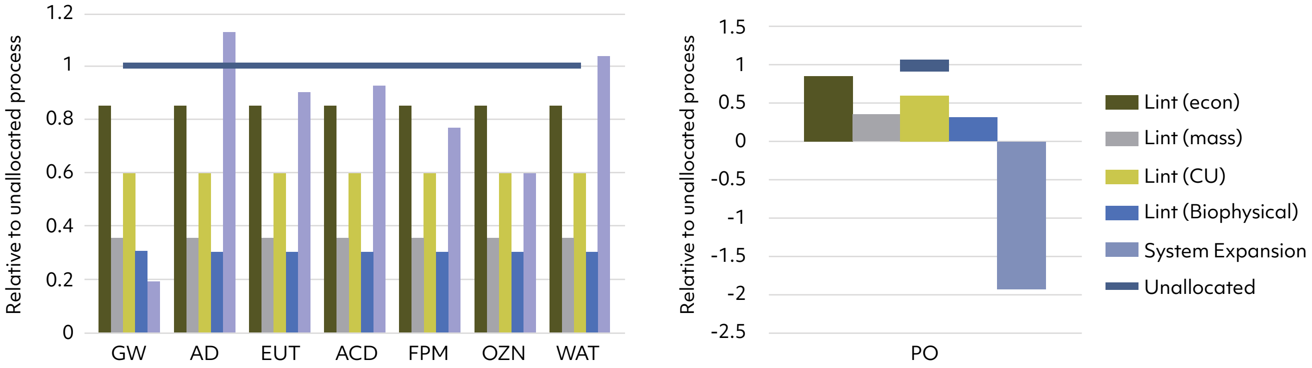
The ISO 14044 (2006b) guidelines recommend using economic allocation only when necessary. Within cotton production specifically, economic allocation is considered the most conservative and is currently widely adopted by the industry, primarily because fiber revenue is perceived as the primary driver for cotton production. Numerous studies cited by Daystar et al. (2024) support economic allocation due to its direct relationship with product utility.

However, it is important to acknowledge potential uncertainty and unintended consequences associated with economic allocation. For instance, regional and temporal variations in cottonseed and lint prices can significantly influence the economic partitioning coefficient. Additionally, the true value of cottonseed might not be fully reflected in economic allocation, given that if cottonseed were absent from the agricultural supply chain, alternative crops would be needed to provide equivalent nutritional benefits. Additionally, avoiding allocation altogether through system expansion can lead to negative Global Warming Potential (GWP) impacts in certain scenarios. However, system expansion introduces greater uncertainty in LCA data, particularly regarding the identification and impacts of the products displaced by cottonseed.

Overall, different allocation methods reveal distinct patterns reflective of their inherent perspectives and there is no single correct approach. Economic allocation consistently attributes the largest share of impacts to fiber production, followed by cereal unit, mass, and finally biophysical allocation. Additionally, the choice of allocation method introduces more variability into the LCA results than upstream inventory uncertainties.

The Daystar et al., paper analyzed allocation approaches, as shown in Figure 20: Allocation results from Daystar et al. paper (Daystar, et al., 2024) below (Daystar, et al., 2024), where categories are split into two groups depending on the range of relative performance for readability. Allocation types are plotted relative to the unallocated process, represented by a line with a value of 1. Results from this study follow this same general trend, with economic allocation for fiber (referred to as lint in the figure below) having the highest impacts, followed by cereal allocation (CU), mass allocation, and biophysical allocation. This study did not consider system expansion.

FIGURE 20: Allocation results from Daystar et al. paper (Daystar, et al., 2024)



In this study, the impacts allocated based on economic values are higher than those impacts resulting from mass allocation since the relative value of fiber per kg of seed cotton is greater than the relative value of seed per kg of seed cotton. Biophysical allocation partitioning of impacts based on the plant construction cost of the seed and fiber and leads to lower allocation to fiber and lower fiber impacts. Cereal unit allocation also leads to lower impacts since cereal unit allocation considers metabolized energy content expressed as barley equivalent units, since fiber has lower metabolized energy content.

Figure 21: Sensitivity analysis to allocation method, per kg of cotton fiber and Table 21 show the change in impact between allocation methods. Compared with economic allocation (baseline), mass allocation had 53% lower impacts, biophysical allocation had 58% lower impacts, cereal unit allocation had 24% lower impacts.

Figure 21: Sensitivity analysis to allocation method, per kg of cotton fiber

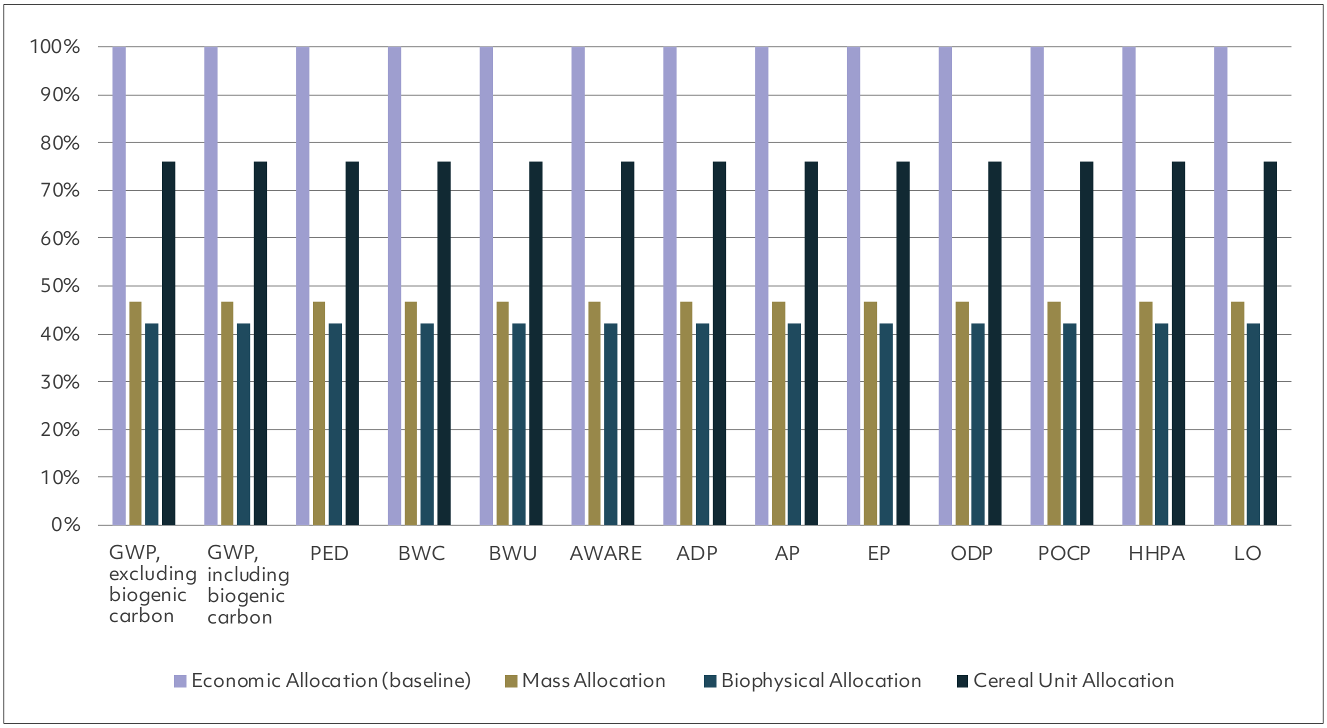


TABLE 21: Sensitivity to allocation method, per kg of cotton fiber

Impacts per kg of cotton fiber	Economic Allocation (baseline)	Mass Allocation		Biophysical Allocation		Cereal Unit Allocation	
Impact Categories	Baseline value	Value	Percent Change	Value	Percent Change	Value	Percent Change
GWP, excluding biogenic ($kg CO_2e$)	1.45E+00	6.79E-01	-53%	6.13E-01	-58%	1.10E+00	-24%
GWP, including biogenic ($kg CO_2e$)	1.26E+00	5.88E-01	-53%	5.31E-01	-58%	9.55E-01	-24%
PED (MJ)	1.79E+01	8.36E+00	-53%	7.54E+00	-58%	1.36E+01	-24%
BWU (L)	1.48E+03	6.94E+02	-53%	6.26E+02	-58%	1.13E+03	-24%
BWC (L)	1.24E+03	5.82E+02	-53%	5.25E+02	-58%	9.45E+02	-24%
AWARE (m^3 world equivalent)	4.21E+01	1.97E+01	-53%	1.78E+01	-58%	3.20E+01	-24%
ADP (MJ)	1.69E+01	7.89E+00	-53%	7.11E+00	-58%	1.28E+01	-24%
AP ($kg SO_2e$)	4.98E-03	2.33E-03	-53%	2.10E-03	-58%	3.78E-03	-24%
EP ($kg PO_4^{3-}$-e)	7.28E-03	3.40E-03	-53%	3.07E-03	-58%	5.53E-03	-24%
ODP (kg R11e)	2.84E-11	1.33E-11	-53%	1.20E-11	-58%	2.16E-11	-24%
POCP (kg ethene equivalents)	3.89E-04	1.82E-04	-53%	1.64E-04	-58%	2.95E-04	-24%
HHPA (kg $PM_{2.5}$ equivalents)	4.78E-04	2.24E-04	-53%	2.02E-04	-58%	3.63E-04	-24%
LO (m^2 × yr.e)	9.55E+00	4.46E+00	-53%	4.03E+00	-58%	7.25E+00	-24%

4.6.2 Nitrous oxide emissions from applied fertilizer and crop residue

According to the IPCC National Greenhouse Gas Inventories, the nitrous oxide field application and crop residue emission factors, as well as the volatilization and leaching factors have a default value and an uncertainty range for wet and dry climatic conditions, as shown in Table 22 below.

TABLE 22: Emissions factors to estimate N_2O emissions from Table 11.1 and Table 11.3 in 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

Direct and Indirect N_2O emission variables	Wet Climate		Dry Climate	
	Default Value	Range	Default Value	Range
Direct N_2O emissions: Synthetic Fertilizer emission factor kg N_2O-N per kg N in fertilizer	1.60E-02	1.30E-02-1.9E-02	5.00E-03	0.00E+00-1.10E-02
Direct N_2O emissions: Other N inputs emission factor (organic amendments, animal manure) kg N_2O-N per kg N in fertilizer	6.00E-03	1.00E-03-1.10E-02	5.00E-03	0.00E+00-1.10E-02
Indirect N_2O emissions (Volatilisation): Synthetic Fertilizer fraction kg NO_x-N per kg N in fertilizer	1.10E-01	2.00E-02-3.30E-01	1.10E-01	2.00E-02-3.30E-01
Indirect N_2O emissions (Volatilisation): Organic Fertilizer fraction kg NO_x-N per kg N in fertilizer	2.10E-01	0.00E+00-3.1E-01	2.10E-01	0.00E+00-3.10E-01
Indirect N_2O emissions (Volatilisation): Fertilizer emission factor kg N_2O-N per kg N in fertilizer	1.40E-02	1.10E-02-1.7E-02	5.00E-03	0.00E+00-1.10E-02
Indirect N_2O emissions (Leaching/ runoff): Emission factor kg NO_x-N per kg N leaching/runoff	1.10E-02	0.00E+00-2.0E-02	–	–
Indirect N_2O emissions (N losses by leaching/ runoff): addition or deposition fraction kg N per kg N additions or deposition by grazing animals	2.40E-01	1.0E-02-7.3E-01	–	–

The baseline results of this study indicate that direct and indirect emissions from applied nitrogen fertilizer as well as emissions from crop residue are the largest contributors to GWP. Indirect emissions are calculated as the product of the fertilizer emission factor and emissions fraction. The calculated emission factors are then scaled up by the amount of fertilizer input to generate the default value, the low-end scenario results and the high-end scenario results. The lower end of the range is used to generate the low scenario N_2O factors and the higher end of the range are used to generate high N_2O scenario factors, as shown in Figure 22 and Table 23.

FIGURE 22: Sensitivity to nitrous oxide emissions from fertilizer application and crop residue for U.S. average, per kg of cotton fiber

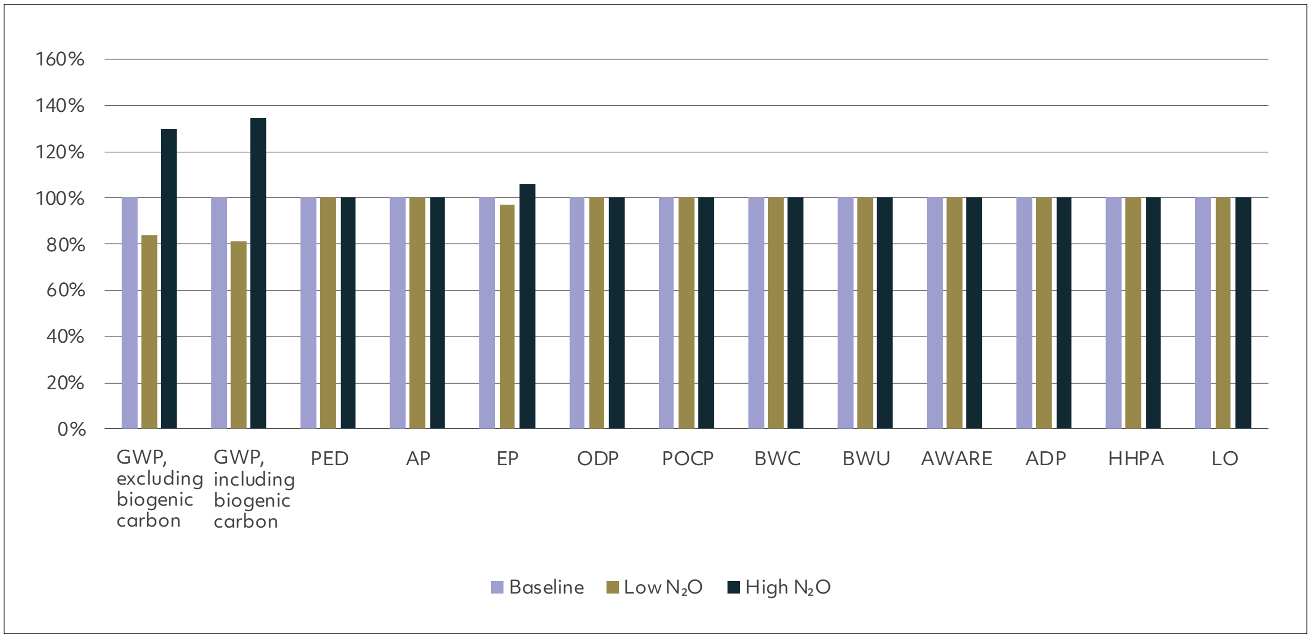


TABLE 23: Sensitivity to nitrous oxide emissions from fertilizer application and crop residue for U.S. average, per kg of cotton fiber

Impacts per kg of cotton fiber	Baseline	Low N_2O	% change	High N_2O	% change
GWP, excluding biogenic ($kg\ CO_2e$)	1.45E+00	1.22E+00	-16%	1.89E+00	30%
GWP, including biogenic ($kg\ CO_2e$)	1.26E+00	1.02E+00	-19%	1.69E+00	34%
PED (MJ)	1.79E+01	1.79E+01	0%	1.79E+01	0%
BWC (L)	1.24E+03	1.24E+03	0%	1.24E+03	0%
BWU (L)	1.48E+03	1.48E+03	0%	1.48E+03	0%
AWARE (m^3 world equiv.)	4.21E+01	4.21E+01	0%	4.21E+01	0%
ADP (MJ)	1.69E+01	1.69E+01	0%	1.69E+01	0%
AP ($kg\ SO_2$ eq.)	4.98E-03	4.98E-03	0%	4.98E-03	0%
EP (kg Phosphate eq.)	7.28E-03	7.05E-03	-3%	7.71E-03	6%
ODP (kg R11 eq.)	2.84E-11	2.84E-11	0%	2.84E-11	0%
POCP (kg Ethene eq.)	3.89E-04	3.89E-04	0%	3.89E-04	0%
HHPA ($kg\ PM_{2.5}$ eq.)	4.78E-04	4.78E-04	0%	4.78E-04	0%
LO ($m^2 \cdot yr$ eq.)	9.55E+00	9.55E+00	0%	9.55E+00	0%

4.6.3 Ecoinvent Background Data

Under this scenario, all data sources from LCA FE were replaced with their ecoinvent equivalent to help understand the changes in impacts between the two sources of data, the hotspots using ecoinvent data, and the allocation results using ecoinvent data.

As shown in Figure 23 and Table 24, the per kg of fiber impacts using LCA FE datasets are drastically different from the results generated using ecoinvent. Land occupation is the only category where the change in impacts is <10%. The large change between the data sources for all other categories heavily depend on how individual flows of chemical exchanges between the technosphere and ecosphere are defined and assigned by these databases. Note ODP percent change exceeds five orders of magnitude and HHPA exceeds 150%. See Table 24 below for details.

FIGURE 23: Sensitivity to background data, per kg of cotton fiber

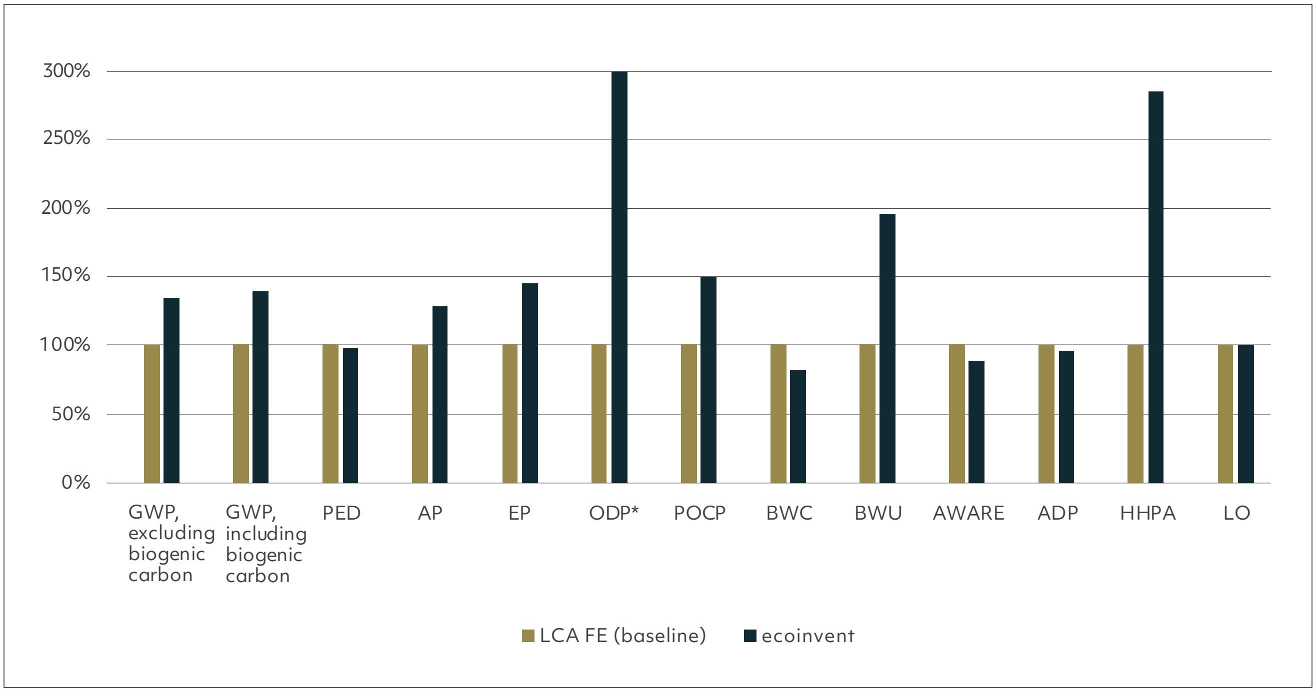


TABLE 24: Sensitivity to background data, per kg of cotton fiber

Impacts per kg of cotton fiber	LCA FE	ecoinvent	Percent Change (LCA FE to ecoinvent)
GWP, excluding biogenic ($kg\ CO_2e$)	1.45E+00	1.94E+00	34%
GWP, including biogenic ($kg\ CO_2e$)	1.26E+00	1.75E+00	39%
PED (MJ)	1.79E+01	1.75E+01	-2%
BWC (L)	1.24E+03	1.01E+03	-19%
BWU (L)	1.48E+03	2.92E+03	97%
AWARE (m^3 world equivalent)	4.21E+01	3.47E+01	-18%
ADP (MJ)	1.69E+01	1.64E+01	-3%
AP ($kg\ SO_2e$)	4.98E-03	6.32E-03	27%
EP ($kg\ PO_4^{3-}$-e)	7.28E-03	1.06E-02	45%
ODP* (kg R11e)	2.84E-11	1.69E-07	594970%
POCP (kg ethene equivalents)	3.89E-04	5.85E-04	51%
HHPA (kg $PM_{2.5}$ equivalents)	4.78E-04	1.35E-03	183%
LO ($m^2 \times yr.e$)	9.55E+00	9.51E+00	0%

* Pesticide production factor in ecoinvent is 5 times larger than that of LCA FE, which causes ODP to be significantly higher in the ecoinvent results. The ecoinvent LCI process is RER: pesticide production, unspecified and the LCA FE process is GLO: Pesticide (average).

The contribution of impacts by stage is broken down in Table 25. The top contributors to the different impact categories are similar between the models that use LCA FE and ecoinvent. In both the LCA FE-data-based model and ecoinvent-data-based-model, the top contributors to GHG emissions, energy demand, acidification, eutrophication, ozone depletion, smog formation, resource depletion and particulate mater impacts are pumping energy, field emissions (diesel impact + direct and indirect N_2O emissions), fertilizer production and pesticide production. In the case of GHG emissions, the ecoinvent-based emissions for pumping energy is 219% higher, field emissions are 38% higher, fertilizer production 76% lower and pesticide production are 91% lower than that of LCA FE-data-based model. Fertilizer models were built differently between the LCA FE and ecoinvent models. Direct inorganic nitrogen, phosphorus and potassium datasets were available in ecoinvent, while urea ammonium nitrate, monoammonium phosphate and potassium chloride datasets, scaled to represent the nitrogen, phosphorus and potassium demand, were used in the LCA FE model. The impact of nitrogen demand and potassium demand are about five times higher and 10 times higher in ecoinvent datasets compared to LCA FE datasets. Phosphorus nutrient impacts from ecoinvent datasets are 50% that of LCA FE impacts. US average electricity emission factors are 9% higher in ecoinvent, but this difference could be higher at the state level since LCA FE and ecoinvent use have different grid topology used. LCA FE has electricity data at the e-grid sub-region level while ecoinvent has electricity data defined at the North American Electric Reliability Corporation (NERC) regions level. This further underscores the significant uncertainty associated with most LCAs and emphasizes that non-comparative LCAs should not be compared, as the underlying data heavily impacts the results.

TABLE 25: Contribution analysis using ecoinvent background data, per kg of cotton fiber

	Pumping energy	Field emissions	Irrigation water	Land occupation	Soil amendments	Fertilizer production	Pesticide production	Micronutrients
GWP, excluding biogenic carbon dioxide ($kgCO_2e$)	14%	42%	0%	0%	3%	7%	0%	0%
GWP, including biogenic carbon dioxide ($kgCO_2e$)	14%	42%	0%	0%	3%	7%	0%	0%
GWP, including biogenic carbon dioxide and fiber temp storage ($kgCO_2e$)	14%	42%	0%	0%	3%	7%	0%	0%
PED (MJ)	23%	4%	0%	0%	4%	13%	2%	0%
AP ($kgSO_2eq.$)	20%	9%	0%	0%	9%	21%	0%	0%
EP (kg PO_4^{3-}eq.)	6%	81%	0%	0%	1%	3%	0%	0%
ODP (kg R11eq.)	1%	0%	0%	0%	0%	70%	0%	0%
POCP (kg Ethene eq.)	19%	9%	0%	0%	10%	19%	1%	0%
BWC (L)	0%	0%	98%	0%	0%	0%	0%	0%
BWU (L)	19%	0%	34%	0%	0%	8%	0%	0%
AWARE (m^3 world equivalent)	0%	0%	97%	0%	0%	0%	0%	0%
ADP (MJ)	21%	4%	0%	0%	5%	13%	2%	0%
HHPA (kg $PM_{2.5}$eq)	36%	1%	0%	0%	5%	7%	0%	2%
LO (m^2·yr e kg)	0%	0%	0%	100%	0%	0%	0%	0%
Key	Highest impacts							Lowest Impacts

***Note:** Due to rounding, some values labeled as 0% are not actually 0, but <1%.

	Harvest	Tillage	Packaging	Transportation to gin	Ginning	Biogenic carbon dioxide (soil)	Biogenic carbon dioxide (fiber)	Total
GWP, excluding biogenic carbon dioxide (kgCO$_2$e)	24%	4%	3%	0%	3%			1.94E+00
GWP, including biogenic carbon dioxide (kgCO$_2$e)	24%	4%	3%	0%	3%	-10%		1.75E+00
GWP, including biogenic carbon dioxide and fiber temp storage (kgCO$_2$e)	24%	4%	3%	0%	3%	-10%	-78%	2.33E-01
PED (MJ)	38%	6%	5%	0%	5%			1.75E+01
AP (kgSO$_2$eq.)	28%	6%	5%	0%	1%			6.32E-03
EP (kg PO$_4^{3-}$eq.)	6%	1%	1%	0%	1%			1.06E-02
ODP (kg R11eq.)	3%	0%	26%	0%	0%			1.69E-07
POCP (kg Ethene eq.)	29%	6%	4%	0%	3%			5.85E-04
BWC (L)	1%	0%	0%	0%	0%			1.01E+03
BWU (L)	22%	5%	9%	0%	3%			2.92E+03
AWARE (m^3 world equivalent)	2%	0%	0%	0%	0%			3.47E+01
ADP (MJ)	39%	6%	5%	0%	5%			1.64E+01
HHPA (kg PM$_{2.5}$eq)	32%	8%	6%	0%	4%			1.35E-03
LO (m^2·yr e kg)	0%	0%	0%	0%	0%			9.51E+00
Key	Highest impacts							Lowest Impacts

***Note:** Due to rounding, some values labeled as 0% are not actually 0, but <1%.

Table 26 provides the impact results per kg of fiber across different allocation procedures when using ecoinvent data.

TABLE 26: Sensitivity analysis of allocation method using ecoinvent background data, per kg of cotton fiber

Impacts per kg of cotton fiber	Economic Allocation	Mass Allocation	Biophysical Allocation	Cereal Allocation
GWP, excluding biogenic carbon dioxide (kg CO_2e)	1.94	0.91	0.819	1.47
GWP, including biogenic carbon dioxide (kg CO_2e)	1.75	0.82	0.736	1.325
PED (MJ)	17.5	8.18	7.38	13.28
AP (kg SO_2e)	6.32E-03	2.96E-03	2.67E-03	4.80E-03
EP (kg PO_4^{3-}e)	1.06E-02	4.95E-03	4.46E-03	8.03E-03
ODP (kg R11e)	1.69E-07	7.90E-08	7.13E-08	1.28E-07
POCP (kg ethene equivalents)	5.85E-04	2.74E-04	2.47E-04	4.44E-04
BWC (L)	1014	474.10	428	770
BWU (L)	2923	1366.63	1233	2,218.73
AWARE (m^3 world e)	34.7	16.22	14.6	26.3
ADP (MJ)	16.4	7.68	6.92	12.46
HHPA (kg $PM_{2.5}$ equivalents)	1.35E-03	6.33E-04	5.71E-04	1.03E-03
LO (m^2 × yr.e)	9.51	4.45	4.01	7.22

4.7 Data Quality Assessment and Uncertainty Analysis

4.7.1 Data Quality Assessment

In an LCA study, the data typically includes a mix of measured, estimated, and calculated values, leading to varying levels of data quality. Some data points are highly reliable, while others are based on estimates. To gauge the quality of the data used for modeling the seed cotton production system and the fiber production system, Data Quality Indicators (DQI) were assigned to each data flow using a data quality matrix. This data quality matrix is called a pedigree matrix which aids in translating expert opinion into scale scores reflecting varying levels of quality, as shown in Table 27. These scores are utilized to evaluate the uncertainties in the data and, consequently, the overall uncertainty of the model and its results.

Geographical resolution has seven levels: global, continental, sub-regional, national, province/state/region, county/city, and site-specific (Edelen & Ingwersen, 2016). The sub-regional level refers to regional descriptions (e.g., United States), and the site-specific level, the most granular level, and includes the physical address of the site. The geographical correlation is scored based on the level of the input data and the level of the dataset that is available.

Technological correlation is represented using four categories: process design, operational conditions, material quality, and scalability. Process design refers to the set of conditions in a process that affects the product. Operational conditions refer to variable parameters such as heat, temperature, and pressure that are needed to make the product. Material quality refers to the type and quality of feedstock material. Scale refers to output per unit time or per production line (Edelen & Ingwersen, 2016).

TABLE 27: Pedigree matrix adapted from the U.S. Environmental Protection Agency (Edelen & Ingwersen, 2016)

	Highest confidence				**Lowest confidence**
Data Quality Indicator	**1**	**2**	**3**	**4**	**5**
Reliability	Primary data from fiber producers, measured data	Primary data from fiber producers, estimated data	Data obtained from literature with an exact match	Data obtained from literature with a proxy match	Data obtained from online sources and not an exact match, limited documentation
Completeness	Representative data from >80% of the relevant market, over an adequate period	Representative data from 60-79% of the relevant market, over an adequate period **or** representative data from >80% of the relevant market, over a shorter period of time	Representative data from 40-59% of the relevant market, over an adequate period **or** representative data from 60-79% of the relevant market, over a shorter period of time	Representative data from <40% of the relevant market, over an adequate period **or** representative data from 60-79% of the relevant market, over a shorter period of time	Unknown **or** data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference	Less than 6 years of difference	Less than 10 years of difference	Less than 15 years of difference	Age of data unknown or more than 15 years
Geographical correlation	Data from same resolution **and** same area of study	Within one level of resolution **and** a related area of study	Within two levels of resolution **and** a related area of study	Outside of two levels of resolution but related area of study	From a different or unknown area of study
Technological correlation	All technology categories are equivalent	Three of the technology categories are equivalent	Two of the technology categories are equivalent	One of the technology categories is equivalent	None of the technology categories are equivalent

Data quality descriptions and average scores for this study are shown in Table 28.

TABLE 28: Data quality descriptions and scores

Data Quality Indicator	Data quality description by phase	Average Score
Reliability	**Fertilizers, micronutrients and soil amendments:** Nutrient and soil amendment data was collected via the 2023 Cotton Growers NRS, though survey data was measured for the subset of farms, a survey response has the potential to have inconsistencies in submissions. The reliability of the nutrient data is representative of the farms in this scope analysis, though they cannot always be verified and may need additional calculations to estimate regional representation. Therefore, the reliability score for fertilizer is 4 & micro-nutrients is 3. **Pumping & Irrigation:** Irrigation volume applied during the season was collected via the 2023 Cotton Growers NRS as measured data with potential inconsistencies in responses and requiring some calculations to estimate regional representation. Pumping energy data was calculated using average depth, average pumping pressure and irrigation application from 2023 Cotton Growers NRS. Thus, the reliability score for pumping and irrigation is 2. **On-farm operations:** On-farm operations, including fertilizer application, field operations, harvest, and tillage data was collected via the 2023 Cotton Growers NRS and equations from literature were used to calculate the on-farm fuel usage. Other field impacts that include direct and indirect leaching and runoff were calculated using IPCC standard equations. Therefore, the reliability score for on-farm operations is 3. **Transportation to gin & Ginning:** The miles to gin data for transportation were collected from the 2023 Cotton Growers NRS and included a subset from each state and an average for each region. Reliability for transportation to gin is a 1. For Ginning data, a combination of literature data, fuel use equations and electricity equations were used to estimate the average ginning energy and fuel usage for each region. Thus, the reliability score for ginning is 3.	**3**

Data Quality Indicator	Data quality description by phase	Average Score
Completeness	**Fertilizers, micronutrients and soil amendments:** Fertilizer, micronutrient and soil amendment data was collected via the 2023 Cotton Growers NRS. The responses for nutrients and soil amendments were inconsistent since some farmers were applying nutrients during the data collection year, while others were not. Farmers also tend to use different fertilizers, while generic nitrogen, phosphorus and potassium fertilizer datasets were used in the model. Hence, the completeness score is 4. **Pumping & Irrigation:** Irrigation volume applied during the season was collected via the 2023 Cotton Growers NRS, and pumping energy data was calculated using average depth, average pumping pressure and irrigation application from 2023 Cotton Growers NRS. Thus, the completeness score for pumping and irrigation is 3. **On-farm operations:** More than 80% of the data for on-farm operations, including fertilizer application, field operations, harvest, tillage, and other field impacts are covered by the 2023 Cotton Growers NRS in this assessment. The completeness score is 3. **Transportation to gin & Ginning:** For the transportation to gin, 100% of the distances came directly from the 2023 Cotton Growers NRS and represent all the studied regions. Thus, completeness is confidently scored as a 1. Ginning, like mentioned above, used a combination of literature data and fuel use/electricity equations, thus the completeness score is 2.	3
Temporal correlation	**Fertilizers, micronutrients and soil amendments:** All fertilizer, micronutrients and soil amendments data inputs are from the 2023 Cotton Growers NRS. The input data used in the model have high representativeness with regards to temporal correlation with a score of 2. **Pumping & Irrigation:** Pumping and irrigation data is from the 2023 Cotton Growers NRS and the 2018 Irrigation and Water Management Survey (U.S. Department of Agriculture, 2019). Therefore, the pumping and irrigation data has a temporal correlation score of 2. **On-farm operations:** The data for on-farm operations, including fertilizer application, field operations, harvest, and tillage are from the 2023 Cotton Growers NRS. Thus, the on-farm operations temporal score is 2. **Transportation to gin & Ginning:** The transport data for distance to ginning were provided as inputs from the 2023 Cotton Growers NRS. This gives the transportation to ginning a temporal correlation with a score of 1. The ginning data was collected from a 2019 survey response and other peer-reviewed literature data from 2016. Thus, the temporal correlation of the ginning data is 3, bringing the average temporal correlation score for transportation to gin & ginning to 2.	2

Data Quality Indicator	Data quality description by phase	Average Score
Geographical correlation	**Fertilizers, micronutrients and soil amendments:** Fertilizer, soil amendment and micronutrient data was collected via the 2023 Cotton Growers NRS from the individual farm level. Because data is from the sites themselves, this was then aggregated up to regional and national level, thus receiving a score of 4. **Pumping & Irrigation:** Pumping and irrigation data is from the 2023 Cotton Growers NRS and the farms themselves and the energy is calculated using Equation 1 developed from Therefore, the pumping and irrigation data has a geographical correlation score of 3. **On-farm operations:** The data for on-farm operations, including fertilizer application, field operations, harvest, and tillage are from the 2023 Cotton Growers NRS. Thus, the on-farm operations score is 3. **Transportation to gin & Ginning:** The transport data for distance to ginning was provided as inputs from the 2023 Cotton Growers NRS, but these numbers themselves are uncertain. This gives the transportation to ginning a score of 2. Since the ginning data was collected from a 2019 survey response and other peer-reviewed literature data from 2016. Thus, the geographical correlation of the ginning data is 2.	3
Technological correlation	**Fertilizers, micronutrients and soil amendments:** Fertilizer, soil amendment and micronutrient data was collected via the 2023 Cotton Growers NRS from the individual farm level. The data was modeled using proxy data that best matches the chemical input. Hence, the production technology associated with all chemical inputs and the proxy data used will not match. The technological correlation score is 4. **Pumping & Irrigation:** Pumping and irrigation data is from the 2023 Cotton Growers NRS and the energy is calculated using Equation 1 developed from Operational conditions regarding fuel use have been laid out clearly from this data, therefore, the pumping and irrigation data has a high technological correlation score of 2. **On-farm operations:** The data for on-farm operations, including fertilizer application, field operations, harvest, and tillage are from the 2023 Cotton Growers NRS. Operations taking place during this phase and the different equipment and feedstocks used here are thorough, thus, the on-farm operations technological score is 2. **Transportation to gin & Ginning:** The transport data for distance to ginning were provided as inputs from the 2022 Cotton Growers NRS. This gives the transportation to ginning with a score of 2. For the ginning data was collection from a 2019 survey response and other peer-reviewed literature data from 2016. Some of these processes have been assumed across regions thus, the temporal correlation of the ginning data is 2.	3

* On-farm operations include fertilizer application, field operations, harvest, tillage, and other field impacts (Direct and Indirect N emissions and runoff)

4.7.2 Uncertainty Analysis Results

The pedigree matrix approach described previously is a qualitative assessment of uncertainty in data, and when used alongside a Monte Carlo assessment provides insight into the uncertainty in the model and examines data uncertainty, offering a range of outcomes that illustrate the environmental impacts of the study.

The quality of fit, or representativeness, of model inputs were evaluated across five indicator categories: reliability, completeness, temporal correlation, geographical correlation, and technological correlation. For each indicator, a score from 1 to 5 was assigned to each model input, where 1 indicates high representativeness of the product system and 5 indicates low representativeness. The assessment was completed across life cycle stages for a final average score (rounded to the nearest whole number) in each indicator Table 29).

Additionally, each measured input or output is also assigned a score based on its basic uncertainty. Inputs to a manufacturing process typically have low uncertainty because they are well-known and often metered. In contrast, transportation has higher uncertainty due to variable factors like weather, construction, and accidents. These uncertainty scores are assigned according to the criteria in the Pedigree matrix, and a Monte Carlo uncertainty analysis is performed to assess how data quality impacts the significance of the study results.

The individual uncertainty scores are provided in Table 29 below.

TABLE 29: Standard deviation of data points and individual pedigree matrix scores

Variable List	Data For Log Normal Distribution for Sd2	Relative Std Dev For Normal Distribution	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
Farm_crop_res_ N_2O	1.64	25%	4	4	3	4	4
Farm_Fert_CO_2	1.64	25%	4	4	3	4	4
Farm_Fert_K	1.64	25%	4	4	3	4	4
Farm_Fert_N	1.64	25%	4	4	3	4	4
Farm_fert_N_2O	1.64	25%	4	4	3	4	4
Farm_Fert_P	1.64	25%	4	4	3	4	4
Farm_FertApp_ Diesel	1.25	11%	3	3	2	3	3
Farm_FieldOps_ Diesel	1.25	11%	3	3	2	3	3
Farm_Harvest_ Diesel	1.25	11%	3	3	2	3	3
Farm_Irrigation_ Water	1.25	11%	3	3	2	3	3
Farm_Land_Occ	1.25	11%	3	3	2	3	3
Farm_Micro_ Gypsum	1.25	11%	3	3	2	3	3

Variable List	Data For Log Normal Distribution for Sd2	Relative Std Dev For Normal Distribution	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
Farm_Micro_Lime	1.25	11%	3	3	2	4	3
Farm_Micro_Sulfur	1.25	11%	3	3	2	3	3
Farm_Pack	1.25	11%	3	3	2	3	3
Farm_Pesticide	1.25	11%	3	3	2	3	3
Farm_Pump_Diesel	1.25	11%	3	3	2	3	3
Farm_Pump_Elec	1.25	11%	3	3	2	3	3
Farm_Pump_NG	1.24	11%	3	2	2	2	3
Farm_runoff_N	1.64	25%	4	4	3	4	4
Farm_runoff_P	1.64	25%	4	4	3	4	4
Farm_Tillage_Diesel	1.25	11%	3	3	2	3	3
Gin_elec	1.25	11%	3	3	2	3	3
Gin_LPG	1.24	11%	3	2	2	2	3
Gin_NG	1.24	11%	3	2	2	2	3
Gin_pack_metal	1.25	11%	3	3	2	3	3
Gin_pack_plastic	1.25	11%	3	3	2	3	3
Tp_Gin_cargo	2	35%	1	1	1	2	2
Tp_Gin_dist	2	35%	1	1	1	2	2

In this study, the Monte Carlo analysis was performed using the following procedure:

- Flows and parameters within the model were changed from deterministic to probabilistic values, i.e. from point estimates to probability distribution functions (PDFs). As is common practice in LCA, log-normal distributions were used.
- Monte Carlo simulations were carried out in LCA FE (10,000 runs). These evaluated the frequency at which one system was preferable to another.

$$SDg95 = \sqrt{exp}[\ln(U1)^2 + \ln(U2)^2 + \ln(U3)^2 + \ln(U4)^2 + \ln(U5)^2 + \ln(U6)^2 + \ln(Ub)^2]$$

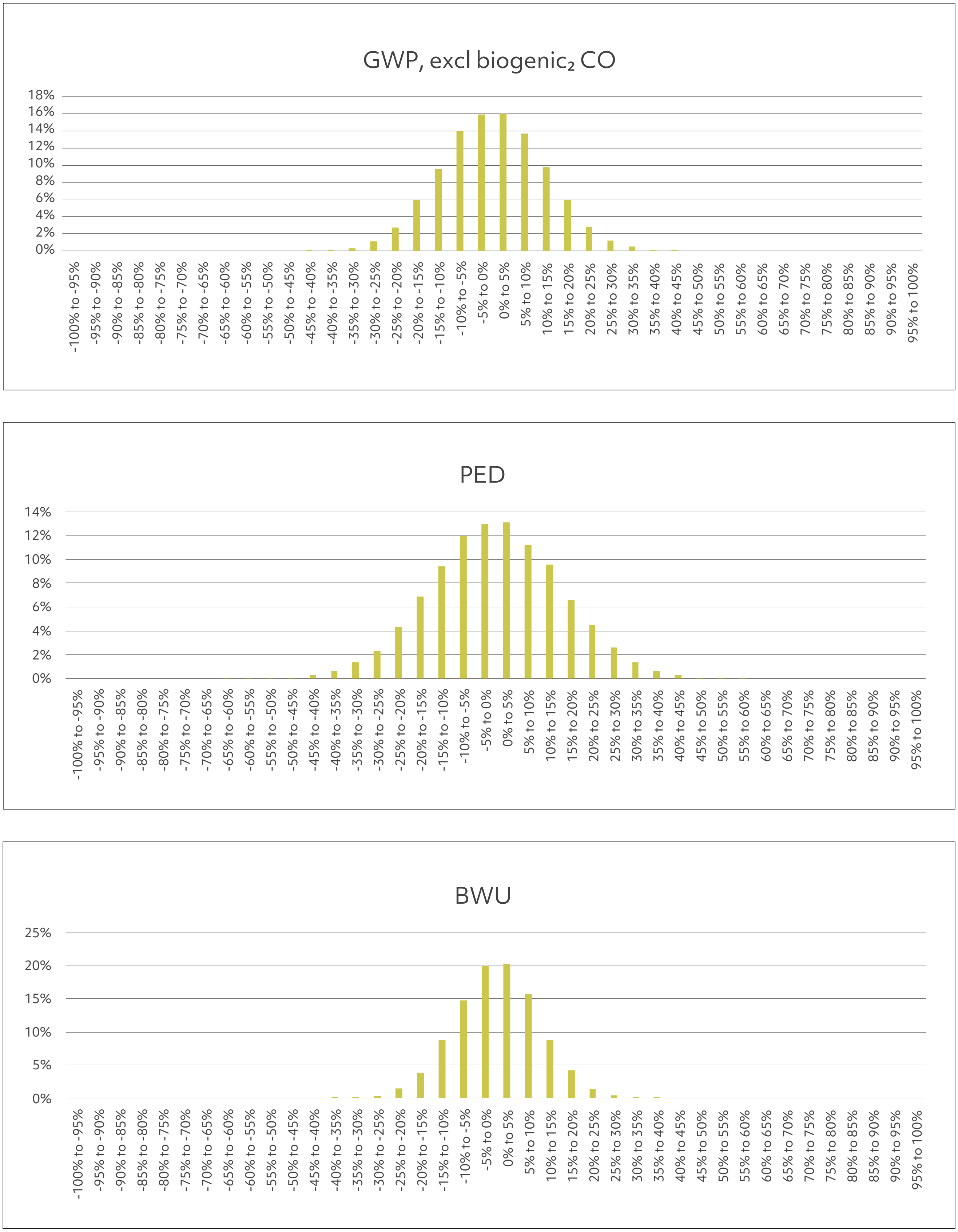
With:

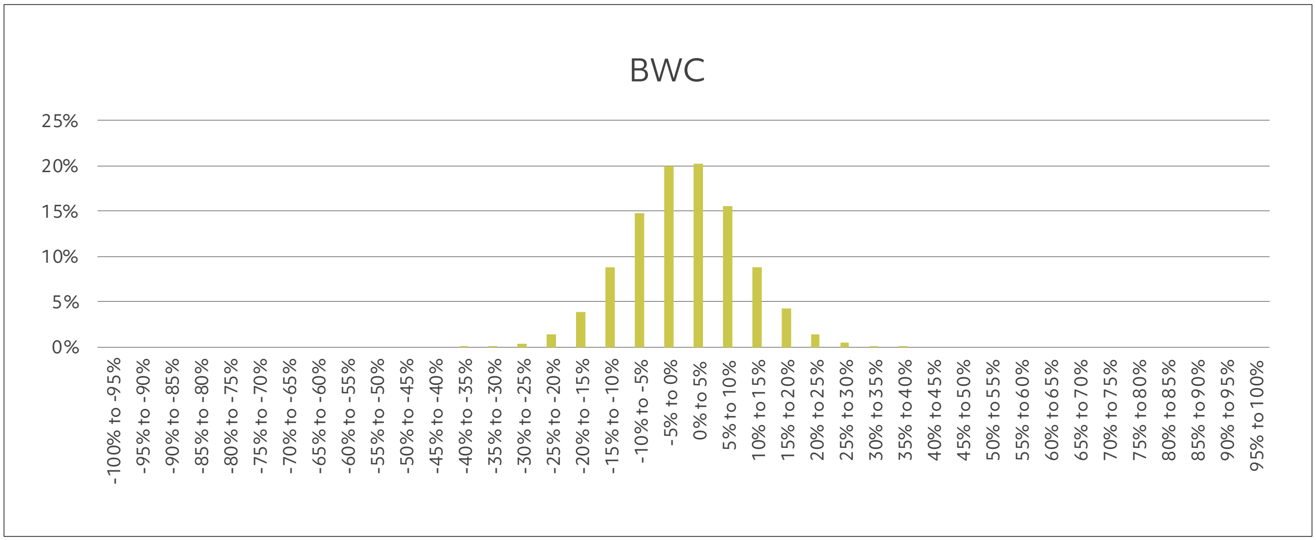
- **U1:** uncertainty factor of reliability
- **U2:** uncertainty factor of completeness
- **U3:** uncertainty factor of temporal correlation
- **U4:** uncertainty factor of geographic correlation
- **U5:** uncertainty of other technological correlation
- **U6:** uncertainty of sample size (obsolete indicator, followed recommendation and did not use)
- **Ub:** basic uncertainty factor driven by expert opinion (PRe, 2016)

The relative standard deviations (RSDs) reported in Figure 24 and Table 30, represent the quantitative output of the Monte Carlo analysis and show that RSDs generally range from approximately 5% to 20% across impact categories.

The histogram plots in Figure 24 plots the distribution of variance in impacts across the 10,000 simulations. The variance in impacts is driven by the value of input variables. The value of the input variable can vary between one standard deviation shown in Table 29. Each combination of input values generates a result that varies by a percentage from the mean.

FIGURE 24: Uncertainty analysis of individual impact categories

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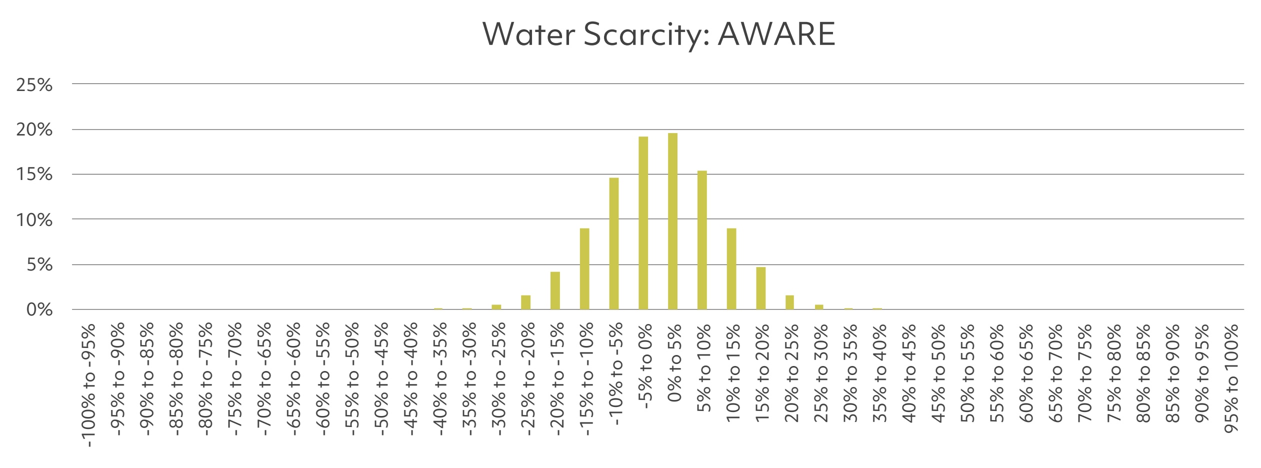
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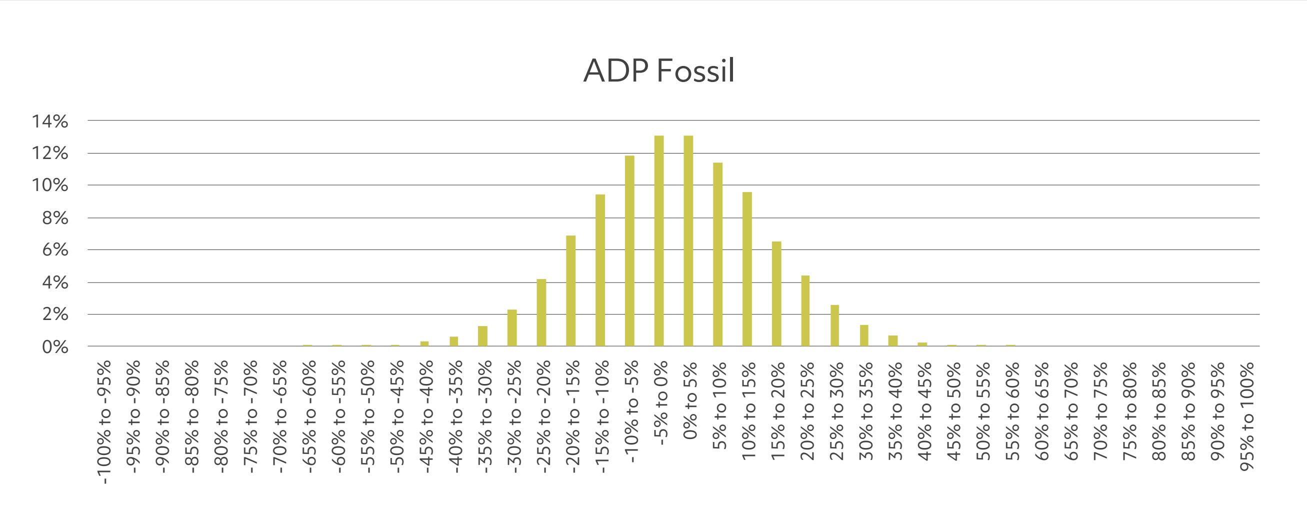
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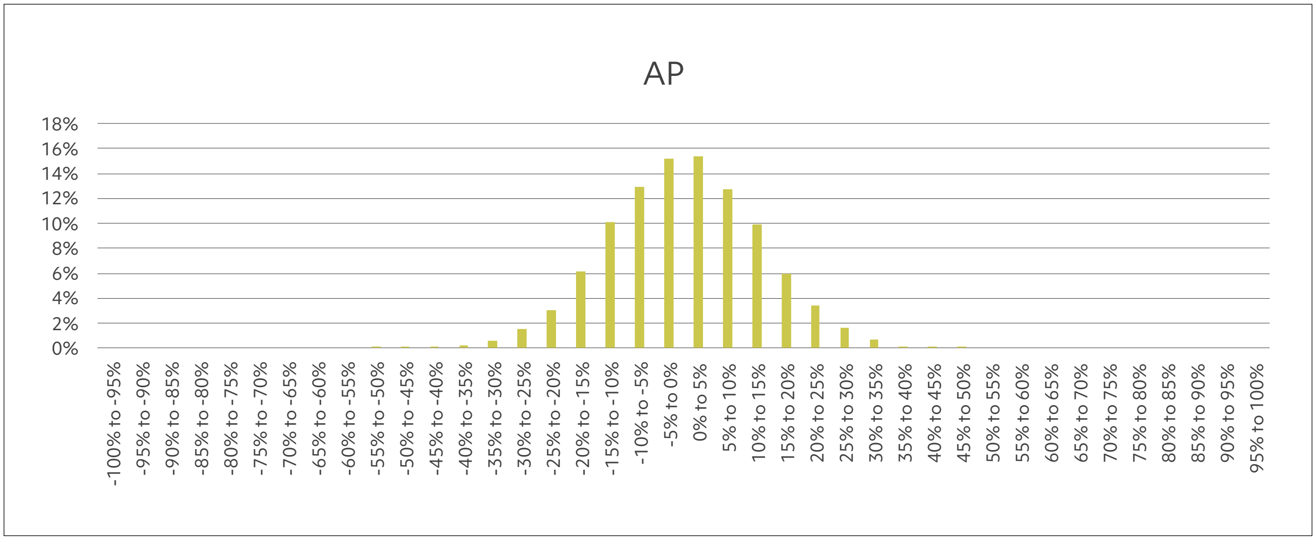
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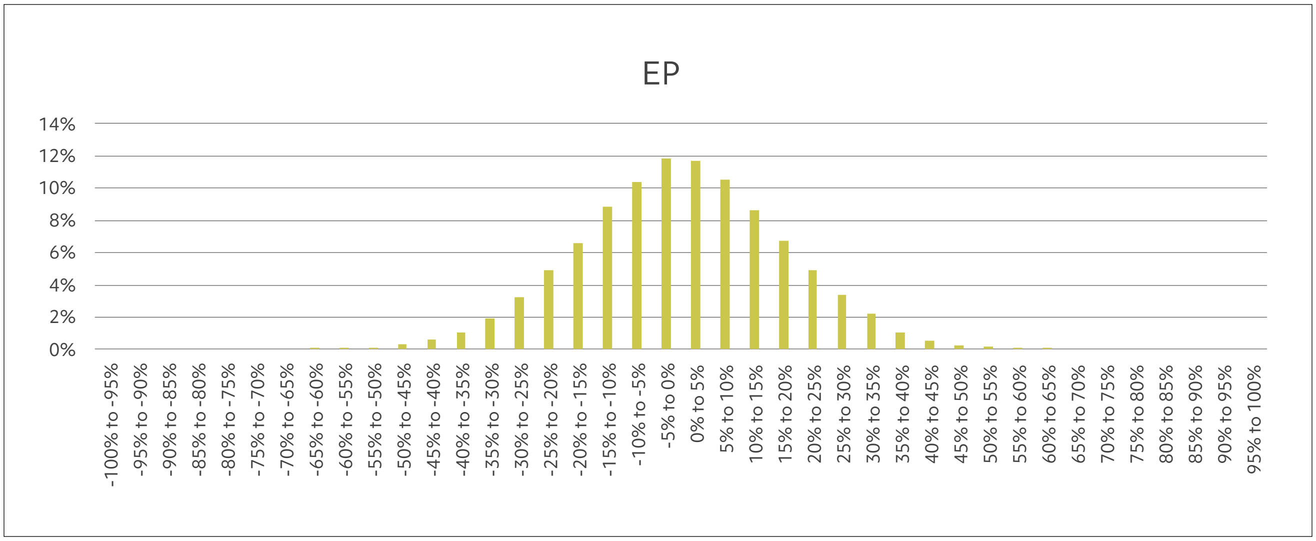
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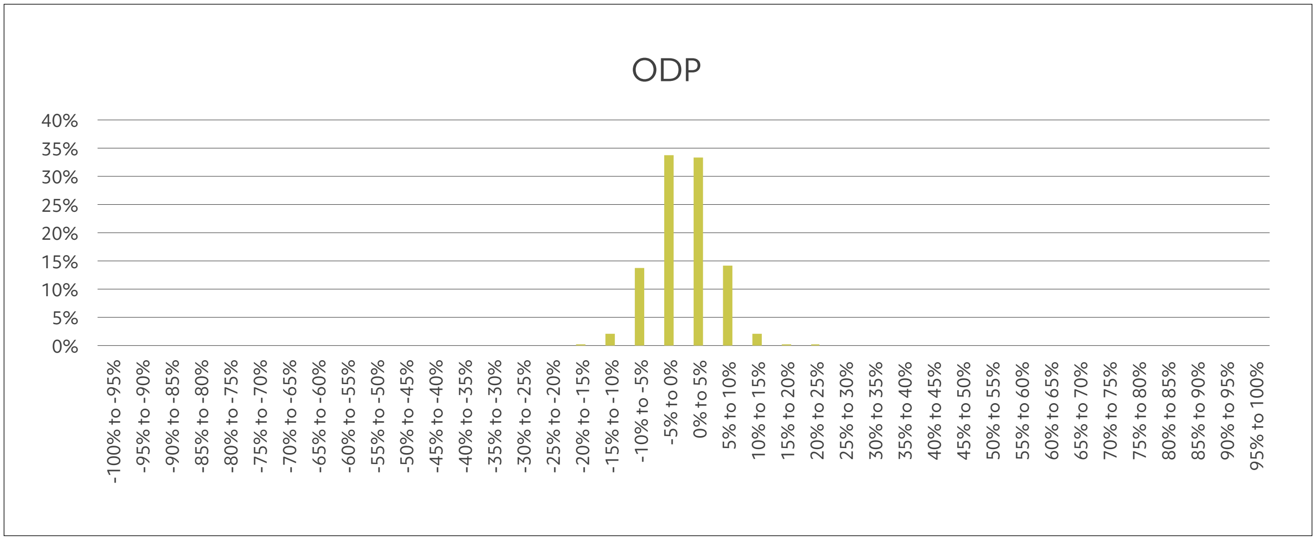
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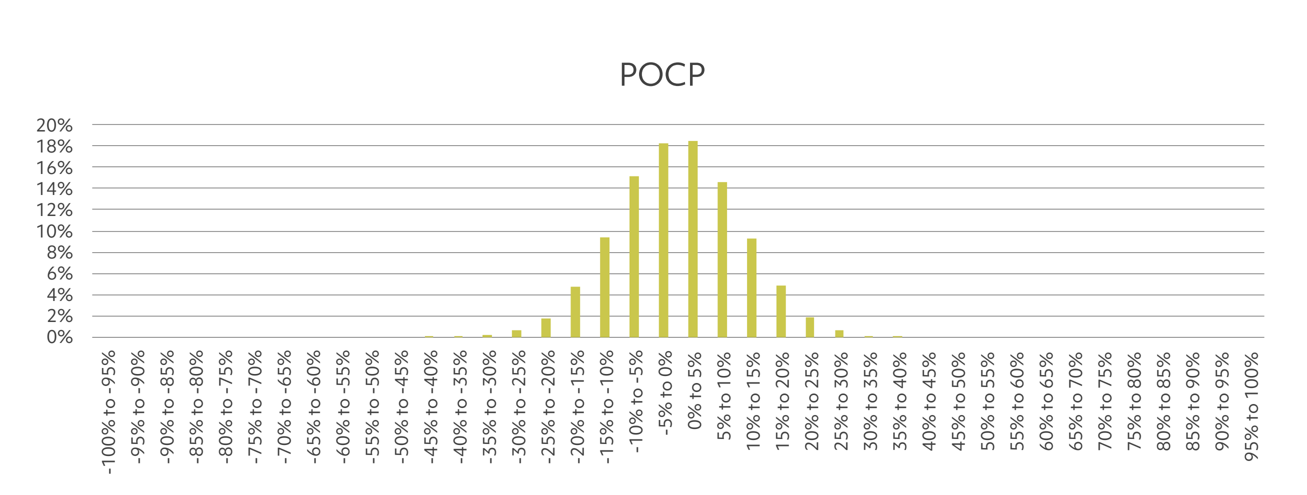
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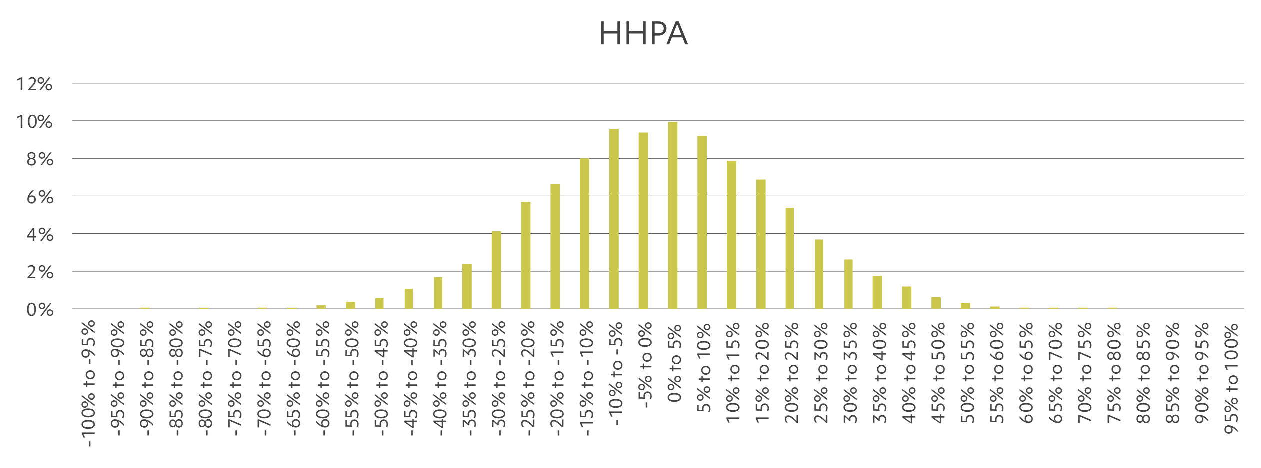
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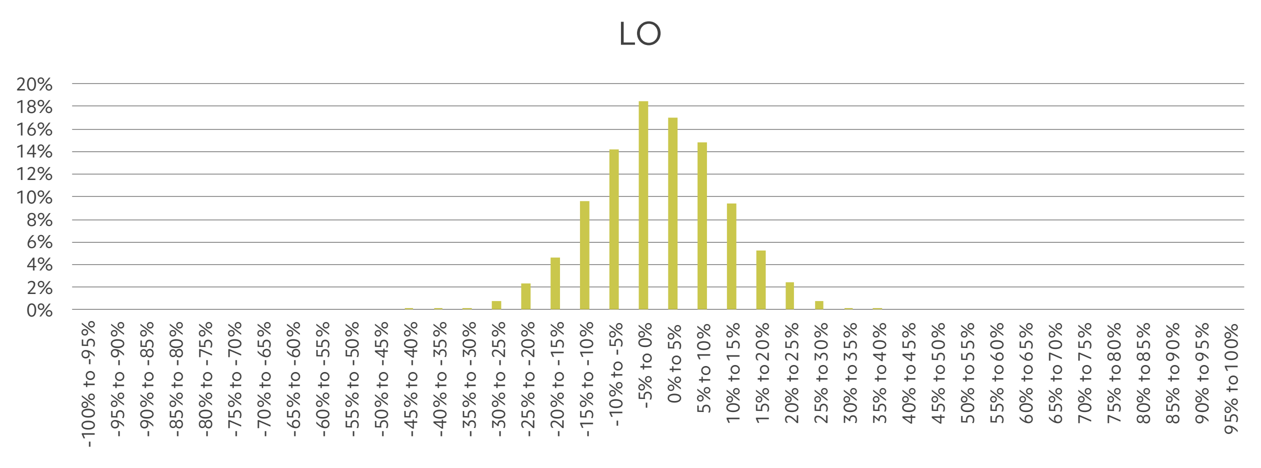
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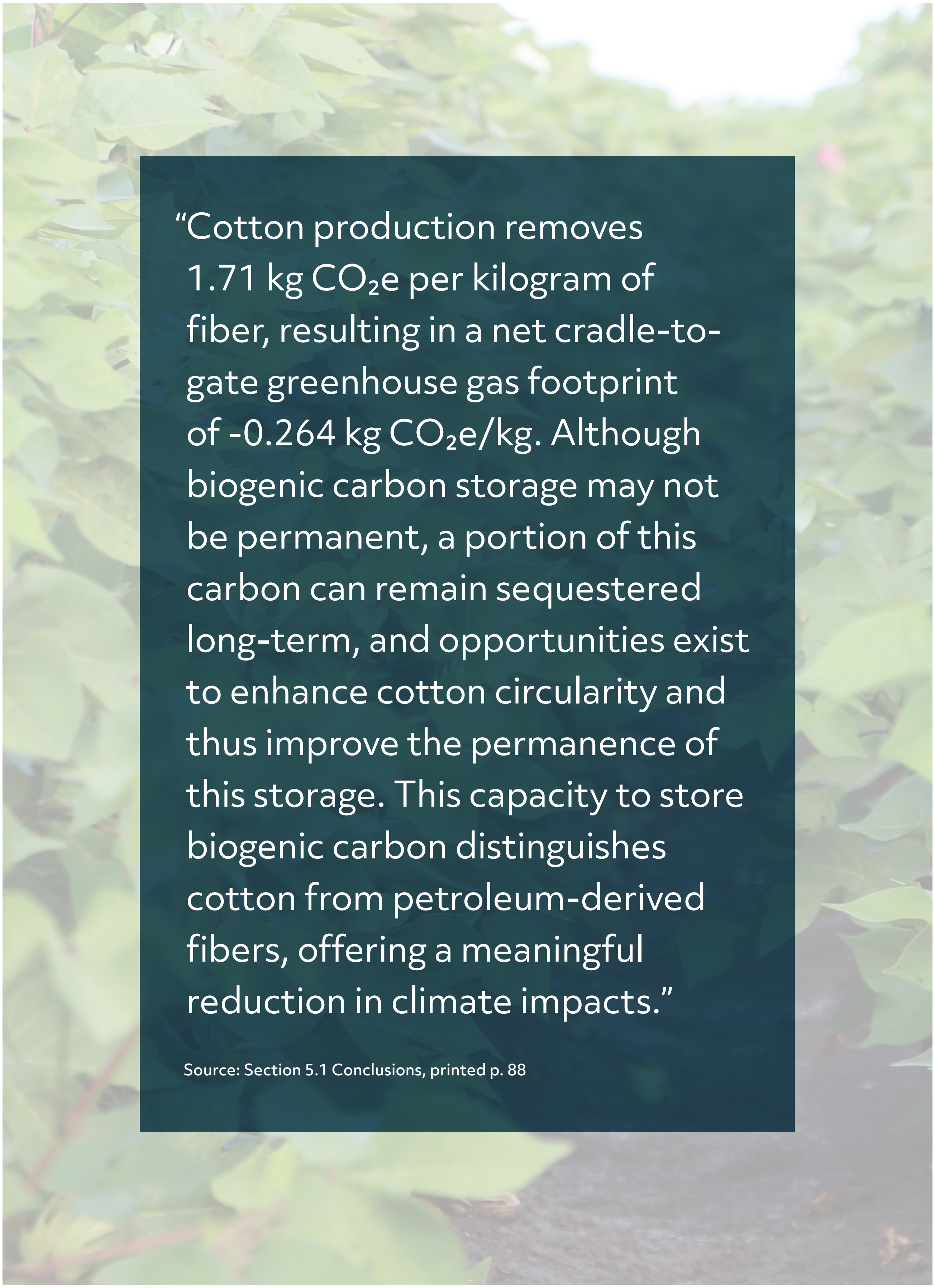
Uncertainty analysis results are further detailed in Table 30.

The methods used to estimate carbon storage in soils from cotton production and other agricultural activities, including the IPCC methods used in this study, carry high uncertainty. Soil carbon accumulation from residual cotton biomass after harvest is a substantial contributor to these results (approximately -13% of cradle-to-gate fossil emissions) and should be considered a high-level estimate.

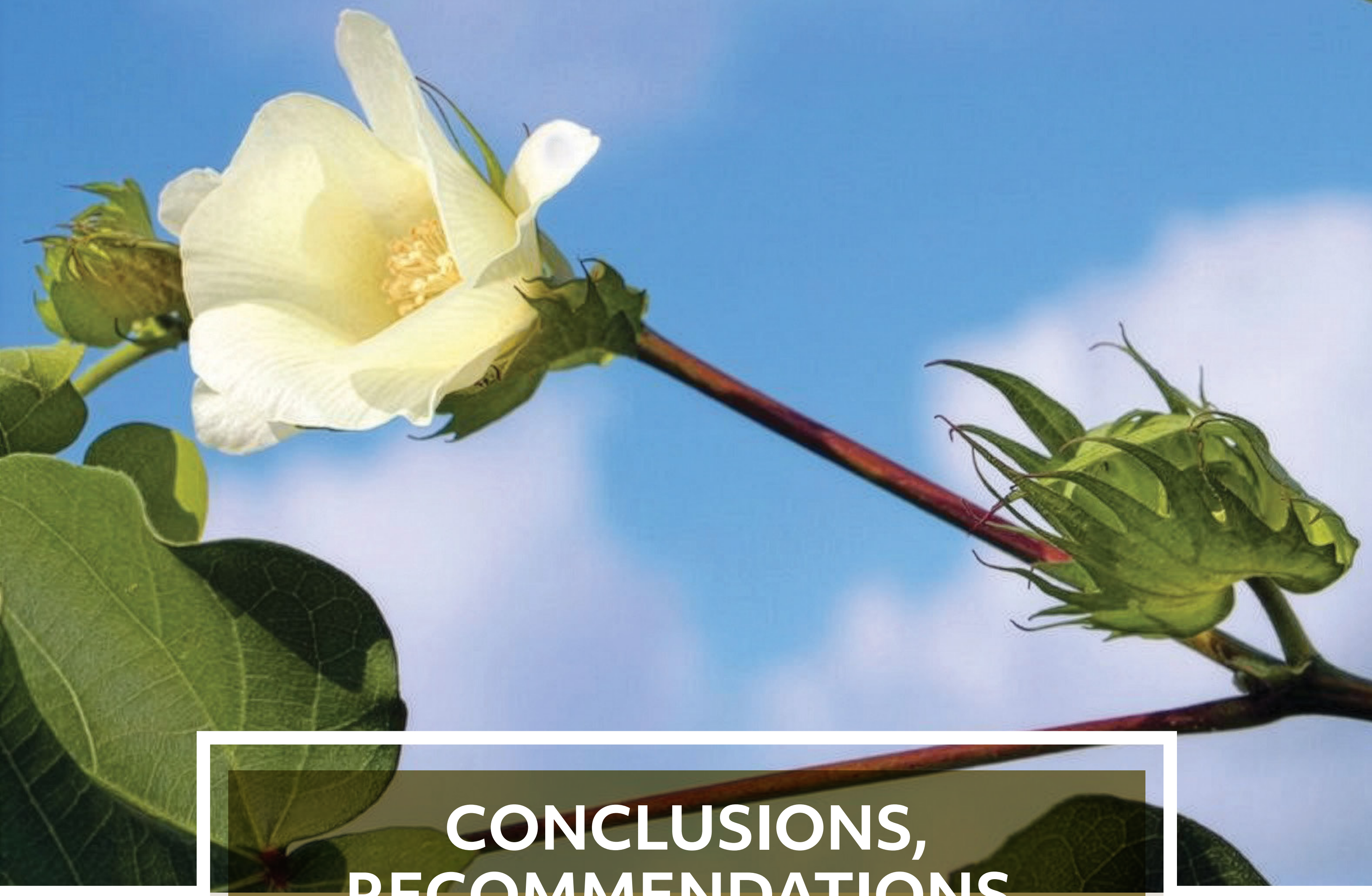
TABLE 30: Uncertainty statistics per kg of cotton fiber

Impact Category	Base scenario	Mean value	Relative Standard deviation	10% Percentile	25% Percentile	Median	75% Percentile	90% Percentile
GWP, excluding biogenic carbon dioxide (kg CO_2e)	1.45E+00	1.46E+00	12.00%	1.23E+00	1.34E+00	1.46E+00	1.57E+00	1.68E+00
LO (m_2 yr e)	9.55E+00	9.55E+00	10.8%	8.24E+00	8.84E+00	9.55E+00	1.03E+01	1.09E+01
PED (MJ)	1.79E+01	1.79E+01	15.20%	1.44E+01	1.61E+01	1.79E+01	1.97E+01	2.14E+01
AP (kgSO_2e)	4.98E-03	4.98E-03	12.80%	4.18E-03	4.56E-03	4.98E-03	5.43E-03	5.80E-03
EP (kg PO_4^{3-}e)	7.28E-03	7.28E-03	17.3%	5.67E-03	6.44E-03	7.28E-03	8.12E-03	8.90E-03
ODP (kg R11e)	2.84E-11	2.85E-11	5.09%	2.66E-11	2.75E-11	2.84E-11	2.95E-11	3.04E-11
POCP (kg Ethene e)	3.89E-04	3.89E-04	10.40%	3.38E-04	3.60E-04	3.89E-04	4.15E-04	4.40E-04
BWC (L)	1.24E+03	1.25E+03	9.62%	1.10E+03	1.17E+03	1.25E+03	1.33E+03	1.40E+03
BWU (L)	1.48E+03	1.49E+03	9.62%	1.31E+03	1.39E+03	1.49E+03	1.58E+03	1.67E+03
AWARE (m^3 world e)	4.21E+01	4.21E+01	10.0%	3.68E+01	3.94E+01	4.21E+01	4.49E+01	4.74E+01
ADP (MJ)	1.69E+01	1.69E+01	15%	1.37E+01	1.52E+01	1.69E+01	1.86E+01	2.01E+01
HHPA (kg $PM_{2.5}$e)	4.78E-04	4.78E-04	20.20%	3.55E-04	4.14E-04	4.78E-04	5.43E-04	6.01E-04



"Cotton production removes 1.71 kg CO_2e per kilogram of fiber, resulting in a net cradle-to-gate greenhouse gas footprint of -0.264 kg CO_2e/kg. Although biogenic carbon storage may not be permanent, a portion of this carbon can remain sequestered long-term, and opportunities exist to enhance cotton circularity and thus improve the permanence of this storage. This capacity to store biogenic carbon distinguishes cotton from petroleum-derived fibers, offering a meaningful reduction in climate impacts."

Source: Section 5.1 Conclusions, printed p. 88



5

CONCLUSIONS, RECOMMENDATIONS, AND LIMITATIONS

5 CONCLUSIONS, RECOMMENDATIONS, AND LIMITATIONS

5.1 Conclusions

The primary objective of this Life Cycle Assessment (LCA) was to provide an updated understanding of the cradle-to-gate environmental impacts of U.S. cotton fiber production.

The results indicated that producing 1 kg of U.S. cotton fiber generates 1.45 kg of fossil CO_2 equivalent emissions. However, when considering the biogenic carbon dioxide stored in the fiber and the soil, cotton production removes 1.71 kg CO_2e per kilogram of fiber, resulting in a net cradle-to-gate greenhouse gas footprint of –0.264 kg CO_2e/kg. Although biogenic carbon storage may not be permanent, a portion of this carbon can remain sequestered long-term, and opportunities exist to enhance cotton circularity and thus improve the permanence of this storage. This capacity to store biogenic carbon distinguishes cotton from petroleum-derived fibers, offering a meaningful reduction in climate impacts. However, the life cycle of most cotton products is less than the 100-year GWP assessment period of this study. An assessment of the cradle-to-grave life cycle GHG emissions of cotton products would include the release of carbon stored for less than 100 years.

When analyzing key impact areas (hotspots), field emissions and fertilizer production emerged as the primary contributors across multiple impact categories. Ginning significantly impacted resource-related categories due to energy use, while irrigation was the dominant factor in water-related categories. These findings align closely with the global cotton LCA published in 2017.

Sensitivity analyses highlighted that methodological choices significantly affect LCA results. Allocation methods substantially influenced outcomes: mass allocation reduced impacts by 53%, biophysical allocation by 58%, and cereal unit allocation by 24% compared to economic allocation (baseline). This underscores that the results presented represent the most conservative, worst-case scenario in terms of allocation methods. Data for all allocation methods were provided to allow greater flexibility and applicability when alternative allocation approaches may be more appropriate. Furthermore, background datasets had a substantial impact on results; for example, greenhouse gas emissions increased by 34% when switching from LCA FE to ecoinvent datasets, primarily due to differences in electricity and fertilizer emission factors. This emphasizes the inherent uncertainty of LCA results and underscores the critical importance of transparent methodological documentation to prevent inappropriate comparisons between studies.

The uncertainty analysis indicated a high statistical likelihood that baseline results typically vary +/- 5% to 20%, supporting the robustness of the overall findings despite the identified limitations.

5.2 Recommendations

To improve future LCA studies and the environmental sustainability of cotton production, the following actions are recommended:

- Enhance primary data collection, especially detailed data on nitrous oxide emissions from fertilizer application, specific fertilizer types, and precise on-farm fuel consumption.
- Promote region-specific precision agriculture practices such as optimized nutrient application, irrigation management, and soil testing to reduce environmental impacts and increase resource use efficiency.
- Support the wider adoption of conservation agricultural practices, including reduced or no-till farming and cover cropping, to improve soil health, enhance water retention, and reduce erosion.
- Improve irrigation efficiency by upgrading pumping systems and, in the longer term, transition toward renewable energy sources to further reduce greenhouse gas emissions.
- Encourage the development and use of environmentally friendly fertilizers (green[9] and blue fertilizers[10]) to decrease the environmental footprint of fertilizer production.

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[9] Green fertilizers are nitrogen fertilizers produced from green ammonia, where hydrogen is made using renewable-powered electrolysis, resulting in low-carbon nitrogen inputs (RMI, 2023).

[10] Blue fertilizers are nitrogen fertilizers produced from blue ammonia, where hydrogen is derived from natural gas but the resulting CO_2 emissions are captured and stored through CCS, lowering the carbon footprint relative to conventional production (Wood Group, 2021).

5.3 Limitations

The interpretation of the results from this study is subject to several limitations:

- The accuracy of the results is impacted by potential human errors in survey responses and reliance on secondary data models for irrigation energy and farm fuel consumption.
- The LCA focused exclusively on environmental aspects and did not evaluate social or economic dimensions, thereby limiting a comprehensive sustainability assessment.
- Variability in methodological approaches, particularly in allocation methods and the choice of background datasets, complicates direct comparisons with other LCAs.
- Plastic leakage and pollution were not considered in this study, as methods for evaluating these impacts within LCA are still under development.

There is a need to enhance primary data, especially with regards to data on nitrous oxide emissions. While this study uses existing data on fertilizer use and manure use to estimate nitrous emissions, nitrous oxide emissions data needs to be refined (e.g. to more accurately account for different fertilizer types) through a deeper research exercise to develop appropriate emission factors. This type of research is expensive and time-consuming. This LCA represents the first comprehensive and rigorously conducted assessment solely in the U.S. of cotton fiber production to date, incorporating extensive primary data collection directly from growers, making it the most detailed and data-driven evaluation conducted thus far. A wide range of scenarios and sensitivities were thoroughly explored, enhancing the depth and utility of the results. As data quality and agricultural practices continue to advance, there is significant potential for cotton to further reduce its environmental impacts and become an increasingly sustainable fiber, meeting the growing demand for lower-impact fiber and textiles.

> “This LCA represents the first comprehensive and rigorously conducted assessment solely in the U.S. of cotton fiber production to date, incorporating extensive primary data collection directly from growers, making it the most detailed and data-driven evaluation conducted thus far.”

Source: Section 5.3 Limitations, printed p. 90

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APPENDIX A:

Cottonseed LCIA Results

The primary objective of this LCA was to provide an updated understanding of cradle-to-gate impacts of U.S. cotton fiber. Those results are presented in the body of the report. Cotton fiber is a co-product of seed cotton, along with cottonseed. Table 31 below presents the cottonseed LCIA results per kg of cottonseed for all four allocation methods.

TABLE 31: Cottonseed LCIA results, per kg of cottonseed

Impacts for cottonseed per kg of cottonseed	Economic allocation	Mass allocation	Biophysical allocation	Cereal allocation
GWP, excluding biogenic (kg CO$_2$e)	2.52E-01	6.79E-01	6.83E-01	3.50E-01
GWP, including biogenic (kg CO$_2$e)	2.18E-01	5.88E-01	5.91E-01	3.03E-01
PED (MJ)	3.10E+00	8.36E+00	8.41E+00	4.31E+00
BWU (L)	8.62E-04	2.33E-03	2.34E-03	1.20E-03
BWC (L)	1.26E-03	3.40E-03	3.42E-03	1.75E-03
AWARE (m^3 world equivalent)	4.93E-12	1.33E-11	1.34E-11	6.85E-12
ADP (MJ)	6.74E-05	1.82E-04	1.83E-04	9.37E-05
AP (kg SO$_2$e)	2.16E+02	5.82E+02	5.85E+02	3.00E+02
EP (kg PO$_4^{3-}$-e)	2.57E+02	6.94E+02	6.97E+02	3.58E+02
ODP (kg R11e)	7.29E+00	1.97E+01	1.98E+01	1.01E+01
POCP (kg ethene equivalents)	2.92E+00	7.89E+00	7.93E+00	4.07E+00
HHPA (kg PM$_{2.5}$ equivalents)	8.28E-05	2.24E-04	2.25E-04	1.15E-04
LO (m^2 × yr.e)	1.65E+00	4.46E+00	4.49E+00	2.30E+00

APPENDIX B:

Custom Characterization Factors for USEtox Chemicals

TABLE 32: Custom Characterization Factors for USEtox Chemicals

	Midpoint Human health characterization factor [cases/kg emitted]				Midpoint Ecotox. Charact. factor [PAF.m^3.d/kg emitted]	
	Emission to cont. rural air		Emission to cont. freshwater		Em.airC	Em.fr. waterC
	cancer	non-canc.	cancer	non-canc.	freshwater	freshwater
ABAMECTIN	0	0.039621	0	0.143543	489691	18516837
ACETAMIPRID	0	5.63E-12	0	2.01E-15	1.4E-18	1.08E-09
AFIDOPYROPEN	0	2.01E-05	0	0.000324	196.028	7258.341
BIFENAZATE	0	3.05E-13	0	9.26E-15	8.87E-17	3.21E-07
CHLORANTRANILIPROLE	0	1.24E-12	0	3.49E-18	4.54E-19	6.09E-10
CHLORPYRIFOS	0	0.003404	0	1.49E-14	2.43E-08	8.78E-07
CLOTHIANIDIN	0	3E-11	0	1.67E-18	1.16E-18	4.84E-11
CYTOKININ (AS KINETIN)	0	3.19E-05	0	4.94E-05	64.38057	141.7549
DINOTEFURAN	0	1.08E-13	0	1.36E-18	5.27E-20	2.89E-11
ETOXAZOLE	0	1.08E-13	0	6.15E-15	1.89E-17	4.63E-07
FENPYROXIMATE	0	8.54E-14	0	7.66E-14	8.63E-17	2.88E-05
FLONICAMID	n/a	8.42E-15	n/a	4.49E-17	7.03E-22	5.29E-11
FLUPYRADIFURONE	0	5.46E-13	0	3.57E-17	7.75E-20	7.8E-11
FLUTRIAFOL	0	6.08E-13	0	8.78E-18	3.2E-19	8.05E-11
INDAZIFLAM	0	3.14E-06	0	1.04E-18	4.24E-11	1.57E-09
INDOXACARB	0	4.78E-05	0	2.47E-14	4.73E-09	1.76E-07
MEFENOXAM	0	3.57E-13	0	3.65E-17	5.43E-20	6.73E-11
METHOXYFENOZIDE	0	1.78E-12	0	0.000617	2.96E-05	35473.67
Novaluron	0	1.86E-14	0	4.93E-16	2.63E-19	2.51E-08
PYRAFLUFEN-ETHYL	n/a	6.28E-14	n/a	1.49E-15	3.26E-14	2.41E-05
SPINETORAM	0	1.46E-05	0	9.29E-17	4.12E-10	1.55E-08
SPIROMESIFEN	0	7.14E-05	0	2.9E-16	3.07E-09	1.12E-07
THIAMETHOXAM	0	4.24E-13	0	7E-18	1.02E-19	5.68E-11
2,4-D, 2-ethylhexyl ester	n/a	n/a	n/a	n/a	21.76585	6205.754

APPENDIX C:

Datasets used for Non-Elemental Flow Inputs

Table 33: Datasets used for non-elemental flow inputs

Input	LCA FE dataset	Ecoinvent 3.9.1 dataset
Farm fertilizer: Nitrogen from nitrogen fertilizer	US: Urea ammonium nitrate (UAN) US: Monoammonium phosphate (MAP)	US: market for inorganic nitrogen fertiliser, as N
Farm fertilizer: Phosphorus from phosphorus fertilizer	US: Monoammonium phosphate (MAP)	US: market for inorganic phosphorus fertiliser, as P2O5
Farm fertilizer: Potassium from potassium fertilizer	US: Potassium chloride (agrarian)	US: market for inorganic potassium fertiliser, as K2O
Farm soil amendment: Gypsum	RER: Gypsum plaster (CaSO4 beta hemihydrate) (EN15804 A1-A3)	RER: market for gypsum, mineral
Farm soil amendment: Dolomitic lime **Farm soil amendment: Lime other**	US: Limestone flour (1mm) US: Limestone flour (0.1mm)	RoW: market for limestone, crushed, washed
Farm micronutrient: Sulfur	US: Sulphur (elemental) at refinery	RER: Sulphur production
Farm diesel use: farm nutrient application, farm operations, harvest, pumping, tillage	US: Diesel, combusted in industrial equipment	US: Diesel, combusted in industrial equipment
Farm Pesticide production	GLO: Pesticide (average)	RER: pesticide production, unspecified
Farm pump energy: Natural gas	RNA: Natural gas, combusted in industrial equipment	RNA: Natural gas, combusted in industrial equipment

Input	LCA FE dataset	Ecoinvent 3.9.1 dataset
Farm pump energy: Electricity **Ginning: Electricity**	US: Electricity grid mix – AZNM US: Electricity grid mix – CAMX US: Electricity grid mix – ERCT US: Electricity grid mix – FRCC US: Electricity grid mix – RFCW US: Electricity grid mix – SPNO US: Electricity grid mix – SPSO US: Electricity grid mix – SRMV US: Electricity grid mix – SRMW US: Electricity grid mix – SRSO US: Electricity grid mix – SRTV US: Electricity grid mix – SRVC	US-MRO: market for electricity, high voltage US-RFC: market for electricity, high voltage US-TRE: market for electricity, high voltage US-WECC: market for electricity, high voltage US-SERC: market for electricity, high voltage US: market group for electricity, high voltage
Ginning: Natural gas	US: Natural gas, combusted in industrial boiler	US: natural gas, burned in gas turbine
Ginning: LPG	US: Liquefied petroleum gas, combusted in industrial boiler	US: natural gas, burned in gas turbine adapted to LPG
Packaging	US: Polyethylene terephthalate bottle grade granulate (PET) via PTA US: Aluminum ingot, production mix, at plant	RER: polyethylene terephthalate production, granulate, bottle grade GLO: aluminium ingot, primary, to aluminium, cast alloy market
Transportation	US: Truck - Medium Heavy-duty Diesel Truck/22,000 lb payload – 7 US: Diesel mix at filling station	RER: transport, freight, lorry 7.5-16 metric ton, EURO3

Appendix D:
Critical Review Statement

Harmony Environmental, LLC
Management • Analysis • Communication
Beyond Sustainability, Striving for Harmony

Critical Review Statement

Date: January 12, 2026

LCA Commissioned by: Cotton Incorporated

LCA Conducted by: Shelly SeveringhausWSP
1300 SW 5th Ave
31ST Floor
Portland, OR 97201 USA

Report Title: Life Cycle Assessment of United States Cotton Fiber Production

Panel Review Conducted by: Terrie K. Boguski, Harmony Environmental, LLC (Chair)
Allan Williams, Cotton Research and Development Corporation
Joël Mertens, Cascale

ISO Referenced Standards: ISO 14040:2006; ISO 14044:2006+Amd1:2017+Amd2:2020;
ISO/TS 14071:2024

Critical Review Process, Scope and Conclusion

In accordance with the international standard, ISO 14044:2006, a 3-person review panel conducted a Critical Review of the life cycle assessment (LCA) report, Life Cycle Assessment of United States Cotton Fiber Production. The cradle-to-gate attributional LCA report developed a detailed U.S. average life cycle inventory (LCI) for cradle-to-gate (seed-to-bale) cotton fiber for use in LCA databases, to fill data gaps, and to conduct an LCA to evaluate environmental impacts to help track continual improvement. Additionally, this study assessed the biogenic carbon dioxide of on-farm operations of U.S. cotton production. The critical review was an end-of-report review, and reviewers received the entire draft report. Review was based on the stipulations in ISO 14044. The review followed guidance in ISO 14071:2024.

The reviewers received the draft report on May 22, 2025 and provided initial comments on June 12, 2025. The reviewers received the revised report on November 21, 2025. The review panel met with the LCA practitioner on December 11, 2025 to discuss the revised report. One additional round of review and comments was completed. All significant comments regarding conformity to ISO 14044 were addressed, and all open issues resolved. The review was primarily conducted by exchanging comments and responses via email. Comments were recorded in an Excel spreadsheet in tabular format based on Annex A of ISO/TS 14071:2024.

The findings of the panel concluded that all required stipulations in ISO 14044:2006 6.1 were met in the revisions to the report (final version dated January 2026). In particular,

- The methods used to carry out the LCA are consistent with this International Standard,
- The methods used to carry out the LCA are scientifically and technically valid,
- The data used are appropriate and reasonable in relation to the goal of the study,
- The interpretations reflect the limitations identified and the goal of the study, and
- The study report is transparent and consistent.

The reviewers did not have access to LCA calculations, underlying data or models. Therefore, the review is primarily limited to the summary data and model results included in the report. Completing the critical review does not mean that the reviewers endorse the results of the LCA study, nor does it mean that they endorse any of the assessed products. Opinions of the reviewers do not necessarily represent the position or policy of their respective organizations.

ISO 14044:2006 requires that this critical review statement, as well as the reviewer's comments and any responses to recommendations made by the reviewers be included in the final LCA report.

Submitted on behalf of the Peer Review Panel by

Terrie Boguski

Terrie Boguski

Attachment: ISO 14044 review comments-CottonInc-2026-01-09-FINAL PDF

Report version: 1.0
Report date: January 2026
WSP USA Inc.

On behalf of WSP USA Inc.

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