# LCA UPDATE OF COTTON FIBER AND FABRIC LIFE CYCLE INVENTORY

Cotton Incorporated

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*On behalf of thinkstep AG and its subsidiaries*

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*If you have any suggestions, complaints, or other feedback, please contact Cotton Incorporated at JPruden@cottoninc.com.*

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# LIST OF ACRONYMS

| | |
|---|---|
| AATCC | American Association of Textile Chemists and Colorists |
| ABA | Agribusiness Associates |
| ADP | Abiotic Resource Depletion Potential |
| AP | Acidification Potential |
| APEX | Agricultural Policy/Environmental eXtender model |
| ASABE | American Society of Agricultural and Biological Engineers |
| BWC | Blue Water Consumption |
| BWU | Blue Water Use |
| CML | Centre of Environmental Science at University of Leiden |
| CRDC | Cotton Research and Development Corporation |
| CTUh | Comparative toxic units [for humans] |
| DOE | Department of Energy |
| ELCD | European Life Cycle Database |
| EoL | End-of-Life |
| EP | Eutrophication Potential |
| EPIC | Environmental Policy Integrated Climate |
| ET | Evapotranspiration |
| ETP | Ecotoxicity Potential |
| GaBi | Ganzheitliche Bilanzierung (German for holistic balancing) |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| HHPA | Human Health Particulate Air |
| HTC | Human Toxicity, Cancer |
| HTNC | Human Toxicity, Non-Cancer |
| ILCD | International Life Cycle Data System |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| $NH_3$ | Ammonia |
| NMVOC | Non-Methane Volatile Organic Compound |
| $N_2O$ | Nitrous Oxide |
| $NO_3$ | Nitrate |
| NRCS | Natural Resources Conservation Service (a division of USDA) |
| NRS | Natural Resource Survey |
| ODP | Ozone Depletion Potential |
| PAF | Percent Affected Fraction |
| PED | Primary Energy Demand (incl. biogenic carbon) |
| PM2.5 | Particulate Matter (>2.5 um size) |
| POCP | Photochemical Ozone Creation Potential |
| $PO_4$ | Phosphate |
| USEtox™ | UNEP (United Nations Environmental Programme)/ SETAC (Society of Environmental Toxicology and Chemistry) Toxicity Model |
| USDA | United States Department of Agriculture |
| SFP | Smog Formation Potential |
| VOC | Volatile Organic Compound |
| WSF | Water Scarcity Footprint |

# GLOSSARY

## Allocation

"Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040:2006, section 3.17).

## Background system

"Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good…." (JRC 2010, pp. 97-98). As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

## Closed-loop and open-loop allocation of recycled material

"An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties."

"A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials."

(ISO 14044:2006, section 4.3.4.3.3)

## Critical Review

"Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment" (ISO 14044:2006, section 3.45).

## Foreground system

"Those processes of the system that are specific to it … and/or directly affected by decisions analyzed in the study" (JRC 2010, p. 97). This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

## Functional unit

"Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20).

## Life cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land, and water.

## Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2).

## Life Cycle Inventory (LCI)

"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 14040:2006, section 3.3).

## Life Cycle Impact Assessment (LCIA)

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14040:2006, section 3.4).

## Life cycle interpretation

"Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 14040:2006, section 3.5).

# EXECUTIVE SUMMARY

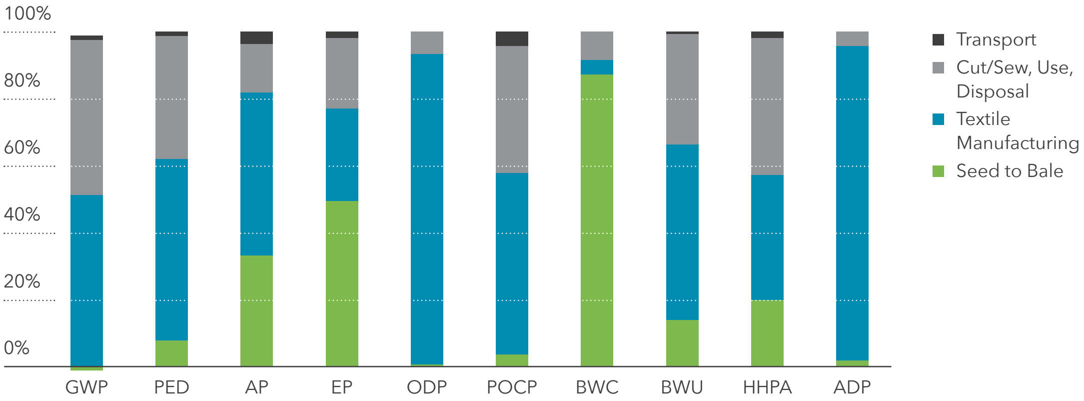
Life Cycle Assessment (LCA) allows the holistic examination of the environmental impacts and resource utilization of a product, from the raw materials used in its creation to its disposal at the end-of-life. A fundamental component of LCA is the Life Cycle Inventory (LCI), a quantification of relevant energy and material input and environmental release data associated with the manufacturing and other processes. The primary purpose of this project was to provide robust and recent LCI data for global cotton fiber production and textile manufacturing ensuring that cotton is accurately represented in LCAs, as well as to provide an update to a similar study completed in 2010. Additionally, Life Cycle Assessments (LCAs) were performed to evaluate the environmental impacts of three cotton garments: t-shirt, knit casual collared shirt, and woven casual pant. The study was conducted according to the principles of the ISO 14040 series and subjected to a critical review.

The LCA was divided into three primary phases: agricultural production (seed to production of a bale of fiber from the gin), textile processing (bale to fabric to cut-and-sew), and use (consumer use and disposal). Agricultural data were collected from the United States, India, China, and Australia to represent average production conditions from 2010 to 2014. These countries represented the top three cotton producing and cotton exporting countries during the study period. In an effort to collect the best quality data, textile mills that have relationships with Cotton Incorporated account representatives were selected based on the products that they manufacture, their level of vertical integration, and their location. Countries and regions of interest (South/Central Asia, East Asia, Eurasia, and Latin America) were identified based on world textile manufacturing volume. Consumer use behavior data were collected by Cotton Council International and Cotton Incorporated using an international, third party market research company to survey respondents in the uppermost consuming countries regarding their use and laundering practices for t-shirts, knit casual collared shirts, and casual woven pants. The survey was conducted from May through June 2015 in the United States, China, Japan, and the European Union.

When the entire cotton life cycle is considered, the textile manufacturing and consumer use phases dominate most of the impact categories despite the product type, as illustrated in Figure ES-1 for the knit collared casual shirt. This is due primarily to garment laundering and high electricity use in fiber processing, and energy expenditures related to conditioning, processing, heating, and eventual drying of water during the preparation, dyeing, and finishing processes. Although agricultural production's contribution to total impact was lower than the consumer use and textile manufacturing phases in most categories, water consumption, eutrophication, acidification, and field emissions associated with nitrogen fertilizer, irrigation, and ginning were identified as major contributors to overall impact.

Continued improvement in the cotton garment production system should focus on several areas within the supply chain. For water consumption and eutrophication, cotton irrigation and fertilizer use within the cotton cultivation process are key parameters which should be further optimized. The textile manufacturing phase contributed the most to all but two impact categories due to high energy usage and use of various process chemicals. Textile manufacturing optimization should focus on energy efficiency, use of cleaner energy sources, and use of more environmentally friendly process chemicals and processes to create finished fabric. The use phase also contributed significantly to most impact categories. Use phase impacts are dominated by consumer use due to laundering. Use phase impact reductions can be made through the modification of laundering behavior by switching from machine drying to line drying, using cold wash water with appropriate detergents, and using more efficient washing machines.

FIGURE ES-1: Relative contribution to each impact category for knit collared casual shirt.



# 1

# GOAL OF THE STUDY

The purpose of this project was to develop and publish detailed global average Life Cycle Inventories (LCIs) for cradle-to-grave production of cotton fiber and fabric. Additionally, Life Cycle Assessments (LCAs) are performed to evaluate the environmental impacts of these LCIs and of cotton garments, specifically t-shirts, knit casual collared shirts, and woven casual pants. Cotton Incorporated commissioned thinkstep to perform these analyses according to the principles of the ISO 14040 series.

LCA is a demonstrated method to objectively and scientifically evaluate the resource requirements of a product and its potential impact on the environment during every phase of its production, use, and disposal. The LCA approach was utilized in initial studies undertaken by the cotton industry to evaluate the environmental impact of farming practices and textile production systems. The initial work led to a greater understanding of how the industry could lower its energy use, carbon emissions, and other environmental impacts. The current study was undertaken to identify additional opportunities for improvement and to ensure that accurate, up-to-date LCI data are available for those evaluating cotton products across the supply chain.

Cotton Incorporated's Agricultural and Environmental Research and Corporate Strategy and Program Metrics divisions were responsible for data collection and quality checks of cotton production and consumer data, respectively. Textile data were collected by the Global Supply Chain Management and the Product Development and Implementation (PDI) divisions. In addition, textile experts from the PDI division quality checked the data submitted by the textile mills. A detailed list of Cotton Incorporated contributors can be found in Appendix H: Cotton Incorporated Contributors.

The goals of this study were to:

1. Support users of cotton and cotton derived products with current and accurate Life Cycle Inventory (LCI) data for cotton fiber production and textile processing.
2. Collect global consumer use data for assessment and decision making.
3. Provide a life cycle assessment of textile products (knit casual collared shirt, t-shirt, and casual woven pants).
4. Monitor progress and measure changes for continuous improvement.
5. Guide decisions about current research priorities and new research initiatives.

Internal stakeholders include those involved in research, marketing and communications, in operations (with the goal of process improvements), and in design (with the goal of design improvements). External stakeholders include importers, suppliers, and other industry players.

Although the objectives of this LCA do not include comparative assertions, the LCI results will be incorporated into searchable LCI databases. Therefore, to ensure the highest level of quality and credibility, a critical review of the study was conducted per Section 7 of ISO 14040.

# 2

# SCOPE OF THE STUDY

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

## **2.1** PRODUCT SYSTEM(S)

The products under study include three basic apparel items made from 100% cotton fabric: a knit t-shirt, a knit collared casual shirt, and woven casual pants. The knit collared casual shirt and woven casual pants are the same products as studied in the 2010 LCA, only the garment descriptions were updated from “golf shirt” and “khaki pants” in order to reflect terms that are more globally-recognizable. In addition to the products included in the last study, a knit t-shirt was added to the scope in response to frequent requests and to reflect the purchasing behavior of the expanded consumer use regions. While only the United States was considered in the consumer use phase in the previous study, consumer behavior scenarios were expanded to include use in Asia and Europe. According to research from CCI & Cotton Incorporated’s Global Lifestyle Monitor™, t-shirt ownership is significantly higher than other top/shirt categories owned (dress shirts, casual shirts, and active shirts).

The base fabric for each of the three products was produced from 100% cotton fiber. Various dyes and finishes may have been added for style effects and performance features, such as applying a stain-resistant finish to the fabric. The fabric for the knit collared shirt was specified to be a single pique knit fabric for the body of the garment and sleeves. A ribbed knit fabric was used to construct the neck and sleeve trim. Additionally, two buttons made from polyethylene copolymer were part of the construction. The t-shirt body, sleeves, and pocket were constructed from a single jersey knit fabric. The casual woven pants were constructed from a 7.5 ounces/square yard twill fabric for the base fabric, belt loops, and back pockets. Additionally, three polyethylene copolymer buttons and a metal zipper were part of the functional design. Pocket liners were constructed from a woven polyester twill fabric. These product specifications were chosen to reflect an average product for each of the studied garments.

## **2.2** PRODUCT FUNCTION(S) AND FUNCTIONAL UNIT

The scope of the study is the cradle-to-grave production of cotton products. The major functional units are separated for knit and woven fabrics, and an intermediate functional unit is also defined as:

- 1,000 kg of fiber; and
- 1,000 kg of finished garments.

For this study, it is assumed that a knit casual collared shirt weighs on average 305 g; for the functional unit of 1,000 kg finished garments, this represents 3,278 shirts. This study assumes that a knit t-shirt weighs on average 215 g; for the functional unit of 1,000 kg finished garments, this represents 4,651 shirts. It is assumed that a pair of woven casual pants weighs on average 488 g; for the functional unit of 1,000 kg finished garments, this represents 2,049 pairs of casual pants.

FIGURE 2-1: Life cycle system boundaries and functional units.

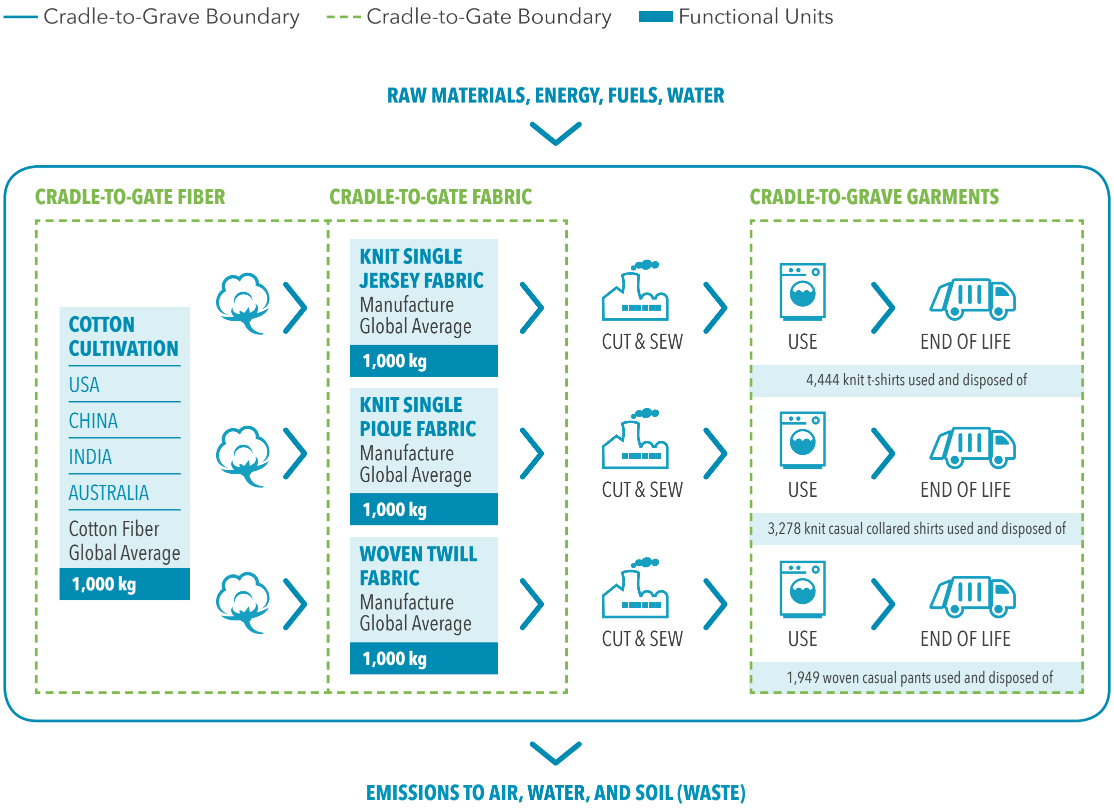


TABLE 2-1: System boundaries.

| Included | Excluded |
|---|---|
| ✓ Cotton growth, cultivation, and ginning | ✗ Human labor |
| ✓ Ancillary material production (dyes, chemicals, etc.) | ✗ Construction of capital equipment |
| ✓ Energy and emissions for fabric production, including facility overhead | ✗ Maintenance and operation of support equipment |
| ✓ Energy and materials for garment creation (cut-and-sew) | ✗ Production and transport of packaging materials |
| ✓ Transport of intermediate and finished products | ✗ Transport from retail to customer |
| ✓ Transport of finished fabric for cut-and-sew | |
| ✓ Fabric use phase washing and drying (in homes only –no dry cleaning considered) | |
| ✓ Fabric end-of-life | |
| ✓ Ecotoxicity Potential | |
| ✓ Human Toxicity Potential | |

## 2.3 SYSTEM BOUNDARIES

The cradle-to-grave LCI for global average fiber covers raw material production from field through ginning. The impacts are calculated for a functional unit of 1,000 kilograms (kg) of fiber. The cradle-to-gate LCIs for global average fabric take the fiber LCI through yarn formation, knitting or weaving, dyeing, finishing, and compacting or sanforizing. The impacts for fabric manufacturing are calculated for a functional unit of 1,000 kg of knit fabric or 1,000 kg of woven fabric, as appropriate. Cradle-to-grave LCA results evaluate the impacts of 1,000 kg of knit casual collared shirts, 1,000 kg of knit t-shirts, and 1,000 kg of woven casual pants through use and disposal. Primary data was collected for the agriculture production, textile manufacturing, and garment use and end-of-life (EoL) phases. Secondary data were used for the cut-and-sew portion of the supply chain. System boundaries are shown in Figure 2-1.

### 2.3.1 Time Coverage

Primary data was collected by Cotton Incorporated through partnerships with researchers, industry, and cooperators and represents the years 2010 to 2014 (agricultural data), 2014 to 2015 (textile data), and 2015 (consumer use data). Agricultural data were collected over a range of years to average out seasonal and short-term weather events such as droughts and floods. With the practical limitations in obtaining proprietary inputs and outputs for a sufficient number of mills in both knits and wovens in the dominant manufacturing countries, textile data collection was limited to only twelve months prior. Consumers were surveyed from May to June 2015 regarding their current use, laundering, and disposal habits. Additional data necessary to model base material production and energy use were adopted from the GaBi ts software system database and are described further in Appendix C: Life Cycle Inventory Databases. Based on knowledge of industry developments, it is assumed that the results are generally valid for a minimum of the next 5 years.

### 2.3.2 Technology Coverage

Data were collected for representative technologies in each region. Growth of cotton was modelled in GaBi ts with the thinkstep agricultural model to appropriately consider the parameters of the different growing systems and to be consistent with the 2010 LCA. For fabric production, representative mills were chosen in each region based on their technology, verticality, and data availability. With many possible unit process paths, the most representative specific combination of processes is evaluated for each country, providing nation-aggregated LCIs, but giving flexibility to consider alternate production paths within the specific technologies of each country.

Ancillary and process material data, such as the production of chemicals, fuels, energy, and power, were adopted as average industry mixes from the GaBi ts software system database (current release GaBi ts, http://www.gabi-software.com). The list of raw materials and corresponding datasets used is described in Annex C: Life Cycle Inventory Datasets.

### 2.3.3 Geographical Coverage

The geographical coverage for this study is as follows:

- Cotton growth & cultivation
  - United States (Far West, Southwest, Mid-south, & Southeast)
  - China (Xianjiang or Northwest, Yellow River, & Yang Tse) with a concentration on the Northwest
  - India (North, Central, & South)
  - Australia
- Cotton fabric manufacture
  - Eurasia
  - Latin America
  - South and Central Asia
  - East Asia
  - Raw & ancillary material production (United States & Europe)
- Consumer use of textiles and end-of-life
  - United States
  - Europe (United Kingdom, Italy, & Germany)
  - China
  - Japan

Cotton growth and cultivation data collection was determined based on the top cotton producing and exporting countries. According to the USDA, the top three cotton-producing countries are China, India, and the United States (67% of world's production in 2014) and the top three exporting countries were the United States, India, and Australia (28% of global exports) for the time period that the data collection represents (USDA, 2015a).

The cotton fabric manufacturing data included yarn production, fabric production, and preparation, dyeing, and finishing operations. Due to the sensitive and detailed data required from mills, companies were chosen based on knowledge of manufacturing processes and relationships with account representatives from Cotton Incorporated. According to ITMF data, Asia is the leading producer of yarn, woven fabric, and knit fabric based on spindles installed and machinery shipments. (ITMF, 2012) Countries in Latin America were included to provide a more global look at the environmental effects of textile manufacturing, which is prone to location shifts as changes in trade policy and labor costs occur.

Europe and the United States were the regions included for raw and ancillary material production. According to the World Trade Organization's International Trade Statistics 2014, the European Union and the United States are the top importing and exporting regions for chemicals. (WTO, 2014)

For the consumer use and EoL data collection, the United States, the European Union, China, and Japan were chosen based on consumption of apparel products.

## 2.4 ALLOCATION

### 2.4.1 Multi-output Allocation

Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step is applied and documented along with the process in Chapter 3.

Allocation of background data (energy and materials) taken from the GaBi 2016 databases is documented online at http://documentation.GaBi-software.com/.

When a process yields more than one valuable output, environmental burden is shared between the different co-products. A notable need for allocation is in the growth of cotton plants. Two valuable co-products come from this system: cotton fiber and seeds. Data from USDA (2015c) were used to establish the average ratio of seed to fiber production in the United States from 2010 to 2014. This ratio was determined to be 1.4. The same data set provided that the price of seed was $0.11 per pound and fiber was $0.80 per pound for the same time period. Therefore, total value of a pound of fiber was $0.80 plus the seed value of 1.4 *$0.11 for a total value of $0.95. Thus 16% of the economic value of the harvested crop is in the seed, so the burdens of producing the crop at the ginning process and upstream are split based on the ratio of the average economic value of both seeds and fiber over the years 2010 to 2014 to account for seasonal and market fluctuations. Data from NBS (2015) were used to verify that this value was also representative of cotton production in China, therefore the 16% value was assumed to represent global average conditions.

During the manufacture of fabric, short fibers, and noils were produced as valuable co-products and sold offsite. An economic allocation of impact to these flows was deemed reasonable because the fibers are used in the same production system of textile manufacturing and the noils are too valuable to be considered waste (approximately $1.00 per kg compared to $1.50 per kg for fiber). Throughout the textile manufacturing unit processes, waste flows recycled internally or sold offsite were treated as byproducts and were cut off from the system boundaries.

Allocation was used in creation of upstream datasets in the GaBi database, such as refinery products. Documentation for upstream data can be provided upon request. No allocation was applied in the consumer phase.

### 2.4.2 End-of-Life Allocation

End-of-life (EoL) allocation generally follows the requirements of ISO 14044, section 4.3.4.3. The EoL allocation has been altered from the previous LCA. Several factors led to this decision. The previous LCA studied consumer use and EoL in the United States only, where survey respondents indicated that a vast majority of clothing is reused or donated to charity at the end of the garment's first life. However, this study has been expanded to include consumption in countries where disposal is significantly more likely to occur. In addition, the EoL assumption has been increased to 100 years for this study, and is not limited to the end of the first life for the garment. Therefore, it is assumed that in that time period, a majority of articles will be disposed of through either landfilling or incineration. The landfill and incineration rates for each country studied were used to allocate the burden to the appropriate disposal method based on typical practices for each country or region.

Energy recovery & landfilling (cut-off approach): Any open scrap inputs into manufacturing remain unconnected. The system boundary includes the waste incineration and landfilling processes following the polluter-pays-principle. In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, and landfill gas capture as well as utilization rates (flaring vs. power production). No credits for power or heat production are assigned.

## 2.5 CUT-OFF CRITERIA

The following cut-off criteria were used to ensure that all relevant environmental impacts were represented in the study:

- **Mass:** If a flow is less than 1% of the cumulative mass of all the inputs and outputs of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- **Energy:** If a flow is less than 1% of the cumulative energy of all the inputs and outputs of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- **Environmental relevance:** If a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it is evaluated with proxies identified by chemical and material experts within Cotton Incorporated and from thinkstep. If the proxy for an excluded material has a significant contribution to the overall LCIA, more information is collected and evaluated in the system.

The sum of the neglected material flows shall not exceed 2% of mass or energy. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts. The choice of proxy data are documented in Chapter 3. The influence of these proxy data on the results of the assessment has been carefully analyzed and is discussed in Chapter 5.

## **2.6** SELECTION OF LCIA METHODOLOGY AND IMPACT CATEGORIES

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-2 and Table 2-3. Various impact assessment methodologies are applicable for use in the European context including, e.g., CML, ReCiPe, and selected methods recommended by the ILCD. This assessment is predominantly based on the CML impact assessment methodology framework (CML 2001 update April 2013). CML characterization factors are applicable to the European context, are widely used and respected within the LCA community, and are required for Environmental Product Declarations under EN 15804.

Global warming potential, including biogenic carbon and non-renewable primary energy demand, were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be one of the most pressing environmental issues of our time. The global warming potential impact category is assessed based on the current IPCC characterization factors taken from the 5th Assessment Report (IPCC, 2013) for a 100-year timeframe (GWP100), as this is currently the most commonly used metric.

Eutrophication, acidification, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NOx, SO2, VOC, and others.

Ozone depletion potential was chosen because of its high political relevance, which eventually led to the worldwide ban of more active ozone-depleting substances; the phase-out of less active substances is due to be completed by 2030. Current exceptions to this ban include the application of ozone depleting chemicals in nuclear fuel production. The indicator is therefore included for reasons of completeness.

Human health particulate air covers particulate matter emissions of various aerodynamic diameters (with a reference substance of particulate emissions with an aerodynamic diameter less than 2.5 µm or PM2.5) and was chosen because it is a key outdoor air quality indicator and a major contributor to respiratory disease around the world, particularly in urban areas. The TRACI 2.1 methodology was used to quantify PM2.5.

Water consumption (i.e. the anthropogenic removal of water from its watershed through shipment, evaporation, or evapotranspiration) as well as the water scarcity footprint (WSF), has also been selected due to its high political relevance. The UN estimates that roughly a billion people on the planet don't have access to improved drinking water, which entails a variety of problems around ecosystem quality, health, and nutrition.

Additionally, the project includes an evaluation of human toxicity and ecotoxicity potentials from employing the USEtox™ characterization model. USEtox™ is currently the best available approach to evaluate toxicity in LCA and is the consensus methodology of the UNEP-SETAC Life Cycle Initiative. The precision of the current USEtox™ characterization factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity (Rosenbaum R. K., et al., 2008). This is a substantial improvement over previously available toxicity characterization models, but still significantly higher than for the other impact categories noted above. Given the limitations of the characterization models for each of these factors, results are reported as "substances of high concern," but are not to be used to make comparative assertions.

The evaluation of land use indicators according to the LANCA method (Beck, et al., 2010) were added as agricultural production for cotton typically requires more land than an industrial process. Since this is a relatively new methodology, this study is an opportunity to begin to gain insight on the associated metrics for cotton production.

TABLE 2-2: Impact category descriptions.

| Impact Category | Description | Unit | Reference |
|---|---|---|---|
| **Global Warming Potential (GWP100)** | A measure of greenhouse gas emissions such as $CO_2$ and methane. 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. | kg $CO_2$ equivalent | (IPCC, 2013) |
| **Abiotic Resource Depletion (ADP elements)** | The consumption of non-renewable resources leads to a decrease in the future availability of the functions supplied by these resources. Depletion of mineral resources are reported separately. Depletion of mineral resources is assessed based on ultimate reserves. | kg Sb equivalent | (van Oers, de Koning, Guinée, & Huppes, 2002) |
| **Eutrophication Potential (EP)** | Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels because of the additional consumption of oxygen in biomass decomposition. | kg $PO_4$ equivalent | (Guinée, et al., 2002) |
| **Acidification Potential (AP)** | A measure of emissions that cause acidifying effects in the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials. | kg SO2 equivalent | (Guinée, et al., 2002) |
| **Photochemical Ozone Creation Potential (POCP)** | A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems, and may also damage crops. | kg C2H4 equivalent | (Guinée, et al., 2002) |
| **Ozone Depletion Potential (ODP)** | A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface, with detrimental effects on humans and plants. | kg CFC-11 equivalent | (Guinée, et al., 2002) |
| **Human Toxicity (HT)** | A measure of toxic emissions which are directly harmful to the health of humans and other species. | CTUh | (Rosenbaum R. K., et al., 2008) |
| **Ecotoxicity (ET)** | | CTUe | |
| **Human Health Particulate Air (HHPA)** | Particulate matter emissions of various aerodynamic diameters (with a reference substance of particulate emissions with an aerodynamic diameter less than 2.5µm or PM2.5) | PM2.5 equivalent | (Enivronment and Human Health, European Environment Agency (EEA), 2013) |
| **Water Scarcity Footprint (WSF)** | A measure of the stress on a region due to water consumption addressed by applying the water stress index (WSI). The WSI is the ratio of total annual freshwater withdrawals to hydrological availability with values ranging from 0 (no water stress) to 1 (high water stress). It is multiplied by the water consumption value to indicate which portion of consumption contributes to water deprivation. | Litres of water equivalent (H2Oe) | (Pfister, Koehler, & Hel, 2009) |

It shall be noted that the above impact categories represent impact potentials, i.e. they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

TABLE 2-3: Other environmental indicators.

| Indicator | Description | Unit | Reference |
|---|---|---|---|
| **Primary Energy Demand (PED)** | A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g., petroleum, natural gas, etc.) and energy demand from renewable resources (e.g., hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g., power, heat, steam, etc.) are taken into account. | MJ (lower heating value) | (Guinée, et al., 2002) |
| **Blue Water Consumption (BWC)** | A measure of the net intake and release of fresh water across the life of the product system. This is not an indicator of environmental impact without the addition of information about regional water availability. | Cubic meters of water | (thinkstep, 2014) |
| **Blue Water Use (BWU)** | A measure of total amount of freshwater withdrawn from a watershed. This is not an indicator of environmental impact without information about regional water availability. | Cubic meters of water | (thinkstep, 2014) |

As this study does not intend to support comparative assertions to be disclosed to third parties, no grouping or further quantitative cross-category weighting has been applied. Instead, each impact is discussed in isolation without reference to other impact categories before final conclusions and recommendations are made.

### 2.6.1 Impacts not Addressed by Study

There is growing scientific interest in the quantification of the impacts of human activities on biodiversity. While there are different assessment methods in some sort of an experimental stage, there is no commonly agreed (i.e. recommended in the ILCD handbook, for PEF studies or similar) method mature enough to be added to the "standard" LCA impact categories. Qualitatively biodiversity was assessed though data collected in the agricultural phase of this study that did find intercropping to be a common practice in regions of India and China. Additionally, cropping patterns in Australia and the United States were diverse and usually included significant inclusions of natural ecosystems in the farmscape.

An area of public concern is the use of genetically modified organisms (GMOs) by agriculture. In this study we did find that the use of GMO cotton was prevalent across all countries and regions evaluated. However, there is no LCA metric available to specifically assess the impact of GMOs, and a recent study found no human health impacts of GMO usage in crops (National Academies of Sciences, Engineering, and Medicine, 2016). While the benefits of GMO cotton usage such as decreased insecticide usage and increase productivity (Brookes, 2014) will impact the metrics reported in this study, none are explicit to GMO usage.

## **2.7** INTERPRETATION TO BE USED

The results of the LCI and LCIA were interpreted according to the goal and scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results.
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations, and recommendations.

Note that in situations where no product outperforms all of its alternatives in each of the impact categories, some form of cross-category evaluation is necessary to draw conclusions regarding the environmental superiority of one product over the other. Because this LCA does not have a goal of comparison to other products, no weightings have been applied and no assertions about comparison are made.

## **2.8** DATA QUALITY REQUIREMENTS

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modeling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modeling choices, data sources, emission factors, or other artifacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.
- Representativeness expresses the degree to which the data match the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in Section 5 of this report.

## 2.9 TYPE AND FORMAT OF THE REPORT

In accordance with the ISO requirements (ISO, 2006b) this document aims to report the results and conclusions of the LCA to the intended audience completely, accurately, and without bias. The results, data, methods, assumptions, and limitations are presented in a transparent manner and 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 model was created using the GaBi ts software system for life cycle engineering developed by thinkstep AG. The GaBi 2016 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

## 2.11 CRITICAL REVIEW

To ensure credibility, a critical review was conducted according to ISO 14044, section 6.3. The review team was chosen based on expertise in LCA, cotton agriculture, and textile manufacturing. The reviewers are:

- Christina Bocher, DEKRA
- Dr. Alan Franzluebbers, USDA, ARS
- Dr. Ian Hardin, University of Georgia

The Critical Review Statement can be found in Annex A: 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.

# 3

# LIFE CYCLE INVENTORY ANALYSIS

## **3.1** AGRICULTURAL DATA COLLECTION AND MODELING PROCEDURE

All primary data were collected using customized data collection templates, which were sent out by email to the respective data providers in the participating companies. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, thinkstep engaged with the data provider to resolve any open issues.

Primary data collection was conducted globally based on regions in the United States, China, India, and Australia representative of specific growing conditions. Primary data collection was accomplished in the form of spreadsheets and questionnaires, supplemented by surveys and conversations with cotton growers and other country specific regional cotton growing experts (i.e. extension agents, grower group executives). In cases where primary data were not available or were inconsistent, secondary data that were readily available from literature, machinery manufacturers, previous Life Cycle Inventory (LCI) studies, and life cycle databases were used for the analysis. The sources for any secondary data used are documented throughout the report.

Average cotton cultivation in the United States, China, India, and Australia for the years 2010 to 2014 was incorporated thinkstep's cultivation model based on regional production-weighted averages. Collecting data over a range of years averages out seasonal and annual variations such as droughts and floods. The United States, Australia, China, and India represented 67.2% of the world's cotton fiber production for the study period (USDA, 2015b). Background data on ancillary materials, energy and fuels, transportation, and end-of-life were taken from the thinkstep's GaBi databases.

Agricultural data were taken from direct grower interviews and surveys, scientific papers, reports, and national statistics. The data were reviewed by experts from different areas and compared with already existing LCA studies (Matlock, M.; et al., 2008; Cotton Foundation, 2012; CMiA, 2014; Textile Exchange, 2014; Zhang, Liu, Xiao, & Yuan, 2015). Standardized questionnaires were developed and adapted to cotton-specific cultivation and post-harvest situations.

The secondary data from literature and the primary data from surveys were compared and matched to obtain highest data quality. Nevertheless, the data used for the four countries (the United States, India, China, and Australia) vary in completeness, representativeness, and age. Data for China were obtained in a lower quality and completeness due to nondisclosure rules and less extensive statistical reporting, but were improved since the last global cotton LCA was conducted.

### **3.1.1** Overview of Agricultural System

The top three producing cotton countries (China, India, and the United States) and top three exporting cotton countries (the United States, India and Australia) were selected for inclusion in this study based on data for USDA (2015a) for study period 2010 to 2014. In many cases those conducting an LCA for a cotton product will not know the country of origin for the fiber, so top producing and exporting countries were considered the most important to characterize. China, India, and the United States all have distinctive growing regions within the countries, where the environment and cultural practices have significant differences. Thus data collection and modeling of the agricultural system were conducted on a regional basis, and then regional production weighted averages were calculated for these countries. Australia has more uniform growing conditions across the country and was treated as a single region. Agricultural production in China and India is conducted on small farm holdings using labor intensive practices, in contrast to the United States and Australia where cotton production is conducted on farm holdings of 500 hectares (ha) or larger and is highly mechanized.

In China the majority of farms are less than 1 ha in size and in India the average farm size ranges from 0.5 to 2 ha. The exceptions for both China and India are in the northern growing regions of both countries where farms tend to be larger and there is a higher level of mechanization.

The land in the southern provinces of China and India are intensively farmed, often using relay and intercropping production practices. Bullocks (or other animals) are used frequently in India and to a lesser extent in China for land preparation and plowing. Some farmers in both countries have access to hand (walk-behind) tractors and many use powered backpack sprayers to apply farm chemicals.

The level of irrigation varies by region with irrigated cotton ranging from 10% to 100% of the cotton area based on climate and average annual rainfalls. Transgenic technology has been adopted globally for cotton, with James (2015) estimating that biotechnology adoption is above 90% in all four countries considered.

Note that all data reported in the following paragraph are based on data from UDSA (2015b) to allow global comparisons using a consistent data source. India had the largest area planted to cotton (11.9 million ha) in the world and was a close second in cotton production (29.1 million 218 kg bales) to China. However, yields of 532 kg per ha are lower than in the other countries for the study period. China, number one in cotton production, harvested 32.5 million bales from 5.1 million ha. Australia had the greatest yield of 1,997 kg per ha, primarily due to the ideal climate for cotton and uniform access to irrigation water. While China and India both have smallholder farms, farmers in China typically have greater access to new technologies than those in India. The United States is third in production with 12.2 million bales harvested from 4.3 million ha. Cotton yields in the U.S averaged 924 kg per ha during the study period. Together the four countries produced an average of 81.8 million bales, 67% of world's cotton production. The United States, India, and Australia also accounted for more than half of the cotton exported in the world from 2010 to 2014.

### **3.1.2** Climate, Water Use and Soil Data

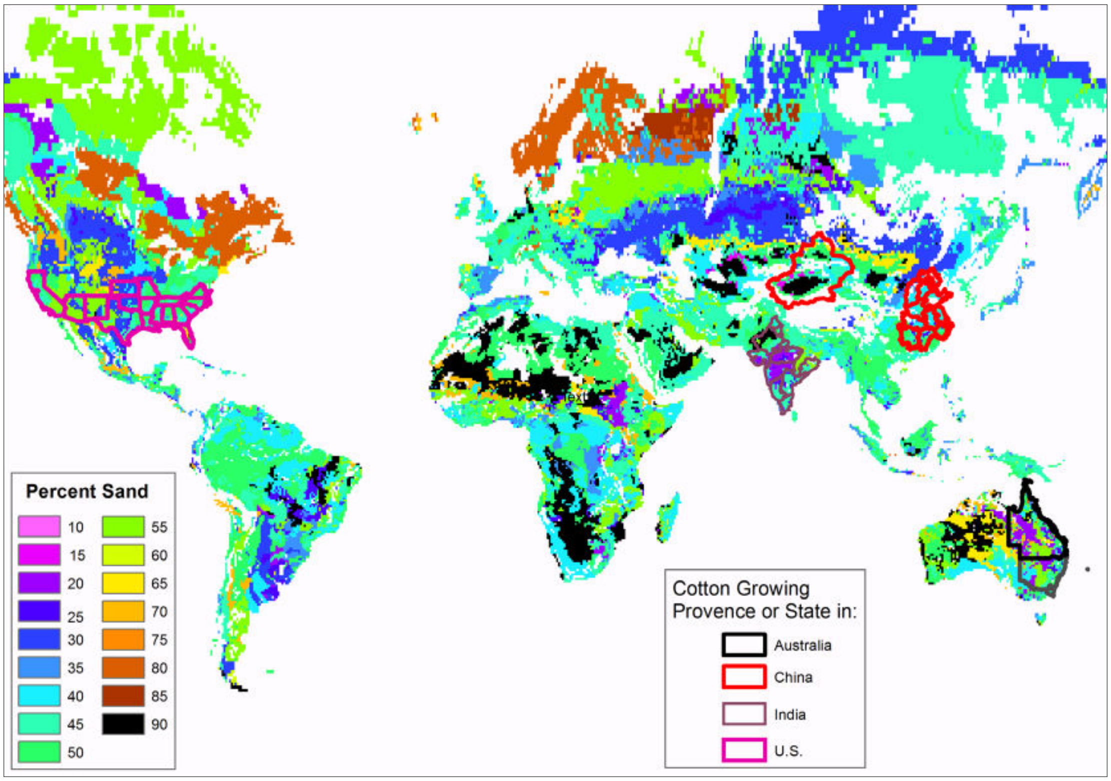
Global climate and soil data sets of relatively high quality were available for all countries considered in the study. The CLIMWAT 2.0 Database (FAO, 2006) was used to extract 30 year average weather station records for each cotton production region modeled. The database includes temperature, rainfall, wind speed, radiation, relative humidity, and rainfall for over 5,000 weather stations worldwide. In most cases, at least six weather stations were available per region within a country and data from these individual stations were combined to create an average condition for each region. These data were used in the thinkstep agricultural model, as well as to verify irrigation levels in each region by using the data with CROPWAT 8.0 (FAO, 2009), a computer program for the calculation of crop water requirements and irrigation requirements based on soil, climate, and crop data using a crop coefficient approach to estimate evapotranspiration. For each region, a custom crop coefficient was created to reflect typical planting and harvest times in that region. Several studies in diverse environments in the United States have shown that there is not a large difference in magnitude of the crop coefficient for cotton, but it is highly dependent on season length that can be accounted for in the CROPWAT program. For example, Hunsaker et al. (2005) found a mid-season crop coefficient (as defined by CROPWAT) of 1.2 in Arizona, Howell et al., (2004) measured a mid-season value of 1.2 in the Northern Texas High Plains, and Fisher (2012) also found a maximum value of 1.2 in the humid Mississippi Delta. The average climate data compiled for each region is provided in Table 3-1. From the data in the table it is clear that cotton is produced in a wide variety of climates and this study captures a wide range of conditions.

TABLE 3-1: Climatic average maximum and minimum monthly temperatures and monthly climatic rainfall totals based on data.

| Month | United States | | | | China | | | India | | | Australia |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Far West | Southwest | Mid-South | Southeast | Northwest | Yangtze | Yellow | North | Central | South | Eastern |
| | **Minimum Temperature (degrees Celsius)** | | | | | | | | | | |
| **January** | 5.2 | -2.3 | 1.0 | 0.0 | -14.5 | -0.9 | -8.1 | 8.0 | 12.1 | 20.9 | 20.6 |
| **February** | 6.8 | -0.1 | 3.0 | 1.0 | -10.0 | 0.6 | -5.8 | 10.4 | 14.5 | 21.6 | 20.4 |
| **March** | 8.5 | 4.3 | 8.0 | 6.0 | -1.3 | 5.2 | 0.7 | 15.4 | 19.3 | 23.4 | 17.8 |
| **April** | 11.0 | 9.6 | 12.0 | 10.0 | 6.5 | 11.1 | 7.6 | 21.3 | 24.0 | 25.4 | 13.3 |
| **May** | 14.5 | 14.4 | 17.0 | 15.0 | 12.3 | 16.4 | 14.0 | 25.9 | 26.0 | 26.3 | 9.2 |
| **June** | 18.4 | 18.9 | 21.0 | 19.0 | 16.2 | 20.8 | 19.2 | 27.6 | 25.6 | 26.3 | 5.9 |
| **July** | 21.5 | 21.1 | 22.0 | 21.0 | 18.1 | 24.4 | 22.0 | 26.2 | 24.0 | 25.7 | 4.7 |
| **August** | 21.2 | 20.5 | 22.0 | 21.0 | 16.5 | 23.9 | 21.0 | 25.3 | 23.0 | 25.2 | 6.2 |
| **September** | 18.7 | 16.7 | 19.0 | 18.0 | 10.8 | 18.8 | 14.8 | 23.9 | 22.6 | 24.8 | 9.1 |
| **October** | 13.9 | 10.5 | 12.0 | 11.0 | 3.2 | 13.1 | 8.7 | 19.0 | 20.0 | 24.0 | 13.3 |
| **November** | 8.6 | 4.3 | 7.0 | 6.0 | -4.7 | 6.7 | 1.0 | 12.6 | 15.3 | 23.0 | 16.3 |
| **December** | 5.3 | -0.7 | 3.0 | 2.0 | -11.5 | 1.2 | -5.6 | 8.8 | 12.7 | 21.6 | 19.1 |
| | **Maximum Temperature (degrees Celsius)** | | | | | | | | | | |
| **January** | 16.6 | 11.2 | 12.7 | 11.0 | -2.3 | 7.0 | 2.7 | 21.5 | 26.9 | 30.2 | 34.3 |
| **February** | 19.4 | 13.9 | 15.2 | 14.0 | 2.3 | 8.5 | 6.0 | 24.5 | 30.3 | 32.4 | 33.7 |
| **March** | 21.5 | 18.5 | 20.1 | 18.0 | 12.5 | 14.0 | 12.5 | 30.1 | 34.9 | 35.0 | 31.1 |
| **April** | 25.4 | 23.6 | 24.7 | 23.0 | 21.4 | 20.3 | 20.7 | 36.3 | 38.4 | 36.3 | 26.9 |
| **May** | 29.6 | 27.6 | 28.2 | 27.0 | 27.2 | 25.8 | 27.5 | 39.9 | 39.4 | 37.5 | 21.9 |
| **June** | 33.9 | 32.1 | 31.9 | 31.0 | 31.3 | 29.5 | 31.7 | 39.0 | 35.9 | 36.7 | 18.5 |
| **July** | 35.9 | 34.2 | 33.5 | 32.0 | 33.1 | 32.2 | 31.5 | 34.4 | 30.4 | 35.7 | 17.8 |
| **August** | 35.2 | 33.4 | 33.2 | 31.0 | 32.1 | 32.0 | 30.2 | 32.8 | 29.0 | 35.3 | 19.7 |
| **September** | 32.9 | 29.4 | 30.2 | 29.0 | 26.5 | 27.0 | 26.3 | 33.7 | 30.3 | 35.0 | 23.6 |
| **October** | 28.1 | 24.4 | 25.5 | 24.0 | 18.6 | 21.9 | 20.6 | 33.1 | 33.3 | 33.0 | 27.6 |
| **November** | 21.4 | 17.7 | 19.7 | 19.0 | 7.9 | 15.6 | 11.9 | 28.7 | 31.5 | 30.6 | 30.9 |
| **December** | 16.6 | 12.6 | 14.7 | 14.0 | -0.1 | 9.5 | 4.6 | 23.7 | 29.1 | 29.7 | 33.7 |
| | **Total Rainfall (mm)** | | | | | | | | | | |
| **January** | 40 | 32 | 104 | 109 | 3 | 34 | 5 | 11 | 2 | 8 | 77 |
| **February** | 33 | 35 | 106 | 111 | 4 | 51 | 7 | 16 | 0 | 10 | 46 |
| **March** | 34 | 44 | 114 | 123 | 5 | 78 | 12 | 10 | 3 | 19 | 49 |
| **April** | 15 | 53 | 113 | 90 | 6 | 106 | 35 | 9 | 1 | 42 | 40 |
| **May** | 5 | 89 | 130 | 98 | 8 | 121 | 34 | 21 | 1 | 59 | 46 |
| **June** | 3 | 86 | 110 | 99 | 10 | 154 | 63 | 61 | 99 | 38 | 25 |
| **July** | 15 | 69 | 112 | 123 | 11 | 185 | 193 | 201 | 250 | 68 | 33 |
| **August** | 17 | 72 | 102 | 110 | 8 | 149 | 151 | 227 | 188 | 80 | 32 |
| **September** | 16 | 76 | 107 | 89 | 6 | 106 | 56 | 99 | 187 | 125 | 28 |
| **October** | 17 | 63 | 89 | 71 | 5 | 75 | 30 | 16 | 28 | 193 | 42 |
| **November** | 30 | 42 | 117 | 82 | 4 | 55 | 18 | 5 | 6 | 140 | 42 |
| **December** | 34 | 34 | 124 | 101 | 3 | 26 | 5 | 8 | 3 | 72 | 48 |
| **Total in Season** | **70** | **391** | **561** | **519** | **43** | **821** | **531** | **607** | **752** | **644** | **303** |
| **Total Amount** | **258** | **694** | **1327** | **1206** | **72** | **1139** | **608** | **680** | **768** | **854** | **507** |

A common global data set was also used to estimate soil properties in each region (percent sand, silt, and clay) using a 0.5 by 0.5 degree soil grid (Batjes, 2005). The data were imported into ArcMap 10.1 (ESRI, 2012) and average soil textural values calculated for each region. In some cases this did "homogenize" the soil properties, but it was deemed the best approach feasible (as opposed to modeling every region at a very fine scale). An example of the percent sand data is provided in Figure 3-1, which also shows the state or province that had cotton production for the four countries in the study.

FIGURE 3-1: Percent sand content with cotton producing state or province outlined for the four countries included in the agricultural phase of this study.



### **3.1.3** Agricultural Data Sheets

For each region within a country, an Excel workbook was created to provide the data to supply thinkstep's questionnaires. Each workbook contained the following sheets:

1. **In-season Field Practices:** Planting and harvest dates, pesticide application dates and rates, a summary of fertilizer application rates, tillage practices, crop rotations, soil erosion rates, summary of irrigation practices and fuel use, and harvest information including yields and by-products.
2. **Ginning Data:** Data on post-harvest processing including electrical energy, fuel use, and packaging materials.
3. **Pumping Energy Calculations:** In irrigation regions, energy to pump water can be significant. However, data were rarely available on total irrigation fuel use per unit area. One of the challenges is a single pump may serve several fields producing different crops, making it difficult to partition out energy to a specific field even when electrical meter readings or total fuel use is known for a given pump. Therefore, energy use for irrigation was estimated based on total lift (pumping depth to ground water plus distance to the water outlet), outlet pressure, volume of water applied, and energy source based on the procedures of Hoffman et al. (1992).

4. **Soil Data:** Data extracted from the Batjes (2005) data set for sand, silt, and clay percentages were stored in this sheet and then averaged for the region.
5. **Fuel Calculations:** For operations involving tractors or other field equipment, it was also necessary to estimate the fuel use for a given operation, as few farmers track fuel use by crop. Similar to the pumping scenario, on any a given day a tractor may be used to plant soybeans, cotton, and wheat with fuel use by field not recorded. Therefore, grower survey data combine with ASABE (2011) procedures were often used to estimate fuel use for specific field operations.
6. **Climatic Data:** The individual station data extracted from CLIMWAT and CROPWAT outputs were exported to this sheet. The regional averages are presented in Table 3-1.

An overview of the data collection procedure and data sources for each country are provided in the following sections.

### **3.1.4** Agricultural Data Collection: United States

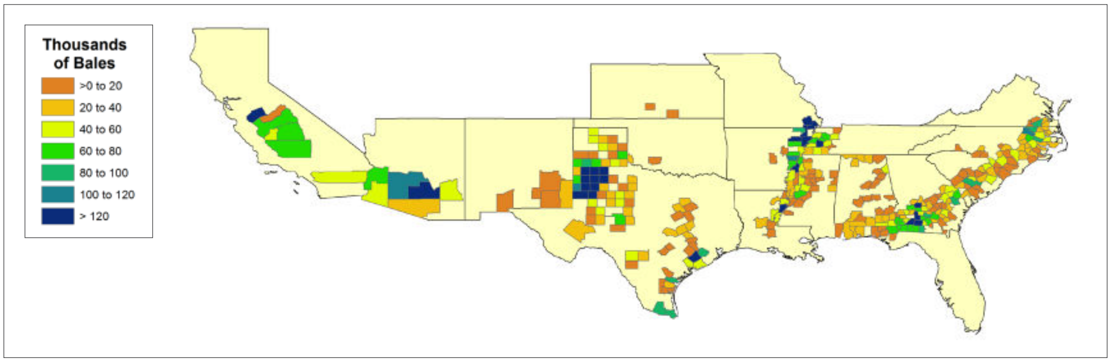
The information provided in this section is an overview of the primary data sources used across all regions in the United States to supply data on cotton production, harvest, and ginning processes. Detailed information on all input data and citations are contained in the original questionnaires provided to thinkstep. Note that similar methodologies to compute energy use and characterize the chemical and physical properties of cotton fiber and cotton gin byproducts were used for all countries.

In order to characterize cotton production practices in the United States, the 17 cotton growing states in the country were assigned to four regions:

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

Where possible, all regional data were calculated as production weighted averages (i.e. more weight to data from states that produced more bales). The goal was to represent the average conditions from 2010 to 2014, and when possible, annual data were averaged for these years before calculating production weighted regional averages. Distribution of cotton production in the United States for the 2012 crop year is represented in Figure 3-2 to illustrate cotton growing areas within each state.

FIGURE 3-2: Number of 480-pound cotton bales produced per county in the United States in 2012.



The primary source of state level production data was from USDA (2015c) that provides annual cotton yield and cotton fiber production by year and state. It was used to assign the production weighting (average number of 480 pounds bales produced in that state from 2010 to 2014), and for all fiber yield data in pounds per acre. The same U.S. Department of Agriculture (USDA) database was also used to establish cottonseed production levels. Table 3-2 provides an example of the production weighting function developed for cotton growing regions in the United States. For example, in the case of the Southwestern states, production impacts in that region will receive a greater weight in computing averages for the United States as it had the greatest cotton production during the five-year period considered.

TABLE 3-2: Regional total harvested area, total production in region, yield, and production weighting function for the United States based on averages from 2010 to 2014.

| Region | Total Area Harvested (ha) | Total 218 kg Bales | Yield (kg per ha) | Weighting Factor |
|---|---|---|---|---|
| **Far West** | 227,568 | 1,726,180 | 1,650 | 11% |
| **Southwest** | 1,684,015 | 5,642,100 | 729 | 35% |
| **Mid-South** | 722,380 | 3,723,800 | 1,122 | 23% |
| **Southeast** | 1,119,385 | 4,951,400 | 962 | 31% |
| **United States** | **3,753,347** | **16,043,480** | **930** | **100%** |

### 3.1.5 Grower Practices

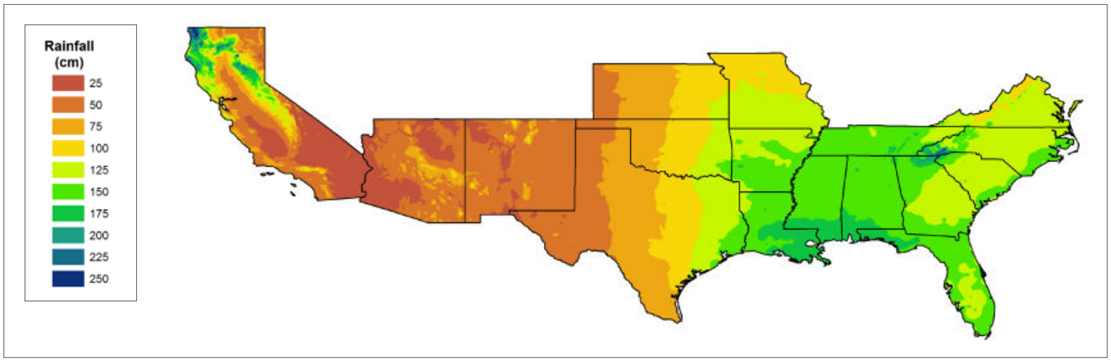
Producer practices were characterized using data from Cotton Incorporated's 2015 Natural Resource Survey (NRS) and cross-compared with data from the USDA Agricultural Resource Management Survey (ARMS). The NRS data were from a comprehensive survey of U.S. cotton producers that included responses from 925 producers and represented 10% of the cotton acres grown in the United States in 2014. Data from these sources were used to characterize producers' tillage systems, number of chemical applications, rotational crops, double cropping practices, cover crops, and timing of operations and to supplement information on irrigation practices.

When there were missing data or questions on production practices in a given region, cotton specialists and other agricultural experts in that region were consulted for the needed information. Over 60 in-person grower interviews were also conducted of U.S. producers serving leadership positions on the boards of Cotton Incorporated or the American Cotton Producers Association. These interviews took place during cotton leadership meetings and consisted of 17 questions provided in Annex B. The NRS also included these 17 questions in addition to a number of other questions about general farming practices, research needs, and demographics. The number of responses by state to the NRS was closely correlated to the production by state.

### 3.1.6 Rainfall and Erosion Data

Figure 3-3 was developed using data from the USDA NRCS National Cartographic and Geospatial Center, Fort Worth, TX (2010) that is based on average annual rainfall from 1971 to 2000 and shows how significantly rainfall varies across the United States. The data from this figure and other state level weather station records were found comparable to the climate data available in CLIMWAT shown in Table 3-1.

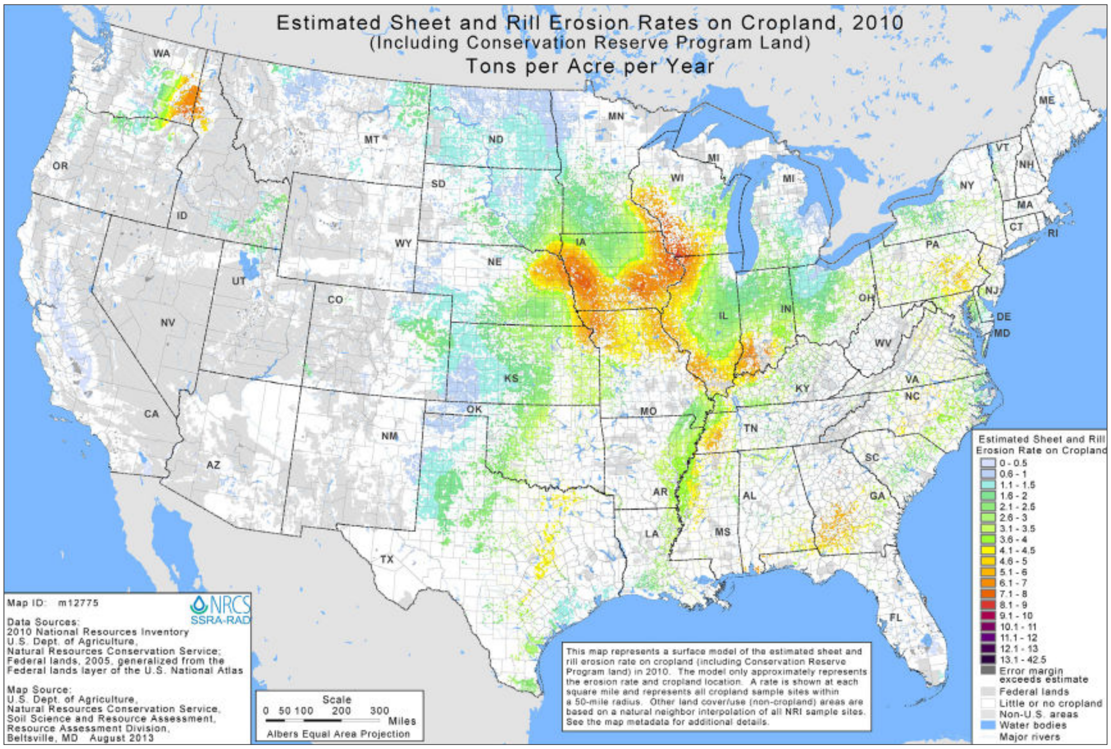
FIGURE 3-3: 30-year average rainfall in the U.S. cotton producing states.



Erosion rates per region were estimated from the USDA, NRCS National Resource Inventory (USDA, 2013a). Data from that inventory are represented in Figure 3-4. Note that only data related to the cotton growing states pictured in Figure 3-2 were considered in the analysis.

In general, the erosion data represented in Figure 3-4 were consistent with RUSLE2 erosion estimates obtained using the Fieldprint® Calculator tool from Field to Market® (Field to Market®, 2015) with data obtained during grower interviews.

FIGURE 3-4: Soil cropland water erosion rates for the United States (USDA, 2013a).



Data Sources:
2010 National Resources Inventory
U.S. Dept. of Agriculture,
Natural Resources Conservation Service;
Federal lands, 2005, generalized from the Federal lands layer of the U.S. National Atlas

Map Source:
U.S. Dept. of Agriculture,
Natural Resources Conservation Service,
Soil Science and Resource Assessment,
Resource Assessment Division,
Beltsville, MD August 2013

This map represents a surface model of the estimated sheet and rill erosion rate on cropland (including Conservation Reserve Program land) in 2010. The model only approximately represents the erosion rate and cropland location. A rate is shown at each square mile and represents all cropland sample sites within a 50-mile radius. Other land cover/use (non-cropland) areas are based on a natural neighbor interpolation of all NRI sample sites. See the map metadata for additional details.

### 3.1.7 Irrigation and Water Use Data

Applied irrigation water and irrigated acreage was determined from the USDA's Farm and Ranch Irrigation survey (USDA, 2013b) that represented conditions in 2013 and combined with similar data from the NRS (97% of NRS responses were for the 2014 growing season). The CROPWAT simulations were also compared to these data and there was typically very good agreement between regional average predicted climatic average irrigation amounts and the regional average based on the 2013 and 2014 data. Much of the consistency can be attributed to: 1) in the far western United States, rainfall plays a minor role in meeting water needs; 2) much of the southwestern United States is deficit irrigated and therefore crop needs cannot be met, resulting in year to year consistency in irrigation levels; and 3) in the more humid regions of the mid-south and southeastern United States, the regions are large enough so that in any given year, some states will have above average rainfall and others will be in some form of drought.

### 3.1.8 Energy Use Estimates

For other tractor-based field operations, data from the NRS were combined with ASABE (2011) procedures to estimate fuel use for field operations. Data reported in Faulkner et al. (2011) to document fuel use in cotton strippers, and Willcutt et al. (2009) for modern spindle harvesters, were used to estimate fuel use in harvest operations. Example fuel use requirements by operation are shown in Table 3-3. 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 NRS. The summation of all operations was used to compute a fuel use rate per hectare.

TABLE 3-3: Example fuel use requirements based on specific equipment configurations.

| Field Operation | Fuel Use Per Operation (l per ha) |
|---|---|
| **Rip / Paratill** | 9.0 |
| **Disk** | 8.6 |
| **Row Clean & Cultivate** | 1.8 |
| **Bed** | 6.7 |
| **Plant** | 2.0 |
| **Spray** | 1.4 |
| **Shred Stalks** | 5.8 |
| **Plant Cover Crop** | 2.8 |
| **Broadcast Fertilizer** | 2.8 |
| **Inject Fertilizer** | 9.1 |
| **Spindle Harvester** | 19.3 |
| **Harvest Support** | 6.2 |

Data for electrical energy use in ginning were largely based on Valco et al. (2015), which based data on 2013 survey results of ginners by each region in the United States. Dryer fuel use data in that survey were found to be highly variable, and measured data from selected gins in the United States reported by Hardin and Funk (2014). Characteristics of gin trash and cotton residues were based on data reported in Holt et al. (2000) and the data in that study were also used to characterize the properties (heat content and carbon levels) of gin byproducts in the other countries. The chemical properties of cotton fiber for all countries was based on data presented in Wakelyn et al. (2006). A summary of key agricultural practices by region in the United States are provided in Table 3-4.

TABLE 3-4: Summary of key data collection metrics by region for the United States.

| Measure | Units | Region | | | |
|---|---|---|---|---|---|
| | | Far West | Southwest | Mid-South | Southeast |
| **Plant** | Date | 15-Apr | 20-May | 8-May | 5-May |
| **Harvest** | Date | 15-Oct | 5-Nov | 15-Oct | 20-Oct |
| **Harvested Area** | ha | 228 | 1,684 | 722 | 1,119 |
| **Soil Data** | | | | | |
| **Clay** | % | 26 | 24 | 30 | 31 |
| **Silt** | % | 25 | 21 | 23 | 22 |
| **Sand** | % | 49 | 55 | 47 | 47 |
| **Soil Erosion Rate** | kg soil ha$^{-1}$ yr$^{-1}$ | 1,098 | 5,460 | 7,683 | 8,288 |
| **Direct Energy and Irrigation** | | | | | |
| **Diesel Use** | l ha-1 | 79.7 | 60.7 | 64.3 | 51.9 |
| **Irrigated Area** | % | 100 | 45 | 44 | 16 |
| **Irrigated Amount*** | mm | 978 | 330 | 254 | 152 |
| **Weighted Irrigation*** | mm | 978 | 149 | 112 | 24 |
| **Irrigation Energy** | kWh ha$^{-1}$/yr. | 4127.16 | 805.2 | 307 | 210 |
| **Fertilizer Rates** | | | | | |
| **N** | kg ha$^{-1}$ | 172 | 77 | 127 | 102.2 |
| **$P_2O_5$** | kg ha$^{-1}$ | 27 | 25 | 50 | 53.9 |
| **$K_2O$** | kg ha$^{-1}$ | 34 | 8 | 87 | 98.9 |
| **Harvest Ginning** | | | | | |
| **Seed Cotton** | kg ha$^{-1}$ | 4210 | 1808 | 3063 | 2467 |
| **Fiber Yield** | kg ha$^{-1}$ | 1,473 | 651 | 1,121 | 962 |
| **Distance to Gin** | km | 19 | 24 | 24 | 37 |
| **Gin Electrical Use** | kWh (227 kg bale)$^{-1}$ | 52 | 47 | 38 | 35 |

**Irrigation amount is the level of water applied in the region if the land is irrigated. The "Weighted Irrigation" was used in the study to adjust the water applied to represent the amount of water that would have been used if distributed across all acres in the region.*

### 3.1.9 Agricultural Data Collection: China

China ranks number one in the world in cotton production. Average production from 2010 to 2014 was 32.5 million, 218 kg bales of fiber representing 27% of the world's cotton during the study period (USDA, 2015a). The primary growing regions are the Northwest, Yellow River Basin, and Yangtze River Basin. Provinces making up these regions are:

5. **Northwest:** Gansu and Xinjiang
6. **Yellow River Basin:** Hebei, Henan, Shaanxi, Shandong, Shanxi, Tianjin, and Beijing
7. **Yangtze River Basin:** Hubei, Hunan, Jiangsu, Jiangxi, Zhejiang, and Anhui

The Northwest region is the largest and most productive growing region in China (Table 3-5) due in part to nearly all the area receiving irrigation water. There are new government policies to continue the migration of cotton to the west.

TABLE 3-5: 2010 to 2014 average harvested area, fiber production, yield, and regional weighting factor for Chinese cotton growing regions based on province level data from NBS (2015).

| Region | Harvested Area (ha) | Number of 218 kg Bales | Yield (kg per ha) | Weighting Factor |
|---|---|---|---|---|
| **Yellow River** | 1,653,244 | 7,714,328 | 1138 | 27% |
| **Yangtze River** | 1,205,544 | 6,229,151 | 1207 | 21% |
| **Northwest** | 1,742,776 | 15,117,302 | 1801 | 52% |
| **China** | **4,601,564** | **29,060,781** | **1382** | **100%** |

### 3.1.11 Data Sources

Data for production practices in China remain limited but have improved since the previous global cotton LCA. Dai and Dong (2014) provide an overview of many of the current cotton production practices across China and Liwen et al. (2014) provide significant details about production practices in the Northwest China. Data from the China Statistical Year Book (NBS, 2015) translated by Mr. Hongzhi Li (Cotton Incorporated) provide data on harvested area, production, yields, and irrigation by region. Many specific details on production practices and equipment use were supplied by questionnaires on cotton production completed by faculty at Anhui University (Anhui University of Finance and Economics, China academy of cooperatives, Bengbu, Anhui Province, Hongye Road No. 255). The 2014 National agricultural product cost and profit compilation of data, issued by the National Development and Reform Commission, contained significant information on fertilizer, energy use, and labor requirements. This information also received translation assistance from Mr. Li. Data on the level of mechanization in each region was provided by China Agricultural Mechanization News published 3 December 2014. The Cotton National Standard provided data on gin energy use and packaging practices in China. Data on pesticide use for the Northwest region was provided by Liwen et al. (2014) and supplemented with data from Anhui University. Pesticide use data for the eastern regions was supplied by Dr. Lu YanHui, Institute of Plant Protection, Chinese Academy of Agricultural. Pumping depth data and hydrological characteristics of the regions were taken from Ahmed et al. (2010).

### 3.1.12 Grower Practices

Much of cotton in China is produced on small farms, often less than 1 ha in size, especially in the Yangtze and Yellow River regions. This allows extensive hand labor and greatly reduces petroleum energy requirements. Chinese cotton farmers employ practices that shorten the cotton-growing season. In the Yellow River and Yangtze River Basins cotton is double cropped. Practices in these regions include the transplanting of seedlings and the use of plastic film as mulch. In the Northwest the growing season is short therefore there is only one crop per year. The plastic mulch protects the seedlings from the broad swings in temperatures during the day and minimizes the loss of soil moisture. While there are benefits from the plastic film, improper removal of the film at the end of the season can leave a significant amount of plastic in the soil. This has resulted in reduced root development, water infiltration and retention, and decreased crop emergence (Liu, 2014).

Mechanization is much more prevalent in the Northwest where the population density is lower and where mechanized cotton harvest exceeds 60%. Intercropping is also a common practice in the Yellow and Yangtze River regions. Table 3-6 provides a summary of grower practices in China.

TABLE 3-6: Summary of key data collection metrics by region in China.

| Measure | Units | Region | | |
|---|---|---|---|---|
| | | North West | Yangtze River | Yellow River |
| **Plant** | Date | 15-Apr | 15-Apr | 15-Apr |
| **Harvest** | Date | 1-Sep | 1-Oct | 1-Oct |
| **Total Harvested Area** | 1000 ha | 1,743 | 1,206 | 1,653 |
| **Soil Data** | | | | |
| **Clay** | % | 29 | 31 | 35 |
| **Silt** | % | 35 | 29 | 27 |
| **Sand** | % | 37 | 40 | 38 |
| **Soil Erosion Rate** | kg soil $ha^{-1}$ $yr^{-1}$ | 1,000 | 10,000 | 6,500 |
| **Direct Energy and Irrigation** | | | | |
| **Diesel Use** | l $ha^{-1}$ | 29 | 11.8 | 11.8 |
| **Irrigated Area** | % | 100 | 20 | 90 |
| **Irrigated Amount*** | mm | 500 | 80 | 162 |
| **Weighted Irrigation*** | mm | 500 | 16 | 145.8 |
| **Irrigation Energy** | kWh $ha^{-1}$ $yr^{-1}$ | 190 | 41 | 83 |
| **Fertilizer Rates** | | | | |
| **N** | kg $ha^{-1}$ | 140.8 | 90.3 | 101.5 |
| **$P_2O_5$** | kg $ha^{-1}$ | 121.6 | 54 | 54 |
| **$K_2O$** | kg $ha^{-1}$ | 36.2 | 34.1 | 34.1 |
| **Harvest Ginning** | | | | |
| **Seed Cotton** | kg $ha^{-1}$ | 4976 | 2963 | 2676 |
| **Fiber Yield** | kg $ha^{-1}$ | 1,891 | 1,126 | 1,017 |
| **Distance to Gin** | Km | 35 | 10 | 10 |
| **Gin Electrical Use** | kWh (227 kg $bale)^{-1}$ | 68.1 | 68.1 | 68.1 |

**Irrigation amount is the level of water applied in the region if the land is irrigated. The "Weighted Irrigation" was used in the study to adjust the water applied to represent the amount of water that would have been used if distributed across all acres in the region.*

### **3.1.12** Agricultural Data Collection: India

India is highly dependent on agriculture. Within the study period approximately 7 million Indian farmers produced almost 30 million, 218 kg bales of cotton. This was 24% of the world's cotton making India second only to China in production. At 12 million ha India ranks number one in area planted to cotton but has lower yields than China and the United States, with the average cotton holdings per farm being about 1.5 ha. The majority of the cotton is grown in ten provinces that are grouped into three different regions: North, Central, and South. Provinces making up these regions are:

8. **North:** Punjab, Haryana, and Rajasthan
9. **Central:** Gujarat, Maharshtra, Madhya Pradesh, and Orissa
10. South: Andhra Pradesh, Karnataka, and Tamil Nadu

A summary of production for the above regions is provided in Table 3-7.

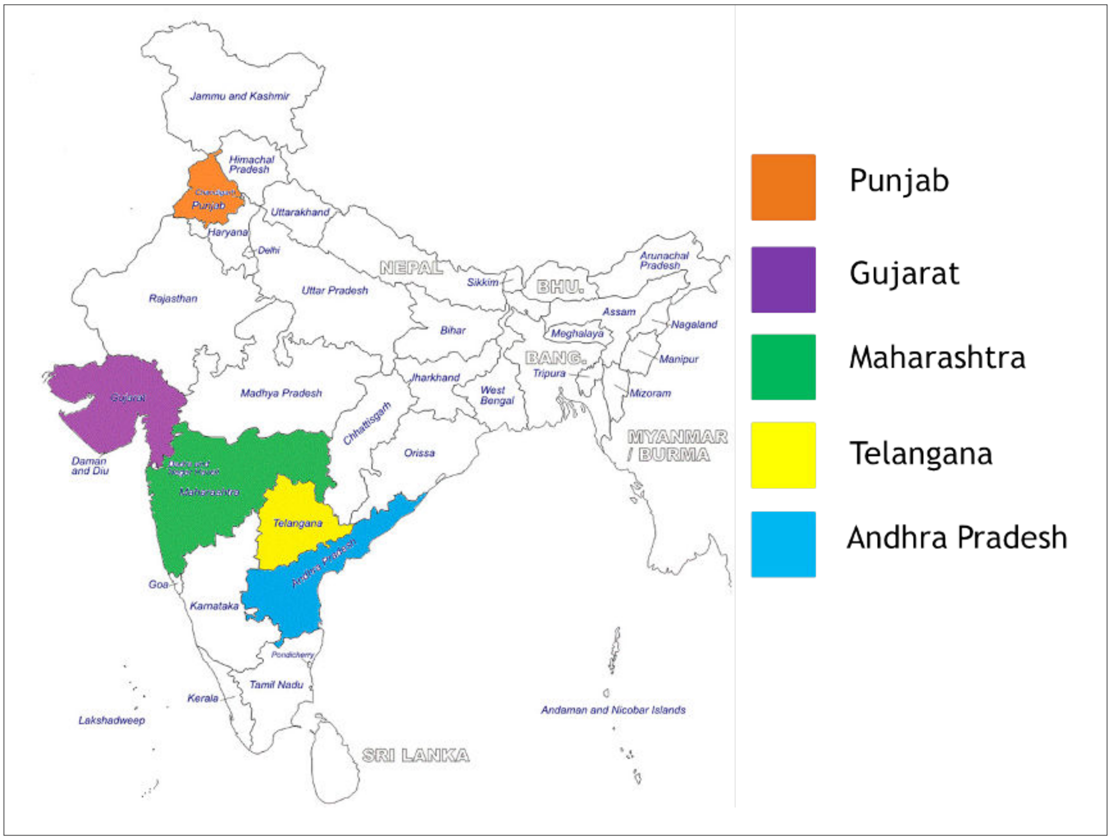
TABLE 3-7: 2010 to 2014 average harvested area, fiber production, yield, and regional weighting factor for Indian cotton growing regions based on province level data (CAB, 2015).

| Region | Harvested Area (ha) | Number of 218 kg Bales | Yield (kg per ha) | Weighting Factor |
|---|---|---|---|---|
| **North** | 1,523,500 | 4,717,890 | 677 | 16% |
| **Central** | 7,501,250 | 16,805,046 | 488 | 56% |
| **South** | 2,949,500 | 7,846,904 | 578 | 26% |
| **India** | **12,134,500** | **29,827,982** | **536** | **100%** |

### 3.1.14 Data Sources

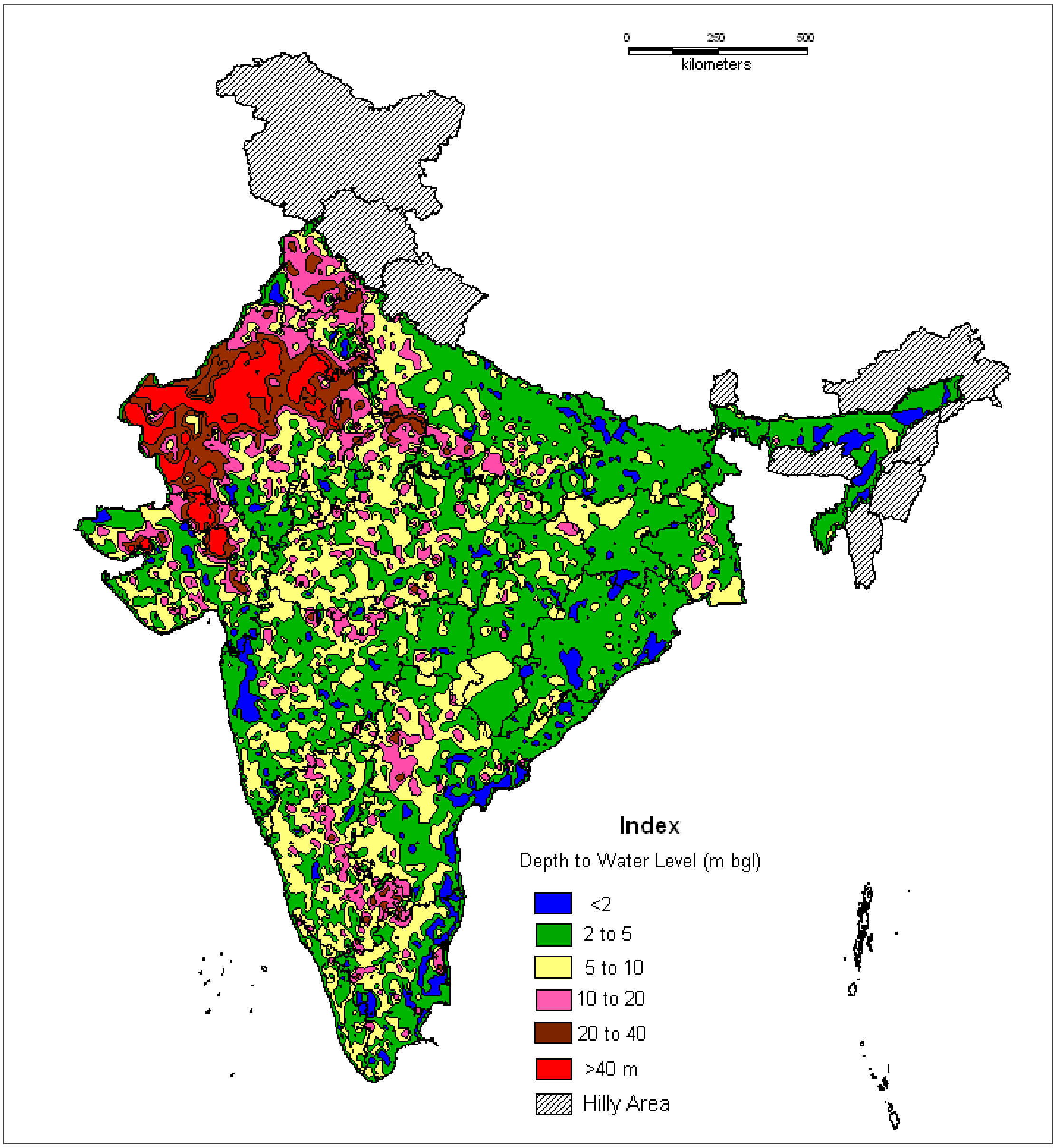
India has a fairly significant set of publically available data sources, such as province level production data by year (CAB, 2015) and grower recommended practices by region, from public university support outreach centers in each province (ICAR, 2014). Cotton Incorporated contracted Agribusiness Associates to interview growers and their advisors in each of the three regions in India at the end of the 2014 growing season. The questions asked were focused on how closely the farms in each region adhered to the recommended practices. Grower interviews were focused in at least one province per region as pictured in Figure 3-5. Approximately 30 to 40 farmers were interviewed by Agribusiness Associates (ABA) representatives in each region.

FIGURE 3-5: Indian provinces where grower interviews were conducted.



The Indian government maintains a very detailed database of ground water levels and this data was used in calculating irrigation energy use (CBWB, 2012). An example of the data from CGWB (2012) is provided in Figure 3-6 showing there are significant variation in levels across the country, with the greatest depth to water in the most arid region in the northwest part of the country. Data on soil erosion was taken from Singh et al. (1992) which provided a contour map of erosion rates for the country. In most regions of India there were few soil conservation measures in place, and as climatic conditions have a significant impact on erosion rates, this source was considered acceptable. Additional data on water and fertilizer practices reported by Buttar et al. (2012) were used to supplement information on soil residual nutrients and irrigation levels. Data on ginning in India was available from Patil and Arude (2014) and energy use for the type of double roller gins used in India was supplemented from Estur and Gergely (2010).

FIGURE 3-6: Indian depth to water map taken from plate VII of CGWB (2012).



### 3.1.15 Grower Practices

India is the only country to grow all four species of cultivated cotton. These are the Asian cottons *G. arboreum* (Desi cotton) and *G. herbaceum*, as well as *G. barbadense* and *G. hirsutum*. Hybrid cottons are planted on 90% of the cotton area. Production practices varied somewhat according to the type of cotton planted.

The North Region is characterized by cotton grown entirely as an irrigated crop. The climate is adverse at planting with high temperatures and the growing period is limited to May to October. The Central Region is characterized by a hot, semi-arid climate. Planting in this region is dependent upon the onset of monsoon (middle of June to July). The South Region is also characterized by a hot semi-arid climate. However, the agro-climate is more suitable for cotton, especially with the bimodal distribution of rainfall in some areas of the South Region. The planting season is primarily August to September but there is also a small summer crop planted in January to February in Tamil Nadu.

Approximately 65% of India's cotton is produced on non-irrigated land and the remaining 35% on irrigated land. The North Region is almost 100% irrigated while the Central and South regions are primarily produced without irrigation. Other characteristics of the regions are given in Table 3-8.

TABLE 3-8: Summary of key data collection metrics by region in India.

| | | Region | | |
|---|---|---|---|---|
| **Measure** | **Units** | **North** | **Central** | **South** |
| **Plant** | Date | 1-May | 15-Jun | 1-Jul |
| **Harvest** | Date | 20-Oct | 15-Nov | 15-Dec |
| **Total Harvested Area** | ha | 1,524 | 7,501 | 2,950 |
| **Soil Data** | | | | |
| **Clay** | % | 20 | 56 | 36 |
| **Silt** | % | 30 | 28 | 23 |
| **Sand** | % | 50 | 16 | 41 |
| **Soil Erosion Rate** | kg soil ha$^{-1}$ and year | 4,000 | 6,000 | 7,000 |
| **Direct Energy and Irrigation** | | | | |
| **Diesel Use** | l ha$^{-1}$ | 20 | 14.82 | 18.5 |
| **Irrigated Area** | % | 100 | 17 | 10 |
| **Irrigated Amount*** | mm | 475 | 200 | 100 |
| **Weighted Irrigation*** | mm | 475 | 34 | 10 |
| **Irrigation Energy** | kWh ha$^{-1}$ yr$^{-1}$ | 618 | 115 | 64 |
| **Fertilizer Rates** | | | | |
| **N** | kg ha$^{-1}$ | 84.5 | 79.5 | 95.6 |
| **$P_2O_5$** | kg ha$^{-1}$ | 45.5 | 22.7 | 17 |
| **$K_2O$** | kg ha$^{-1}$ | 7.8 | 2.3 | 2.3 |
| **Harvest Ginning** | | | | |
| **Seed Cotton** | kg ha$^{-1}$ | 1782 | 1287 | 1521 |
| **Fiber Yield** | kg ha$^{-1}$ | 677 | 489 | 578 |
| **Distance to Gin** | Km | 1 | 2 | 1 |
| **Gin Electrical Use** | kWh (227 kg bale)$^{-1}$ | 31.8 | 31.8 | 31.8 |

**Irrigation amount is the level of water applied in the region if the land is irrigated. The "Weighted Irrigation" was used in the study to adjust the water applied to represent the amount of water that would have been used if distributed across all acres in the region.*

### **3.1.15** Agricultural Data Collection: Australia

During the study period of 2010 to 2014, Australia was the third largest cotton exporter in the world and the seventh largest cotton producing country (USDA, 2015b). It also has the highest yields of any country in the world due to its access to irrigation water, ideal environmental conditions, and well-adapted varieties. Compared to the other countries in the study, Australian cotton production practices are relatively consistent across the country; due in part to the fact cotton is entirely grown in the eastern part of the country (see Figure 3-7). The area devoted to cotton cultivation, production, and yield average for the study period in Australia is provided in Table 3-9.

TABLE 3-9: Average harvested area, production and yield during 2010 to 2014 study period for Australia.

| Harvested Area (ha) | Number of 218 kg Bales | Yield (kg per ha) |
|---|---|---|
| 465,000 | 4,120,000 | 1,957 |

### **3.1.17** Data Sources

The Cotton Research and Development Corporation (CRDC) coordinated data collection in Australia. Australian cotton production is relatively homogenous and therefore the data set chosen is based on cotton production in the Namoi valley. In particular, it is focused on data from the Australian Cotton Research Institute, where much of the industry's research is conducted and which provides access to detailed published data and research results. Nevertheless, where industry-wide data is available it was used, for example pesticide use and water use figures. Climate data is taken from the long-term data set published by the Bureau of Meteorology. Yield figures (5 year average) were based on data published in the Australian Cotton Grower derived from data from the Australian Bureau of Statistics. Industry production practices are derived from a 2013 survey of cotton growers conducted by Roth Rural Pty Ltd on behalf of CRDC. Survey responses covered 92,687 ha of irrigated cotton (23% of the total irrigated crop) and 9,853 ha of dryland cotton production (27% of the total dryland crop in 2012 to 2013). Energy use and tillage operations on farms were from an industry survey on energy use conducted by the National Centre for Engineering in Agriculture. Energy use at the gin is derived from surveys of the two major ginning companies operating in the Namoi valley. Water use is an industry wide average per Roth (2013). Pesticide use is also an industry wide 5-year average, based on information provided by professional crop consultants responsible for pest inspection and pesticide application recommendations. The area covered by the consultants who provide information averages approximately 60 % of the crop.

FIGURE 3-7: Cotton growing areas in Australia (map from Cotton Australia).

## 3.1.18 Grower Practices

The average Australian cotton farm is family owned and operated and grows 495 hectares of cotton. Australian growers supplement cotton with other crops including wheat, chickpeas, and sorghum and many Australian cotton farmers also graze sheep and cattle. There are more than 1,200 cotton farms in Australia, roughly half in NSW and half in Queensland.

While most of Australian cotton is irrigated, it is mostly grown in the 400-800 mm summer rainfall zone of country, so rainfall meets nearly half of the crop’s water needs most years. Like the United States, production practices in Australia are highly mechanized. A summary of some key measures derived from the data collection process is given in Table 3-10.

TABLE 3-10: Some key measures of Australian cotton production.

| Measure | Units | Value |
|---|---|---|
| **Planting** | Date | 15-Oct |
| **Harvest** | Date | 15-Apr |
| **Diesel Use** | l ha$^{-1}$ | 114 |
| **Irrigated Area** | % | 90 |
| **Irrigated Amount*** | mm | 601 |
| **Weighted Irrigation*** | mm | 541 |
| **Nitrogen Rate** | kg ha$^{-1}$ | 192 |
| **Gin Electrical Use** | kWh (227 kg bale)$^{-1}$ | 34.05 |

**Irrigation amount is the level of water applied in the region if the land is irrigated. The "Weighted Irrigation" was used in the study to adjust the water applied to represent the amount of water that would have been used if distributed across all acres in the region. Irrigation units are mm of depth of water on 1 ha of land.*

### 3.1.19 FARM Model

Agrarian systems belong to the most complex production systems within LCA due to their dependence on environmental conditions that are variable in time (e.g., within a year, from year to year) and in space (e.g., varies by country, region, site conditions). The following factors contribute to the complexity of agricultural modeling:

- The variety of different locations
- Small scale soil variability within locations
- The large number and diversity of farms
- The variety of agricultural management practices employed
- Technically, no determined border to the environment
- Complex and indirect dependence of the output (harvest, emissions) from the input (fertilizers, location conditions, etc.)
- Variable weather conditions within and between different years
- Variable pest populations (insects, weeds, disease pathogens, etc.)
- Different crop rotations

Due to the inherent complications characterizing an agricultural system, a nonlinear complex agrarian model was used for plant production (developed by thinkstep and the University of Stuttgart, Germany). This model covers a multitude of input data, emission factors, and parameters. This part of the GaBi model is used for cradle-to-gate (seed-to-bale) environmental impact assessment associated with planting, growing, harvesting, processing, handling, and distribution of cotton. For annual crops, a cultivation period starts immediately after the harvest of the preceding crop and ends after the harvest of the respective crop.

## 3.2 LCA METHODOLOGY

### 3.2.1 System Boundary

Provided within the agrarian plant model is the entire production of cotton (and its by-products) including harvest processes up to the field edge. The model includes cradle-to-gate burdens of all relevant input materials for the cultivation process itself (commercial fertilizer including lime, organic fertilizer, pesticides, and seeds including their production and transport). The model includes the cradle-to-gate burdens of fuel consumed in the field for operations (e.g., equipment) including direct emissions to air from the combustion of the fuel. The model includes irrigation (excluding equipment production) and excludes agricultural infrastructure and farm buildings. All relevant processes taking place on the area under cultivation including emissions into air and ground water (lower limit of rooted soil zone) are integrated. Heavy metals remaining in soil are considered as emissions in soil. Integration of erosive loss of Norg (organic nitrogen) and Corg (organic carbon) as well as of nutrients (e.g., phosphorus) in water is considered.[1]

### 3.2.2 Reference System

The reference system is an inverse process used to assess the behavior of land that is not used agriculturally or influenced anthropogenically. In particular losses of nitrate to groundwater and emission of gaseous nitrogen compounds that result from nitrogen deposition onto this land are considered. This takes place in both the main cropping system as well as on land not under cultivation. Therefore, not all occurring emissions can be assigned to the crop as they also occur on non-cultivated land, e.g., if this is fallow or a nature reserve. Here it is assumed that the nitrogen balance is neutral for the reference system, as any entry of nitrogen with rainfall is re-emitted from the systems in various forms into groundwater and air.

In addition to the emissions of nitrogen compounds, the soil erosion is mapped including the associated conditional entries of organic carbon contained in the soil and some heavy metals in surface waters. The same principle is applied that this erosion occurs to a lesser extent also in non-utilized natural systems and therefore cannot be assigned completely to the main crop.

### 3.2.3 Land Use Change

Data from USDA (2015b) indicates that the total global area devoted to cotton cultivation has stayed between 30 and 35 million hectares since 1960. Therefore, no emissions from land use change were considered in this study as all areas in the regions under study were under agricultural cultivation for more than 20 years. Indirect land use change (iLUC) is also not considered.

### 3.2.4 Water Modeling

Water use is modelled based on the framework of ISO 14046 (please refer to Annex G for a detailed description of the terms used). Surface and groundwater use for irrigation were modeled based on primary data and statistical data collected specifically for this project (Pfister, Koehler, & Hel, 2009). Water used for irrigation is assumed to be 100% consumptive use (Pfister, Koehler, & Hel, 2009). Green water consumption is assessed using CROPWAT 8.0 data, following the approach described by the water footprint network (Franke, Boyacioglu, & Hoekstra, 2013).

### 3.2.5 Carbon Modeling

Carbon-based emissions such as $CH_4$, CO, and $CO_2$ are considered in foreground and background datasets. Background datasets include emissions resulting from the production of fertilizer, pesticides, electricity, and diesel, while foreground datasets contain emissions such as $CO_2$, due to combustion of fossil fuels by the tractor or irrigation engines, and application and decomposition of urea fertilizer in the soil.

Soil carbon is another potential source or sink of carbon dioxide. Soil carbon balances are used to describe any increase or decrease in soil organic carbon (SOC) content caused by a change in land management, with the implication that increased/decreased soil carbon (C) storage mitigates or enhances climate change. The net effect of cotton cultivation is highly variable and depends on various factors such

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[1] Throughout this report, the term ‘organic’ is used to describe materials and compounds containing carbon, not to be confused with the designation for products made without synthetic fertilizer, etc.

as fertilization or soil cultivation practices. Conservation tillage techniques are especially seen as promising approaches to increase SOC. It is estimated by applying no tillage in the Southeastern United States, SOC increases on average by 0.48±0.56 t C $ha^{-1}$ $yr^{-1}$ compared to conventional tillage (Causarano, Franzluebbers, Reeves, & Shaw, 2006). Assuming that all of the carbon can be stored in the soil in the long term a $CO_2$ reduction of 0.59 kg $CO_2$eq per kg of seed cotton can be realized (assuming a yield of 3,000 kg fw $ha^{-1}$, 2,676 lb fw/ac and an average carbon storage rate of 0.48 t C ha-1 yr-). This would imply a significant potential reduction of the GHG footprint of cotton fibers. However, limitations of C sequestration for climate change mitigation include the following constraints: (i) the quantity of C stored in soil is finite, (ii) the process is reversible, and (iii) even if SOC is increased there may be changes in the fluxes of other greenhouse gases, especially nitrous oxide ($N_2O$) and methane. Due to these variations and related uncertainties (Powlson, Whitmore, & Goulding, 2011) carbon sequestration could have been significant, but it is not considered within the scope of this study. Furthermore, the end-of-life of gin waste is excluded, leaving the system burden-free and without any benefits to the main product. Gin waste consists of broken seeds, fibers, and plant remains (residues). In the worst case, its storage and processing could be associated with additional environmental impacts. On the other hand, it is occasionally returned back to the land as organic fertilizer. Therefore, attributing no burdens to the gin waste is a neutral approach, neglecting a small potential environmental impact and also annulling a similarly small environmental benefit (fertilizer use).

Beside emissions, positive effects (sinks) due to natural conversion of gases in the soil were considered. Gaseous sinks are related predominantly to the methane depression function of natural soils due to their oxidizing and microbial transformation of methane. A default value of 1.5kg $CH_4$ $ha^{-1}$ was assumed for fields and value of 2.5 $CH_4$ $ha^{-1}$ as default in the reference system process (Dämmgen 2009).

The biogenic $CO_2$ sequestered in the cotton plant and its fiber is directly accounted for in the inventory as an input or uptake of carbon dioxide. For cradle-to-gate cotton fiber, this resulted in both positive and negative GWP values for different growth regions depending upon the anthropogenic emissions associated with the regional agriculture practices. Some of the carbon sequestered in cotton will eventually return to the air at EoL during landfilling or incineration and some carbon will be sequestered in the landfill even beyond the 100 year GWP timescale.

### **3.2.6** Nutrient Modeling

Nitrogen plays a fundamental role for agricultural productivity and is also a major driver for the environmental performance of an agricultural production system. For these reasons it is essential to evaluate all relevant nitrogen flows within, to, and from the agricultural system. The thinkstep agriculture model accounted for the nitrogen cycle that occurs in agricultural systems.

The different N-based emissions are calculated as follows:

- $NH_3$ emissions to air from mineral and organic fertilizers are adapted from the model of Brentrup. F. et al. (Brentrup, 2000) and modeled specifically for the cropping system dependent on the fertilizer-$NH_4$+ content, the soil-pH, rainfall, and temperature. The following emission factors are used by default and adjusted in case more specific information is available. For ammonium nitrate, calcium ammonium nitrate, monoammonium phosphate, diammonium phosphate, and ammonium sulphate 2% of fertilizer N input, for urea ammonium nitrate 8% and for urea 15% are emitted. These values are identical with data from Döhler et al. 2002 (with exception of the ammonia emissions).
- $N_2$ is the final product of denitrification. Denitrification is a process of microbial nitrate reduction that ultimately produces molecular nitrogen through a series of intermediate gaseous nitrogen oxide products. $N_2$ emissions are assumed to be 9% of the N-fertilizer input based on a literature review made by Van Cleemput (1998). $N_2$ emissions are also taken into consideration to determine the nitrate leaching potential.
- NO is an intermediate product produced in microbial denitrification. NO emissions are calculated from the reference system after N-input from air plus 0.43% of the N-fertilizer input specific for the cultivation system as NO according to Bouwman et al. (2002).

- $N_2O$ is an intermediate product produced in microbial denitrification. According to IPCC 2006, $N_2O$ emissions were calculated as 1% of all nitrogen available including nitrogen applied with fertilizers, atmospheric deposition, microbial nitrogen fixation, nitrogen available from previous crop cultivation, and indirect emissions.
- $NO_{3-}$ emission to groundwater is calculated based on available nitrogen derived from a nitrogen balance (N not lost in gaseous form or taken up by the plant, stored in litter, storage in soil, etc.). Depending on the leaching water quantity and soil type, a fraction of this available nitrogen is calculated to be leached as nitrate. Water available for leaching is estimated based on CROPWAT 8.0. The actual amount of water leached depends on the water retention capacity of the soil (considered in the study based on soil type).
- Norg and $NO_{3-}$ emissions to water occur due to erosive surface run-off. See Soil Erosion section for a description of soil erosion modelling.

Besides nitrogen-based emissions to water and air, phosphorus emissions are taken into consideration in the model. Phosphorous emissions are typically dominated by surface runoff of soil to surface water, causing eutrophication of water bodies, thus they are directly related to soil erosion. Please refer to the Soil Erosion section for a description of soil erosion modelling.

### **3.2.7** Soil Erosion

Data on soil types and soil erosion rates are described in a previous section on agricultural data collection for each country. It is assumed that 10% of the eroded soil accesses the waters, based on evaluation of different literature sources, while the rest accumulates to colluviums on other surfaces and is assumed irrelevant in the life cycle assessment (Fuchs & Schwarz, 2007; Hillenbrand, 2005; Helbig, Moller, & Schmidt, 2009; Nearing, Kimoto, & Nichols, 2005). The nutrient content of the soil entering surface water with soil erosion was assumed to be 0.05% for phosphor, 0.6% for nitrogen (organic bound), and 0.4% for nitrate – representing values from literature independent from soil management practices.

### **3.2.8** Pesticide Emission Modeling

For land in the previous global cotton LCA, a simple pesticide emission model was used that only addressed the emissions at the time of application and then relied on the factors in first version of USEtox™ (Rosenbaum R., et al., 2008) to address off-site fate and transport of the pesticides. Experiences with that version of USEtox indicated the model was not appropriate to characterize the fate and transport of pesticides applied to agricultural lands. Therefore, one emission model used in this study was to use the EPIC (Environmental Policy Integrated Climate) component of APEX (Agricultural Policy/Environmental eXtender) model (Williams, et al., 1996; Williams & Izaurralde, 2006). EPIC was used to conduct 40-year weather simulations for different soil scenarios at three locations in the United States (Georgia, Arkansas, Texas, and California). As EPIC is a field level model, the simulations were specific to a field in each of those states, so the results will not be completely representative of the regions. Furthermore, the data sets needed to conduct the EPIC simulations in India and China were not readily available, so pesticide emission factors for regions in those countries were estimated by matching climates and soil types to those of the U.S. regions. In the event a pesticide was used in India or China, but not simulated in the United States, a proxy was determined by finding a pesticide that was simulated with similar chemical properties, especially focused on matching the soil organic carbon-water partitioning coefficient ($K_{oc}$). Because use of EPIC did rely on a number of assumptions to generate emission factors for each global region, a second approach to pesticide emissions was to assume 1% was emitted to the atmosphere and the remainder was emitted to the soil.

### **3.2.9** Land Use

Land use was considered in this study and assessed following the LANCA method (Beck, et al., 2010). Please refer to Annex E: Evaluation of Land Use (LANCA) for an overview on land use modelling and results. For a full description of the LANCA land use modelling approach please refer to Beck et al. 2010.

### **3.2.10** Labor

Currently, resources associated with labor are not commonly addressed in LCA since for many products, labor differences are not significant. However, there are considerable differences in labor use between mechanized and non-mechanized agricultural production systems. This resulted in significant differences in agricultural labor requirements between countries. The implications of these differences are difficult to quantify from an LCA perspective and were not addressed in this study.

### **3.2.11** Equipment

Impacts associated with the energy used by agricultural equipment were accounted for in the agricultural phase of the study. Because of the life time of equipment and the large areas it covers, the impact of manufacturing agricultural equipment is typically small from an LCA perspective, but there can be exceptions that include harvesting equipment in some specific cases (Frischknecht et al. 2007). However, in this study much of the cotton was hand harvested, and when that was not the case, the harvest was conducted by machines covering large areas. Nemeck and Kagi (2007) use a value of 10 MJ per kilogram of machine weight as an approximation of energy use for agricultural machinery. A six row spindle cotton harvester has a mass of approximately 23,000 kg, so the energy for manufacturing is fairly large. However, assuming an 8 year life, Nemecek and Kagi (2007) use 12 years for combine harvesters and 600 ha of cotton harvested per year with a yield of 1,000 kg per ha, thus the manufacturing energy only represents 0.05 MJ per kg of cotton harvested. Therefore, the impact of equipment manufacturing was not considered in this study.

## **3.3** TEXTILES DATA COLLECTION AND MODELING

### **3.3.1** Textiles Data Collection

The textile manufacturing data were measured or calculated from primary sources, and supplemented with literature and industry averages. All textile unit processes were completely considered and were calculated to create global averages for each process. All background data were derived from the GaBi database, which has its representativeness and completeness documented here: http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

Primary textile data were collected from 15 textile mills (6 knit mills and 9 woven mills); however, only data from 13 were used in the LCA due to errors or missing information.

Every mill reported material flows separately for knit or woven fabrics. The mills were vertically integrated at different levels and may buy and sell intermediate materials. For this reason, each process was isolated and compared across all the mills reporting for that process. This enables the creation of a horizontal average at each step. Unit processes are grouped together to create global averages. There was a change in the grouping of processes versus the collection groupings for the 2010 study. Due to complexity, time constraints, and the inability of most mills to accurately generate flows for individual processes that happen continuously, several of the processes were combined as shown below in Table 3-11.

TABLE 3-11: Textile unit processes grouping.

| Knit Fabric (2015) | Knit Fabric (2010) | Woven Fabric (2010) | Woven Fabric (2015) |
|---|---|---|---|
| **Yarn Production** | **Opening, Cleaning, Mixing** | **Opening, Cleaning, Mixing** | **Yarn Production** |
| | Carding | Carding | |
| | Predraw | Predraw | |
| | Combing | Combing | |
| | Drawing | Drawing | |
| | Roving | Roving | |
| | Spinning | Spinning | |
| | | Repackaging (Fill) | Beaming, Slashing, Drying (Warp Yarn) |
| | | Beam/ Slash/ Dry (Warp) | |
| Knitting | Knitting | Weaving | Weaving |
| Preparation | Preparation | | |
| Batch Dyeing | Preparation | | |
| Continuous Dyeing | Preparation | | |
| Batch Dyeing | | | Continuous Dyeing |
| Finishing (Wet and Foam) | Finishing–Wet (Pad, Curing) | Finishing–Wet (Pad, Curing) | Finishing (Wet and Foam) |
| Compacting | Compacting | Sanforizing | Sanforizing |

### **3.3.2** Textile Manufacturing

In an effort to collect the best quality data, textile mills were selected based on the products that they manufacture, their level of verticality, and their location. Countries and regions of interest (Eurasia, East Asia, South/Central Asia, and Latin America) were identified based on world textile manufacturing volume. Preference was given to mills with vertically integrated operations. However, not all participating mills were vertically integrated. A total of 39 textile mills from major textile-producing regions were identified and asked to participate in data collection. Mills were sent an introduction letter and received follow-up calls from account representatives to explain the process and answer questions. Of the 39 mills contacted, 22 initially agreed to participate and signed nondisclosure agreements.

Each textile mill received a data collection template in Excel format, with different tabs for each unit process. The most vertically integrated mills took raw bales of cotton through spun yarn and then knitted or wove the yarn into dyed, finished fabric. Many mills purchase intermediate products such as spun yarn, so each mill only reported data for its own specific processes in-house. Due to confidentiality, specific mill data cannot be shared, but a 'hybrid' data collection template is shown in Annex F: Example Textile Data to convey the level of detail the mills reported. The unit process data in this template are combined from different mills to protect confidentiality, but it gives the reader a feel for the types of information collected.

Cotton Incorporated experts worked collectively with all mills to review and approve data submitted. At the end of the data collection deadline, 15 surveys were received: 9 from woven fabric manufacturers and 6 from knit fabric manufacturers. Each survey was quality checked by a team of textile experts from Cotton Incorporated and clarification questions were returned to the mills. From the surveys received, 13 contained usable data (7 woven fabric manufacturers and 6 knit fabric manufacturers). A second round of quality control was performed on the data by thinkstep.

The fabric production steps varied depending on the intended use and characteristics of the garment, so each unit process step was modeled independently for greater flexibility. The different unit processes and their inputs and outputs are displayed below in Figures 3-8 and 3-9.

For each unit process, each mill's annual inputs and outputs were divided by the annual output for that unit process to create an inventory of normalized inputs and outputs. Mill data were then rolled together by production volume at each unit process to create the global average LCIs.

FIGURE 3-8: Woven fabric unit process chain (bale to finished fabric).

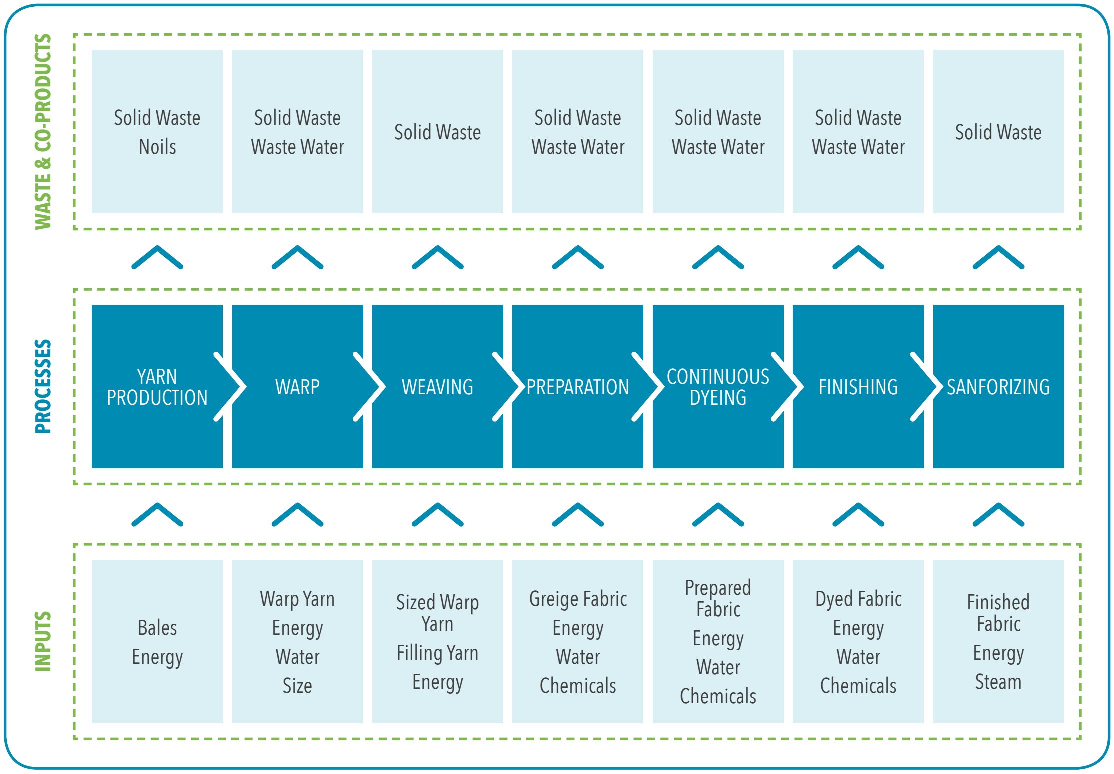
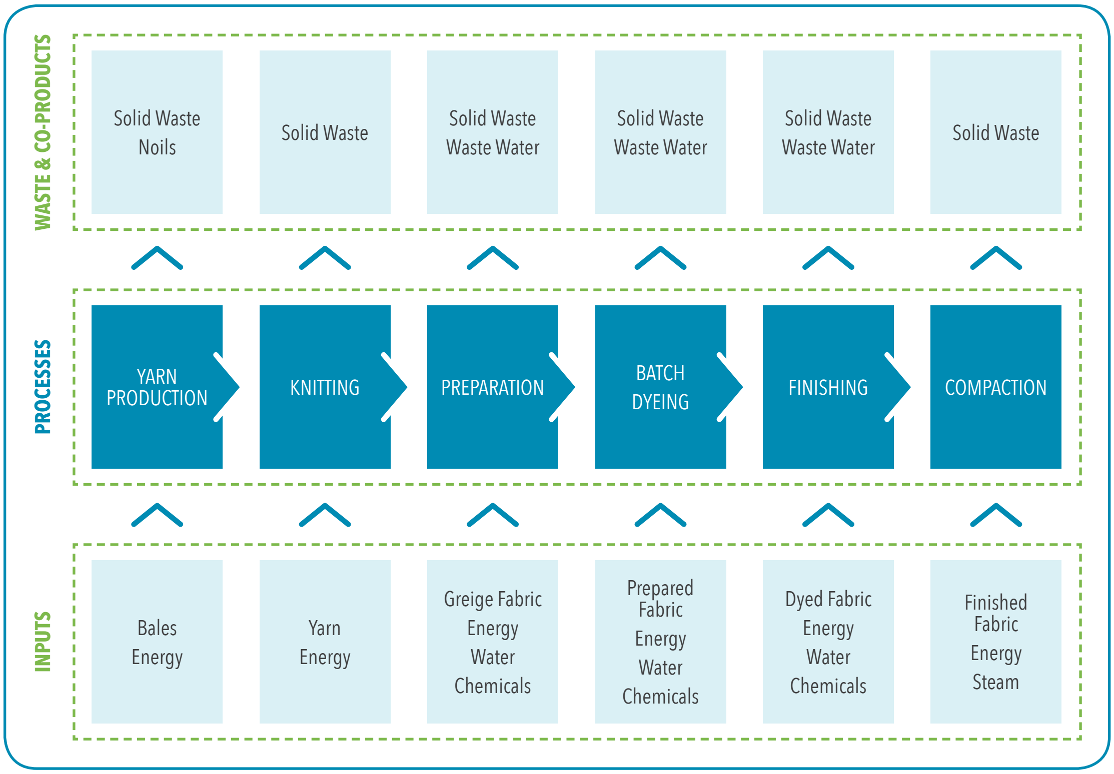


FIGURE 3-9: Knit fabric unit process chain (bale to finished fabric).



In an effort to collect more detailed information on chemicals used in the preparation, dyeing, and finishing processes, the questionnaire was updated from the 2010 study to include more specific chemical types. For example, 'Scouring Agents', 'Alkali', 'Acids', and 'Other Chemicals' were presented as separate line items on the 2015 data collection sheet, allowing for more precise data collected from the mills and limiting the need to use expert estimations to allocate the chemicals.

In addition to material inputs and outputs, process energy was collected. Mills were asked to provide data for each unit process, but many could only supply energy for yarn production or preparation/dyeing/finishing processes combined. Therefore, for mills that only provided total energy, energy and inputs were allocated for each unit process according to industry average weighting. For mills that could not provide data, industry average proxies were used.

Equipment manufacturers' energy demand data are reported below in Table 3-12 for reference. Note that only ring spinning is presented; all sliver for ring spinning was combed. Combed sliver was drawn and made into roving before ring spinning. Because there were not enough mills to maintain confidentiality for rotor or air-jet spinning, data for all spinning methods were rolled together into a production weighted average for the global average spinning process.

TABLE 3-12: Process machinery energy from equipment manufacturers. Energy is reported in MJ/1000 kg.

| Fabric Type | | Electricity | Steam and Natural Gas |
|---|---|---|---|
| **Knits/Wovens** | Opening, Cleaning, Mixing* | 299.66 | |
| **Knits/Wovens** | Carding* | 384.34 | |
| **Knits/Wovens** | Predraw Prep* | 105.44 | |
| **Knits/Wovens** | Combing (Ring Spinning only)* | 194.65 | |
| **Knits/Wovens** | Drawing* | 210.17 | |
| **Knits/Wovens** | Roving (Ring Spinning only)* | 637.32 | |
| **Knits/Wovens** | Ring Spinning* | 7280.04 | |
| **Knits/Wovens** | Rotor Spinning* | 5288.86 | |
| **Knits/Wovens** | Finishing | | 2211.93 |
| **Knits** | Prep and Yarn Dyeing | 623.00 | 9308.25 |
| **Knits** | Backwinding | | |
| **Knits** | Creeling | | |
| **Knits** | Knitting | 926.00 | |
| **Knits** | Prep and Batch Dyeing | 697.57 | 10023.93 |
| **Knits** | Compaction | 75.89 | 4589.56 |
| **Wovens** | Repackaging (Fill) | | |
| **Wovens** | Beam Slash Dry (Warp) | | 2211.93 |
| **Wovens** | Weaving | 10430 | |
| **Wovens** | Prep and Continuous Dyeing | 331 | 4202 |
| **Wovens** | Sanforizing | 74 | 4313 |

### 3.3.3 Cut-and-Sew

Cut-and-sew energy and waste data were obtained (TC2, 2009) for the original 2010 study. Since new process data could not be obtained from garment manufacturers and because few process improvements have occurred in this portion of the supply chain in the last five years, the 2009 data were used in this study. The materials in a knit collared casual shirt, t-shirt, and woven casual pant were measured by deconstructing high-end and low-end garments purchased in the United States.

The average knit casual collared shirt, average t-shirt, and average woven casual pant are calculated by arithmetic averages of the low-end and high-end garments' components. Material inputs are shown below in Table 3-13: Garment components [grams/garment]. A decision was made to retain the 305 g mass of a collared knit shirt from the first study, instead of using the new weight, for possible comparisons. The range of possible shirt weights based on construction variables and ordinary processing variability would include 305 g. The same decision was not made for the casual pants since import data shows that pants have been trending toward lighter weights over the past five years.

TABLE 3-13: Garment components [grams/garment].

| Garment Component | Material | Average Knit Casual Collared Shirt | Average Knit T-Shirt | Average Woven Casual Pant |
|---|---|---|---|---|
| **Body Fabric Component** | 100% Cotton | 247.02 | 225.07 | 401.60 |
| **Buttons** | Polyethylene Copolymer | 0.55 | NA | 1.80 |
| **Tags** | Polyester, Nylon | 0.59 | NA | 1.05 |
| **Lining** | Polyester | NA | NA | 23.48 |
| **Pockets** | 100% Cotton | NA | NA | 25.96 |
| **Seam Reinforcements/ Zipper Lining** | 100% Cotton | NA | NA | 10.78 |
| **Waistline/Collar/Sleeve** | 100% Cotton | 27.09 | NA | 31.68 |
| **Zipper (metal)** | Brass | NA | NA | 13.20 |
| **Belt Loops** | 100% Cotton | NA | NA | 5.33 |
| **Zipper (Plastic)** | Polyester | NA | NA | 9.00 |
| **Total**** | | **275.25*** | **225.07*** | **512.76*** |

**Values may not add due to rounding.*

***Zipper used in total is an average zipper (metal and plastic are averaged together even though no single garment would have both a metal and plastic zipper.).*

For this study, it is assumed that a knit casual collared shirt weighs on average 305 g; for the functional unit of 1,000 kg finished garments, this represents 3,278 shirts (Table 3-14). Presence or absence of sleeve trim, number and types of buttons, pockets and aesthetic design elements, and variations in type of knit fabric for trims and collars (e.g., rib vs. interlock) can all affect this total weight.

This study assumes that a knit t-shirt weighs on average 225 g; for the functional unit of 1,000 kg finished garments, this represents 4,444 shirts. Generally, legally required information and sizing are imprinted or added by decals that cannot be weighed.

It is assumed that a pair of woven casual pants weighs on average 513 g; for the functional unit of 1,000 kg finished garments, this represents 1,949 pairs of casual pants. For all garments, the calculated number of garments includes cut-and-sew losses, and only provides the cotton portion of the garments.

TABLE 3-14: Mass of garments, cut-and-sew loss, and number of garments per 1,000 kg of finished garment.

| Garment Type | g*/Garment | Cut-and-Sew Loss (%) | # of Garments/1,000 kg of Garments |
|---|---|---|---|
| **Knit Collared Shirt** | 305 | 15.2% | 3,278 |
| **Knit T-shirt** | 225 | 15.0% | 4,444 |
| **Woven Pants** | 513 | 12.4% | 1,949 |

**Grams of cotton per garment.*

The energy used in the cut-and-sew phase assumed a grid energy mix with the following breakdown: China 42%, EU 28%, India 7%, Turkey 5%, Bangladesh 1%, Vietnam 2%, United States 5%, Rep of Korea 5%, Pakistan 4%, and Indonesia 2%. The source of this relative contribution by country and region is World Trade Organization (WTO) textile exports by country (WTO, 2014).

Due to the lack of data on water emissions from all the textile manufacturing partners, water emissions were supplemented by using the applicable regulatory threshold values, which are summarized in. Table 3-15: There is not enough empirical data available from the countries of manufacture to conclude whether using threshold values is a best case or worst case estimate on average.

TABLE 3-15: Wastewater treatment emissions thresholds for effluent water in regions of textile manufacturing.

| | East Asia[1] | South and Central Asia[2] | Latin America[3] | Eurasia[4] |
|---|---|---|---|---|
| **Total Kjeldahl Nitrogen as NH3** | | 100 | | |
| **Nitrate Nitrogen** | | 10 | | |
| **Ammonia Nitrogen** | 10 | | | |
| **Total N** | 15 | | | 5 to 25 |
| **Total Inorganic N** | | | | 5.0 to 20 |
| **Ammonia Nitrogen** | 10 | | | |
| **dissolved Phosphates (as P)** | 0.5 | 5 | | 1.9 to 2.3 |
| **Total P** | 0.5 | | | 0.50 to 3.0 |
| **Total Organic Carbon (TOC)** | | | | 10 to 33 |
| **TSS** | 50 | 100 | 30 | 5.0 to 35 |
| **COD** | 250 | 250 | | 30 to 100 |
| **BOD** | 20 | 30 | 30 | |
| **pH** | 6 to 9 | 5.5 to 9.0 | 5 to 10 | |

**Where ranges are given, the average between the min and max was used.*

*Source:*

1 *http://www.sgsgroup.us.com/en/Our-Company/News-and-Media-Center/News-and-Press-Releases/2015/07/SafeGuardS-12115-China-Discharge-Standards-of-Water-Pollutants-for-Dyeing-and-Finishing-of-Textile.aspx*

2 *http://cpcb.nic.in/GeneralStandards.pdf page 545-6*

3 *http://www.cep.unep.org/publications-and-resources/marine-and-coastal-issues-links/wastewater-sewage-and-sanitation class 1 used*

4 *http://www.csb.gov.tr/db/ippceng/icerikbelge/icerikbelge865.pdf Page 93, table 3.1*

### 3.3.4 Consumer Use

Consumer use behavior data were collected by Cotton Council International and Cotton Incorporated using an international, third-party market research company to survey respondents in the uppermost fraction of apparel-consuming countries regarding their use and laundering practices for t-shirts, knit casual collared shirts, and casual woven pants. The survey was conducted from May through June 2015 in five countries including the United States, China, Japan, Italy, the United Kingdom, and Germany. The United States, Japan, Italy, the United Kingdom, and Germany were self-administered quantitative online surveys using the research company's multi-million member panel as well as their certified partner panels. An internet-only methodology was used for those countries having 60% or greater internet penetration. In order to secure a representative sample in China, a mixed mode methodology was used which included 40% self-administered online surveys and 60% face-to-face interviews. The questionnaires were similar across countries, with minor differences to account for cultural distinctions.

Approximately 1,000 consumers were surveyed per country with a total sample of just over 6,000 respondents. Respondents were ages 18 and older and were representative of each country's demographics. In order to qualify for the survey, respondents had to own at least one t-shirt, one casual collared shirt, and one pair of casual woven slacks. Each respondent had to wear and launder (hand or machine wash) their own garments.

TABLE 3-16: Sample size by country.

| Country | Sample Size |
|---|---|
| **United States** | 9.0 |
| **China** | 8.6 |
| **Japan** | 1.8 |
| **Italy** | 6.7 |
| **United Kingdom** | 2.0 |
| **Germany** | 1.4 |
| **Total** | **5.8** |

Laundering details are reported in Table 3-17 Washing machine data and Table 3-18 Dryer Data. Most of the energy and water requirements that were used to calculate global averages for washer and dryer cycles were taken from government sources and academic publications. Washer load size was averaged based on government and academic publications for each country. Definitions of hot and cold water vary by region. For instance, in Asia, no water that is initially being used for laundering is heated for that purpose, though bath water may be reused for laundering. Cold water is assumed to be the most efficient condition and hot water least efficient, so ranges are shown in Table 3-17.

TABLE 3-17: Washing machine data.

| Parameter | Quantity | Unit | Source |
|---|---|---|---|
| **Unit–lbs** | | | |
| **Wash Load Size (small load)** | 3.70 | lbs/load | (CDR(EU), 2010), (Yamaguchi, Seii, Itagaki, & Nagayama, 2011) (BS EN, 2011), (Federal Register, 2010) |
| **Wash Load Size (average load)** | 8.88 | lbs/load | |
| **Wash Load Size (x-large load)** | 14.55 | lbs/load | |
| **Average Load Detergent** | 82.75 | grams/load | (Schenck, 2013) |
| **Unit–kg** | | | |
| **Wash Load Size (small load)** | 1.68 | kg/load | (CDR(EU), 2010), (Yamaguchi, Seii, Itagaki, & Nagayama, 2011), (BS EN, 2011), (Evans, 2014), (Federal Register, 2010) |
| **Wash Load Size (average load)** | 4.04 | kg/load | |
| **Wash Load Size (x-large load)** | 6.61 | kg/load | |
| **Average Load Detergent** | 82.75 | grams/load | (Schenck, 2013) |
| **Most Efficient Washer*** | | | |
| **Water Consumption per unit** | 66.62 | (L/load)/unit | (EPA, 2015), (China National Institute of Standardization, 2013), (CDR(EU), 2010), (Yamaguchi, Seii, Itagaki, & Nagayama, 2011) |
| **Water Temperature**** | 20 – 30 | C | |
| **Electricity Consumption (kWh/Load) per unit** | 0.69 | (kWh/load)/unit | |
| **Least Efficient Washer*** | | | |
| **Water Consumption (L/Load) per unit** | 89.05 | (L/load)/unit | (Federal Register, 2010), (China National Institute of Standardization, 2013), (CDR(EU), 2010), (Yamaguchi, Seii, Itagaki, & Nagayama, 2011) |
| **Water Temperature** | 23 - 60 | C | |
| **Electricity Consumption (kWh/Load) per unit** | 1.36 | (kWh/load)/unit | |

**Least Efficient cannot be compared to Most Efficient due to metrics changing for DOE data.*

TABLE 3-18: Dryer data.

| Parameter | Quantity | Unit | Source |
|---|---|---|---|
| **Dryer Load Size (small load)** | 3.70 | lbs/load | (CDR(EU), 2010), (Yamaguchi, Seii, Itagaki, & Nagayama, 2011), (BS EN, 2011), (Evans, 2014), (Federal Register, 2010) |
| **Dryer Load Size (average load)** | 9.10 | lbs/load | |
| **Dryer Load Size (x-large load)** | 14.63 | lbs/load | |
| **Energy Efficient Dryer** | | | |
| **Electricity Consumption (kWh/Load) per unit** | 0.89 | (kWh/load)/ unit | (Yamaguchi, Seii, Itagaki, & Nagayama, 2011), (BS EN, 2011) (CDR(EU), 2010), (CDR(EU), 2012), (CFR, 2015) |
| **Gas Consumption (kWh/Load) per unit** | 0.27 | (kWh/ load)/ unit | (CFR, 2015) |
| **Conventional Dryer** | | | |
| **Electricity Consumption (kWh/Load) per unit** | 3.12 | (kWh/load)/ unit | (Yamaguchi, Seii, Itagaki, & Nagayama, 2011), (BS EN, 2011), (CDR(EU), 2012), (CFR, 2015) |
| **Gas Consumption (therms/Load) per unit** | 0.35 | (therms/ load)/unit | |

The following equation demonstrates the calculation of washings per life as calculated from the Global Laundering Study consumer data. The same calculation method holds true for t-shirts, casual collared shirts, and casual woven slacks:

Assuming each pair/shirt owned is worn and washed evenly:

$$\frac{\text{Lifetime x Loads}}{\text{Garments}} = \text{Lifetime}_G$$

Using the Global Laundering Study data (Table 3-19) the calculated washings for the lifetime of a t-shirt is 18, 22 washings for a casual collared shirt, and 24 washings for a pair of woven casual slacks.

TABLE 3-19: Summary of Cotton Council International and Cotton Incorporated's Global Laundering Study data.

| | Description | T-Shirts | Casual Collared Knit Shirts | Casual Woven Pants |
|---|---|---|---|---|
| **Lifetime** | Average months a garment is owned and worn on a regular basis (first life) | 38.8 | 40.9 | 43.9 |
| **Loads** | Average number of washings per month | 7.0 | 5.0 | 4.5 |
| **Garments** | Average number of garments owned | 14.9 | 9.2 | 8.4 |
| **$\text{Lifetime}_G$** | Total Washings in a Lifetime (first lifetime) | (38.8 x 7.0) / 14.9 = 18.2 | (40.9 x 5.0) / 9.2 = 22.2 | (43.9 x 4.5) / 8.4 = 23.5 |

For the WWT of effluent from municipal wastewater generated from laundering in the use phase, there is no sludge to be treated as with traditional municipal wastewater treatment. Therefore, the existing municipal wastewater treatment processes were adapted based on the Total Solids (TS), Total Organic Carbon (TOC), Nitrogen total (N total) and Phosphorous total (P total) by taking the mean value for municipal wastewater for each region. The mean values are summarized in Table 3-20 and the range of values are illustrated in Figure 3-10. Note that the average values are higher than the median values, therefore using the average values rather than the median values represents a worst case scenario for this process.

TABLE 3-20: Laundry wastewater treatment effluent values and sources (kg value / kg water).

| Year | Country | Wastewater Type | TS | TOC | N Total | P Total |
|---|---|---|---|---|---|---|
| **2014[1]** | **India** | Laundry | 5.86E-04 | 1.89E-04 | 1.89E-05 | 1.90E-05 |
| **2009[2]** | **Australia** | Laundry | | | 4.91E-06 | 2.20E-07 |
| **2013[3]** | **Brazil** | Commercial Laundry | | 5.70E-04 | 7.98E-06 | 3.45E-05 |
| **2010[4]** | **Turkey** | Grey water | | 9.83E-05 | 6.66E-06 | 7.30E-06 |
| **2013[5]** | **England** | Grey water | | 8.30E-05 | 2.30E-05 | 8.50E-06 |
| **1976[6]** | **n/a** | Laundry | 1.75E-03 | 3.80E-04 | 2.70E-05 | 7.80E-05 |
| **1998[7]** | **n/a** | Laundry | 6.58E-04 | 1.10E-04 | 1.23E-05 | 1.01E-04 |
| **1999[8]** | **n/a** | Laundry | | | 4.00E-06 | 2.10E-05 |
| **1974[9]** | **USA** | Laundry | | 2.42E-04 | 1.26E-05 | 1.71E-04 |
| **2014[10]** | **Dubai** | Laundry | | 8.33E-04 | | |
| **2003[11]** | **Slovenia** | Laundry | | 9.33E-05 | 2.75E-06 | 9.90E-06 |
| **2014[12]** | **China** | Laundry | 5.86E-04 | 1.89E-04 | 1.89E-05 | 1.90E-05 |
| **Mean** | | | **9.98E-04** | **2.69E-04** | **1.20E-05** | **4.50E-05** |
| **CoV** | | | **65%** | **94%** | **70%** | **123%** |

*Source:*

1 *http://rd.springer.com/article/10.1007/s13201-013-0128-8/fulltext.html*

2 *http://www.clw.csiro.au/publications/waterforahealthycountry/2009/wfhc-contaminant-origins-household-wastewater.pdf*

3 *http://file.scirp.org/Html/2-2200743_41855.htm*

4 *http://onlinelibrary.wiley.com/doi/10.1002/jctb.2423/abstract;jsessionid=0431A23BCA07A23CBE83D0DA891529A8.f04t01?systemMessage=Wiley+Online+Library+will+be+unavailable+on+Saturday+27th+February+from+09%3A00-14%3A00+GMT+%2F+04%3A00-09%3A00+EST+%2F+17%3A00-22%3A00+SGT+for+essential+maintenance.++Apologies+for+the+inconvenience.&userIsAuthenticated=false&deniedAccessCustomisedMessage=*

5 *https://books.google.com/books?hl=en&lr=&id=juicry4LaRgC&oi=fnd&pg=PA240&dq=(grey,+gray)+wastewater+(laundry,+washing)+(characteristics,+composition)&ots=CHRe1q5b-t&sig=BNVUVwfCkhb3xEthpBWM3bdmaoM%20-%20v=onepage&q&f=false#v=onepage&q&f=false*

6 *http://www.researchgate.net/profile/Mogens_Henze/publication/257587685_Characteristics_of_grey_wastewater/links/0a85e52dd93473e947000000.pdf*

7 *https://www.researchgate.net/publication/229451650_Grey-Water_Reclamation_for_Non-Potable_Re-Use*

8 *http://www.sciencedirect.com/science/article/pii/S1462075899000084*

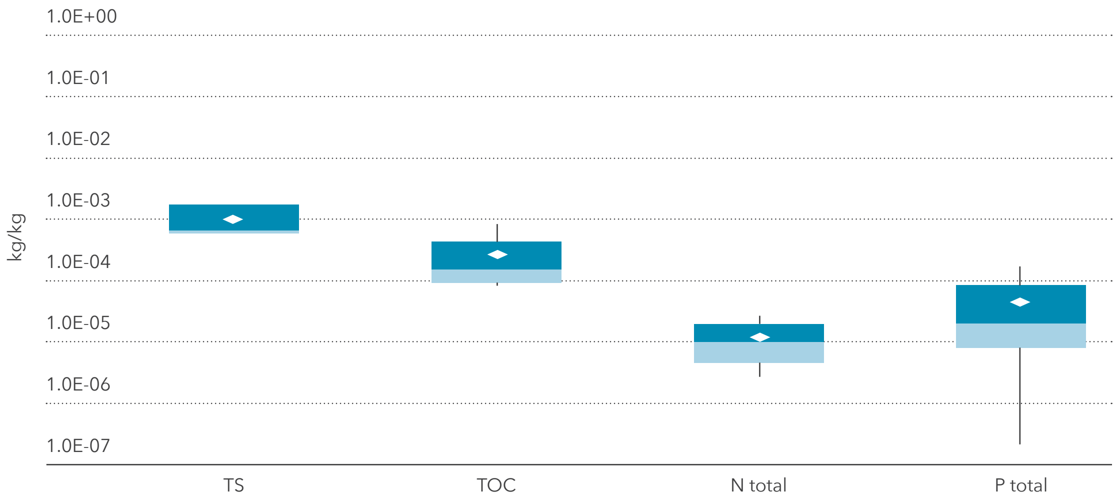
9 *https://archive.org/stream/characteristicso00bran/CHARACTERISTICSO_00_BRAN_05270_djvu.txt*

10 *http://www.slideshare.net/MelvinEldin/90-recycling-of-laundry-wastewater-through-membranes*

11 *http://www.sciencedirect.com/science/article/pii/S0921344904001818*

12 *https://www.infona.pl/resource/bwmeta1.element.elsevier-32109e41-3175-39a9-a090-11529a95de34*

FIGURE 3-10: Median, 90/10 percentiles, and min/max values for wastewater emissions from laundry (arithmetic mean marked with white diamond).



## 3.3.5 End-of-Life

Consumer data from the Global Laundering Study indicated complex disposal patterns for garments at EoL. The vast majority of cotton garments were shown to be reused or repurposed; an average of one-fourth of consumers indicate they throw away the items surveyed (25% of consumers throw away t-shirts, 24% throw away causal collared shirts, and 26% throw away casual woven slacks). Since the lifetime (even considering multiple uses or users) of garments was less than the time period used to evaluate GHG effects (100 years), the EoL for garments was modeled simply as a direct release of the sequestered carbon as a $CO_2$ emission to air.

Although not the case in most instances, the garments are assumed to be disposed of at EoL rather than reused or recycled.

Table 3-21 shows the percent of the total garment waste that goes to landfill and incineration at EoL. In the case of China, it was found that some waste goes uncollected and, of what is collected, some goes to undesignated disposal sites or informal landfills. This was modeled as littering in terms of an informal landfill that does not have modern equipment or standards for the treatment of leachate or landfill gases.

With regards to biogenic carbon, it is not assumed that all of the carbon sequestered during growth of the cotton plant is released as biogenic carbon dioxide since some of carbon is likely to be emitted as biogenic methane depending on the type of waste treatment in the landfill at EoL. For incineration, all of the biogenic carbon is assumed be released as carbon dioxide, though it is possible that some carbon will be released as methane or carbon monoxide. For landfilling, the GaBi model uses set percentages for the amount of carbon that is released as either carbon dioxide or methane based on the EPA WARM[2] model for the United States for example. Furthermore, it is common practice in U.S. and EU landfills to employ landfill gas capture technology. In this case, the biogenic methane captured is burned and released as biogenic carbon dioxide. Accurate data on the implementation of landfill gas capture in Japan and China were not available, therefore they were not assumed to capture and burn landfill methane.

[2] http://www3.epa.gov/warm/

TABLE 3-21: Percent of garment waste to respective EoLs in considered regions of use.

| Parameter | US[1] | EU[2] | Japan[3] | China |
|---|---|---|---|---|
| **Percent to Landfill** | 80% | 30% | 80% | 57%* |
| **Percent to Incineration** | 20% | 70% | 20% | 13% |
| **Percent to Other[4]** | 0% | 0% | 0% | 30% |

*Source:*

1 *US EPA Table 3, total waste not recycled or composted http://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_fs.pdf*

2 *Eurostat: http://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics*

3 *http://www.nytimes.com/2005/05/12/world/asia/how-do-japanese-dump-trash-let-us-count-the-myriad-ways.html?_r=1*

4 *Undesignated places such as informal landfills or littering*

### **3.3.6** Background Data

#### **3.3.6.1** Fuels and Energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2016 databases. Table 3-22 shows the most relevant LCI datasets used in modeling the product systems. Electricity consumption was modeled using national and regional grid mixes that account for imports from neighboring countries and regions.

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

TABLE 3-22: Key energy datasets used in inventory analysis.

| Energy | Dataset Name | Primary Source | Year | Geography |
|---|---|---|---|---|
| **Hard coal** | Thermal energy from hard coal | thinkstep | 2012 | BR, CN |
| **Heavy fuel oil** | Thermal energy from heavy fuel oil (HFO) | thinkstep | 2012 | BR, IN |
| **Electricity** | Electricity grid mix | thinkstep | 2012 | CN, EU-27, ID, IN, JP, KR, MX, TH, TR, US |
| | Electricity from natural gas | thinkstep | 2012 | CN |
| | Electricity from hard coal | thinkstep | 2012 | CN |
| **Natural gas** | Thermal energy from natural gas | thinkstep | 2012 | BR, CN, EU-27, IN, JP, TR, US |
| **Liquified petroleum gas** | Thermal energy from LPG | thinkstep | 2012 | EU-27, US |
| **Steam** | Process steam from natural gas 90% | thinkstep | 2012 | IN |

### 3.3.6.2 Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2016 database.

Table 3-23 shows the most relevant LCI datasets used in modeling the product systems. Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/. Additional datasets used as proxy datasets are given in

Table 3-23 and Table 3-24. Datasets used in the agricultural modeling are given in Table 3-25.

TABLE 3-23: Key material and process datasets used in inventory analysis.

| Material/Process | Dataset Name | Primary Source | Year | Geography |
|---|---|---|---|---|
| **Acetic acid** | Acetic acid from methanol (low pressure carbonylation) (Monsanto process) | thinkstep | 2015 | US |
| **Antimicrobial agent** | Silver antimicrobial | thinkstep | 2012 | DE |
| **Brass zipper** | Brass (CuZn20) | thinkstep | 2015 | EU-27 |
| | Steel cold rolled coil | worldsteel | 2007 | GLO |
| **Catalase** | Enzyme (estimation over glucose) | thinkstep | 2013 | DE |
| **Catalyst** | Sodium chloride (rock salt) | thinkstep | 2015 | US |
| **Cationic fixative** | Ammonium chloride | thinkstep | 2015 | DE |
| **Coating finishing agent** | Polymethylmethacrylate granulate (PMMA) | thinkstep | 2015 | DE |
| **Cotton fibers** | Ginned Cotton (Region Mix, Cotton Incorporated 2015) | Cotton Incorporated | 2015 | GLO |
| **Dispersant** | Dispersing agent (unspecific) | thinkstep | 2015 | GLO |
| **Disperse dye** | Disperse dyes | thinkstep | 2015 | GLO |
| **DMDHEU** | Urea formaldehyde resin in- situ foam (EN15804 A1-A3) | thinkstep | 2015 | DE |
| **Dye fixative** | Ammonium chloride | thinkstep | 2015 | GLO |
| **Fire retardant** | Monoammonium phosphate (MAP) | thinkstep | 2015 | US |
| **Hydrogen peroxide** | Hydrogen peroxide (50%, $H_2O_2$) | thinkstep | 2015 | US |
| **Hydrogen peroxide stabilizer** | Calcium silicate | thinkstep | 2015 | EU-27 |
| **Landfill** | Hazardous waste (non-specific) (c rich, worst scenario) | thinkstep | 2012 | GLO |
| | Plastic waste on landfill | thinkstep | 2015 | EU-27 |
| | Textiles on landfill | thinkstep | 2015 | EU-27 |
| | Glass/inert waste on landfill | thinkstep | 2015 | EU-27 |
| | Landfill of cotton textile waste | thinkstep | 2015 | CN, EU-27, US |
| | Landfill of cotton textile waste (wild landfill, estimation) | thinkstep | 2015 | CN |
| | Ferro metals on landfill | thinkstep | 2015 | EU-27 |
| **Lubricants** | Lubricants at refinery | thinkstep | 2012 | BR, EU-27 |
| **Magnesium chloride** | Sodium chloride (rock salt) | thinkstep | 2015 | EU-27 |
| **Nylon zipper** | Polyamide 6.6 (PA 6.6) GF injection moulded part (0,02 - 0,2kg) | thinkstep | 2015 | DE |

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| Material/Process | Dataset Name | Primary Source | Year | Geography |
|---|---|---|---|---|
|  | Polyamide 6.6 granulat (PA 6.6) (HMDA via adipic acid) | thinkstep | 2015 | US |
|  | Compounding (plastics) | thinkstep | 2015 | GLO |
| **Optical brightener** | Aniline (Phenyl amine, Amino benzene) | thinkstep | 2015 | DE |
| **Pigment** | Titanium dioxide pigment (sulphate process) | thinkstep | 2015 | EU-27 |
| **Polyester fabric** | Polyester resin unsaturated (UP) | thinkstep | 2015 | DE |
| **Polyethylene terephthalate fibres** | Polyethylene terephthalate fibres (PET) | thinkstep | 2015 | DE |
| **Polyethylene terephthalate granulate** | Polyethylene terephthalate granulate (PET via DMT) | thinkstep | 2015 | DE |
| **Polyethylene terephthalate resin** | Polyethylene terephthalate resin (via PTA) | thinkstep | 2015 | US |
| **Reactive dye** | Reactive dyes | thinkstep | 2015 | GLO |
| **Sequestering agent** | EDTA | thinkstep | 2015 | GLO |
| **Sewability agent** | Polyethylene Low Density Granulate (LDPE/PE-LD) | thinkstep | 2015 | US |
| **Size** | Starch/PVA blend | thinkstep | 2013 | DE |
| **Soil resist agent** | C-6 flourocarbon | thinkstep | 2014 | DE |
| **Soda** | Soda (Na2CO3) | thinkstep | 2015 | US |
| **Sodium bicarbonate** | Sodium bicarbonate | thinkstep | 2015 | US |
| **Sodium dithionite** | Sodium dithionite | thinkstep | 2015 | GLO |
| **Sodium hydroxide** | Sodium hydroxide (caustic soda) mix (100%) | thinkstep | 2015 | US |
| **Sodium sulphate** | Sodium sulphate | thinkstep | 2015 | GLO |
| **Softener** | Softener (fatty acids amino compounds) | thinkstep | 2015 | GLO |
| **Starch** | Dried starch (corn wet mill) (economic allocation) | thinkstep | 2015 | US |
| **Sulfur dye** | Vat dye | thinkstep | 2014 | GLO |
| **Surfactant** | Tensides (alcohol ethoxy sulfate (AES)) | thinkstep | 2015 | US |
| **Vat dye** | Vat Dye | thinkstep | 2014 | US |
| **Waste incineration** | Textiles in municipal waste incineration plant | thinkstep | 2015 | EU-27 |
| **Wastewater treatment** | Laundry wastewater treatment (sludge treatment mix) | thinkstep | 2016 | EU-27 |
|  | Laundry wastewater treatment mix | thinkstep | 2016 | US |
|  | Laundry wastewater treatment mix | thinkstep | 2016 | CN |
| **Water** | Process water | thinkstep | 2015 | EU-27 |
|  | Tap water | thinkstep | 2015 | EU-27 |
| **Water resistant textile finishing agent** | C-6 flourocarbon | thinkstep | 2014 | DE |
| **Wetting agent** | Non-ionic surfactant (fatty acid derivate) | thinkstep | 2015 | GLO |

TABLE 3-24: Additional datasets uses as proxy datasets.

| Material/Process | Dataset Name | Primary Source | Year | Geography |
|---|---|---|---|---|
| **DMDHEU proxy** | Urea formaldehyde resin in-situ foam (EN15804 A1-A3) | thinkstep | 2015 | DE |
| **Hydrogen peroxide stabilizer proxy** | Calcium silicate | thinkstep | 2015 | EU-27 |
| **Catalase proxy** | Enzyme (estimation over glucose) | thinkstep | 2013 | DE |
| **Polyacrylate proxy** | Soaping agent (sodium polycarboxylate) | thinkstep | 2015 | GLO |
| **Sulfur dye proxy** | Vat dye | thinkstep | 2014 | GLO |
| **Magnesium chloride proxy** | Sodium chloride (rock salt) | thinkstep | 2015 | US |
| **Antimicrobial agent** | Silver antimicrobial | thinkstep | 2014 | DE |
| **Soil resist agent** | C-6 flourocarbon | thinkstep | 2014 | DE |
| **Water resistant textile finishing agent** | C-6 flourocarbon | thinkstep | 2014 | DE |

TABLE 3-25: Datasets used in agricultural modeling.

| Material/Process | Dataset Name | Primary Source | Year | Geography |
|---|---|---|---|---|
| **Ammonia** | Ammonia (NH3) | thinkstep | 2015 | US |
| **Ammonium sulphate** | Ammonium sulphate, by product acrylonitrile, hydrocyanic acid | thinkstep | 2015 | US |
| **DAP** | Diammonium phosphate granular fertilizer (DAP) | thinkstep | 2015 | DE |
| **Diesel** | Diesel mix at filling station | thinkstep | 2015 | AU;IN;US;CN |
| **Electricity** | Electricity grid mix | thinkstep | 2015 | AU;IN;US;CN |
| **Fungicide** | Fungicide unspecific | thinkstep | 2015 | DE |
| **Herbicide** | Herbicide unspecific | thinkstep | 2015 | DE |
| **Insecticide** | Insecticide unspecific | thinkstep | 2015 | DE |
| **Jute** | Flax - fabric | thinkstep | 2015 | EU-27 |
| **PE film** | Polyethylene film (LDPE/PE-LD) ts | thinkstep | 2015 | US |
| **Plant growth regulator** | Plant growth regulator unspecific | thinkstep | 2015 | DE |
| **Potassium chloride** | Potassium chloride (KCl/MOP, 60% K2O) | thinkstep | 2015 | EU-27 |
| **Seed treatment** | Seed treatment unspecific | thinkstep | 2015 | DE |
| **Urea** | Urea (agrarian) | thinkstep | 2015 | US |

### **3.3.6.3** Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials to production and assembly facilities. Transport to the consumer phase was assumed to be 100 miles by truck from cut-and-sew to consumer phase.

The GaBi 2016 database was used to model transportation. Truck transportation within the United States was modeled using the GaBi U.S. truck transportation datasets. The vehicle types, fuel usage, and emissions for these transportation processes were developed using a GaBi model based on the last U.S. Census Bureau Vehicle Inventory and Use Survey (2002) and U.S. EPA emissions standards for heavy trucks in 2007. The 2002 VIUS survey is the latest available data source describing truck fleet fuel consumption and utilization ratios in the United States based on field data (Langer 2013), and the 2007 EPA emissions standards are considered to be the appropriate data available for describing current U.S. truck emissions. Fuels were modeled using the geographically appropriate datasets.

Transportation distances and modes are given in Table 3-26. Datasets used to model transportation are given in Table 3-27.

TABLE 3-26: Transportation distances by cargo ship and truck.

| Fabric | Transport between Phases | Global Average Ship | Average Truck |
|---|---|---|---|
| **Woven Production (pants)** | | | |
| | Fiber Production to Fabric | 13,474 km | |
| | Fabric to Cut-and-Sew | 13,252 km | |
| | Cut-and-Sew to Consumer Use | 9,530 km | |
| | Consumer Use to EoL | | 32km |
| **Knit Production (shirts)** | | | |
| | Fiber Production to Fabric | 12,270 km | |
| | Fabric to Cut-and-Sew | 10,155 km | |
| | Cut-and-Sew to Consumer Use | 9,530 km | |
| | Consumer Use to EoL | | 32km |

TABLE 3-27: Transportation and road fuel datasets.

| Mode | Dataset Name | Primary Source | Year | Geography |
|---|---|---|---|---|
| **Heavy fuel oil** | Heavy fuel oil at refinery (0.3wt.% S) | thinkstep | 2012 | US |
| **Heavy fuel oil** | Heavy fuel oil at refinery (1.0wt.% S) | thinkstep | 2012 | BR, CN, EU-27, IN |
| **Diesel** | Diesel mix at refinery | thinkstep | 2012 | BR, CN, EU-27, IN, US |
| **Rail** | Rail transport cargo - Diesel | thinkstep | 2015 | GLO |
| **Ship** | Bulk commodity carrier | thinkstep | 2015 | GLO |
| **Truck** | Truck-trailer | thinkstep | 2015 | GLO |

## 3.4 LIFE CYCLE INVENTORY ANALYSIS RESULTS

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment." As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results. Table 3-28 gives the LCI results for all garment types per functional unit of 1,000 kg garments and represents emissions that are 90% of each impact category.

TABLE 3-28: LCI results of garments.

| Input or Output per ton of Garment | | | | |
|---|---|---|---|---|
| **INPUT–per ton of garment** | | | | |
| **Energy resources** | | Casual pants | Polo shirt | T-shirt |
| **Nonrenewable energy resources** | | | | |
| **Crude oil** | MJ | 32,700 | 37,800 | 35,500 |
| **Hard coal** | MJ | 96,900 | 56,500 | 51,400 |
| **Lignite** | MJ | 14,400 | 16,300 | 15,800 |
| **Natural gas** | MJ | 107,000 | 157,000 | 149,000 |
| **Uranium** | MJ | 15,800 | 16,600 | 15,000 |
| **Renewable energy resources** | | | | 0 |
| **Primary energy from hydro power** | MJ | 9,910 | 11,100 | 10,500 |
| **Primary energy from solar energy** | MJ | 65,500 | 90,400 | 89,800 |
| **Primary energy from wind power** | MJ | 4,540 | 5,090 | 4,750 |
| **Material resources** | | | | |
| **Water** | kg | 30,200,000 | 33,900,000 | 32,500,000 |
| **Carbon dioxide** | kg | 2,590 | 3,660 | 3,620 |
| **OUTPUT–per ton of garment** | | | | |
| **Valuable** | | | | |
| **Garment** | kg | 1,000 | 1,000 | 1,000 |
| **Emission to air** | | | | |
| **Inorganic emissions to air** | | | | |
| **Carbon dioxide** | kg | 18,100 | 18,000 | 17,000 |
| **Carbon dioxide (biotic)** | kg | 2,060 | 2,130 | 1,960 |
| **Nitrous oxide (laughing gas)** | kg | 2.22 | 3.10 | 3.09 |
| **Ammonia** | kg | 18.4 | 25.1 | 25.0 |
| **Nitrogen oxides** | kg | 44.5 | 41.8 | 40.3 |
| **Sulphur dioxide** | kg | 71.1 | 59.0 | 57.3 |
| **Carbon monoxide** | kg | 18.7 | 16.0 | 15.1 |
| **Organic emissions to air** | | | | |

Continued on next page ›

| Input or Output per ton of Garment | | | | |
|---|---|---|---|---|
| **Group NMVOC to air** | kg | 18.0 | 17.7 | 15.5 |
| **Methane** | kg | 48.4 | 47.6 | 44.5 |
| **Methane (biotic)** | kg | 50.5 | 51.2 | 47.4 |
| **Metal emissions to air** | | | | |
| **Mercury (+II)** | kg | 0.00484 | 0.000383 | 0.000363 |
| **Lead (+II)** | kg | 0.0222 | 0.01130 | 0.01020 |
| **Zinc (+II)** | kg | 0.0294 | 0.01450 | 0.01330 |
| **Emission to fresh water** | | | | |
| **Metal emissions to fresh water** | | | | |
| **Arsenic** | kg | 0.168 | 0.00649 | 0.00648 |
| **Chromium (+VI)** | kg | 0.00266 | 0.00346 | 0.00344 |
| **Zinc** | kg | 0.0158 | 0.164 | 0.164 |
| **Inorganic emissions to fresh water** | | | | |
| **Ammonium / ammonia** | kg | 2.46 | 3.60 | 3.41 |
| **Nitrogen organic bounded** | kg | 5.44 | 7.62 | 7.58 |
| **Phosphate** | kg | 1.28 | 1.80 | 1.80 |
| **Phosphorus** | kg | 0.462 | 0.612 | 0.551 |
| **Emissions to soil** | | | | |
| **Metal emissions to soil** | | | | |
| **Lead (+II)** | | 0.00366 | 0.0245 | 0.0243 |
| **Mercury (+II)** | | 0.0000204 | 0.00016 | 0.000159 |
| **Zinc (+II)** | | 0.0236 | 0.0784 | 0.0754 |
| **Nickel (+II)** | | 0.00126 | 0.00823 | 0.00814 |
| **Cadmium (+II)** | | 0.000141 | 0.000738 | 0.000728 |
| **Inorganic emissions to soil** | | | | |
| **Ammonia** | kg | 4.79 | 4.86 | 4.58 |
| **Phosphorus** | kg | 0.174 | 0.168 | 0.144 |

# 4

# LCIA RESULTS

This chapter contains the results for the impact categories and additional metrics defined in section 2.6. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e. they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, exceeding of thresholds, safety margins, or risks.

## 4.1 RESULTS: COTTON PRODUCTION (CRADLE-TO-GATE)

The following sections show results of the study for each Life Cycle Impact Assessment (LCIA). The results of the cultivation model are presented per 1,000 kg of cotton fiber at gin gate (after ginning). The agricultural results are based on the latest version of the cultivation model developed by thinkstep within the GaBi ts software. The global average fiber results are presented for a production-weighted average of cotton fiber in the four respective countries. Graphs are split into main contributor as described herein:

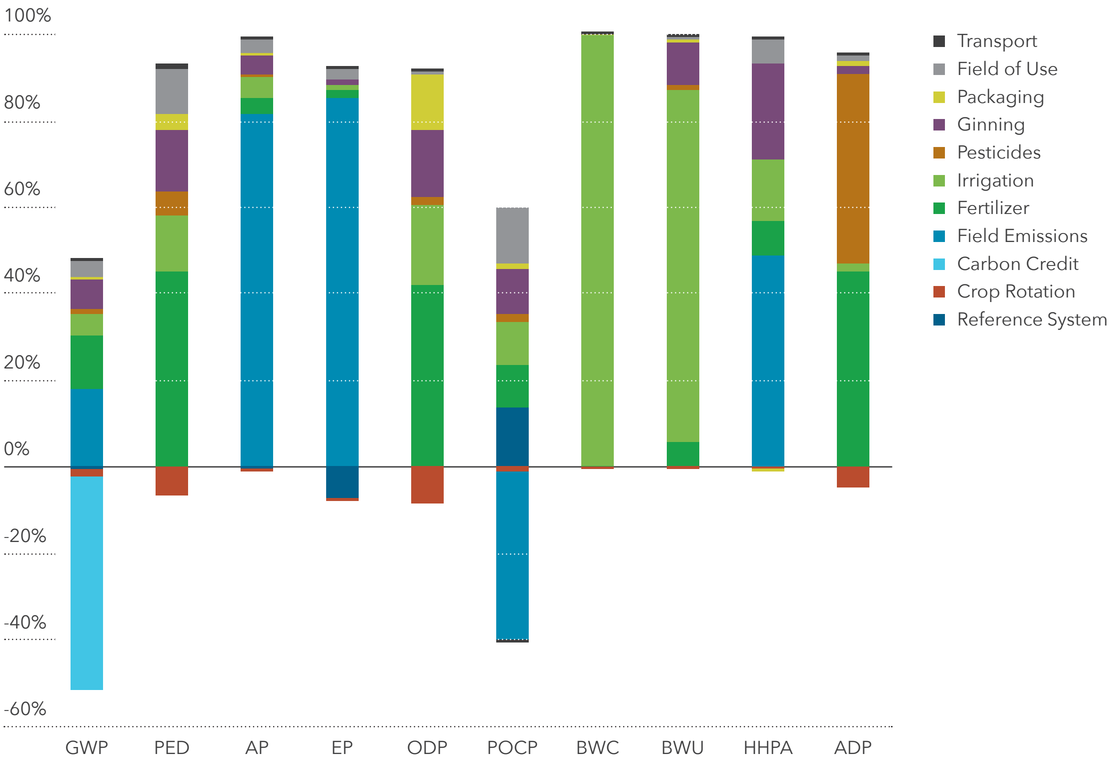
- **Crop Rotation:** Credits or impacts due to nutrient surplus or deficit. Depends on crop specific nutrient efficiency, soil parameters, previous and following crop, and management practices.
- **Fertilizers Production:** Emissions from fertilizer production.
- **Field Emissions:** Emissions to groundwater, air, and soil from degradation of mineral and organic nitrogen in the soil.
- **Irrigation:** Emissions from operating generators for irrigation pumps.
- **Pesticides Production:** Emissions from pesticide production.
- **Pesticide Application:** Refers to active ingredients applied. Impact is related to the chemical characteristics (toxicity, stability, radiative forcing, etc.) of the applied substances.
- **Post Harvest:** Transport to cotton gin, cotton gin itself, and packaging at field border and after ginning.
- **Reference System:** The reference system is used to model the system's behavior without human use. In particular, losses of nitrate to groundwater and gaseous nitrogen compounds captured in precipitation are mapped. This discharge and conversion to different emissions are relevant for both the main cropping system as well as on unused land. Therefore, not all of these emissions can be assigned to the crop since they also occur in the case of non-cultivation, e.g., for a fallow or nature reserve. For the reference system it is assumed that the nitrogen balance is balanced, as any entry of nitrogen with rainfall is re-emitted from the systems in various forms into ground water and air.
- **Seeds:** Seed transport from planting seed distributor to farm and field.
- **Tractor Operations:** Field operations (e.g., sowing, fertilizing, harvesting).
- **Transportation:** Transports from production facility to farm (e.g., fertilizer, lime, pesticides, diesel).

The relative contribution of each in-field process to the total impact for each impact category for global cotton fiber production is illustrated in Figure 4-1 and actual values are listed in Table 4-1. The results represent global averages per 1,000 kg of cotton fiber after ginning based on a production-weighted percentage of cotton fiber from U.S, China, India and Australia. Although field emissions were identified to be a major contributor to eutrophication potential (EP), acidification potential (AP), and global warming potential (GWP), they produced a positive effect on photochemical ozone creation potential (POCP) due to the prediction of the interaction of POCP with increases in soil nitrogen. Another important contributor was fertilizer manufacture, which showed high impact on primary energy demand (PED), GWP, abiotic depletion (ADP), and ozone depletion potential (ODP). Detailed discussion of each impact category is provided in the following sections.

TABLE 4-1: Measured impacts for each stage of cotton production per 1,000 kg of fiber.

| | Crop Rotation | Reference System | Field Emissions | Fertilizer | Irrigation | Pesticides | Ginning | Packaging | Field fuel Use | Transportation | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **GWP [kg CO2-Equiv.]** | -59.4 | -16.1 | -982 | 390 | 163 | 39 | 200 | 26.6 | 109 | 17.1 | **-113** |
| **PED [MJ]** | -1084.5 | 0.0 | 0.0 | 7226 | 2015 | 835 | 2295 | 626 | 1619 | 189 | **13720** |
| **AP [kg SO2-Equiv.]** | -0.1 | -0.2 | 22.0 | 1.0 | 1.3 | 0.1 | 1.2 | 0.0 | 0.9 | 0.1 | **26.4** |
| **EP [kg Phosphate-Equiv.]** | -2.54E-02 | -6.87E-01 | 7.89E+00 | 1.75E-01 | 1.16E-01 | 1.07E-02 | 8.65E-02 | 1.72E-02 | 2.10E-01 | 1.97E-02 | **7.8** |
| **ODP [kg R11-Equiv.]** | -4.65E-09 | 0.00E+00 | 0.00E+00 | 2.39E-08 | 1.05E-08 | 1.07E-09 | 8.54E-09 | 7.55E-09 | 4.07E-10 | 6.68E-11 | **4.7E-08** |
| **POCP [kg Ethene-Equiv.]** | -9.00E-03 | 1.13E-01 | -3.16E-01 | 8.02E-02 | 8.08E-02 | 1.39E-02 | 8.32E-02 | 1.00E-02 | 1.07E-01 | -4.78E-04 | **0.2** |
| **BWC [kg]** | -2.37E+02 | 0.00E+00 | 0.00E+00 | 1.66E+03 | 1.56E+06 | 2.29E+02 | 1.29E+03 | 1.56E+02 | 1.35E+02 | 2.38E+01 | **1.56E+06** |
| **BWU [kg]** | -1.57E+04 | 0.00E+00 | 0.00E+00 | 1.34E+05 | 1.84E+06 | 3.88E+04 | 2.16E+05 | 1.91E+04 | 5.61E+03 | 3.62E+02 | **2.24E+06** |
| **HHPA [kg PM2,5-Equiv.]** | -6.57E-03 | 0.00E+00 | 8.92E-01 | 1.51E-01 | 2.48E-01 | 1.05E-02 | 3.96E-01 | -4.88E-03 | 1.09E-01 | 4.84E-03 | **1.8** |
| **ADP [kg Sb-Equiv.]** | -4.49E-05 | 0.00E+00 | 0.00E+00 | 4.14E-04 | 1.62E-05 | 4.03E-05 | 1.37E-05 | 1.43E-05 | 7.95E-06 | 1.36E-06 | **8.3E-04** |
| **LOI [sqm*yr]** | -0.6 | 0.0 | 10615 | 3.7 | 3.1 | 1.5 | 1.9 | 6.6 | 2.1 | 0.3 | **10634** |

FIGURE 4-1: Relative contribution to each impact category for cotton fiber production.

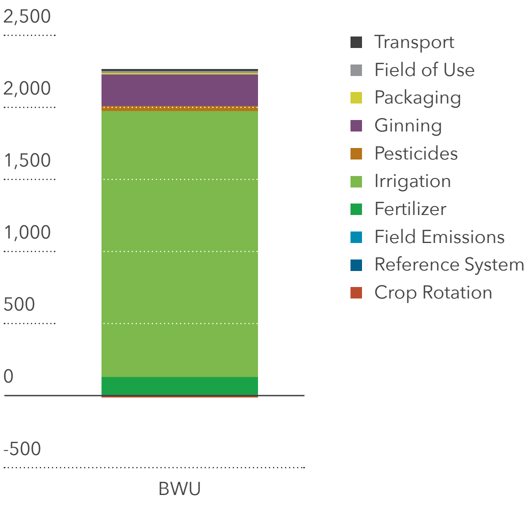


### 4.1.1 Water Use

Results in this section describe water usage (degraded + consumed) as well as water consumption (consumed only) of cotton cultivation and ginning in terms of cubic meters per kg of cotton fiber [m³ / 1,000 kg cotton fiber]. Note that an LCA considers both direct and indirect water use. Direct water use refers to water used directly in the production of cotton products such as irrigation water, water to dye and finish textile products, and water used in the washing machine. Indirect water use can come from several sources, but a major source is the water associated with power generation.

Figure 4-2 shows the water demand of cotton cultivation and processing at the gin (post-harvest). In total around 2,235 m3 of blue water are used to produce 1,000 kg of cotton fiber; this consists of groundwater, river, and surface water used for cotton irrigation. Approximately 82% of the water is used directly for irrigation. Cooling water evaporated during electricity production and other indirect uses are also included in the water use metric. Thus, the value represents blue water consumed divided by all cotton produced whether produced with irrigation or not.

FIGURE 4-2: Blue water usage in cotton production [m3/1,000 kg cotton fiber] by process stage.



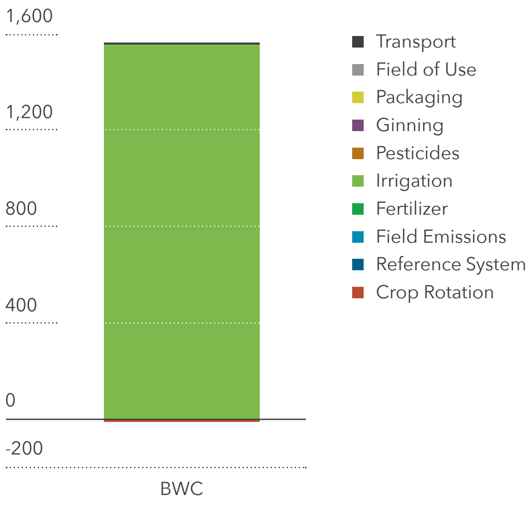
Note that this value excludes precipitation; it is assumed that precipitation would follow the natural hydrologic cycle regardless of the land type and therefore has no environmental burden from an LCA perspective. Approximately 6,000 m³ of water in the form of precipitation during the cultivation period is associated with a 1,000 kg of global average cotton, calculated as a production weighted average of the climatic rainfall that reaches cotton growing areas during the growing season. Depending on the environment, stage of plant growth, site conditions, and soil type, precipitation in the form of rainfall is either used by the plant, evaporates from the soil, infiltrates the soil to recharge the water table, or runs off the field and into rivers and lakes.

The water usage examination presented in Figure 4-2 focuses on the system water input, but it does not say anything about the effective crop water requirement which would be calculated in a water footprint calculation.

### 4.1.2 Water Consumption

Figure 4-3 shows the water consumption in cotton production. All water used for irrigation is assumed to be consumed and is the dominate source of water consumed in the fiber phase. Additional water consumption takes place in upstream processes, especially in the provision of energy. However, this represents less than 1% of the overall reported water consumption.

FIGURE 4-3: Blue water consumption in cotton production [m3/1,000 kg cotton fiber].



### 4.1.3 Water Stress Index

The water stress index (WSI) is based on a withdrawal to availability ratio and takes into account temporal variability of water availability. WSI values between 0 and 0.1 are classified as “no water stress”. Values between 0.1 and 0.5 indicate “moderate water stress”. Values from 0.5 to 0.9 stand for “severe water stress” and values >0.9 indicate “extreme water stress”. The global average WSI value is 0.602, indicating that the world as a whole is already under severe water stress. The water stress index is used to characterize water consumption according to regional availability. Then, the water stress index is normalized by using the global average water stress index. The resulting unit is kg of water equivalents (kg water eq.) and termed the water scarcity footprint.

The global mean water stress index for cotton was 0.77, which is higher than the world average with a standard deviation of 0.25. There was significant variation of water stress indexes for the different growing regions within this study. When multiplying the water consumption times the mean global cotton water stress index (0.77) divided by the average water stress index (0.602), the water scarcity footprint is 1,993 kg water eq. per 1,000 kg of cotton fiber.

### 4.1.4 Primary Energy Demand

Figure 4-4 illustrates the global average primary energy demand (PED) from fossil sources for cotton cultivation and gin processing (post-harvest) expressed as megajoules per kg cotton fiber [MJ/1,000 kg]. Most of the energy is used in fertilizer production processes (46%) followed by ginning (14%), irrigation (13%), and tractor operations (10%). Residual fertilizer remaining in the soil that can be used for the next crop provides a credit, representing about 7% of the PED used (note: between season losses due to volatilization and leaching of nitrogen were accounted for with thinkstep’s cultivation model).

FIGURE 4-4: Primary energy demand from fossil sources [MJ/1,000 kg of cotton fiber] by contributors.

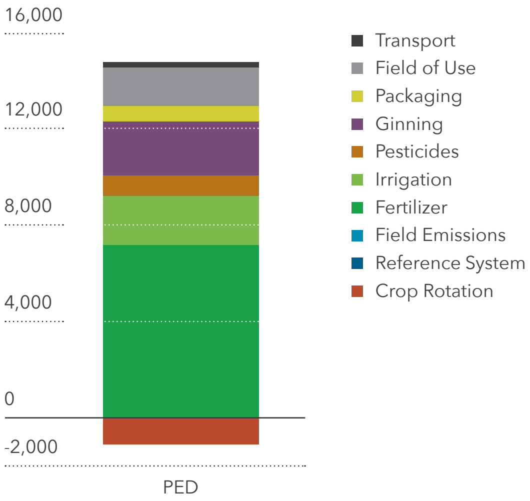
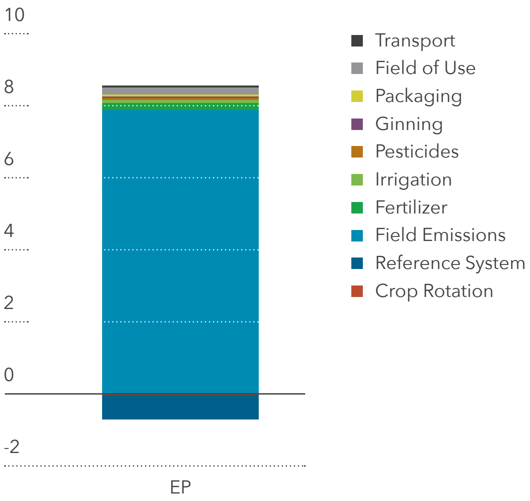


FIGURE 4-5: Eutrophication potential [kg PO43- eq./1,000 kg of cotton fiber] by contributors.



## **4.1.5** Eutrophication Potential

Figure 4-5 illustrates the impact of cotton cultivation and ginning on eutrophication potential (EP) in kg PO43- equivalents/1,000 kg cotton fiber. Emissions from the field represent 93% of the agriculture related EP. The potential leaching of nitrate (NO3-) into groundwater was the main contributor to EP in this study. Because eutrophication is predominantly influenced by emissions of nutrients to water, agricultural systems are one of the largest contributors to eutrophication. Surface runoff of nitrate and phosphorus contributes to eutrophication and it can be a local environmental problem depending on climate, soil conditions, and available nitrogen for leaching. The main effects are seen in areas where nutrients from agriculture are accumulated by a water system, such as in the 'dead zone' in the Gulf of Mexico at the mouth of the Mississippi river. This example is used to illustrate the term "eutrophication potential" – the primary source of nutrient loading to the Mississippi river is the tile-drained regions of Minnesota, Iowa, Illinois, Indiana, and Ohio (David, 2010).

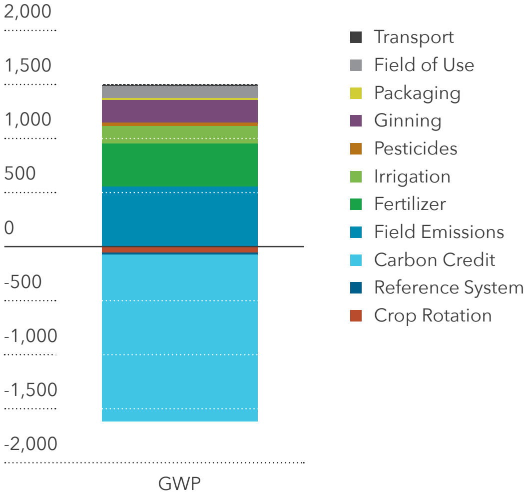
## **4.1.6** Global Warming Potential

Figure 4-6 illustrates the impact of cotton cultivation and ginning on global warming potential (GWP) in kg CO2 equivalents/1,000 kg cotton fiber. A credit of 1,540 kg CO2 eq. was taken to account for the carbon stored in the fiber in the agricultural phase that will be later released in the EoL phase (Figure 4-35: Global warming potential by post production phase.). The data in Figure 4-6 represents the gross GHG emissions during agricultural production and processing at the gin. When incorporating the credit, the cradle-to-gate global mean GWP was -112 kg CO2 eq. per 1,000 kg of fiber. This indicates that on a global average, cotton cultivation absorbed more carbon CO2 than the emissions associated with cultivation activities and required materials.

As indicated above, the carbon taken in by the cotton growth stores carbon for a period of time in the form of a fiber until the end-of-life where it slowly decays in a landfill or is eventually released through other means. The end-of-life release of biogenic carbon, or carbon that was previously absorbed from the environment, is assumed to be within the 100 year time horizon used to calculate the GWP and thus the temporary carbon storage is assigned no credit. The value of temporary carbon storage is not commonly considered in LCAs, however, recent research by Levasseur et al. 2010 indicates that storing carbon for time periods less than 100 years can translate into reduced environmental warming within the 100 year time horizon. This approach was not used for this study, however, it is worth noting that the temporary carbon storage could result in lower GWP impacts when using methods as those described by Levasseuer et al. 2010 and Daystar et al. 2016.

The largest of the life cycle GWP burdens come from fertilizer production (27%) and emissions from the decomposition of the fertilizer in the field (35%). During natural conversion processes nitrogen is transferred into the greenhouse gas nitrous oxide (N2O). Post-harvest activities contribute to GWP due to emissions from energy, transportation, and packaging. Fertilizer not used during cotton cultivation can be used by the next crop, so it is treated as a credit for avoided production of mineral fertilizer (shown as a negative emission). Irrigation and ginning represent 14% and 11% of the total emissions, respectively. Tractor operations for sowing, spraying, fertilizing, weeding, and harvesting are responsible for 7% of the total GWP. The crop rotation process captured carbon in the soil due to increased root matter from cotton cultivation and created a negative emission. The reference system compared to cotton cultivation created a negative emission as well.

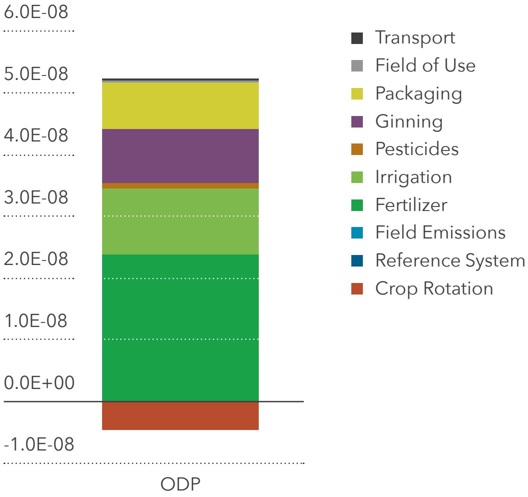
FIGURE 4-6: Global warming potential [kg CO2 eq./1,000 kg of cotton fiber] by contributors.



### 4.1.7 Ozone Depletion Potential

Figure 4-7 illustrates the impact of cotton cultivation and ginning on ozone depletion potential (ODP) in kg R11 equivalents/1,000 kg cotton fiber. Since most ozone-depleting chemicals (mostly refrigerants) were phased out of common use after the Montreal Protocol was implemented in 1989 (UNEP Ozone Secretariat), the remaining ODP emissions are usually minimal and are related to electricity production. As fertilizer production, pesticide production, post-harvest, and the nutrient allocation in crop rotation have electricity production in their upstream life cycles, they were dominant sources of ODP. In addition, R11, R12, R22, and R114 emissions occur during fertilizer and pesticide production.

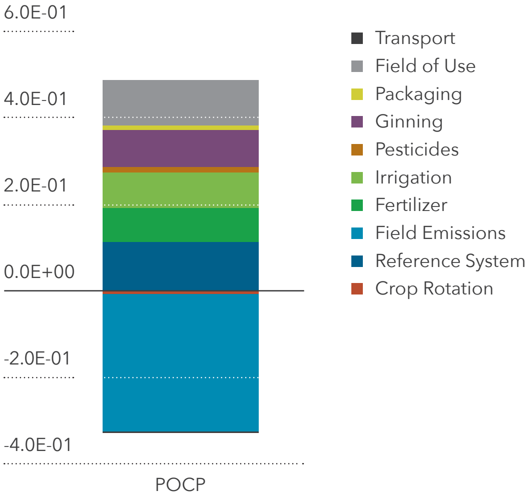
FIGURE 4-7: Ozone depletion potential [kg R11 eq./1,000 kg of cotton fiber] by contributors.



### 4.1.8 Photochemical Ozone Creation Potential

Figure 4-8 illustrates the impact of cotton cultivation and ginning on photochemical ozone creation potential (POCP) in kg C2H4 equivalents/1,000 kg cotton fiber. POCP is commonly referred to as smog creation potential. POCP is significantly influenced by Non-Methane Volatile Organic Compounds (NMVOCs), carbon monoxide, and nitrogen oxides from combustion processes in the tractor, in the generators used to run irrigation pumps and in the natural gas and propane used to dry cotton at the gin. Nitrous oxide emissions resulting from the natural degradation of mineral and organic fertilizer nitrogen in and on the soil are additional contributors to POCP. Negative values (e.g., crop rotation, field emissions) were due to specific cause and effect relationships between nitrogen monoxide (NO) emissions and the POCP. According to the CML method, NO emissions have a positive (reductive) effect on the creation of ozone (O3).

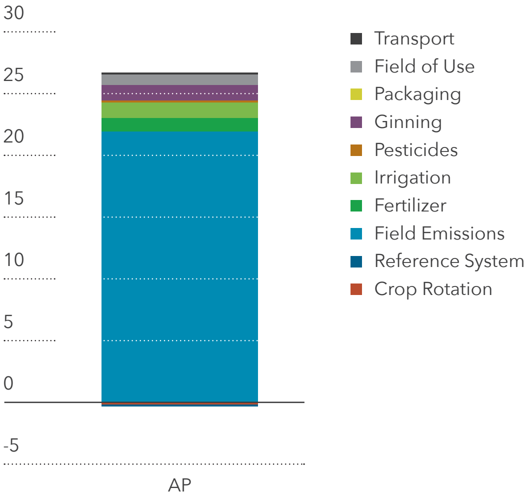
FIGURE 4-8: Photochemical ozone creation potential [kgC2H4 eq./1,000 kg of cotton fiber] by contributors.



## 4.1.9 Acidification Potential

Figure 4-9 illustrates the impact of cotton cultivation and ginning on acidification potential (AP) in kg SO2 equivalents/1,000 kg cotton fiber. AP, also known as acid rain potential, is strongly affected by ammonia (NH3) emissions from the field (82%). NH3 is created during transformation of mineral and organic nitrogen fertilizer and has the potential to react with water in the atmosphere to form "acid rain", resulting in reduced pH in natural habitats (e.g., lakes) thereby causing ecosystem impairment. Acidification is strongly affected by NH3 emissions from field operations. Emissions from post-harvest operations arise from the combustion of fossil fuels and the disposal of packaging materials. Irrigation and tractor operations are a source of nitrogen oxides which contribute to potential acidification. Processes related to pesticide and seed production had essentially no contribution to AP.

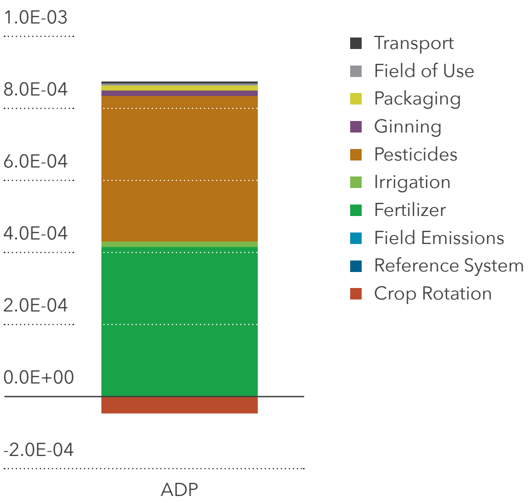
FIGURE 4-9: Acidification potential [kg SO2 eq./ 1,000 kg of cotton fiber] by contributors.



## 4.1.10 Abiotic Depletion

Abiotic depletion (ADP) represents the use or consumption of natural resources including metals, crude oil, and other non-living natural resources. These impacts are often associated with fossil fuel use in energy production systems. As such, the energy intensive process of fertilizer productions also has a high ADP (48%). The other agriculture process stage contributing to the ADP was pesticides that contributed 46% to the overall impact. Pesticides within the model used for this analysis did not create a large PED. This indicates that ADP elements are required in the production process that contribute to the relative high ADP of the pesticides instead of energy usage.

FIGURE 4-10: Abiotic depletion (ADP elements) [kg Sb-Equiv./1,000 kg of cotton fiber] by contributor.



## 4.1.11 Toxicity Metrics

One area where there was a high degree of uncertainty in the agricultural model was the emission factors to estimate the fate of a chemical, particularly pesticides, at the time of application. While the best possible estimates were made, the values 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, and type of application equipment used. There is further uncertainty in the factors used to predict the fate and transport of the compound once it does come to rest.

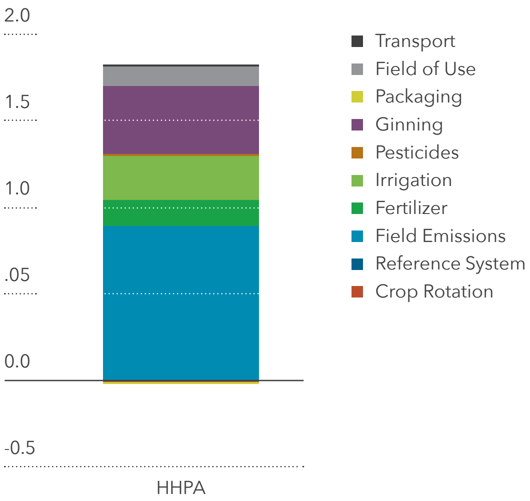
The precision of the characterization model as used in this study was within a factor of 100–1,000 for HTP and 10–100 for ETP. Although this is a substantial improvement over previously available toxicity characterization models, the uncertainty of this metric is substantially higher than for the other impact categories in this study. Risk assessment, which is outside the scope of LCIA, is considered by agricultural researchers to be a better measure of potential impacts for pesticides. Such studies are reported during registration for regulation in the U.S. and elsewhere, and, in some cases conflicts with hotspots identified in LCIA.

Due to the high variability and lack of true risk assessment, no detail reporting of the toxicity results are presented in this report. It was determined that the assumptions surrounding the pesticide emission factors to air, plant, soil and water had a significant impact on the final toxicity results. In this study, using EPIC to predict emissions from the field reduced the prediction toxicity potential from 66% to as much as 99% versus assuming all pesticide emissions were to the soil.

## 4.1.12 Human Health Particulate

Particulate matter is known to cause health issues in humans and cotton growth directly and indirectly contributes to particulate emissions. The largest contributor to human health particulate air (HHPA) emissions is field emissions where particulates are generated from soil and emissions from the machinery used for cultivation, Figure 4-11. Other stages that were energy intensive such as ginning, irrigation, and fertilizer production had significant particulate emissions corresponding to the energy required in each process stage.

FIGURE 4-11: Human health particulate emissions to air, [kg PM2.5-eqiuv./ 1,000 kg of cotton fiber] by contributor.

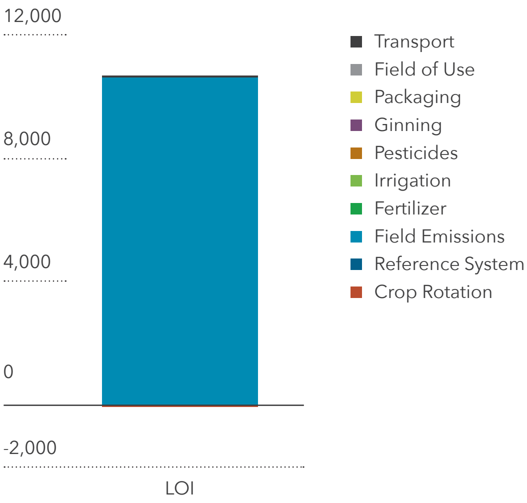


## 4.1.13 Land Occupation Indicator

The land occupation indicator (LOI) displays the area land used (m2) over a time period (a year) for the production of 1,000 kg of cotton and the duration, given in m²*yr. The land occupation is also highest for the cultivation process, approximately 1 ha for one year to produce

1,000 kg of cotton. Other process stages do contribute minimally to the overall impact, however, the overall impact is dominated by field emissions stage. This impact is inversely correlated to yield meaning when yield increases land occupation decreases. As yield increases through continued research and development, land use impacts will likely decrease.

FIGURE 4-12: Land occupation indicator [square meter per year / 1,000 kg of cotton fiber] by contributors.



## 4.1.14 Limitations

While extensive data were collected to quantify agricultural impacts, agricultural systems are inherently difficult to generalize. Differences in yearly weather conditions, spatial variations in soil type, topography, and individual grower management practices all introduce considerable variability for agricultural data. Where possible, this was partially addressed by using five year averages. In each country where a large percentage of the acres are irrigated, there is significant uncertainty surrounding irrigation pumping depths, and the estimates of energy use are highly influenced by this measurement.

A measure of the variability in the agricultural phase is provided in Table 4-2 which shows the standard deviation of country averages compared to the global mean value. For many of the impact categories, the standard deviation was well over 50% of the measured value and for GWP the standard deviation was greater than the absolute value of the mean. This high standard deviation compared to the mean results from accounting for the carbon absorbed in the cotton fiber that creates a “credit” or negative emission. With this credit, the overall emissions are reduced to a mean of -112 kg CO2 eq. while the standard deviation among the countries is 282kg CO2 eq. This variation also results from different practices used for growing cotton in the different regions. Additionally, the acidification potential standard deviation is high due to different field conditions and growing practices between regions. Most of the variation in the acidification potential were primarily from the different field emissions that account for more than 80% of the overall impact. Likewise, for eutrophication potential, the standard deviation is again large due mainly to field emissions for different regions and growing practices. The field emission models also introduce some uncertainty into the results as there are many variables that are difficult to accurately model field emissions.

The depletion of abiotic resources (ADP) is variable, however, is considered to be insignificant with values less than a gram per 1,000 kg fiber. As a result of this, the variation seen between countries is also insignificant. The ozone depletion potential (ODP) for the different countries was varied with a standard deviation over 75% of the value, however, the value is considered to be insignificant with values less than a thousandth of a gram.

There is little variation in PED. While energy to pump irrigation water can be significant, irrigation also increases productivity, thus, on an energy used per unit fiber basis, the variability from irrigation is decreased. Variation in WC and WU is expected as the data set includes irrigated and non-irrigated production systems as well as different growing climates and conditions. As the metrics in this study focused only on blue water use and consumption, for which non-irrigated regions the value is 0, thus the variability.

The variability of agricultural systems also presents challenges in modeling the fate and transport of pesticides and fertilizers. For this study, it was necessary to use models capable of representing aggregated areas. Future work will try to assess the impact of this aggregation by using site specific models capable of hydrologic routing on daily time steps for a select number of case studies to better understand what actually leaves the field boundary.

A final comment is that the data density for agricultural production was greatest for the United States, where a majority of the data were available at a regional or smaller level from official government estimates. Data for India was not as extensive, but were robust enough to adequately represent growing regions within the country. Data for China was the most limited and had the highest level of uncertainty. Despite the limitations, it was clear that for most of the inputs to the LCA model, the differences between regions within a country exceeded the differences between the mean values of a country owing primarily to differences in the growing environment. In order to identify any detailed changes in practices that need to be considered by a farmer, impact metrics need to be evaluated at the regional level.

TABLE 4-2: Mean and standard deviation for impact measures of the 11 different growing regions considered in the agricultural phase resulting from 1,000 kg of cotton fiber production.

| Impact Category | Units | Global Mean | Standard Deviation |
|---|---|---|---|
| **GWP (with credit)** | [kg CO2-Equiv.] | -113 | 518 |
| **GWP (without credit)** | [kg CO2-Equiv.] | 1,326 | 518 |
| **AP** | [kg SO2-Equiv.] | 26.4 | 10.0 |
| **EP** | [kg Phosphate-Equiv.] | 7.8 | 6.4 |
| **ADP** | [kg Sb-Equiv.] | 8.26E-04 | 2.08E-04 |
| **ODP** | [kg R11-Equiv.] | 4.74E-08 | 8.20E-08 |
| **POCP** | [kg Ethene-Equiv.] | 1.62E-01 | 0.197 |
| **PED** | [MJ] | 13,720 | 6,263 |
| **HHPA** | [kg PM2,5-Equiv.] | 1.80 | 0.812 |
| **ET** | [CTUe] | 3,892 | 3,765 |
| **HTC** | [CTUh] | 9.90E-07 | 3.18E-07 |
| **HTNC** | [CTUh] | 8.07E-05 | 3.52E-05 |
| **WC** | [m^3] | 1,559 | 2,120 |
| **WU** | [m^3] | 2,236 | 3,070 |
| **LOI** | [sqm*a] | 10,634 | 4,628 |

### 4.1.15 Conclusions: Cotton Production (Cradle-to-Gate)

- Field emissions were a major contributor to several environmental impact categories: eutrophication potential was strongly influenced by nitrate, acidification potential was influenced by ammonia, and global warming potential was influenced by nitrous oxide. The photochemical ozone creation potential was reduced by nitrogen monoxide emissions which are known to have a reductive effect on the creation of ozone. All these substances originate from the transformation process of biogenic and chemical nitrogen. Precision management of nitrogen fertilizer will continue to be a high priority for the cotton producers around the world.
- Fertilizer production is another important contributor with a high impact on primary energy demand, global warming potential, and photochemical ozone creation potential. Nitrogen fertilizer represents a majority of that contribution, reinforcing the need for careful nitrogen management.

- Despite a high uncertainty of toxicity effects in the impact categories of ecotoxicity potential and human toxicity potential, it is evident that field application of pesticides was the main contributor to impact based on the parameters in the current USEtox™ 2.0 model. Further studies will be conducted to determine how well USEtox™ represents the fate and transport of pesticides.
- The net GHG emissions during the agricultural phase of the LCA were relatively low and close to the same magnitude of the carbon dioxide equivalents represented by the carbon contained in the fiber. The potential benefits of storing carbon in cotton products was not examined in this work, however, could reduce the GWP impacts.
- The global mean water scarcity index for cotton growing regions was higher than the global average. The scarcity index for cotton was used to generate a water scarcity footprint that relates water use to the water resources available in the cotton growing regions. Water use is dominated by the irrigation stage with less than 1% resulting from upstream processes.

## **4.2** TEXTILE MANUFACTURING

### **4.2.1** Textile Manufacturing: Knit T-shirt and Casual Collared Shirt Results

A summary of life cycle results for knit fabric are shown in Figure 4-13, where the figure illustrates the relative contributions of knit fabric production processes. The relative contribution shown in Figure 4-13 only displays t-shirt results, however, they are nearly identical to the casual collared shirt's relative contributions. Each impact will be displayed separately and discussed for both t-shirt and casual collared shirt fabric production.

The following sections show results of the study for each impact category per 1,000 kg of knit fabric. Graphs are broken out by full life cycle step:

1. **Yarn production:** Energy for opening, cleaning, mixing, carding, pre-drawing, combing, drawing, and spinning cotton fiber into yarn.
2. **Knitting:** Energy for knitting yarn into fabric.
3. **Fabric preparation:** Energy, chemicals, emissions to water, and wastewater treatment.
4. **Dyeing:** Energy, dyes and chemicals, emissions to water, and wastewater treatment processes related to inversion, staging, jet dyeing, extraction, and relax drying.
5. **Finishing:** Energy, chemicals, and emissions to water related to the wet finishing, drying, and curing of knit fabric.
6. **Compaction:** Energy used to reduce length shrinkage.

#### **4.2.1.1** Knit Fabric Textile Manufacturing Results Summary

Figure 4-13 shows the potential impacts by specific processes for knit collared casual shirts. Knit yarn spinning accounted for more than 45% of the textile impact in six of the thirteen categories considered. GWP, AP, HHPA, POCP, BWU, and PED are all directly related to energy use. Although BWU would not necessarily be a power-related indicator, as explained previously, the high water use reported for the textile manufacturing phase is attributed to the high energy demand in the yarn preparation step and in wet preparation and dyeing, and is much larger than the direct water withdrawal for those wet processing steps. This higher energy demand in the yarn spinning can be partially attributed to the fact that a majority of the mills participating in this study used ring spinning and produced combed yarns, which require more steps than either rotor spinning or air jet spinning. As expected, the dyeing and finishing processes contributed to ODP, PED, ADP, EP, WC, ET, HHC, and HHNC. The fabric preparation contributed primarily to the ODP and BWC. Unlike the BWU metric, BWC, EP, ET, HHC, and HHNC are related to the wet processing steps due to the water that is evaporated from the fabric and the wastewater that is released. Both the t-shirt and collared casual shirt had similar impacts for all impact categories and are not individually discussed in the following sections. The impact values, however, are given for both garments in Table 4-3 and Table 4-4.

FIGURE 4-13: Relative contribution to each life cycle impact category for knit collared casual shirt.

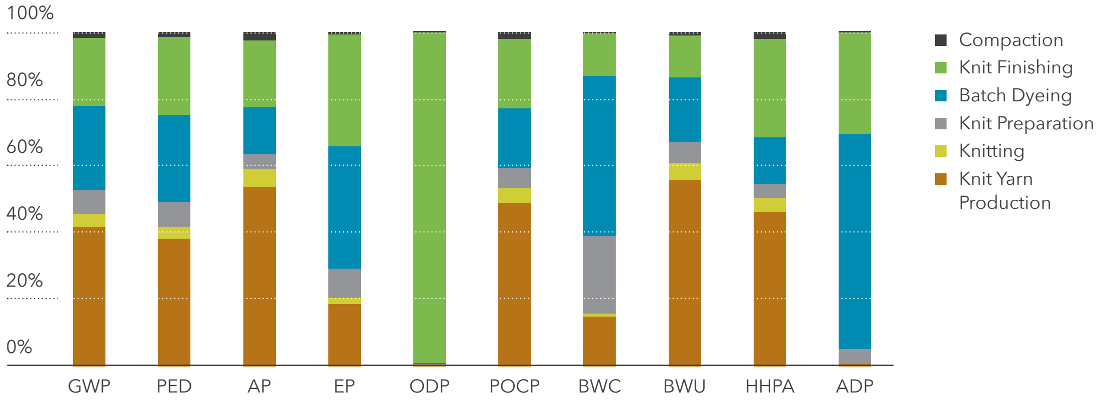


TABLE 4-3: Cotton collared casual shirt life cycle stage results by contributor. Red cells correspond to higher impact values and green cells correspond to lower impact values for each impact category.

| Impact | Unit | Total | Knit Yarn Production | Knitting | Knit Preparation | Batch Dyeing | Knit Finishing | Compaction |
|---|---|---|---|---|---|---|---|---|
| **GWP** | kg CO2 eq | 10,184 | 4,231 | 388 | 738 | 2,577 | 2,093 | 157 |
| **PED** | MJ | 154,124 | 59,135 | 5,217 | 11,384 | 40,193 | 36,038 | 2,159 |
| **AP** | kg SO2 eq | 64 | 34.4 | 3.17 | 2.87 | 9.09 | 12.9 | 1.41 |
| **EP** | kg PO4 eq | 7.1 | 1.31 | 0.14 | 0.63 | 2.61 | 2.37 | 0.05 |
| **ODP** | [kg R11-Equiv.] | 4.43E-05 | 1.29E-07 | 2.41E-10 | 2.22E-05 | 2.19E-05 | 6.68E-08 | 3.40E-08 |
| **POCP** | kg C2H4 eq | 3.8 | 1.88 | 0.18 | 0.23 | 0.69 | 0.80 | 0.08 |
| **BWC** | kg H2O | 237,484 | 34,612 | 2,772 | 55,044 | 114,417 | 30,123 | 516 |
| **BWU** | kg H2O | 13,981,263 | 7,795,407 | 694,262 | 927,648 | 2,692,389 | 1,726,213 | 145,343 |
| **HHPA** | kg PM2.5 eq | 5.6 | 2.58 | 0.24 | 0.22 | 0.80 | 1.65 | 0.10 |
| **ADP** | kg Sb eq | 6.49E-02 | 4.29E-04 | 2.85E-05 | 2.71E-03 | 4.21E-02 | 1.97E-02 | 7.65E-06 |

TABLE 4-4: Cotton t-shirt shirt life cycle stage results by contributor. Red cells correspond to higher impact values and green cells correspond to lower impact values for each impact category.

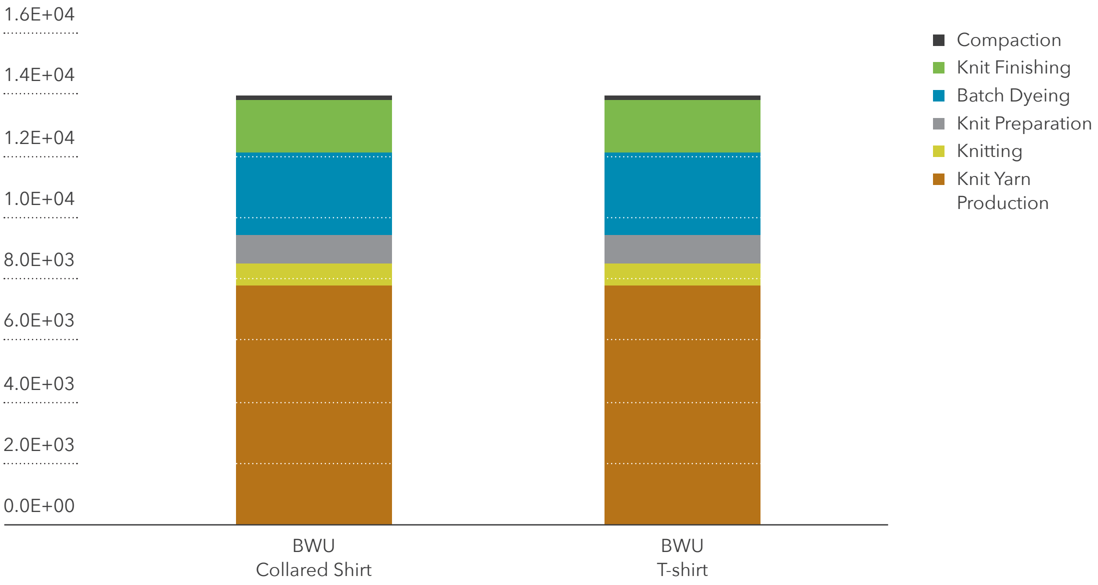
| Impact | Unit | Total | Knit Yarn Production | Knitting | Knit Preparation | Batch Dyeing | Knit Finishing | Compaction |
|---|---|---|---|---|---|---|---|---|
| **GWP** | kg CO2 eq | 10,169 | 4,225 | 388 | 737 | 2,573 | 2,090 | 156 |
| **PED** | MJ | 153,896 | 59,047 | 5,209 | 11,367 | 40,133 | 35,984 | 2,156 |
| **AP** | kg SO2 eq | 63.7 | 34.3 | 3.17 | 2.86 | 9.08 | 12.9 | 1.41 |
| **EP** | kg PO4 eq | 7.1 | 1.30 | 0.13 | 0.63 | 2.61 | 2.37 | 0.05 |
| **ODP** | [kg R11-Equiv.] | 2.21E-05 | 3.40E-08 | 3.22E-09 | 6.67E-08 | 1.29E-07 | 2.19E-05 | 2.40E-10 |
| **POCP** | kg C2H4 eq | 3.8 | 1.87 | 0.18 | 0.22 | 0.69 | 0.80 | 0.08 |
| **BWC** | kg H2O | 237,132 | 34,561 | 2,768 | 54,962 | 114,247 | 30,078 | 515 |
| **BWU** | kg H2O | 13,960,536 | 7,783,850 | 693,233 | 926,273 | 2,688,398 | 1,723,654 | 145,128 |
| **HHPA** | kg PM2.5 eq | 5.6 | 2.57 | 0.24 | 0.22 | 0.80 | 1.65 | 0.10 |
| **ADP** | kg Sb eq | 6.48E-02 | 4.28E-04 | 2.85E-05 | 2.71E-03 | 4.20E-02 | 1.97E-02 | 7.63E-06 |

### 4.2.1.2 Textile Manufacturing Impacts by Impact Category

#### *4.2.1.2.1 Water Use*

Water usage for knit fabric, which was measured in kg of water per 1,000 kg of fabric [kg H2O/1,000 kg] for each textile processing step, is shown in Figure 4-14. The burden for knits was primarily associated with the water required for electricity generation during the yarn production processes (81%) with a small amount actually apportioned to the wet preparation and dyeing processes (19%).

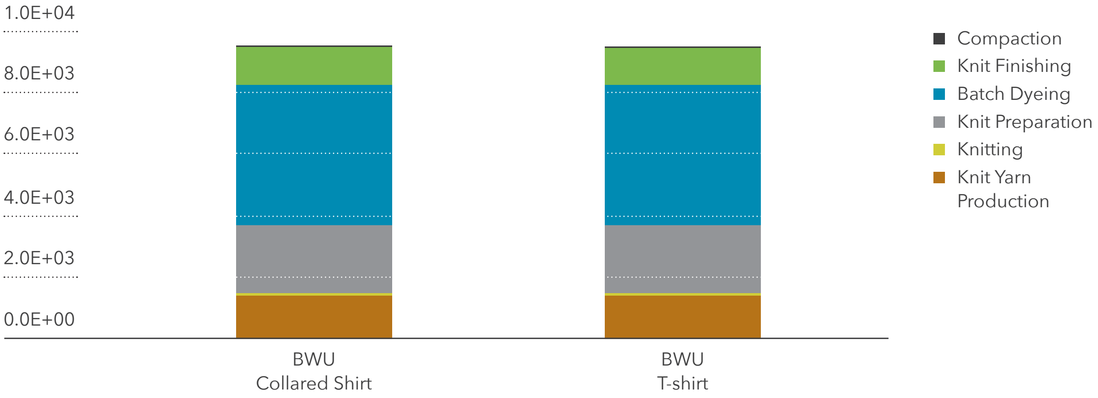
FIGURE 4-14: Water usage for knit fabric manufacturing by textile process step [m3 Water /1000 kg cotton fabric].



#### *4.2.1.2.2 Water Consumption*

Water consumption for knit fabric, which was measured in m3 of water per 1,000 kg of fabric [m3 H2O / 1,000 kg] for each textile processing step, is shown in Figure 4-15. Unlike water usage, batch dyeing contributed 48% to the total water consumption. Water that is sent to wastewater treatment (such as rinse water) and that eventually returns the water to the same watershed as it originated is not counted in WC. The balance of the water consumption was evenly split among the other stages, except compaction, and is primarily due to water consumption associated with electricity production.

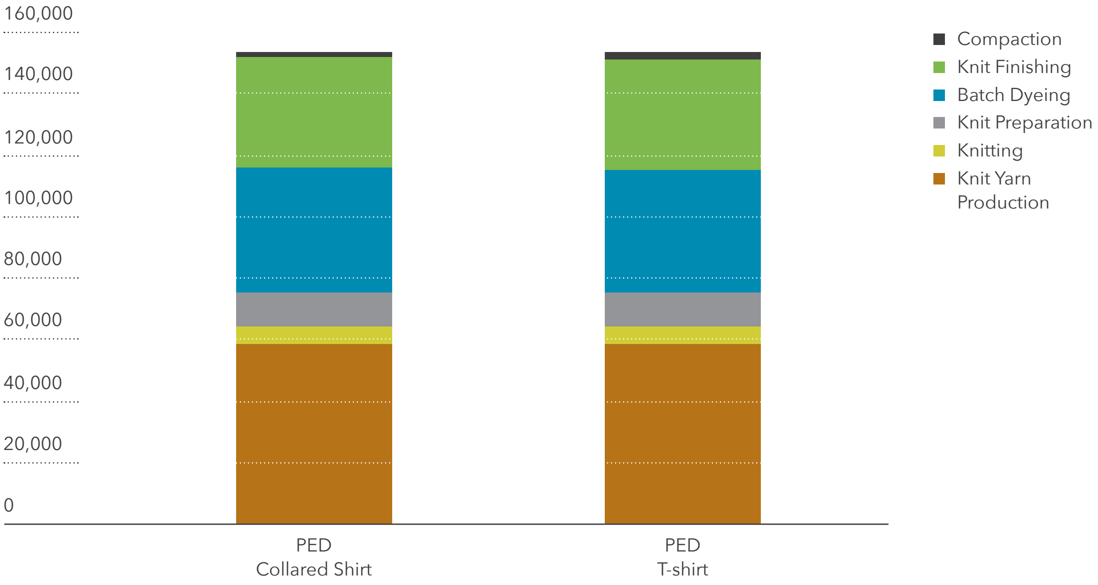
FIGURE 4-15: Water consumption for knit fabric by textile process step [m3 Water /1000 kg cotton fabric].



#### *4.2.1.2.3 Primary Energy Demand*

Primary energy demand (PED) from fossil sources for knit textile processes expressed as mega joules per 1,000 kg cotton fabric [MJ/1,000 kg] is shown in Figure 4-16. The burden is primarily associated with electricity use during the yarn production processes (46%), water conditioning and treatment in the dyeing processes (26%), and drying and curing in knit finishing (23%).

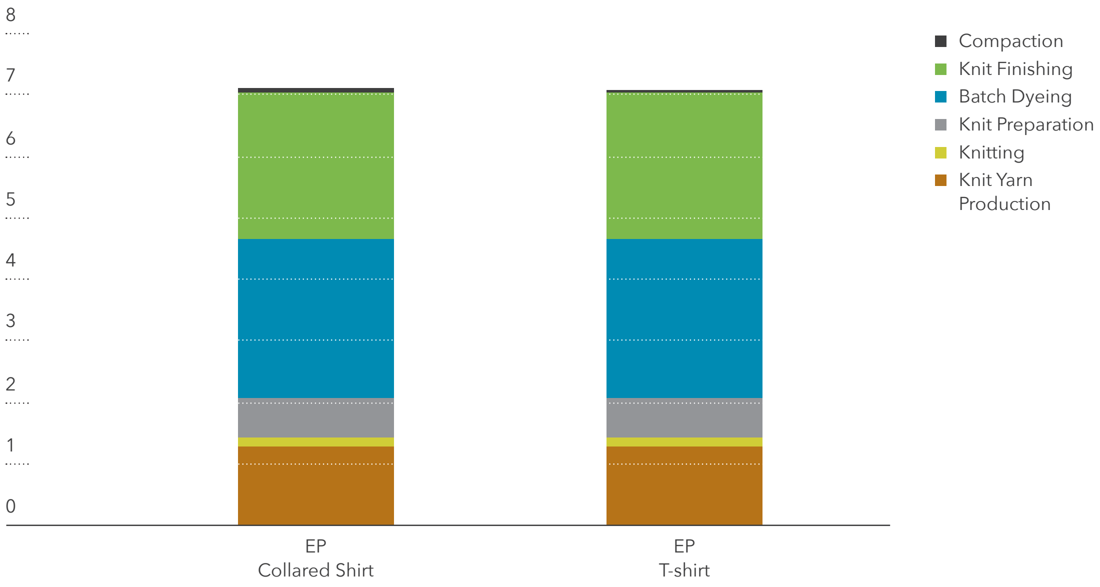
FIGURE 4-16: Primary energy demand for knit fabric manufacturing by textile process step [MJ /1000 kg of cotton fabric].



#### **4.2.1.2.4** *Eutrophication Potential*

Eutrophication potential (EP) for the manufacturing of knit fabric in kg PO4 equivalents/1,000 kg knit fabric is shown in Figure 4-17. The EP burden in textile manufacturing was related to wastewater emissions, with a smaller amount attributed to waste impacts from power generation. Finishing of knit fabric represents 33% of the burden. The remainder of the burden was due to yarn production (27%) and dyeing processes (38%). Within the dyeing and finishing processes, the burden comes from nitrogen and ammonia emissions in the wastewater, as well as power generation emissions. The EP burden from yarn production was related to emissions from power generation in the spinning process.

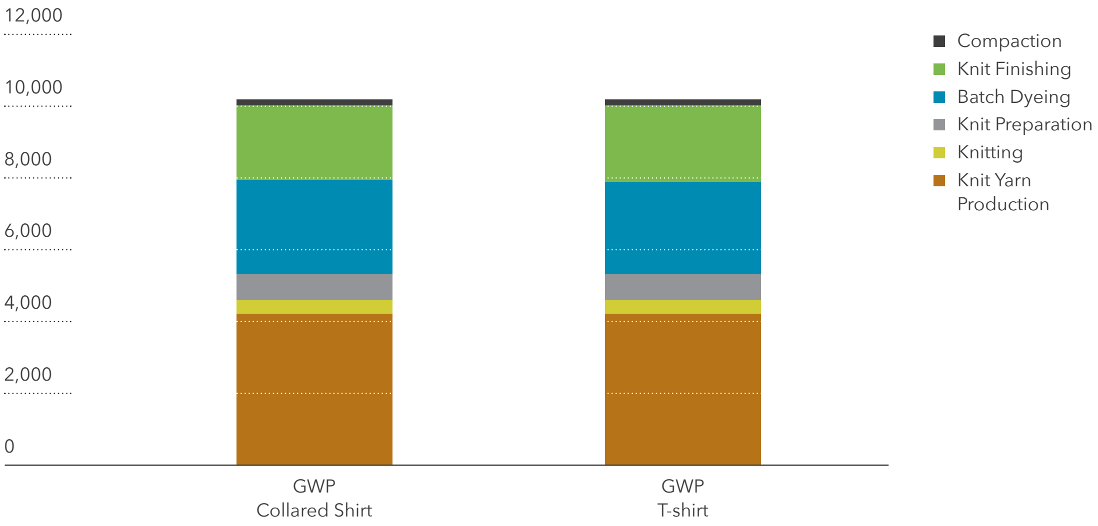
FIGURE 4-17: Eutrophication potential for knit fabric manufacturing by textile process step [kg PO4- eq./1000 kg cotton fabric].



#### **4.2.1.2.5** *Global Warming Potential*

Global warming potential (GWP) for the manufacturing of knit fabric in kg CO2 equivalents/1,000 kg knit fabric is shown in Figure 4-18. The largest portion of the GWP burden in textile manufacturing is related to electricity consumption during the yarn production processes (49%), with the second highest GWP (25%) related to energy use in batch dyeing. The knit finishing contributed 21% to the GWP while both knitting and compaction contributed minimally (4% and 2% respectively).

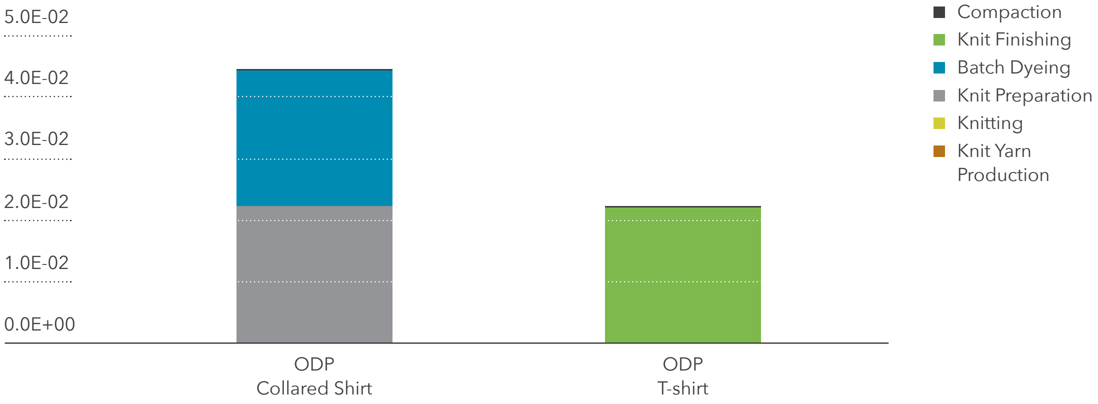
FIGURE 4-18: Global warming potential for knit fabric manufacturing by textile process step [kg CO2 eq./1000 kg cotton fabric].



#### 4.2.1.2.6 *Ozone Depletion Potential*

Ozone depletion potential (ODP) for the manufacturing of knit fabric in kg R11 eq. per 1,000 kg knit garments is shown in Figure 4-19. Since most ozone depleting chemicals (mostly refrigerants) were phased out of common use after the Montreal Protocol (UNEP Ozone Secretariat), ODP emissions today are usually minimal and related to electricity production. Due to the elimination of these products, there are no direct emissions that impact ODP from the textile manufacturing process. Although the values were negligible, the ODP burden was associated primarily with knit finishing (99%).

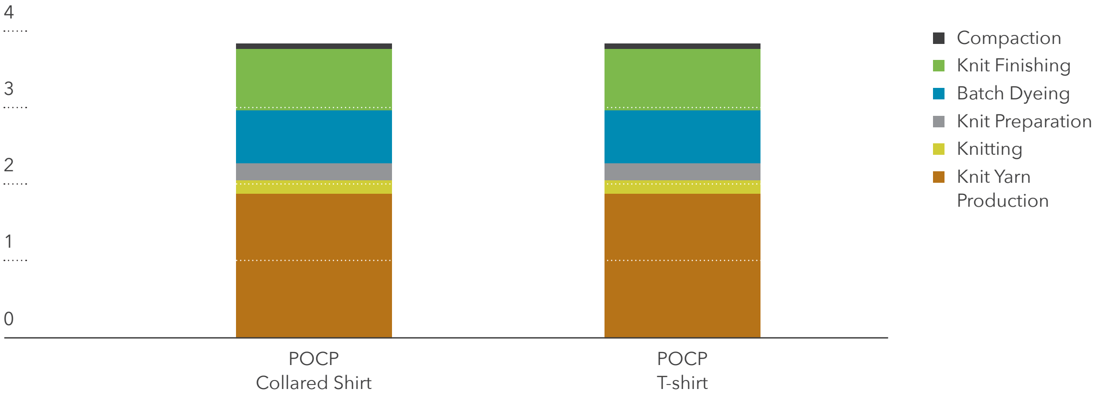
FIGURE 4-19: Ozone depletion potential for knit fabric by textile process step [kg R11 eq./1000 kg cotton fabric].



#### 4.2.1.2.7 *Photochemical Ozone Creation Potential*

Photochemical ozone creation potential (POCP) for the manufacturing of knit fabric in kg ethane equivalents/1,000 kg knit fabric is shown in Figure 4-20. POCP is commonly known as smog creation potential. The smog creation burden for knit fabrics is primarily associated with energy use in the yarn production processes (74% and 76% respectively) and dyeing processes and finishing (18% and 16% respectively).

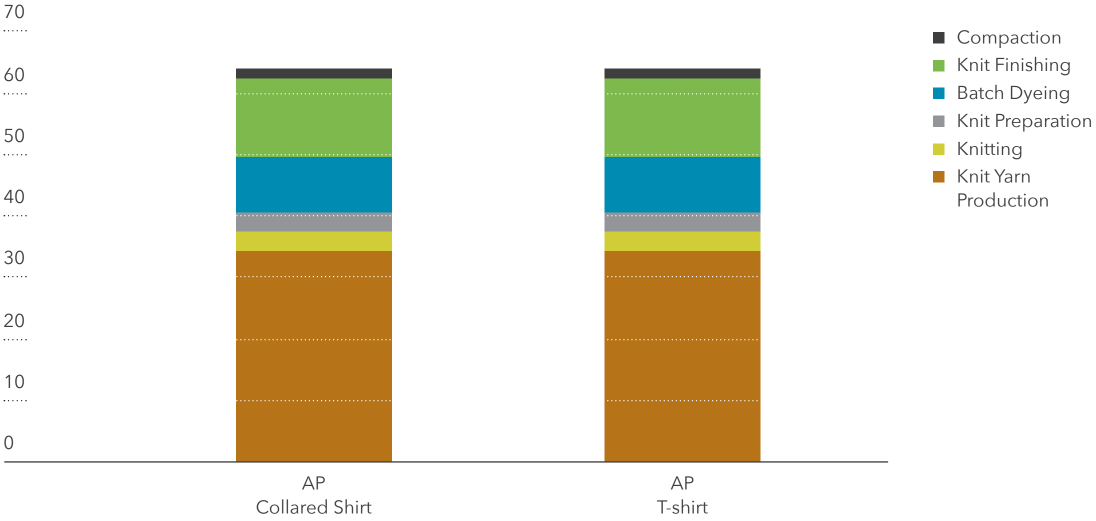
FIGURE 4-20: Photochemical ozone creation potential for knit fabric by textile process [kg C2H4 eq./1000 kg cotton fabric].



#### 4.2.1.2.8 *Acidification Potential*

Figure 4-21 illustrates the acidification potential (AP) for the manufacturing of knit fabric measured in kg SO2 equivalents/1,000 kg knit fabric. AP is also known as acid rain potential and is related to electricity consumption in textile manufacturing. The yarn production process carried the majority of the burden (54%), with smaller contributions from knit finishing (20%) and (14%) dyeing.

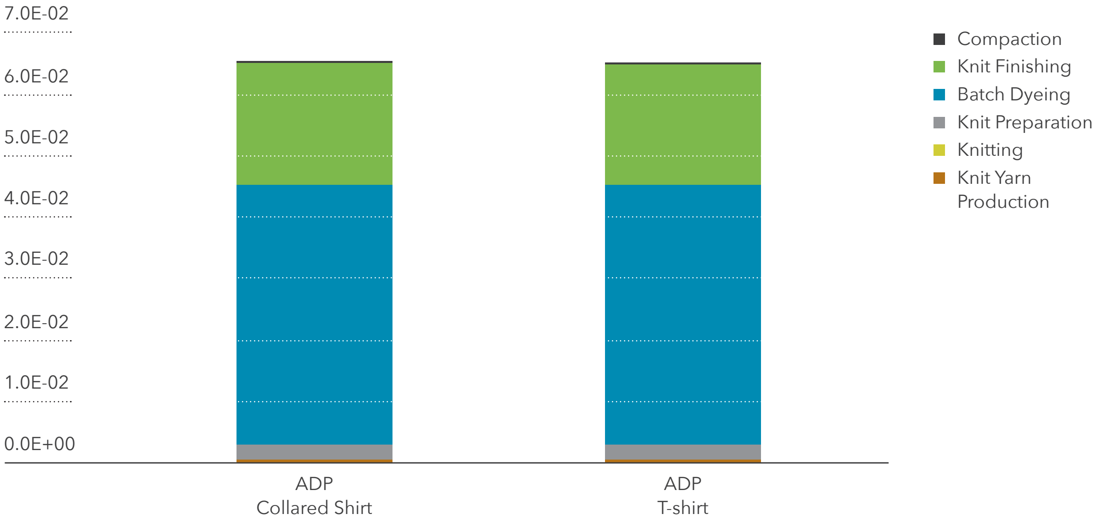
FIGURE 4-21: Acidification potential for knit fabric manufacturing by textile process [kg SO2 eq./1000 kg cotton fabric].



#### 4.2.1.2.9 *Abiotic Depletion Potential*

Abiotic depletion potential (ADP) represents the use or consumption of natural resources including metals, crude oil, and other non-living natural resources. These impacts are often associated with fossil fuel use in energy production systems. The dyeing and finishing stages contribute 65% and 30% to the ADP. Process chemicals and energy use were the major contributing factors to the ADP. The other impact categories contributed only 5% to the total ADP.

FIGURE 4-22: Abiotic depletion potential for knit fabric manufacturing by textile process [kg Sb-Equiv./1000 kg cotton fabric].



### **4.2.1.2.10** *Toxicity Metrics*

As previously stated, there is significant uncertainty surrounding the impact metrics associated with in estimating toxicity potential; however, some discussion of the predicted distribution of toxicity impacts with the textile phase are provided in this section. The impacts to the ecosystem, or ecotoxicity (ET), which are a measure of toxic emissions that are directly harmful to plant and animal species, was primarily created by the fabric preparation (21%), dyeing (45%) and finishing processes (33%). No other stage impacted ET. The preparation, dyeing and finishing processes require dyes and chemicals and also create a significant amount of wastewater that contributes to the ET.

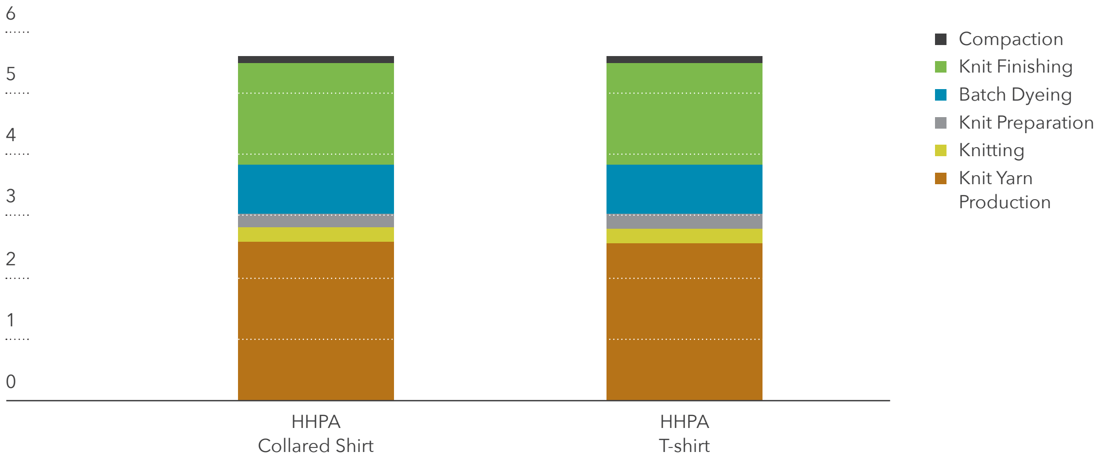
Human toxicity cancer (HTC) impacts are also associated with fabric preparation (20%), dyeing (45%) and finishing (32%) accounting for 97% of the overall impacts. Similar to ecotoxicity, chemical production and use and wastewater emissions are the major contributing factors to HTC. Wastewater alone contributed 72% to the overall HTC impacts. In addition to wastewater process, chemicals such as softeners, detergents, and wrinkle resist chemicals are used and contribute to the HTC. The other 3% of the HTC impacts are attributed to the remaining textile manufacturing phases and are primarily associated with energy production.

The dyeing and finishing process steps dominate the Human toxicity non-cancer (HTNC) impacts contributing 95% of the total impact. Of the total impacts, process chemicals such as softeners used in these processes contribute 84% to the total HTNC impacts. Wastewater treatment also contributed 4% to the HTNC. The other process stages contributed less than 5% to the overall HTNC through the use of other process chemicals and energy.

### **4.2.1.2.11** *Human Health Particulate Air*

The human health particulate emissions to air from knit textile manufacturing track closely with the energy use (PED), Figure 4-23. The yarn production (46%), knit finishing (29%), and dyeing (14%) are the major contributors to the HHPA impacts and major users of process electricity. In addition to HHPA impacts associated with energy production and use, the processes also directly emitted particulate matter. The other process stages contribute a total of 12% to the HHPA.

FIGURE 4-23: Human health particulate air impacts for knit fabric manufacturing by textile process [kg PM2,5-Equiv./1000 kg cotton fabric].



## **4.2.2** Textile Manufacturing: Woven Pants Results

### **4.2.2.1** Woven Fabric Textile Manufacturing Results Summary

The following sections show results for 1,000 kg of woven fabric. Although kg is not a unit typically used to represent woven production (usually square meters is used), the results were normalized in this way in order to compare with the knit outcomes.

More specifically, the impacts of the following woven manufacturing processes are highlighted:

1. **Yarn production:** Energy for opening, cleaning, mixing, carding, predrawing, combing, drawing, and spinning cotton fiber into yarn.
2. **Beam / Slash / Drying:** Energy and chemicals for beaming, slashing, and drying warp yarn.
3. **Weaving:** Energy for weaving warp and fill yarn into fabric.
4. **Woven fabric preparation:** Energy, chemicals, emissions to water, and wastewater.
5. **Continuous Dyeing:** Energy, dyes and chemicals, emissions to water, and wastewater treatment processes related to dyeing.
6. **Finishing:** Energy, chemicals, and emissions to water related to the wet finishing, drying, and curing of woven fabric.
7. **Sanforizing:** Energy for sanforizing the finished fabric.

The woven fabric overall results from all processes and impact categories are shown in Figure 4-24. Impacts from woven preparation and dyeing dominate the toxicity metrics. Impacts from woven yarn production, beam, slash, dry processing of warp yarn, and sanforizing were primarily related to energy use. Impacts from woven preparation, dyeing, and finishing are related to energy but also to chemicals used in those processes and the resulting wastewater effluent. The woven finishing dominated the ODP impacts.

FIGURE 4-24: Percent impact contribution by textile process step for woven fabric.

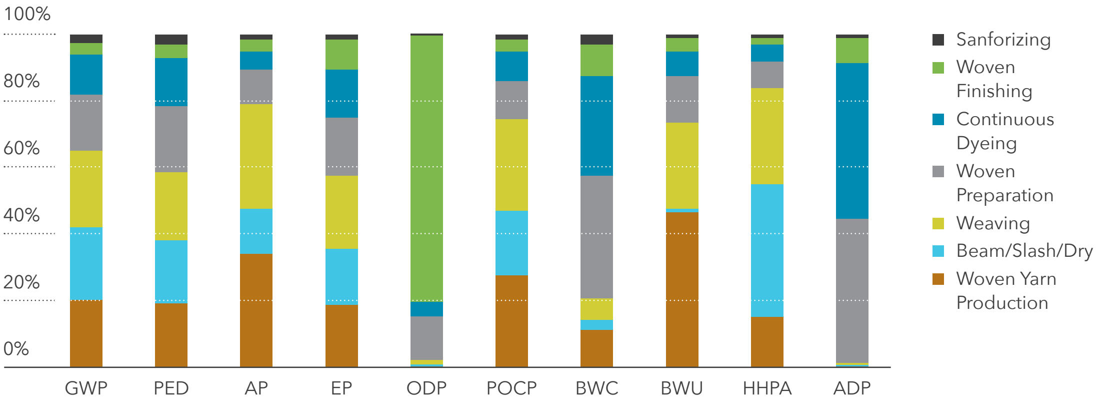


TABLE 4-5: Cotton woven pant life cycle stage results by contributor. Red cells correspond to higher impact values and green cells correspond to lower impact values for each impact category.

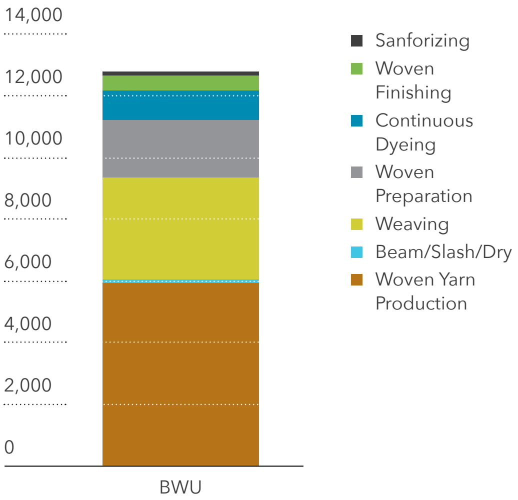
| Impact | Unit | Total | Woven Preparation | Woven Yarn Production | Beam / Slash / Dry | Weaving | Continuous Dyeing | Woven Finishing | Sanforizing |
|---|---|---|---|---|---|---|---|---|---|
| **GWP** | kg CO2 eq | 10,701 | 1,835 | 2,172 | 2,350 | 2,445 | 1,267 | 368 | 264 |
| **PED** | MJ | 132,763 | 26,157 | 25,698 | 25,286 | 26,852 | 19,225 | 5,711 | 3,833 |
| **AP** | kg SO2 eq | 79.6 | 8.18 | 27.49 | 10.36 | 25.19 | 4.61 | 2.76 | 1.06 |
| **EP** | kg PO4 eq | 4.43 | 0.76 | 0.84 | 0.75 | 0.97 | 0.64 | 0.39 | 0.08 |
| **ODP** | kg Sb eq | 1.78E-06 | 2.33E-07 | 7.06E-09 | 6.51E-09 | 2.67E-08 | 8.22E-08 | 1.42E-06 | 4.45E-09 |
| **POCP** | kg C2H4 eq | 4.90 | 0.57 | 1.36 | 0.95 | 1.35 | 0.43 | 0.16 | 0.08 |
| **BWC** | M^3 H2O | 182 | 66 | 21 | 6 | 12 | 54 | 18 | 5 |
| **BWU** | M^3 H2O | 12,789 | 1,821 | 5,954 | 131 | 3,296 | 969 | 485 | 132 |
| **HHPA** | kg PM2.5 eq | 15.1 | 1.16 | 2.31 | 6.07 | 4.33 | 0.75 | 0.36 | 0.13 |
| **ADP** | kg Sb eq | 2.53E-02 | 1.09E-02 | 1.88E-04 | 1.01E-04 | 1.01E-04 | 1.18E-02 | 1.90E-03 | 2.07E-04 |

### **4.2.2.2** Textile Manufacturing Impacts by Process

#### ***4.2.2.2.1*** *Water Use*

Water use [m3 H2O/1,000 kg fabric] for continuously dyed woven fabric for each textile processing step is shown in Figure 4-25. The water use burden was primarily associated with the continuous dyeing processes (8%), and the water required for electricity generation for the yarn production processes (47%) and weaving (20%). Water used in electricity production is often referred to as indirect water as it is not directly used in the processes required to manufacture the fabric, rather, it is used to produce electricity.

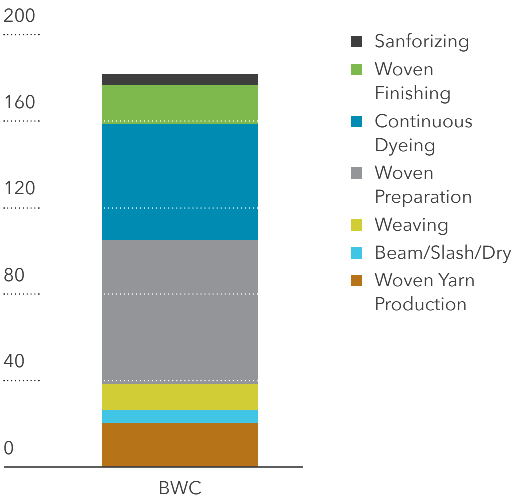
FIGURE 4-25: Water use for woven fabric manufacturing by textile process [m3 Water /1000 kg cotton fabric].



#### ***4.2.2.2.2*** *Water Consumption*

Water consumption for woven fabric, which was measured in m3 water per 1,000 kg of fabric [m3 H2O/1,000 kg] for each textile processing step, is shown in Figure 4-26. The WC impacts were primarily associated with wet processing steps in textile manufacturing and were highest for woven preparation (37%) and continuous dyeing (30%). The woven yarn production and woven finishing contributed 11% and 10%, respectively, to the WC. The remaining process stages contributed the balance of 13% to the WC. The WC was only 1.4% of the total water use and is minimal when compared to the other life cycle stages.

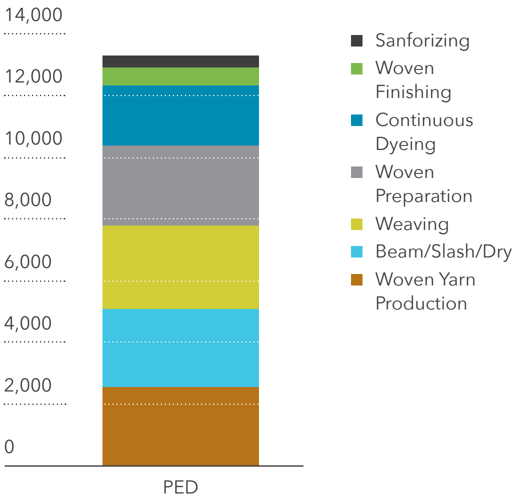
FIGURE 4-26: Blue water consumption for woven fabric by textile process [m3 Water /1000 kg cotton fabric].



#### ***4.2.2.2.3*** *Energy*

Primary energy demand (PED) from fossil sources [MJ/1,000 kg woven fabric] by textile process for continuously dyed woven fabric is illustrated in Figure 4-27. The burden was primarily associated with electricity in the yarn production processes (47%), weaving (26%), and woven preparation processes (14%).

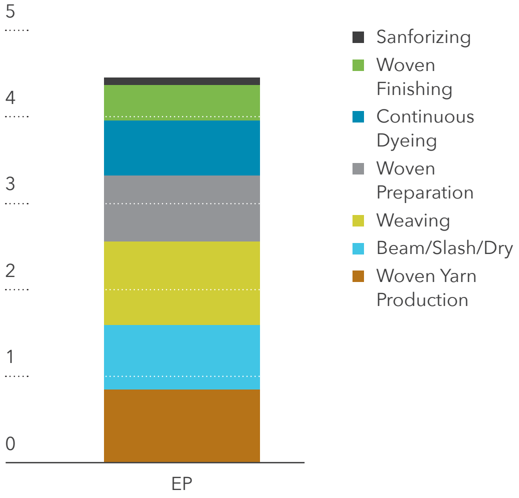
FIGURE 4-27: Primary energy demand from fossil sources for woven fabric manufacturing by textile process [MJ /1000 kg of cotton fabric].



#### *4.2.2.2.4 Eutrophication Potential*

Eutrophication potential (EP) for the manufacturing of continuously dyed woven fabric in kg Phosphate equivalents/1,000 kg woven fabric is shown in Figure 4-28. The EP burden in textile manufacturing is related to wastewater emissions. Finishing contributes the largest amount to the EP (58%) followed by yarn processing (23%). The EP associated with finishing processes is partially attributed to nitrogen and ammonia emissions in the wastewater, but also to the emissions from the power plants due to the energy intensive nature of curing processes for woven finishing. Eutrophication potential associated with energy production is the primary contributor for the energy intensive yarn production process.

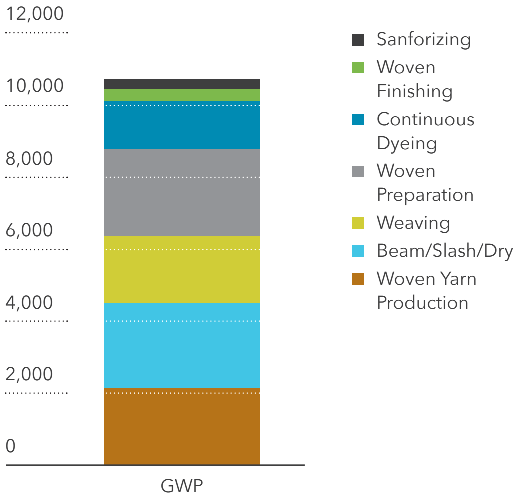
FIGURE 4-28: Eutrophication potential for woven fabric manufacturing by textile process step [kg PO4- eq./1000 kg cotton fabric].



#### *4.2.2.2.5 Global Warming Potential*

Global warming potential (GWP) for the manufacturing of continuously dyed woven fabric in kg CO2 equivalents/1,000 kg woven fabric is shown in Figure 4-29. The GWP burden in woven textile manufacturing is evenly distributed to all processes prior to finishing and is related to electricity consumption. Actual percentages are yarn production processes (20%), beam/slash/dry (22%), weaving (23%), and woven preparation (17%).

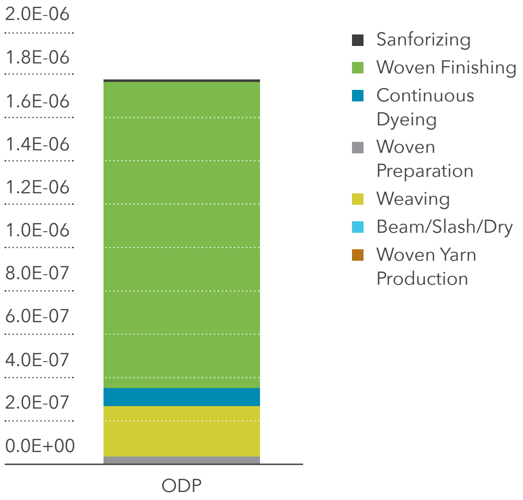
FIGURE 4-29: Global warming potential for woven fabric manufacturing by textile process [kg CO2 eq./1000 kg cotton fabric].



#### *4.2.2.2.6 Ozone Depletion Potential*

Ozone depletion potential (ODP) for the manufacturing of continuously dyed woven fabric in kg R11 equivalents/1,000 kg woven fabric is shown in Figure 4-30. Since most ozone depleting chemicals (mostly refrigerants) were phased out of common use after the Montreal Protocol (UNEP Ozone Secretariat), ODP emissions today are usually minimal and related to electricity production. Due to the elimination of these products, there are no direct emissions from the textile manufacturing process that impact ODP. Although the numbers are negligible, the ODP burden is primarily associated with the finishing process (80%), primarily from the production of fluorochemical durable water repellent. The woven preparation (13%), dyeing (5%), and weaving (2%) contributed small amounts to the ODP.

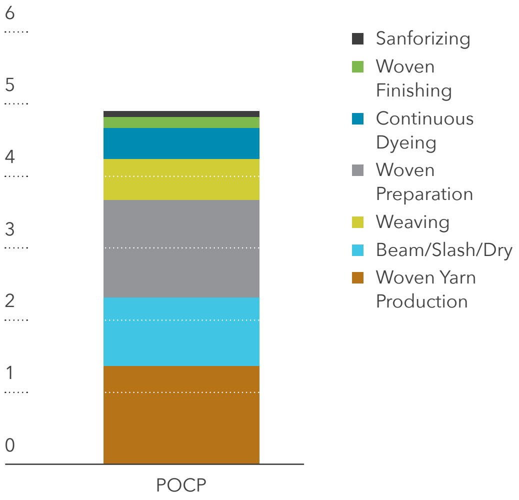
FIGURE 4-30: Ozone depletion potential for woven fabric manufacturing by textile process [kg R11 eq./1000 kg cotton fabric].



### *4.2.2.2.7 Photochemical Ozone Creation Potential*

Photochemical ozone creation potential (POCP) for the manufacturing of continuously-dyed woven fabric in [kg ethane equivalents/1,000 kg woven fabric] is shown in Figure 4-31. POCP is commonly known as smog creation potential. The smog creation burden for woven fabrics is associated primarily with the energy use which is highest in the yarn production process (28%), beam/slash/dry (19%), and weaving (28%).

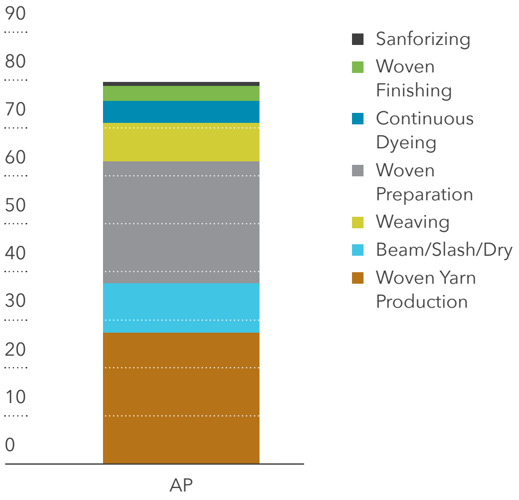
FIGURE 4-31: Photochemical ozone creation potential for woven fabric manufacturing by textile process [kg C2H4 eq./1000 kg cotton fabric].



### *4.2.2.2.8 Acidification Potential*

Acidification potential (AP), also known as acid rain potential, for the manufacturing of continuously dyed woven fabric in [kg SO2 equivalents/1,000 kg woven fabric] is shown in Figure 4-32. AP is related to electricity consumption in textile manufacturing. The yarn production contributed 35% to the AP followed by weaving (32%), beam/slash/dry (13%), and woven preparation (10%). These impact contributions closely track the PED impacts due to energy usage and corresponding emissions that contribute to the AP.

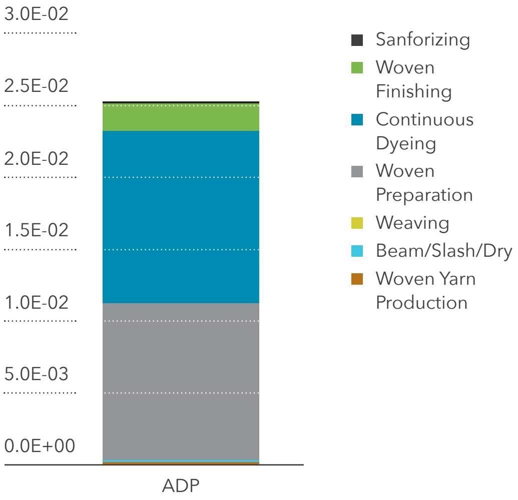
FIGURE 4-32: Acidification potential for woven fabric manufacturing by textile process [kg SO2 eq./1000 kg cotton fabric].



### *4.2.2.2.9 Abiotic Depletion*

Abiotic depletion potential (ADP) represents the use or consumption of natural resources including metals, crude oil, and other non-living natural resources and is shown in Figure 4-33. These impacts are often associated with fossil fuel use in energy production systems. The woven preparation and dyeing stages contribute 43% and 47% to the ADP, respectively. Because yarn production and weaving are not prominent contributors to ADP in this case, the production of process chemicals was the source of impact. The other stages contributed only 10% to the total ADP.

FIGURE 4-33: Abiotic depletion potential for knit fabric manufacturing by textile process [kg Sb-Equiv./1000 kg cotton fabric].



#### 4.2.2.2.10 *Toxicity*

As previously stated, there is significant uncertainty surrounding the impact metrics associated with in estimating toxicity potential; however, some discussion of the predicted distribution of toxicity impacts with the textile phase are provided as was done in the knits section. The ecotoxicity (ET), a measure of toxic emission which are directly harmful to plant and animal species, was primarily created by the woven preparation (72%), continuous dyeing (17%) and finishing processes (5%). The woven preparation, dyeing and finishing processes require dyes and chemicals and create a significant amount of wastewater that contributes to the ET. The required wastewater treatment contributed 82% to the overall ET while production of softeners contributed 15%.

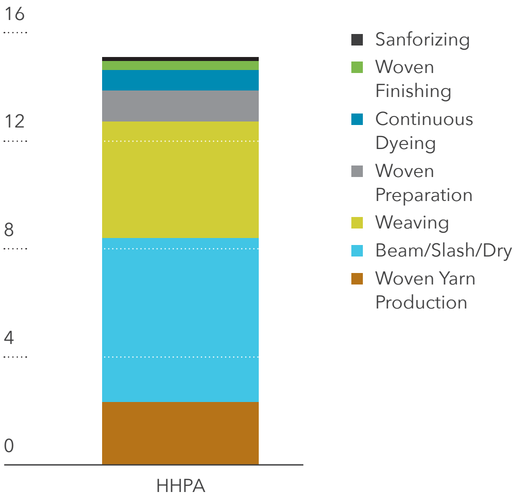
Human toxicity cancer (HTC) impacts are also associated with woven preparation (65%) and dyeing (27%) accounting for 92% of the overall impacts. Similar to ecotoxicity, chemical production and use, and wastewater emissions are the major contributing factors to HTC. As a known carcinogen, formaldehyde from wrinkle resist product and use impacts the cancer potential in finishing. Other process chemicals that seem to influence HTC include softeners and detergents. The other 8% of the HTC impacts are attributed to the remaining textile manufacturing phases and are primarily associated with energy production.

The woven preparation and dyeing steps dominate the human toxicity non-cancer (HTNC) impacts contributing 61% and 26% of the total impact, respectively. The production of process chemicals used in fabric preparation and dyeing were the major contributors to the HTNC. The other woven manufacturing phases contributed 13% to the total HTNC with contributions from production of other process chemicals used in the woven finishing and beam/slash/dry.

#### 4.2.2.2.11 *Human Health Particulate Air*

The human health particulate emissions to air from woven textile manufacturing track closely with the energy use (PED). The yarn production (15%), beam/slash/dry (40%), and weaving (29%) are the major contributors to the HHPA impacts and major users of process electricity. In addition to HHPA impacts associated with energy production and use, the processes also directly emit particulate matter. The other process stages contribute a total of 16% to the HHPA.

FIGURE 4-34: Human health particulate air for woven fabric manufacturing by textile process [kg PM2,5-Equiv./1000 kg cotton fabric].



### **4.2.3** Limitations

While primary data was collected for the textile manufacturing process (gate-to-gate), the quality of the primary data has a degree of uncertainty. In an ideal situation, researchers would have been able to visit each mill to collect data directly from machines and energy or water meters. Because this was not possible, a mixture of primary and secondary data was used as was described in 3.3 . Equipment data was used to corroborate data received from the mills, and all submitted data was subjected to rigorous review by Cotton Incorporated industry experts. Although the overall data quality of the project is high, additional data on energy demands, chemical inputs, and wastewater outputs will enhance future studies. In addition, a larger mill sample size would provide greater detail for certain processes and help to smooth out variability in reported values. However, as seen in the spinning sensitivity analysis for the previous 2010 cotton LCA, a large variability in energy data, even for such an important process, did not have a significant effect on the calculated LCIA values.

Data used to model the textile manufacturing was collected from various mills in different regions around the world. Care was taken to survey a representative sample of 14 textile mills in regions that produce and export most of the world's textiles. Within the global average there is significant variation among mills. This variation results from many factors, for example, local laws and environmental regulations, regional electricity production methods or grids, types of machinery and processes, and age of textile mills and technology. Data collected for this study was self-reported by each mill and may be estimated leading to under or over reporting. To maintain confidentiality of data, results for textile manufacturing were not calculated on a per country or region basis as the cotton production was calculated. As a result of only horizontal averaging calculations, standard deviations describing the range of results based on country are not available.

### **4.2.4** Conclusions

- Yarn production is the main contributor for global warming potential, acidification potential, photochemical ozone creation potential, blue water use, and primary energy demand due to the high electricity demand. Energy for weaving is also a major contributor for these impacts in the woven pants scenario.
- Energy for conditioning, processing, heating, and eventual drying of the water in the preparation and dye processes is also a significant contributor within the textile manufacturing life cycle stage.
- The relevant contributors to eutrophication potential in the textile manufacturing phase are more complex than the other impacts. For wovens, wastewater emissions from continuous preparation and dyeing are primary influencers to EP. For the knit fabric manufacturing processes, upstream impacts from manufacturing of chemicals for preparation, dyeing, and finishing as well as emissions from power generation processes can have as much impact on the EP as the actual wet processes.
- Though considerable amounts of water are used in preparation, dyeing, and finishing, much of that water is returned to the watershed so is not considered in the water consumption metric. The water consumed in manufacturing is spread between wet processes and the upstream production of energy. These manufacturing water flows are far outweighed by water consumed during irrigation and consumer washing.
- The toxicity metrics were most influenced by woven preparation in the woven pants scenario and the dyeing and knit finishing phases for the knit garments. The upstream emissions associated with production of process chemicals used are a major contributor in addition to emissions of chemicals in the wastewater effluent.

## 4.3 POST PRODUCTION: CUT-AND-SEW, CONSUMER USE, AND END-OF-LIFE

The post production phase of the cradle-to-grave LCA system boundary included garment cut-and-sew, consumer use, and garment end-of-life. Results for the use phase are described in this section.

### 4.3.1 Consumer Use Phase Survey Results

To determine the use phase impacts for laundering and product lifetime, a survey was conducted examining use phase behavior for China, Japan, Italy, Germany, the United Kingdom, and the United States. Approximately one thousand responses were received from all countries with an even split on male to female respondents, as seen in Table 4-6: Use phase survey responses by country.

TABLE 4-6: Use phase survey responses by country.

| Country | Respondents |
|---|---|
| **China** | 1,003 |
| **Japan** | 1,000 |
| **Italy** | 1,004 |
| **Germany** | 1,005 |
| **United Kingdom** | 1,014 |
| **United States** | 1,015 |

The number of garment washes per life time highly influences the use phase impacts. The global average number of garment washes was determined for each garment type and listed in Table 4-7. Respondents reported t-shirts as having the fewest number of washes and woven pants with the highest number of washes.

TABLE 4-7: Use phase survey responses for total washes in first garment life.

| Garment | Number Washes First Life |
|---|---|
| **T-Shirts** | 18.2 |
| **Collared Casual Shirts** | 22.2 |
| **Woven Pants** | 23.5 |

Clothes drying is an important parameter when modeling garment use phase. Line drying uses no fossil fuel energy while machine drying is energy intensive requiring electricity or natural gas for heat. The use phase survey questions surrounding the drying methods show that as a global average, 69% of the respondents line dried their clothes. Around 19% of the respondents indicated machine drying and the remaining respondents indicated using both line and machine drying. For ease of calculation in the LCA model, those who do both types of drying were split equally between line drying and machine drying, which is shown in Table 4-8. The clothes drying methods highly influence the use phase results and also showed high levels of variability between countries. This variability introduces uncertainty into the use phase results as the global average was used for this analysis. The standard deviations of use phase impacts are reported in the use phase limitations section.

TABLE 4-8: Global average clothes drying methods.

| Drying Methods Used | Air dry (line, lay flat, drip dry) | In a machine dryer |
|---|---|---|
| **T-Shirts** | 74.7% | 25.3% |
| **Collared Casual Shirts** | 76.1% | 23.9% |
| **Woven Pants** | 76.5% | 23.5% |

TABLE 4-9: Global textile drying methods by drying type and country.

| | Air dry (line, lay flat, drip dry) | In a machine dryer | Combination of machine |
|---|---|---|---|
| **China** | 80% | 3% | 17% |
| **Germany** | 77% | 12% | 11% |
| **Italy** | 90% | 4% | 5% |
| **Japan** | 91% | 3% | 7% |
| **United Kingdom** | 69% | 12% | 19% |
| **United States** | 13% | 73% | 14% |
| **Average** | 70% | 18% | 12% |

## 4.3.2 Summary

The post production phase including cut-and-sew, consumer use, and end-of-life contributes significantly to the overall impacts of the garments. Within this phase, the use phase stands out as the primary contributor in all impact categories except in one scenario, as noted below in the ADP section. Generally, the impacts from the post production phase tracked with the consumer use and product life time. The t-shirt had the lowest number of total washes and the woven pant had the highest number of washes over the product lifetimes. These differences in use behavior results in consistently higher impacts for the woven pants and consistently lower impacts for the t-shirt. Impacts in this phase were measured on a basis of 1,000 kg of garments which included impacts from zippers and other materials, as well as material losses associated with the cut-and-sew process.

TABLE 4-10: Post production impacts for cut-and-sew, use, and end-of-life phases.

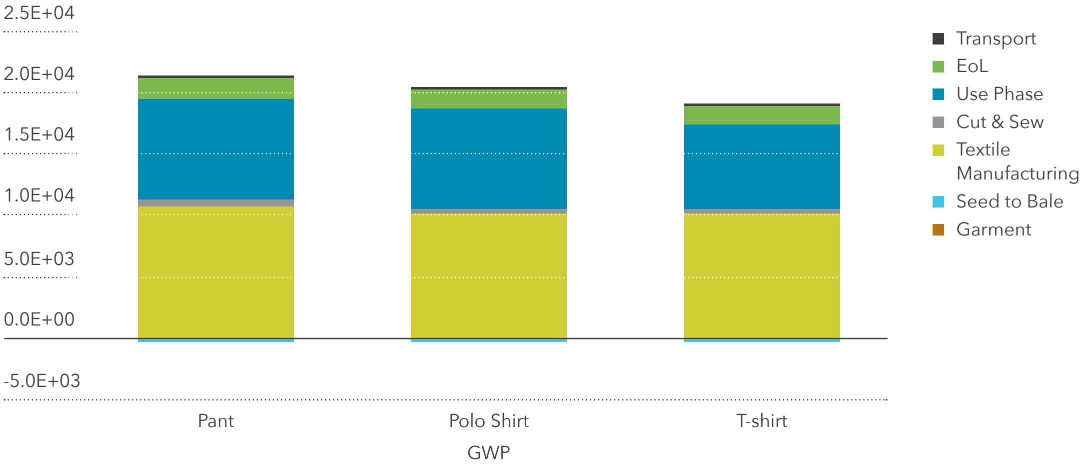
| | | Woven Pants | | | Collared Casual Shirt | | | T-shirt | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Cut-and-Sew | Use | EoL | Cut-and-Sew | Use | EoL | Cut-and-Sew | Use | EoL |
| GWP | [kg CO2-Equiv.] | 6.38E+02 | 8.16E+03 | 1.62E+03 | 3.68E+02 | 8.12E+03 | 1.62E+03 | 3.85E+02 | 6.76E+03 | 1.62E+03 |
| PED | [MJ] | 8.82E+03 | 1.05E+05 | 6.91E+02 | 1.05E+03 | 1.05E+05 | 6.91E+02 | 1.27E+03 | 8.73E+04 | 6.91E+02 |
| AP | [kg SO2-Equiv.] | 1.03E+00 | 1.78E+01 | 9.55E-01 | 4.32E-01 | 1.80E+01 | 9.55E-01 | 5.72E-01 | 1.51E+01 | 9.55E-01 |
| EP | [kg Phosphate-Equiv.] | 3.93E-01 | 4.18E+00 | 1.49E+00 | 4.19E-01 | 4.04E+00 | 1.49E+00 | 4.21E-01 | 3.34E+00 | 1.49E+00 |
| ODP | [kg R11-Equiv.] | 3.16E-08 | 1.04E-06 | 3.55E-09 | 9.27E-09 | 1.06E-06 | 3.55E-09 | 1.25E-08 | 8.93E-07 | 3.55E-09 |
| POCP | [kg Ethene-Equiv.] | 2.46E-01 | 2.55E+00 | 2.88E-01 | 1.00E-01 | 2.51E+00 | 2.88E-01 | 1.09E-01 | 2.09E+00 | 2.88E-01 |
| BWC | [kg] | 1.96E+03 | 2.50E+05 | 2.22E+03 | 5.17E+02 | 2.39E+05 | 2.22E+03 | 6.55E+02 | 1.97E+05 | 2.22E+03 |
| BWU | [kg] | 3.04E+05 | 8.70E+06 | 3.58E+04 | 1.15E+05 | 8.91E+06 | 3.58E+04 | 1.53E+05 | 7.50E+06 | 3.58E+04 |
| HHPA | [kg PM2,5-Equiv.] | 2.46E-01 | 5.99E+00 | 1.54E-01 | 1.82E-01 | 6.08E+00 | 1.54E-01 | 2.27E-01 | 5.10E+00 | 1.54E-01 |
| ADP | [kg Sb-Equiv.] | 1.16E-02 | 2.96E-03 | 1.82E-05 | 1.32E-05 | 2.85E-03 | 1.82E-05 | 1.52E-05 | 2.35E-03 | 1.82E-05 |

## 4.3.3 Impacts by stage

### 4.3.3.1 Global Warming Potential

The global warming potential (GWP) impact generated during post production processes is dominated by the consumer use phase as seen in Figure 4-35. The use phase contributed 78%, 80%, and 77% to the GWP for pants, collared casual shirts, and t-shirts, respectively. Since the use phase is heavily dependent on consumer behavior, the GWP is highly influenced by laundering parameters and types of equipment used for laundering. The cut-and-sew phase contributed 5% to the GWP and the end-of-life contributed 16% to the GWP based on averages of all three fabric types. There was little variation between the cut-and-sew and end-of-life results for the three garments.

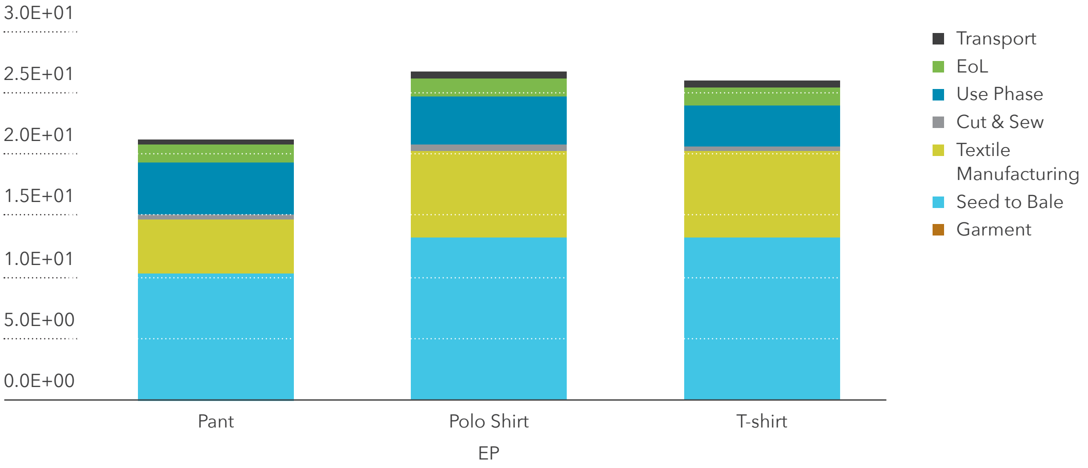
FIGURE 4-35: Global warming potential by post production phase [kg CO2 eq./1000 kg cotton garment].



### 4.3.3.2 Eutrophication Potential

The post production eutrophication potential (EP) impacts are dominated by the use phase Figure 4-36. These impact results from waste-water associated with the washing as well as energy used in the laundering process. The use phase contributes 69%, 68%, and 64% for woven pants, collared casual shirts, and t-shirts, respectively. The end-of-life contributed 25% for woven pants and collared casual shirts and 28% for t-shirts. The cut-and-sew contribution was small at approximately 7% for all three garment types.

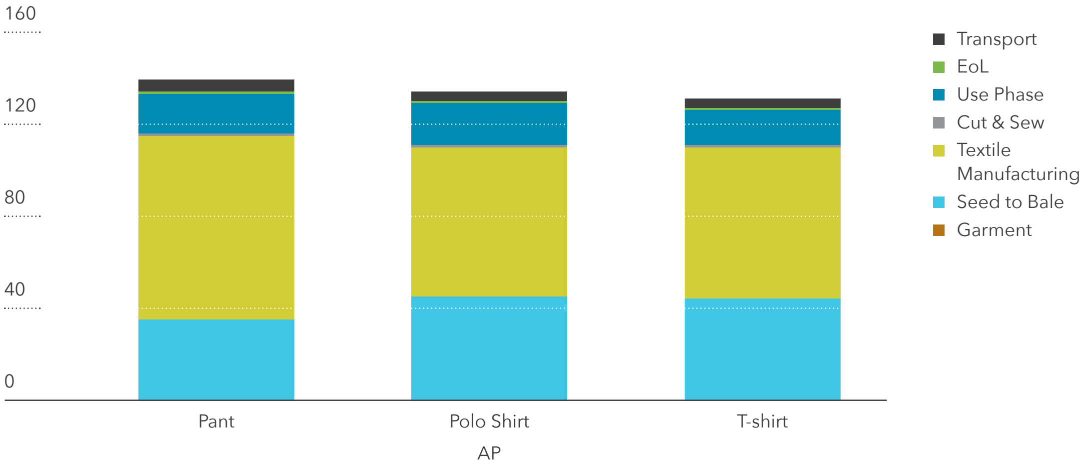
FIGURE 4-36: Eutrophication potential by post production phase [kg PO4- eq./1000 kg cotton garment].



### 4.3.3.3 Acidification Potential

The acidification potential (AP) impacts for the post processing phases are dominated by the use phase, as shown in Figure 4-37. Production and use associated with laundering processes were the primary contributors to the use phase AP impacts. Out of the post processing phases, the use phase contributed over 90% to the AP impact for all three garment types. The AP impacts are sensitive to the electrical grid used by the consumer, thus there is a high degree of variation for different countries. The cut-and-sew phase and end-of-life contributed on average 4% and 5% to the overall AP impacts for each garment.

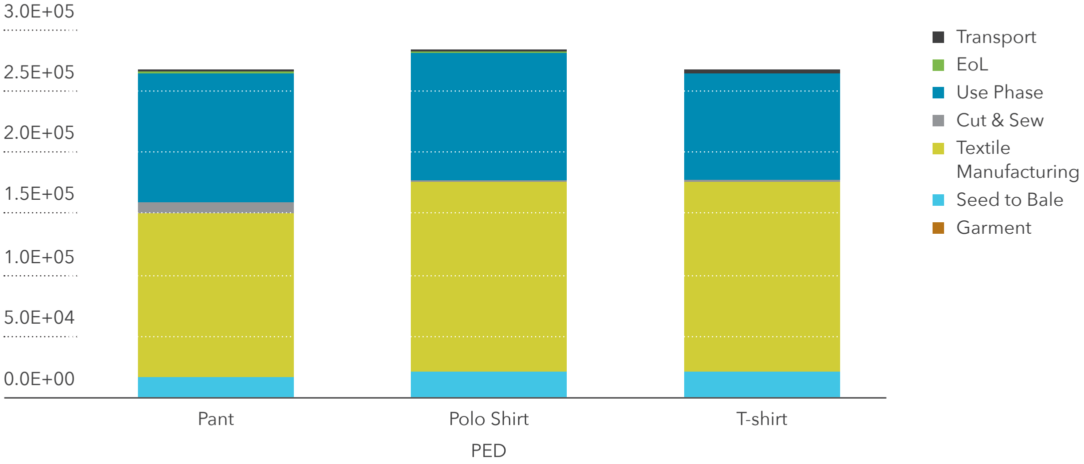
FIGURE 4-37: Acidification potential by post production phase [kg SO2-Equiv.1000 kg cotton garment].



### 4.3.3.4 Primary Energy Demand

The primary energy demand (PED) for the post production phases are dominated by the use phase, Figure 4-38. The energy used throughout the post production phases is a primary contributor to many of the other measured impact categories. Of the post production processes, the use phase contributes 98% to the collared casual shirt and t-shirts and the woven pants use phase contributed 92% to the total. The cut-and-sew phase for the pants resulted in higher PED than the shirts, in part due to different energy grids modeled based on textile manufacturing location. The primary energy demand for the use phase is also highly dependent on the energy grid used, which creates regional variations.

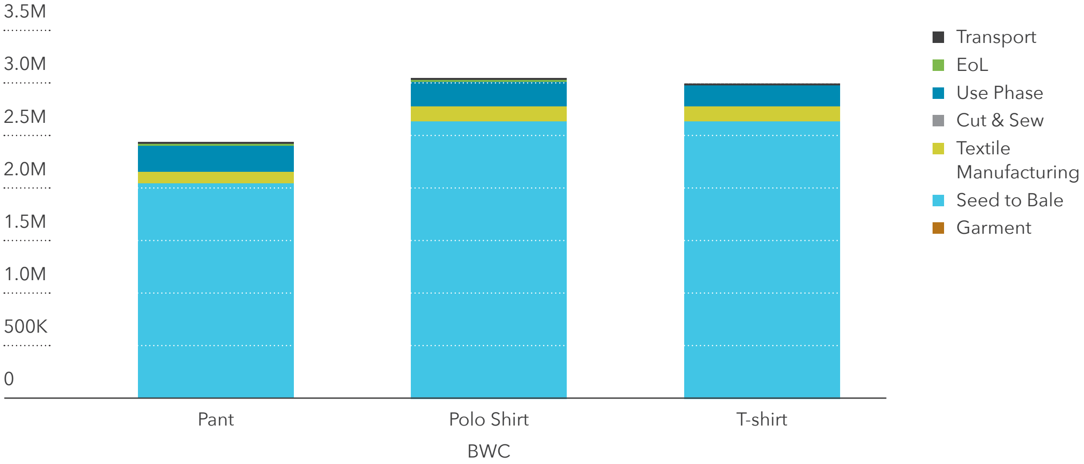
FIGURE 4-38: Primary energy demand by post production phase [MJ /1000 kg of cotton garment].



### 4.3.3.5 Blue Water Consumption

The blue water consumption (BWC) for post-production processes was dominated by the use phase, as seen in Figure 4-39. The water evaporated from the garments during clothes drying and the water consumed during energy production processes are divers of the BWC impact. In total, the use phase contributes 98% to the overall BWC.

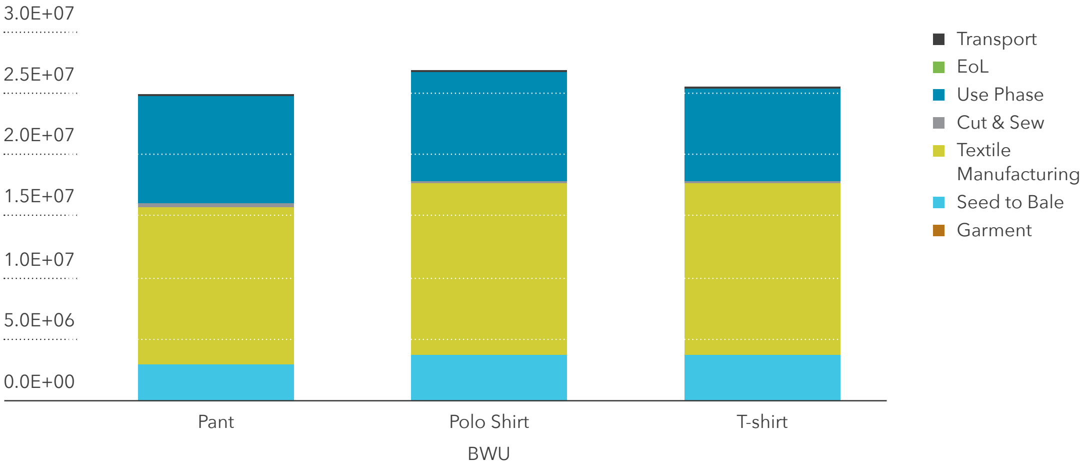
FIGURE 4-39: Blue water consumption by post production phase [kg /1000 kg of cotton garment].



### **4.3.3.6** Blue Water Use

The blue water use (BWU) for post-production processes was also dominated by the use phase, as shown in Figure 4-40. The BWU measures the water that is used in processes that is later returned to the same watershed as it was sourced. The BWU within the use phase results primarily from water used in energy production required for laundering and water used in laundering that is returned to the watershed. Of the post production phases, the use phase contributed 98% to the total BWU. The energy use associated with cut-and-sew process contributed 1-2% to the BWU.

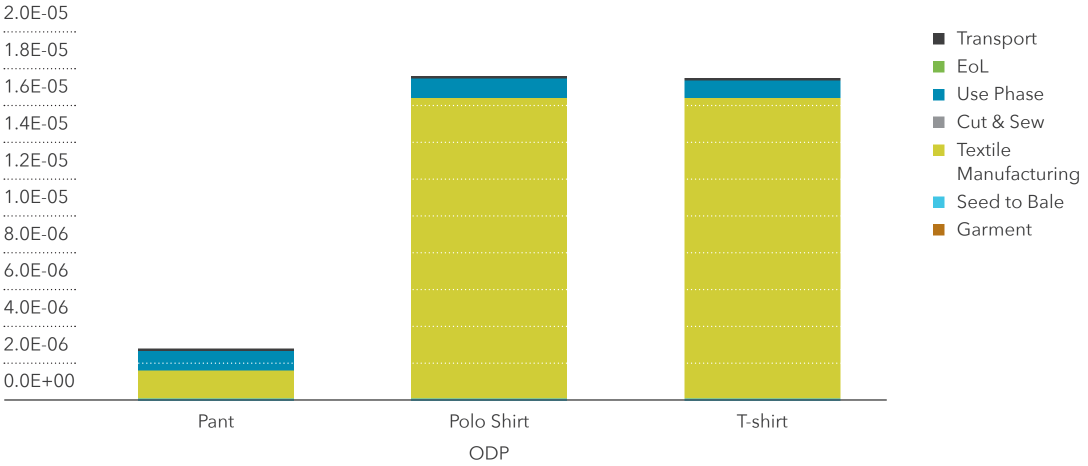
FIGURE 4-40: Blue water use by post production phase [kg /1000 kg of cotton garment].



### **4.3.3.7** Ozone Layer Depletion Potential

The ozone layer depletion potential (ODP) post production impacts are driven by the use phase, Figure 4-41. The ODP impacts are generated by electricity production processes that are required for the use phase and cut-and-sew processes. The use phase contributes 98% to the total ODP with the cut-and-sew process making up the balance.

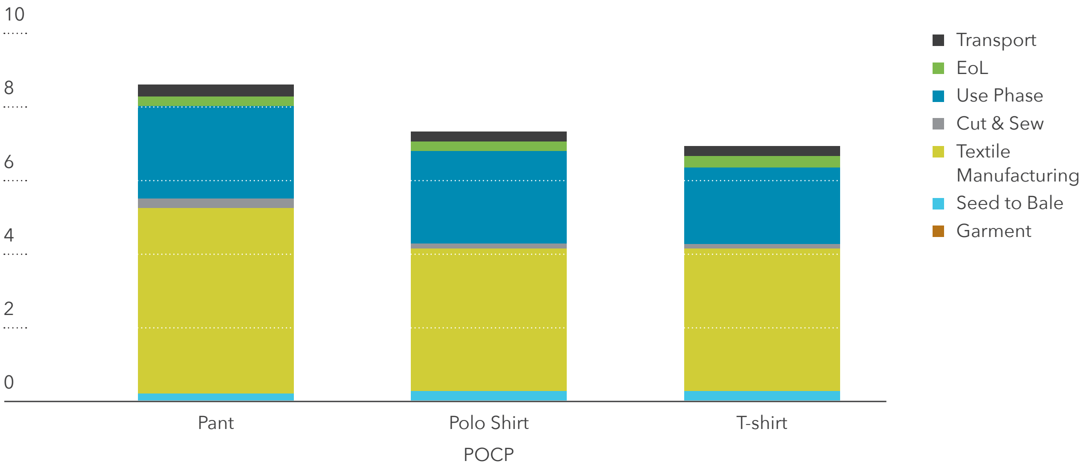
FIGURE 4-41: Ozone layer depletion potential by post production phase [kg R11 eq./1000 kg cotton garment].



#### 4.3.3.8 Photochemical Ozone Creation Potential

The photochemical ozone creation potential (POCP) post production impacts are driven by the use phase, Figure 4-42. The POCP impacts are generated by electricity production processes that are required for both the use phase and cut-and-sew processes. The use phase contributes 84% to the total for the three garments. The cut-and-sew POCP was higher for the pants due to different use of electrical grids. Emissions from cotton decomposition in the landfill also contributed to the POCP impacts, accounting for approximately 10% of the total POCP.

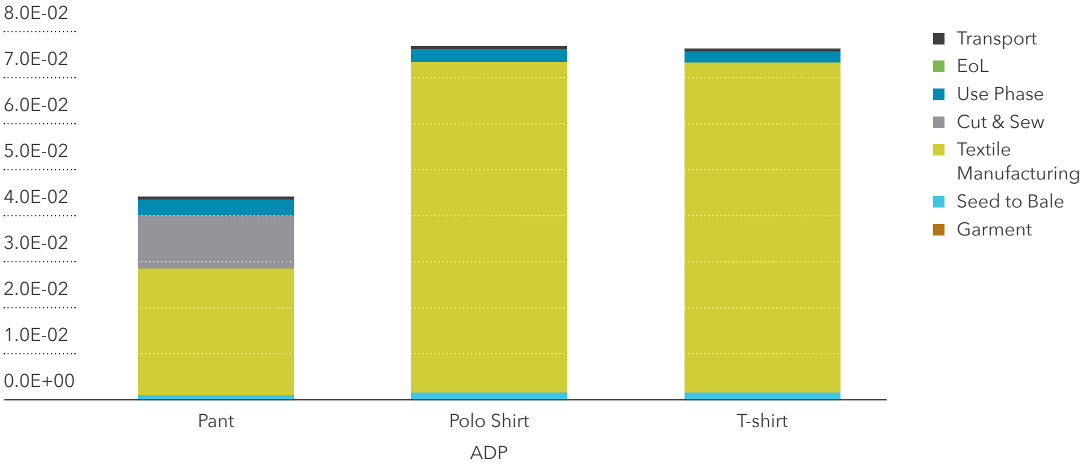
FIGURE 4-42: Photochemical ozone creation potential by post production phase [kg C2H4 eq./1000 kg cotton garment].



#### 4.3.3.9 Abiotic Depletion

The abiotic depletion potential (ADP) was dominated by the use phase for the collared casual shirt and T-shirt, however, the cut-and-sew process dominated the ADP for the pants, Figure 4 43. The ADP for the woven pants was around five times higher than the ADP for the shirts. This major difference stems from the use of a brass zipper in the pants. Extraction (mining) of metals depletes resources and has a larger impact than plastics for buttons, which is the only trim used in cut-and-sew for the shirt. For the collared casual shirt and T-shirt, the use phase ADP accounted for 99% of the overall impact. The use phase ADP for woven pants, however, contributed only 20% while the cut-and-sew process contributed 80% to the ADP.

FIGURE 4-43: Abiotic depletion potential by post production phase [kg Sb-Equiv./1000 kg cotton garment].



### 4.3.3.10 Toxicity

The As with the other phases of this study, detailed results on the toxicity metrics are not provided due to the high uncertainty associated with the methodology, but the predicted distribution of toxicity impacts with within the use phase follows. The ecotoxicity (ET) impacts were again dominated by the use phase. The shirts use phase contributed 99% to the ET and relates to the energy used during laundering. The woven pants ET use phase contributed 96% to the pant total with 4% stemming from the cut and sew process. The differences in the woven pants and shirts ET results from the different cut and sew locations and thus different energy grids used. It should be noted that there is great uncertainty around the ET and other toxicity measures used in this study. This high level of uncertainty is common among all toxicity measures using UseTox. Due to this uncertainty, these results should be used for hot spot analysis but not to compare to other studies.

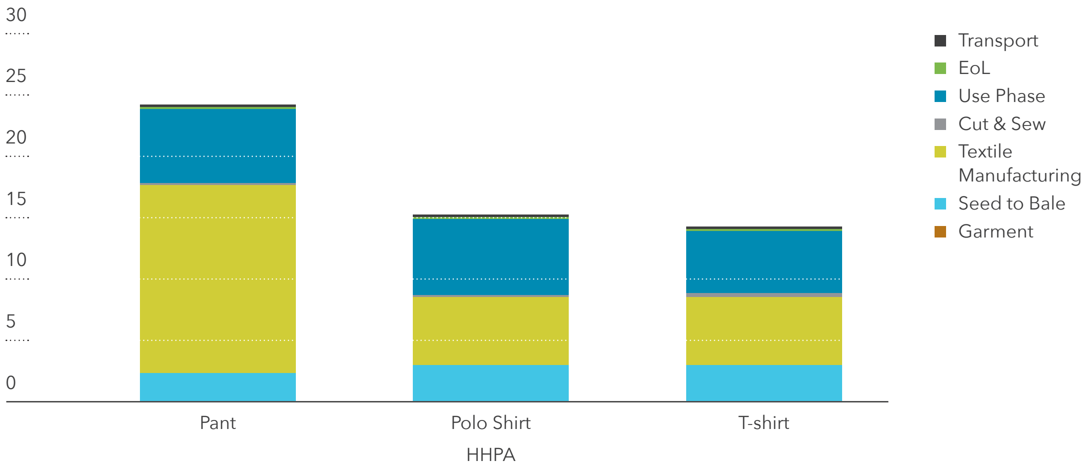
The human toxicity cancer (HTC) impacts were also dominated by the use phase,. The shirt use phase contributed 92% to the HTC and the woven pant use phase contributed 74% to the HTC. The cut and sew phase contributed more to the woven pant due to the different energy grid used in that process. The EOL contributed on average 6% to the total HTC. The HTC impacts are primarily generated by electricity production and thus track with the product systems energy requirements.

The human toxicity non-cancer (HTNC) impacts were similar to the other toxicity measures with the majority of the HTNC impacts resulting from the use phase. The HTNC impacts are primarily associated with energy use involved in the laundering process. The woven pant cut and sew process has a higher HTNC impact due to a different energy grid used for that process.

### 4.3.3.11 Human Health Particulate Air

The human health particulate air (HHPA) impacts were dominated by the use phase for each garment, Figure 4-44. The use phase contributed 94% to the overall HHPA impacts for the garments. HHPA impacts are primarily associated with energy production to meet the laundering energy demand. The end-of-life (3%) and cut-and-sew (4%) process make up the remaining percentages.

FIGURE 4-44: Human health particulate air (HHPA) [kg PM2.5-Equiv.].



## 4.3.4 Limitations

Data describing the global consumer use phase varied greatly by region due to different regional laundering behaviors, laundering equipment efficiencies, and consumer use washing behavior. The consumer use data modeled in the use phase was collected through a comprehensive survey of consumers from the United States, Italy, Germany, the United Kingdom, China, and Japan. The choice to line/air dry or use a mechanical dryer heavily influenced the use phase impacts. Additionally, the use of hot water during washing required high levels electricity and increased the impacts associated with electricity production.

Despite the highly regionalized use phase characteristics, this LCA focused on the global averages. Table 4-12 provides the standard deviations for each impact category calculated based on the results from the six different countries. The standard deviations for the use phase were different for each garment. However, the use phase standard deviation was the same for the end-of-life phase for each garment type. The cut-and-sew data was not modeled for each of the six countries, rather it was modeled with an average cut-and-sew operation and thus no standard deviation was calculated. Consistently for all the use phase scenarios, the HTC and ET had the highest standard deviation of over 100% of the average value. When considering all impact categories for each garment, the average standard deviation as a percent of the average value is 84%, 76%, and 83% for the t-shirt, collared casual shirt, and woven pants, respectively. For the end-of-life, the average standard deviation as a percent of the total was 39%.

TABLE 4-11: Use phase standard deviations for garment use and EoL.

| | Woven Pants | Collared Casual Shirt | T-shirt | All |
|---|---|---|---|---|
| | Use | Use | Use | EoL |
| **BWC** | 217,463 | 189,809 | 202,250 | 1,572 |
| **PED** | 95,177 | 70,224 | 44,990 | 59 |
| **GWP** | 5,762 | 4,098 | 2,745 | 233 |
| **AP** | 19 | 16 | 11 | 1 |
| **HHPA** | 1.88 | 4.10 | 3.88 | 0.06 |
| **EP** | 1.80 | 1.84 | 1.75 | 0.92 |
| **POCP** | 1.11 | 0.87 | 0.57 | 0.19 |
| **ADP** | 1.93E-03 | 1.52E-03 | 9.13E-04 | 5.21E-06 |

TABLE 4-12: Standard deviations as percentage of total impacts for each garment type (data organized highest to lowest % for the woven pants use phase).

| | Woven Pants | Collared Casual Shirt | T-shirt | All |
|---|---|---|---|---|
| | Use | Use | Use | EoL |
| **AP** | 100% | 82% | 68% | 70% |
| **PED** | 90% | 67% | 51% | 8% |
| **BWC** | 87% | 79% | 103% | 71% |
| **GWP** | 70% | 50% | 40% | 14% |
| **ADP** | 65% | 53% | 39% | 28% |
| **POCP** | 43% | 34% | 27% | 66% |
| **EP** | 42% | 44% | 51% | 62% |
| **HHPA** | 31% | 67% | 75% | 36% |

### **4.3.5** Conclusions

- The use phase dominated the post production process impacts and were sensitive to the number of washes per garment first life.
- There was little to no difference in the impact categories for the knit shirts and woven pants, with the exception of abiotic depletion associated with cut-and-sew for woven pants.
- Use phase impacts had high levels of uncertainty based on regional use modeling. This suggests that where the product is used highly influences the use phase impacts due to regional laundering behaviors and regional energy grids.
- Within the use phase parameters, the most important variable that consumers can influence is the drying method used. Air drying clothing reduces energy use and lowers the overall impacts of the consumer use phase. The other important choices consumers can make to reduce environmental impacts are to avoid small laundering loads and to use cold wash water when possible.

## 4.4 CRADLE-TO-GRAVE IMPACTS

This section contains Life Cycle Inventory Assessment (LCIA) results pertinent to all phases of the cotton life cycle, from cradle-to-grave. Detailed results specific to each life cycle phase are reported in the cotton fiber production, textile manufacturing, and use phase sections of this report.

Global average LCIA results for 1,000 kg t-shirts, 1,000 kg of collared casual shirts, and 1,000 kg of woven pants are shown in Table 4-13. It should be noted that this LCA is not a comparative LCA between the three different garments, rather this analysis provides useful data and identifies hotspots within the garment life cradle-to-grave life cycle.

TABLE 4-13: Global average LCIA results for t-shirt, collared casual shirt, and woven pants.

| Impact | Units per 1,000 kg of garment | T-Shirt | Collared Casual Shirt | Woven Pants |
|---|---|---|---|---|
| **GWP** | [kg CO2-Equiv.] | 18,885 | 20,234 | 21,156 |
| **PED** | [MJ] | 266,663 | 284,099 | 267,226 |
| **AP** | [kg SO2-Equiv.] | 131.7 | 134.6 | 139.3 |
| **EP** | [kg Phosphate-Equiv.] | 26.1 | 26.8 | 21.3 |
| **ODP** | [kg R11-Equiv.] | 1.73E-05 | 1.75E-05 | 2.70E-06 |
| **POCP** | [kg Ethene-Equiv.] | 6.93 | 7.35 | 8.59 |
| **BWC** | [kg] | 2,981,350 | 3,027,711 | 2,419,607 |
| **BWU** | [kg] | 25,442,811 | 26,845,721 | 24,834,227 |
| **HHPA** | [kg PM2,5-Equiv.] | 14.34 | 15.29 | 24.28 |
| **ADP** | [kg Sb-Equiv.] | 7.57E-02 | 7.63E-02 | 4.34E-02 |

The relative contribution of each phase (agricultural production, textile manufacturing, cut-and-sew, use and disposal) of the cradle-to-grave life cycle of cotton knit and woven fabric is shown in Table 4-14. The results were modeled using global average consumer use data. The life cycle phases were defined as follows:

1. **Agricultural production:** Crop growth and cultivation, including ginning.
2. **Textile manufacturing:** Yarn prep, knitting or weaving, dyeing, and finishing fiber into fabric.
3. **Post production:** cut-and-sew, consumer use, disposal: Average garment creation, average use scenario (washing and drying), and average disposal (split between landfill and cutoff subsequent lives).
4. **Transportation:** Average transportation occuring across the product life cycle.

TABLE 4-14: Relative contribution to each impact category by garment.

| | T-Shirt | | | | Collared Casual Shirt | | | | Woven Pants | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Seed to Bale | Textile Manufacturing | Cut/Sew, Use, Disposal | Transport | Seed to Bale | Textile Manufacturing | Cut/Sew, Use, Disposal | Transport | Seed to Bale | Textile Manufacturing | Cut/Sew, Use, Disposal | Transport |
| **GWP** | -1% | 54% | 46% | 1% | -1% | 50% | 50% | 1% | -1% | 51% | 49% | 1% |
| **PED** | 8% | 58% | 33% | 1% | 8% | 54% | 37% | 1% | 6% | 50% | 43% | 1% |
| **AP** | 34% | 50% | 13% | 4% | 33% | 49% | 14% | 3% | 25% | 58% | 14% | 3% |
| **EP** | 51% | 27% | 20% | 2% | 49% | 27% | 22% | 2% | 48% | 21% | 28% | 2% |
| **ODP** | 0% | 94% | 5% | 0% | 0% | 93% | 6% | 0% | 2% | 58% | 40% | 0% |
| **POCP** | 4% | 56% | 36% | 4% | 4% | 53% | 39% | 4% | 2% | 59% | 36% | 3% |
| **BWC** | 89% | 5% | 7% | 0% | 87% | 5% | 8% | 0% | 85% | 5% | 11% | 0% |
| **BWU** | 15% | 55% | 30% | 0% | 14% | 52% | 34% | 0% | 12% | 52% | 36% | 0% |
| **HHPA** | 21% | 39% | 38% | 2% | 20% | 36% | 42% | 2% | 10% | 63% | 26% | 1% |
| **ADP** | 2% | 95% | 3% | 0% | 2% | 94% | 4% | 0% | 3% | 64% | 34% | 0% |

When the entire cotton life cycle is considered, the textile manufacturing and consumer use phases dominated most of the impact categories, see Figure 4-45, Figure 4-46 and Figure 4-47. This is due primarily to garment laundering and high electricity use in fiber processing and energy expenditures related to conditioning, processing, heating, and eventual drying of water during the preparation, dyeing, and finishing processes. Although agricultural production's contribution to total impact was lower than the consumer use and textile manufacturing phases in most categories, water consumption, eutrophication, acidification, field emissions associated with nitrogen fertilizer, irrigation, and ginning were identified as major contributors to overall impact.

FIGURE 4-45: Relative contribution to each impact category for knit t-shirt.

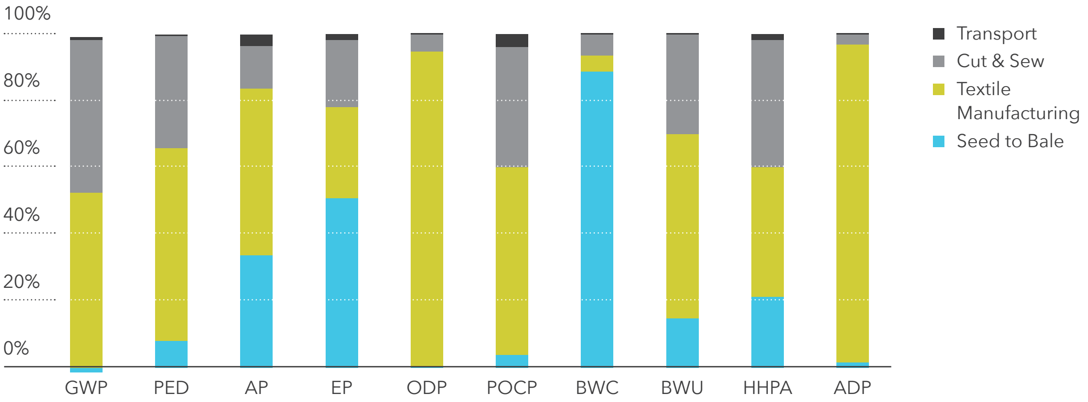


FIGURE 4-46: Relative contribution to each impact category for knit collared casual shirt.

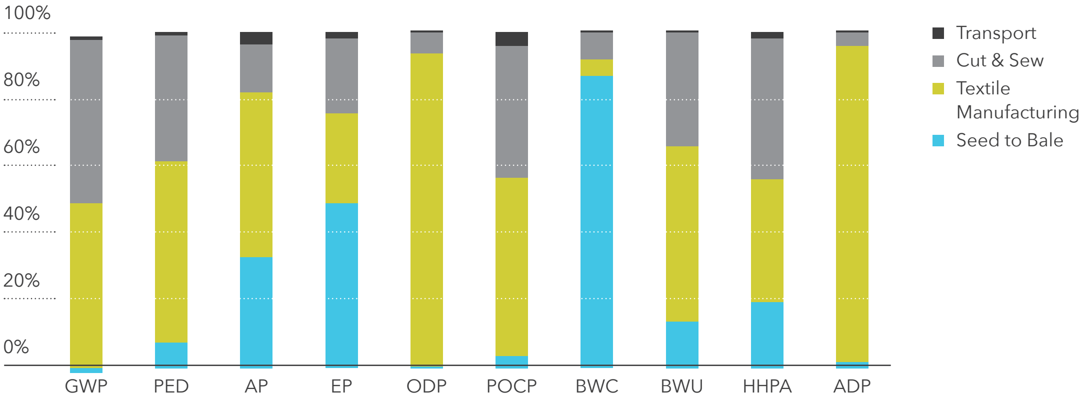
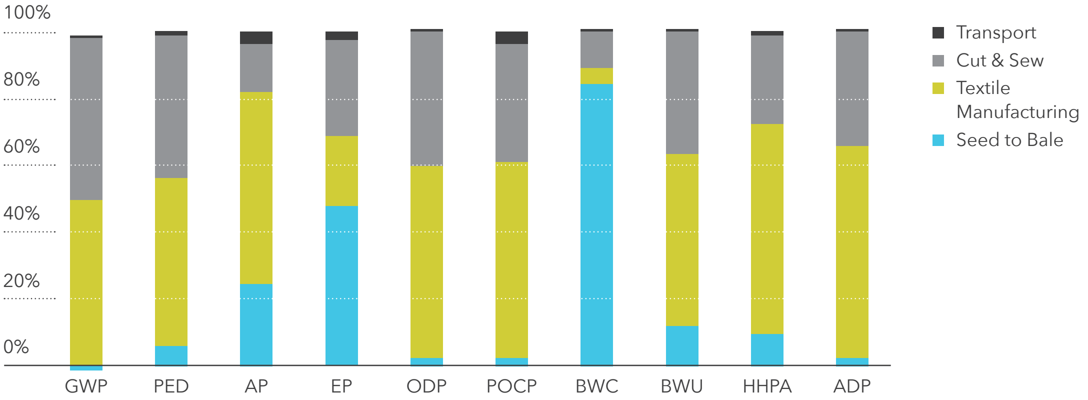


FIGURE 4-47: Relative contribution to each impact category for woven pant.



## Conclusions: Cotton Life Cycle (Cradle-to-Grave)

- The textile manufacturing was the largest contributor to all impact categories modeled except blue water consumption and eutrophication potential. Textile plant wastewater emissions, upstream production of energy, and process chemicals drive eutrophication, acidification potential, and the toxicity measures. Yarn spinning was the main contributor for global warming potential, acidification potential, photochemical ozone creation potential, human health particulate air emissions, blue water use, and primary energy demand due to the energy intensive yarn production process. Energy for conditioning, processing, heating, and eventual drying fabric in the preparation and dyeing processes was also a significant contributor within the textile manufacturing life cycle stage.
- Consumer use phase contributed the most to global warming potential, primary energy demand, photo chemical ozone creation, human health particulate air, and blue water use. The consumer use phase including laundering contributed more towards all the impact categories than the cut-and-sew and end-of-life processes, except for the abiotic depletion potential within the woven pants scenario. The results were very sensitive to assumptions since the number of lifetime washings and the impacts of those launderings can vary widely in practice and by region. Since this data was a global average, there is high degree of variability within the use parameters.

- It is important to note that compared to East Asia, Eurasia, Latin America, and South/Central Asia, the emissions profile of U.S. electricity has considerably less AP, EP, GWP, and POCP per kWh. Since the textile manufacturing data in this study was derived from countries other than the United States, the burdens from energy-intense textile processes drove up these impact categories compared to the use phase, which was modeled with energy grids from the six studied countries.
- With the exception of water consumed and eutrophication potential, agricultural production's contribution to total impact was lower than textile manufacturing in all of the categories evaluated. However, field emissions and fertilizer production were major contributors to several environmental impact categories: eutrophication potential was strongly influenced by nitrate, acidification potential was influenced by ammonia, global warming potential was influenced by nitrous oxide, and toxicity impacts were influenced by pesticides and herbicides applied in the field. The ginning process and energy required for irrigation played a role in primary energy demand.
- Despite a high uncertainty of toxicity effects in ecotoxicity potential and human toxicity potential impact categories, it is evident that textile manufacturing process chemicals and associated upstream emissions are the primary contributor. Although the USEtox™ model is currently the most precise LCA model for evaluating toxicity, there are still wide ranges in uncertainty around the actual effects of the compounds contributing to the toxicity measures. Thus, interpretation of the toxicity potential indices is challenging and the findings of this study are meaningful only for identifying compounds of concern.
- Carbon sequestered during the growth of cotton is modeled as a CO2 emission at end-of-life, even though garments won't necessarily be thrown away after their first useful life. The reuse and recycle of garments can hold carbon for a number of years and could potentially hold carbon beyond the temporal scope of this study of 100 years. When carbon is locked up in products for periods longer than 100 years, the end-of-life emissions are often emitted as they are considered outside of the study scope. Furthermore, there is a growing understanding of the value of temporary carbon storage that when considered could also influence the results by lowering the global warming potential over a set time period.
- Continued improvement in the cotton garment production system should focus on several areas within the supply chain. For water consumption and eutrophication, cotton irrigation and fertilizer use within the cotton cultivation process are key parameters which should be further optimized. The textile manufacturing phase contributed the most to all but two impact categories due to high energy usage and use of various process chemicals. Textile manufacturing optimization should focus on energy efficiency, use of cleaner energy sources, and using more environmentally friendly process chemicals and processes to create finished fabric. The use phase also contributed significantly to most impact categories. Use phase impacts are dominated by consumer use due to laundering. Use phase impact reduction can be made through the change of laundering behavior by switching from machine drying to line drying, using cold wash water with appropriate detergents, and using more efficient washing machines.

# 5

# INTERPRETATION

## 5.1 IDENTIFICATION OF RELEVANT FINDINGS

- The textile manufacturing was the largest contributor to all impact categories modeled except blue water consumption and eutrophication potential.
- With the exception of water consumed and eutrophication potential, agricultural production's contributions to total impacts were lower than textile manufacturing in all of the categories evaluated.
- Despite a high uncertainty of toxicity effects in ecotoxicity and human toxicity potential impact categories it is evident that textile manufacturing process chemicals and associated upstream emissions are the primary contributor.
- Consumer use phase impacts are highly dependent on laundering practices such as choice to use line drying or machine drying, as well as the number of launderings per product lifetime.
- The leading source of negative impacts across several metrics by phase were:
  - **Agriculture production:** Nitrogen and water use
  - **Textile manufacturing:** Energy in yarn creation; chemical use in dyeing and finishing
  - **Consumer use:** Mechanical dryer use

## 5.2 ASSUMPTIONS AND LIMITATIONS

Overall the data and models used in this study are considered sufficient to obtain a reasonable global mean for a majority of the impact metrics considered across the three primary life cycle phases evaluated. In the agricultural production phase the highest uncertainty in data was around India, including the actual amount of manure use to supplement synthetic fertilizer applications, and agricultural chemical use in China. Also, several assumptions were necessary in order to estimate pesticide emissions factors from the EPIC simulations. For the textile phase, a limited number of textile mills could be sampled and there are not extensive public databases on textile production practices as can be found for agriculture. Primary data for cut-and-sew was not obtained and secondary data was used.

## 5.3 RESULTS OF SENSITIVITY, SCENARIO, AND UNCERTAINTY ANALYSIS

### 5.3.1 Sensitivity Analysis

Sensitivity analyses were performed to test the influence of parameter values that are based on assumptions or otherwise uncertain on the overall cradle-to-grave results. This study performed a sensitivity analysis on attributes from each of the three major process stages of seed to bale, garment manufacturing, and use & end-of-life, Figure 5-1 and Figure 5-2. The sensitivity analysis was only performed with the knit t-shirts and woven pants scenarios, as the collared shirt scenario is nearly identical to the t-shirt. The results from this analysis aim to provide insight into how uncertainty and modeling assumptions influence the overall cradle-to-grave results.

FIGURE 5-1: Cradle-to-grave sensitivity analysis results for t-shirts and collared shirts (abbreviations for the impact categories on the x-axis are provided in Table 2-2 and 2-3).

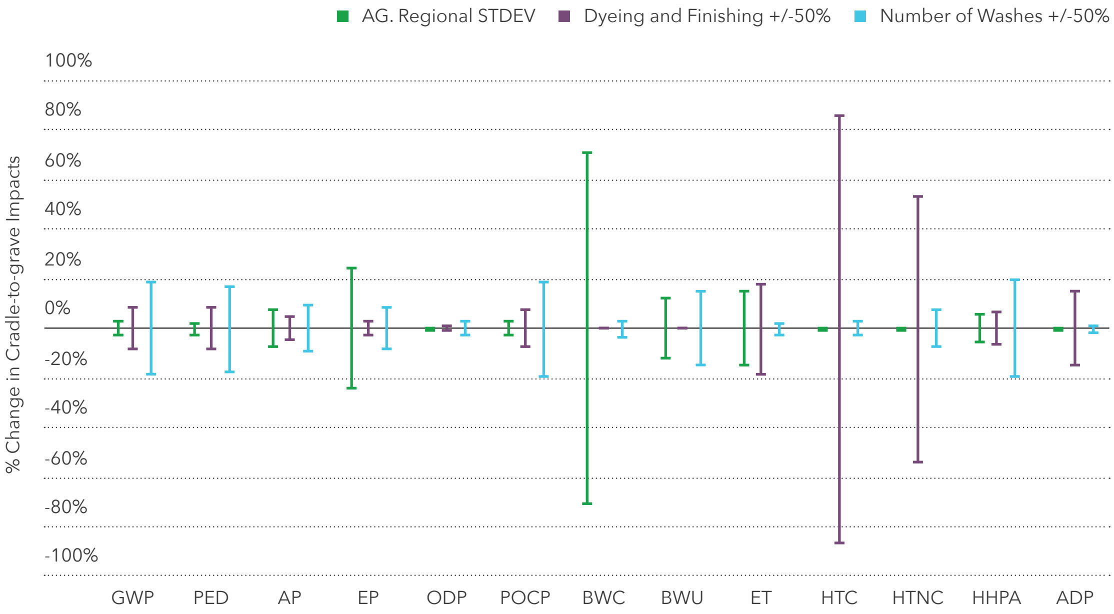
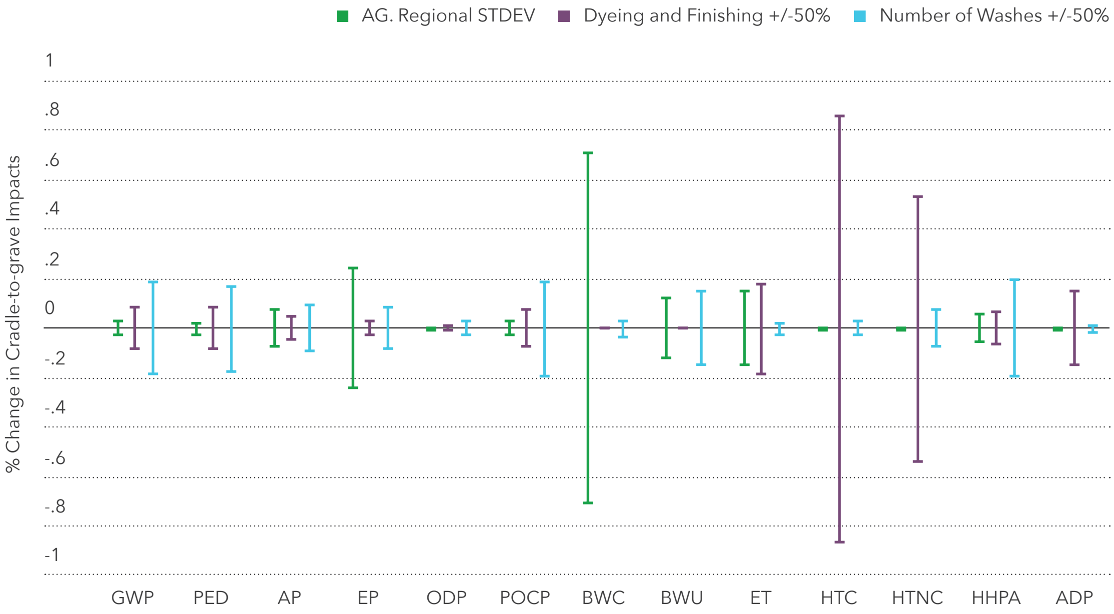


FIGURE 5-2: Cradle-to-grave sensitivity analysis results for woven pants (abbreviations for the impact categories on the x-axis are provided in Table 2-2 and 2-3).



#### **5.3.1.1** Agriculture

To examine the how the growing region influences the overall cradle-to-grave results, the regional impact standard deviations (STDEV) were used to adjust the seed to bale impacts. These results are shown in Figure 5-1 and Figure 5-2 where the adjusted cradle-to-grave value (global average +/- STDEV) is divided by the "base case" non-adjusted value and shown as a percentage [(impact global average +/- impact STDEV)/( impact global average)]. The sensitivity analysis incorporating regional agricultural impacts show that water consumption impacts are highly dependent on growing region. Using one standard deviation adjustment from the global t-shirt average, the cradle-to-grave water use would increase or decrease by 71%. The seed to bale eutrophication potential (EP) impacts were also dependent upon the growing region and adjusting these impacts by one STDEV influenced the cradle-to-grave EP impacts by 24%. Due to regional pest and weed pressures as well as growing practices, the ecotoxicity (ET) impacts were also influence by the region. The cradle-to-grave ET impacts were increased or decreased by 15% when the results were adjusted by one STDEV. The influence of the seed to bale phase on the other cradle-to-grave results were lower than 13% of the overall impacts and are shown in Figure 5-1. When examining the influence regional impacts of cotton growing on the woven pants, nearly identical trends were observed, Figure 5-2. The only difference in the agricultural sensitivity results stem from minor differences in losses when making the final garments.

#### **5.3.1.2** Textile Manufacturing

For the knit shirts, the textile manufacturing stage sensitivity examined the influence of increasing the batch dying and knit finishing impacts by 50% and lowering them by 50%. These two processes were used as a sensitivity due to the relatively high impacts associated with these processes and lower primary data quality. For the woven pants, the woven preparation and dyeing steps were chosen as they represented the hotspots for the woven pants. The woven processes impacts were also increased and decreased by 50% to determine the influence of these processes on the overall results.

Increasing and decreasing the knit dyeing and finishing impacts had the greatest influence on the toxicity measures of HTC, HTNC, and ET, Figure 5-1. The cradle-to-grave HTC impacts increased or decreased by 86% when this sensitivity analysis was performed. The HTNC and ET cradle-to-grave impacts changed by 54% and 18%, respectively. Another impact category showing a relatively high sensitivity to the dyeing and finishing stages was the ADP where it changed by 15%. The other impact categories all showed less than 10% change while performing the sensitivity analysis.

The woven pants sensitivity that increased and decreased the fabric prep and dyeing impacts also influenced the cradle-to-grave toxicity measures the most, Figure 5-2. The HTC, HTNC, and ET impacts changed by 34%, 34%, and 26% respectively when the sensitivity analysis was performed. The cradle-to-grave ADP was also highly influenced by these processes and showed a change of 30%. The cradle-to-grave primary energy demand showed a 10% change. The other impact categories all changed less than 10% and were not highly sensitivity to the woven preparation and dyeing processes.

#### **5.3.1.3** Use phase

Consumer use behaviors surrounding the laundering habits are a major driver of overall garment environmental impacts. The number of times an individual launders their garment over the garment life time plays a significant role in the use phase impacts. Since number of total launderings can vary drastically by the user and also more generally by country, a sensitivity was performed on the total number of garment launderings. The number of total launderings during the garments life was increased and decreased by 50% to determine the influence of the use phase impacts on the total cradle-to-grave impact results. The influence of the laundering habits on the cradle-to-grave results, as seen in Figure 5-1 and Figure 5-2, were similar for both the knit shirts and the woven pants and the results are discussed without specific mention to either garment type, except for the ODP impacts which are discussed separately.

The laundering process requires a considerable amount of energy inputs and increasing or decreasing this energy requirement influences several impact categories that are primarily associated with energy use. The PED, GWP, POCP, and the HPA cradle-to-grave impacts were the most sensitive to the use phase laundering and changed by 17%, 19%, 19%, and 20%, respectively. These impact categories are also highly dependent on the energy grid mix of the location of use, where the use phase would be less influential in countries with cleaner energy production systems and more influential in countries with more polluting energy production systems. Cradle-to-grave blue water use was also sensitive to the number of launderings as each laundering cycle uses a significant amount of water and the cradle-to-grave blue water use changed by 15% with the sensitivity analysis. The influence of the use phase on the cradle-to-grave ODP was notably different for the knit and woven garments. The ODP impacts for the knit garments were an order of magnitude higher than those of the woven garment. As such, any change in due to the use phase influences the knit cradle-to-grave impacts less than the woven pants. For the knit shirts, the use phase perturbation influenced the ODP by only 3% and influenced the woven cradle-to-grave OPD impacts by 19%. The other impact categories were influenced by as little as 3% (BWC) and up to 12% (EP).

### **5.3.2** Scenario Analysis

Scenario analysis was performed to compare results between different sets of assumptions or modeling choices. For this analysis, the garments were assumed to be disposed of after the first life of use. In reality, many garments go on to have additional “lives” through donations to thrift stores and reuse or as down cycled products such as rags or insulation. When examining the cradle-to-grave impacts without the burden associated with the EoL, the t-shirt cradle-to-grave impacts for GWP and EP are most influenced and decrease by 11% and 5%, respectively. Removing the EoL impacts reduced the other impact categories 1% or less. The woven pants and collared shirt exhibited similar reductions in cradle-to-grave impacts when the EoL impacts were removed.

Something not considered in this scenario analysis is the potential burden offset as the material is reused or recycled. In theory, when a recycled material is used a new material is not produced creating a potential environmental savings. This type of environmental burden offset is not considered herein, however, could in some scenarios be significant. An alternative method to address the multiple lives of the garments is to allocate some portion of the cotton growth and textile manufacturing phase impacts to the additional product life times. Allocation of these impacts to additional product life times would reduce the impacts of the first life as examined in this report.

### **5.3.3** Uncertainty Analysis

With all life cycle assessment studies, there is a significant amount of uncertainty within the results that can stem from several different causes. Data uncertainty is commonly explored through a Monte Carlo uncertainty analysis which can provide a range of results describing the environmental impacts. A Monte Carlo uncertainty analysis was not performed for this study. However, within each of the life cycle stages sections the variability and uncertainty surrounding the data was explored. For agriculture, there was much variability on water consumption as some fields are irrigated while others are not. Standard deviations of the regional responses were provided for this and other impacts associated with cotton cultivation. As a way to show the influence of these regional differences and uncertainty, the sensitivity analysis examined how the cradle-to-grave results were influenced by adjusting the seed to bale impacts by one standard deviation.

Another area which is inherently uncertain is the number of launderings a garment experiences in the first life. Laundering behavior data was collected through surveys with over 4,000 responses. From these responses, averages were calculated and used for this study. The actual impact which would occur in real life is highly dependent on the user’s behavior surrounding the washing and drying methods and also how many launderings occur before the end of the garment’s first life. The influence of the number of washes during the garments first life was also explored within the sensitivity analysis and showed that impacts relating to energy usage were the most influenced by laundering behavior.

## 5.4 DATA QUALITY ASSESSMENT

Primary agricultural data were validated with mass balance checks and consistency of energy use and emissions generated for similar processes. Nitrogen balances were set up by taking as much soil, dry and wet nitrogen precipitation, and organic and chemical direct and indirect fertilizer data as possible into consideration. Surplus or deficit nitrogen rates were compensated by a balancing tool within the cultivation model. Sensitive data, (e.g., pesticide application rates) were tested using sensitivity analysis. Finally data were compared with existing Life Cycle Assessment studies of cotton fibers (e.g., Grace, 2009; and Levi's 501 Jean Study at: http://www.levistrauss.com/sustainability/product/life-cycle-jean).

Primary textile manufacturing data were collected from mills around the world. At each unit process, the inputs and outputs were normalized to comparable units, i.e. kg/1,000 kg intermediate output. Normalizing the input data to a 1,000 kg output provided for easier comparison across the mills who reported data for each process. Technical and feasibility checks were also performed by PE International and Cotton Incorporated experts. Outlying data points were confirmed or corrected with the mills if possible.

Internal quality assurance (QA) was applied at different stages of the project. The objective of the QA process was to ensure that the data collection, the development of the LCI model, and the final results are consistent with the scope of the study, and that the study delivers the required information. The QA included a check of the LCI datasets used, general model structure, results applicability, and report documentation. Inventory data quality is judged by its precision (measured, calculated, or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied), and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi 2016 database were used. The LCI datasets from the GaBi 2016 database are widely distributed and used with the GaBi 6 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal, as well as in many critically reviewed and published, studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

### 5.4.1 Precision and Completeness

- **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high. Seasonal variations/variations across different manufacturers were balanced out by using yearly averages/weighted averages. All background data are sourced from GaBi databases with the documented precision.
- **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data are considered to be high. All background data are sourced from GaBi databases with the documented completeness.

### 5.4.2 Consistency and Reproducibility

- **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases.
- **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modeling approaches.

### 5.4.3 Representativeness

- **Temporal:** All primary data were collected for the year 2014. All secondary data come from the GaBi 2016 databases and are representative of the years 2010-2013. As the study intended to compare the product systems for the reference year 2014, temporal representativeness is considered to be high.
- **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- **Technological:** All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

## 5.5 MODEL COMPLETENESS AND CONSISTENCY

### 5.5.1 Completeness

All relevant process steps for each product system were considered and modeled to represent each specific situation. Data collection for cotton cultivation, textile manufacturing, and use phases was taken from representative samples of cotton growers, industry, and users. In the textile manufacturing phase, however, some proxies' process chemicals were used as the process chemicals did not yet exist in the GaBi database. The use of these proxies would not likely influence the overall results heavily, but could have some influence on the toxicity measure for the textile manufacturing stage.

Overall, the process chain and corresponding data is considered sufficiently complete and detailed with regard to the goal and scope of this study.

### 5.5.2 Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by predominantly using LCI data from the GaBi 2016 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

## 5.6 CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS

### 5.6.1 Conclusions

When considering the three primary life cycle phases (agricultural production, textile manufacturing, and product use), textile manufacturing was often the largest contributor to the impact categories considered. Textile plant wastewater emissions, upstream production of energy, and process chemicals were major sources for these impacts as was the energy use in yarn manufacturing. The agricultural phase also had significant impacts on eutrophication and blue water consumption. Sources for these impacts were primarily related to nitrogen fertilizer and irrigation water use. While the use phase did not have the great impact on any single metric, it closely followed the textile manufacturing section on several metrics. The consumer use phase was very sensitive to the number of launderings and indirectly the number of launderings can be related to garment life. That is, a garment that is well constructed and has a long life is more likely to have a greater number of launderings and would increase the impact of the use phase. Thus lowering the impact of the use phase by decreasing the useful life of a garment would not have the desired positive impact on the environment.

### 5.6.2 Limitations

This study represents global average practices associated with the life cycle of typical cotton apparel products. While it can provide some context to comparison to other studies, it represents global average conditions, and as such, cannot be used to infer the impact of a new practice unless evaluated in the same global context. For example, the agricultural data is very sensitive to the regional climate—therefore, if the data to evaluate the impact of changing an agricultural practice is not collected in same global context, the data from this study cannot be used to make claims about the impact of that practice. Similarly for textile and consumer data, the difference in an energy grid in a specific country relative to the global average could overwhelm any difference in changes in a textile process or consumer behavior. Additional, this LCA has been focused on the environmental impacts and does not address social or economic aspects of a product’s raw materials, creation, and use.

### 5.6.3 Recommendations

Continued improvement in the cotton garment production system should focus on several areas within the supply chain. For water consumption and eutrophication, cotton irrigation and fertilizer use within the cotton cultivation process are key parameters which should be further optimized. The textile manufacturing phase contributed the most to all but two impact categories due to high energy usage and use of various process chemicals. Textile manufacturing optimization should focus on energy efficiency, use of cleaner energy sources, and use of more environmentally friendly process chemicals and processes to create finished fabric. The use phase also contributed significantly to most impact categories. Use phase impacts are dominated by consumer use due to laundering. Use phase impact reduction can be made through the change of laundering behavior by switching from machine drying to line drying, using cold wash water with appropriate detergents, and using more efficient washing machines.

# 6

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# 7

# ANNEXES

## **7.1** ANNEX A: CRITICAL REVIEW STATEMENT

## **7.3** ANNEX B: FIELDPRINT® CALCULATOR EXPRESS SURVEY FORM

Field to Market
The Keystone Alliance for Sustainable Agriculture

# Fieldprint Calculator – Express Survey

# Cotton Pilot

**Name:____________________Cell:____________________Email:_________________________**

*Welcome to the Field to Market Cotton Survey. Your feedback is very important to us! Please choose one cotton field that best represents typical yield, soils, and management practices on a particular farm in your operation.*

1. What is the production year for the data you are about to provide? ___________
2. Where is the field located?
    a. State: _____________________
    b. County or parish:____________
    c. Field location: Latitude: __ __ __ . __ __ __ __ Longitude __ __ __. __ __ __ __
    Optional: use this tool to pinpoint the center of the field http://www.latlong.net
    d. Field Size acres:____________
    e. Field Name:_________________________________
3. Are fertilizer application rates based on soil test recommendations? ___________
4. Please complete the following table providing the pounds (lbs) of applied Nitrogen, Phosphate and Potash as well as details related to their application. (This includes all applications on this field including pre-plant, at-planting and side-dress fertilizers.)

| | Total lbs/acre* | Number of Applications | Is the Rate Below, At, or Above Soil Test Recommendation? | Dominant Source ** | Dominant Application Method*** |
|---|---|---|---|---|---|
| Nitrogen - (N) | | | | | |
| Phosphate - ($P_2 0_5$) | | | | ■ | ■ |
| Potash - ($K_2 0$) | | | | ■ | ■ |

* Examples – 100 lbs Urea = 46 lbs of N, 28.2 gal UAN 32 = 100 lbs of N, and 100 lbs 0-0-60 = 60 lbs of $K_2 0$
** Examples – Dry Blend, Liquid Blend, Anhydrous Ammonia, Urea, and UAN 32
*** Examples – Injected, Broadcast, Broadcast and Incorporated, and Fertigation

5. Not including fertilizer applications through an irrigation system, how many trips (ground or air) were necessary to apply all fertilizer products? _______
6. What is the planting date? ________________________

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7. What is the primary tillage method used on this field? (Check one system and timing if applicable)

○ No-till/strip-till - The soil is left undisturbed from harvest to planting except for strips up to 1/3 of the row width (strips may involve only residue disturbance or may include soil disturbance).

○ Conservation Tillage including ridge-till, mulch-till, stale seedbed, or reduced till (approximately 15% to 30%) or more crop residue is left on the soil surface after planting.

Indicate number of trips (1, 2, 3…) and timing (fall or spring) for tillage operations:

| | Row Cleaners | Chisel | In-row Chisel | Disk | Field Cult. | Bed/ Hip/List | Other |
|---|---|---|---|---|---|---|---|
| Fall | | | | | | | |
| Spring | | | | | | | |

○ Conventional-Till - Full width tillage which disturbs all the soil surface and is performed prior to and/or during planting. Weeds are controlled by herbicides and/or mechanical cultivation.

Indicate number of trips (1, 2, 3…) and timing (fall or spring) for tillage operations:

| | Mold-board | Rip | Chisel | Disk | Field Cult. | Bed/ Hip/List | Other |
|---|---|---|---|---|---|---|---|
| Fall | | | | | | | |
| Spring | | | | | | | |

○ Other (please describe):____________

8. What was your seasonal rainfall? ____________

9. Is this field irrigated? (Check One) Yes _____ No _____.

10. If yes – how many inches of irrigation were applied during the season? ________ Don't know_____

    a. Do you utilize: Irrigation scheduling programs______, Moisture monitoring equipment______, Flow meter______, Other tools______ to improve irrigation efficiency?

    b. How many irrigation events occurred during the season? ______________

    c. What type of irrigation system was used: (Check One) Surface (furrow or basin) _____,
       Sprinkler with high pressure nozzles _____, Drip (surface or subsurface) _____,
       Sprinkler with low pressure drop nozzles_____.

    d. If pumping from a well, what is the static water level? (Check One) 0- 25ft_____, 26-75 ft._____, 76-175 ft._____, Greater than 175 ft.___, Don't know_____.

    e. Location of pressure gauge? Pump _____, Irrigation system_____, No gauge_____.

    f. What is the pressure? (Check One) 0-5 psi______, 6-10 psi_____ 11-15 psi______, 16-20 psi_____, 21-30 psi______, 31-40 psi______, 41-50 psi______, 51-60 psi______, Greater than 60 psi_____, Don't know____.

    g. What is the dominant energy source for your wells? (Check One) Diesel______, Electric______, Natural Gas______, Other_________________.

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11. What was the lint yield in pounds per acre? ___________

    a. If this field was irrigated, what is your estimate of what the yield would have been if it had been grown without irrigation? ___________

12. What type winter cover was used? (Check One) The soil had residue from the previous crop most of the winter____, The soil was bare most of the winter___, Native vegetation ___, Planted cover crop____, The field was double cropped___.

13. How often is cotton planted on this field? (Check One) Every year___, 2 of 3 years___, every other year___, 1 of 3 years___, Other ___________.

14. Considering the use of herbicides, insecticides, plant growth regulators, fungicides, nematicides, defoliants, desiccants, and boll-openers applied by ground or air including all burndown and post-harvest applications;

    a. About how many separate application trips were made on this field? _____.

    b. On average about how many different products were used in each application? (*for example if a tank mix of two insecticides and one herbicide were applied, that would be 3 chemicals for that application)* (Check one) 1___, 1.5___, 2 ___, 2.5___, 3 or more___.

15. What were moisture conditions at picking? (Check one) Cotton was dryer than normal____, Normal_____, Wetter than normal_____.

16. Considering conservation practices associated with this field: (Select all that apply.)

Sediment basin___,
Riparian forest buffer ___,
Filter Strip ___,
Field strip cropping ___,
Vegetative border___,

Grass Waterway___,
Water and sediment control basin ___,
Contour buffer strip___,
Conservation cover ___,
Stream habitat improvement ___,

Tailwater recovery system ___,
Contour strip cropping___,
Field Borders ___,
Riparian herbaceous cover ___,
Drop pipes for erosion control___.

Precision leveled (0.1 to 0.3 % grade) ___,

Recycle farm plastic (pesticide containers, poly pipe…) and/or paper and cardboard ___,

17. How many miles is this field from the gin? _________

***Thank you for your time!***

# 7.3 ANNEX C: LIFE CYCLE INVENTORY DATASETS

This is a summary of the Life Cycle Inventory (LCI) datasets used in the model.

| Material/Process | Data Set | Primary Source | Year |
|---|---|---|---|
| **Acetic acid** | Acetic acid from methanol (low pressure carbonylation) (Monsanto process) | thinkstep | 2015 |
| **Amylase** | | | |
| **Antimicrobial agent** | Silver antimicrobial 1 | thinkstep | 2014 |
| **Brass Zipper** | Brass (CuZn20) | thinkstep | 2015 |
| | Steel cold rolled coil | worldsteel | 2007 |
| **Catalyst** | Sodium chloride (rock salt) | thinkstep | 2015 |
| **Cationic fixative** | Ammonium chloride | thinkstep | |
| **Coating finishing agent** | Polymethylmethacrylate granulate (PMMA)2 | thinkstep | 2015 |
| **Cotton fibers** | Ginned Cotton (Region Mix, Cotton Inc. 2015) | Cotton Inc. | 2016 |
| **Dispersant** | Dispersing agent (unspecific) | thinkstep | 2015 |
| **DMDHEU** | Urea formaldehyde resin in- situ foam (EN15804 A1-A3) | thinkstep | 2015 |
| **Dye fixative** | same as cationic fixative above | thinkstep | 2015 |
| **Enzymes** | Enzyme (estimation over glucose) | thinkstep | 2013 |
| **Fire retardant** | Monoammonium phosphate (MAP) | thinkstep | 2015 |
| **Hydrogen peroxide** | Hydrogen peroxide (50%, H2O2) | thinkstep | 2015 |
| **Hydrogen peroxide stabilizer** | Calcium silicate | thinkstep | 2015 |
| **Landfill** | Hazardous waste (non-specific) (c rich, worst scenario) | thinkstep | 2012 |
| | Plastic waste on landfill | thinkstep | 2015 |
| | Textiles on landfill | thinkstep | 2015 |
| | Glass/inert waste on landfill | thinkstep | 2015 |
| | Landfill of cotton textile waste | thinkstep | 2015 |
| | Landfill of cotton textile waste (wild landfill, estimation) | thinkstep | 2015 |
| | Ferro metals on landfill | thinkstep | 2015 |
| **Lubricants** | Lubricants at refinery 2 | thinkstep | 2012 |
| **Magnesium chloride** | Sodium chloride (rock salt) | thinkstep | 2015 |
| **Nylon zipper** | Polyamide 6.6 (PA 6.6) GF injection moulded part (0,02 - 0,2kg) | thinkstep | 2015 |
| | Polyamide 6.6 granulat (PA 6.6) (HMDA via adipic acid) | thinkstep | 2015 |
| | Compounding (plastics) | thinkstep | 2015 |
| **Optical brightener** | Aniline (Phenyl amine, Amino benzene) | thinkstep | 2015 |
| **Pigment** | Titanium dioxide pigment (sulphate process) | thinkstep | 2015 |
| **Polyethylene terephthalate granulate** | Polyethylene terephthalate granulate (PET via DMT) | thinkstep | 2015 |

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| Material/Process | Data Set | Primary Source | Year |
|---|---|---|---|
| **Polyethylene terephthalate resin** | Polyethylene terephthalate resin (via PTA) | thinkstep | 2015 |
| **Reactive dye** | Reactive dyes | thinkstep | 2015 |
| **Sequestering agent** | EDTA | thinkstep | |
| **Sewability agent** | Polyethylene Low Density Granulate (LDPE/PE-LD) | thinkstep | 2015 |
| **Size** | Starch/PVA blend | thinkstep | 2015 |
| **Soil resist agent** | C-6 fluorocarbon 1 | thinkstep | 2014 |
| **Soda ash** | Soda ($Na_2CO_3$) | thinkstep | 2015 |
| **Sodium bicarbonate** | Sodium bicarbonate | thinkstep | 2015 |
| **Sodium dithionite** | Sodium dithionite | thinkstep | 2015 |
| **Sodium hydroxide** | Sodium hydroxide (caustic soda) mix (100%) | thinkstep | 2015 |
| **Sodium sulphate** | Sodium sulphate | thinkstep | 2015 |
| **Softener** | Softener (fatty acids amino compounds) | thinkstep | 2015 |
| **Starch** | Dried starch (corn wet mill) (economic allocation) | thinkstep | 2015 |
| **Sulfur Dye** | Vat Dye 1 | thinkstep | 2015 |
| **Surfactant** | Tensides (alcohol ethoxy sulfate (AES)) | thinkstep | 2015 |
| **Vat dye** | Vat Dye 1 | thinkstep | 2014 |
| **Waste incineration** | Textiles in municipal waste incineration plant | thinkstep | 2015 |
| **Waste water treatment** | Laundry waste water treatment (sludge treatment mix) | thinkstep | 2016 |
| | Laundry waste water treatment (treatment mix) | thinkstep | 2016 |
| | Laundry waste water treatment mix | thinkstep | 2016 |
| **Water** | Process water | thinkstep | 2015 |
| | Tap water | thinkstep | 2015 |
| **Water resistant textile finishing agent** | C-6 fluorocarbon 1 | thinkstep | 2014 |
| **Wetting agent** | Non-ionic surfactant (fatty acid derivate) | thinkstep | 2015 |

## 7.4 ANNEX D: TEXTILE PRODUCTION, CUT-AND-SEW, USE PHASE AND EOL INPUT-OUTPUT VALUES

TABLE 7-1: Wovens textile production, cut-and-sew, use phase, and end-of-life input-output values.

| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Woven Yarn Production** | | | 2015 |
| **Inputs** | Cotton fiber | 1320 | kg |
| | Electricity | 9470 | MJ |
| | Thermal energy from hard coal | 4150 | MJ |
| | Thermal energy from heavy fuel oil | 94.3 | MJ |
| | Thermal energy from LPG | 48.8 | MJ |
| **Outputs** | Yarn | 1120 | kg |
| | Plant bark and contaminants to landfill | 12 | kg |
| | Inorganic waste to landfill | 7.69 | kg |
| | Fiber waste to landfill | 1.57 | kg |
| | Organic waste sold for other uses | 0.512 | kg |
| | Fiber waste to recycling | 0.401 | kg |
| | Comber Noils | 0 | kg |
| | Short fiber | 0 | kg |
| **Beam/Slash/Dry** | | | 2012 |
| **Inputs** | Yarn | 1120 | kg |
| | Electricity | 142 | MJ |
| | Thermal energy from hard coal | 20700 | MJ |
| | Water (desalinated; deionised) | 1270 | kg |
| | Thermal energy from natural gas | 1100 | MJ |
| | Starch (Polyglucose) | 39.4 | kg |
| | Steam | 17.2 | kg |
| | Polymethylmethacrylate granulate (PMMA) | 11.3 | kg |
| | Thermal energy from LPG | 10.9 | MJ |
| | Thermal energy from heavy fuel oil | 9.81 | MJ |
| | Size | 0.959 | kg |
| **Outputs** | Sized warped yarn | 1110 | kg |
| | Water to wastewater treatment | 446 | kg |
| | Recycled process water | 446 | kg |
| | Water vapour | 382 | kg |
| | Yarn waste to recycling | 12.2 | kg |
| | Size to recycling | 2.13 | kg |
| | Inorganic waste to landfill | 0.485 | kg |
| | Organic waste to recycling | 0.409 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.00429 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.00567 | kg |
| | Aniline [Hydrocarbons to fresh water] | 0.000283 | kg |
| | Antimony [ecoinvent long-term to fresh water] | 0.0000283 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.0104 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 0.0318 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.000142 | kg |
| | Chromium [Heavy metals to fresh water] | 0.0000047 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.000142 | kg |
| | Copper [Heavy metals to fresh water] | 0.00000339 | kg |
| | Nickel [Heavy metals to fresh water] | 0.00000104 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.0107 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.00166 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.000374 | kg |
| | Solids (suspended) [Particles to fresh water] | 0.0213 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.000283 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.00112 | kg |
| | Zinc [Heavy metals to fresh water] | 0.00000287 | kg |
| **Weaving** | | | |
| **Inputs** | Size warped yarn | 1110 | kg |
| | Electricity | 5070 | MJ |
| | Steam | 252 | kg |
| | Thermal energy from hard coal | 9720 | MJ |
| | Thermal energy from heavy fuel oil | 105 | MJ |
| **Outputs** | Greige fabric | 1070 | kg |
| | Yarn waste to recycling | 32.3 | kg |
| | Fabric waste to recycling | 10.1 | kg |
| | Inorganic waste to recycling | 4.28 | kg |
| | Inorganic waste to landfill | 0.0516 | kg |
| | Waste fabric | 0.019 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Woven Preparation** | | | |
| **Inputs** | Greige fabric [Cotton] | 1070 | kg |
| | Acetic acid [Organic intermediate products] | 29.7 | kg |
| | Calcium silicate [Minerals] | 0.0543 | kg |
| | Electricity [Electric power] | 1350 | MJ |
| | Electricity from hard coal [System-dependent] | 304 | MJ |
| | Enzymes, saccharification [Operating materials] | 5.08 | kg |
| | Hydrogen peroxide (50%) [Inorganic intermediate products] | 37.2 | kg |
| | Non-ionic surfactant [Operating materials] | 0.0507 | kg |
| | Sequestering agent [Operating materials] | 3.97 | kg |
| | Soda (sodium carbonate) [Inorganic intermediate products] | 0.476 | kg |
| | Sodium chloride (rock salt) [Inorganic intermediate products] | 3.89 | kg |
| | Sodium hydroxide (100%; caustic soda) [Inorganic intermediate products] | 496 | kg |
| | Sodium sulphate [Inorganic intermediate products] | 3.1 | kg |
| | Steam (mp) [steam] | 913 | kg |
| | Surfactants (tensides) [Operating materials] | 0.0134 | kg |
| | Thermal energy from hard coal (MJ) [Thermal energy] | 556 | MJ |
| | Thermal energy from Heavy Fuel Oil [Thermal energy] | 12.5 | MJ |
| | Thermal energy from LPG [Thermal energy] | 26.9 | MJ |
| | Thermal energy from Nat Gas [Thermal energy] | 4550 | MJ |
| **Outputs** | Prepared fabric | 1050 | kg |
| | Fabric waste to recycling | 0.429 | kg |
| | Fabric waste to landfill | 0.281 | kg |
| | Water to wastewater treatment | 15900 | kg |
| | Recycled process water | 26300 | kg |
| | Water vapour | 31200 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.117 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.0413 | kg |
| | Aniline [Hydrocarbons to fresh water] | 0.00749 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.168 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.423 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.000103 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 1.08 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.00478 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
|  | Chromium [Heavy metals to fresh water] | 0.00206 | kg |
|  | Chromium (+VI) [Heavy metals to fresh water] | 0.000749 | kg |
|  | Copper [Heavy metals to fresh water] | 0.00272 | kg |
|  | Cyanide [Inorganic emissions to fresh water] | 0.00324 | kg |
|  | Fluorine [Inorganic emissions to fresh water] | 0.000206 | kg |
|  | Iron [Heavy metals to fresh water] | 0.00206 | kg |
|  | Lead [Heavy metals to fresh water] | 0.0000103 | kg |
|  | Manganese [Heavy metals to fresh water] | 0.00103 | kg |
|  | Mercury [Heavy metals to fresh water] | 0.000206 | kg |
|  | Nickel [Heavy metals to fresh water] | 0.0000516 | kg |
|  | Nitrate [Inorganic emissions to fresh water] | 0.000206 | kg |
|  | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.423 | kg |
|  | Oil (unspecified) [Hydrocarbons to fresh water] | 0.00385 | kg |
|  | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.00206 | kg |
|  | Phosphorus [Inorganic emissions to fresh water] | 0.0254 | kg |
|  | Selenium [Heavy metals to fresh water] | 0.00556 | kg |
|  | Solids (dissolved) [Analytical measures to fresh water] | 0.065 | kg |
|  | Solids (suspended) [Particles to fresh water] | 0.622 | kg |
|  | Sulphide [Inorganic emissions to fresh water] | 0.00955 | kg |
|  | Total organic bounded carbon [Analytical measures to fresh water] | 0.0103 | kg |
|  | Vanadium [Heavy metals to fresh water] | 0.0031 | kg |
|  | Zinc [Heavy metals to fresh water] | 0.00357 | kg |
| **Continuous Dyeing** |  |  |  |
| **Inputs** | Prepared fabric | 1050 | kg |
|  | Electricity | 369 | MJ |
|  | Thermal energy from natural gas | 6130 | MJ |
|  | Thermal energy from LPG | 11.8 | MJ |
|  | Electricity from hard coal | 320 | MJ |
|  | Thermal energy from hard coal | 657 | MJ |
|  | Thermal energy from heavy fuel oil | 14.8 | MJ |
|  | Sulfur dye | 5.61 | kg |
|  | Surfactants | 19.8 | kg |
|  | Titanium dioxide | 5.17 | kg |
|  | Reactive dye | 11 | kg |
|  | Non-ionic surfactant | 0.0167 | kg |
|  | Steam | 2400 | kg |
|  | Vat dye | 2.69 | kg |
|  | Water (desalinated; deionised) | 74900 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Sodium thiosulfate | 0.044 | kg |
| | Polyacrylate granulate | 3.98 | kg |
| | Enzymes | 1.07 | kg |
| | Disperse dye | 0.0139 | kg |
| | Acetic acid | 5.11 | kg |
| | Antimigrant | 2.67 | kg |
| | Sodium hydroxide (100%; caustic soda) | 67.3 | kg |
| | Sodium sulphate | 0.506 | kg |
| | Sodium dithionite | 2.48 | kg |
| | Soda (sodium carbonate) | 7.56 | kg |
| | Sodium chloride (rock salt) | 129 | kg |
| **Outputs** | Dyed fabric | 1030 | kg |
| | Fabric waste to recycling | 0.707 | kg |
| | Fabric waste to landfill | 8.03 | kg |
| | Recycled process water | 26700 | kg |
| | Water to wastewater treatment | 34500 | kg |
| | Water vapour | 13700 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.04 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.0149 | kg |
| | Aniline [Hydrocarbons to fresh water] | 0.00227 | kg |
| | Antimony [ecoinvent long-term to fresh water] | 0.000227 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.00036 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.514 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.0036 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 1.18 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.00294 | kg |
| | Chromium [Heavy metals to fresh water] | 0.00449 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.00132 | kg |
| | Copper [Heavy metals to fresh water] | 0.00604 | kg |
| | Cyanide [Inorganic emissions to fresh water] | 0.00036 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.0036 | kg |
| | Iron [Heavy metals to fresh water] | 0.0054 | kg |
| | Lead [Heavy metals to fresh water] | 0.00018 | kg |
| | Manganese [Heavy metals to fresh water] | 0.0036 | kg |
| | Mercury [Heavy metals to fresh water] | 0.000018 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0056 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.018 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.317 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.239 | kg |
| | Phenol (hydroxy benzene)<br>[Hydrocarbons to fresh water] | 0.0018 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.0285 | kg |
| | Selenium [Heavy metals to fresh water] | 0.00009 | kg |
| | Solids (dissolved)<br>[Analytical measures to fresh water] | 0.0226 | kg |
| | Solids (suspended) [Particles to fresh water] | 0.819 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.00587 | kg |
| | Total organic bounded carbon<br>[Analytical measures to fresh water] | 0.212 | kg |
| | Vanadium [Heavy metals to fresh water] | 0.00036 | kg |
| | Zinc [Heavy metals to fresh water] | 0.00954 | kg |
| **Woven Finishing** | | | |
| **Inputs** | Dyed fabric | 1030 | kg |
| | Thermal energy from heavy fuel oil | 13.1 | MJ |
| | Electricity from hard coal | 70.7 | MJ |
| | Thermal energy from natural gas | 1460 | MJ |
| | Thermal energy from LPG | 18.8 | MJ |
| | Thermal energy from hard coal | 581 | MJ |
| | Electricity | 506 | MJ |
| | Water | 24000 | kg |
| | Fire Retardant | 0.107 | kg |
| | Antimicrobial | 0.0383 | kg |
| | Polyethylene compound | 0.0279 | kg |
| | Enzymes | 0.0796 | kg |
| | Aniline | 0.325 | kg |
| | Catalyst | 0.422 | kg |
| | Acetic acid | 5.2 | kg |
| | Softener | 16.7 | kg |
| | Cyclohexane (hexahydro benzene) | 0.0113 | kg |
| | Water resist (textile finishing agent) | 1.17 | kg |
| | Wrinkle resist | 2.51 | kg |
| | Polymethylmethacrylate compound (PMMA) | 0.0728 | kg |
| **Outputs** | Woven fabric | 1030 | kg |
| | Plastic waste to landfill | 0.39 | kg |
| | Fabric waste to recycling | 0.222 | kg |
| | Recycled process water | 8540 | kg |
| | Water to wastewater treatment | 8600 | kg |
| | Water vapour | 6840 | kg |
| | Adsorbable organic halogen compounds<br>(AOX) [Analytical measures to fresh water] | 0.0104 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Ammonia [Inorganic emissions to fresh water] | 0.00862 | kg |
| | Aniline [Hydrocarbons to fresh water] | 0.000433 | kg |
| | Antimony [ecoinvent long-term to fresh water] | 0.0000433 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.0000916 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.044 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.000916 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 0.569 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.000675 | |
| | Chromium [Heavy metals to fresh water] | 0.0015 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.000262 | kg |
| | Copper [Heavy metals to fresh water] | 0.00179 | kg |
| | Cyanide [Inorganic emissions to fresh water] | 0.0000916 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.000916 | kg |
| | Iron [Heavy metals to fresh water] | 0.00137 | kg |
| | Lead [Heavy metals to fresh water] | 0.0000458 | kg |
| | Manganese [Heavy metals to fresh water] | 0.000916 | kg |
| | Mercury [Heavy metals to fresh water] | 0.00000458 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0015 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.00458 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.135 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.0154 | kg |
| | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.000458 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.014 | kg |
| | Selenium [Heavy metals to fresh water] | 0.0000229 | kg |
| | Solids (dissolved) [Analytical measures to fresh water] | 0.00133 | kg |
| | Solids (suspended) [Particles to fresh water] | 0.215 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.00135 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.139 | kg |
| | Vanadium [Heavy metals to fresh water] | 0.0000916 | kg |
| | Zinc [Heavy metals to fresh water] | 0.00265 | kg |
| **Sanforizing** | | | |
| **Inputs** | Woven fabric | 1030 | kg |
| | Diesel | 0.0372 | kg |
| | Electricity | 155 | MJ |
| | Electricity from hard coal | 35.3 | MJ |
| | Thermal energy from hard coal (MJ) | 249 | MJ |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
|  | Thermal energy from Heavy Fuel Oil | 5.61 | MJ |
|  | Thermal energy from LPG | 8.34 | MJ |
|  | Thermal energy from Nat Gas | 2440 | MJ |
|  | Water (desalinated; deionised) | 4970 | kg |
| **Outputs** | Woven fabric | 1020 | kg |
|  | Landfill of plastic waste | 0.173 | kg |
|  | Steam | 1960 | kg |
|  | Fabric waste to recycling | 0.203 | kg |
|  | Water to wastewater treatment | 3020 | kg |
|  | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.0906 | kg |
|  | Oil (unspecified) [Hydrocarbons to fresh water] | 0.0453 | kg |
|  | Solids (suspended) [Particles to fresh water] | 0.0906 | kg |

### Cut-and-Sew Unit Process Data

|  |  |  |  |
|---|---|---|---|
| **Inputs** | Woven fabric | 1020 | kg |
|  | Brass component | 15 | kg |
|  | Electricity | 299 | MJ |
|  | Nylon 6.6 GF part (PA 6.6 GF) | 5.36 | kg |
|  | Polyester resin (unsaturated; UP) | 80 | kg |
|  | Polyethylene terephthalate fibers (PET) | 4.49 | kg |
| **Outputs** | Cotton garment | 1000 | kg |
|  | Waste (unspecified) | 127 | kg |

### Use phase Unit Process Data

|  |  |  |  |
|---|---|---|---|
| **Inputs** | Cotton garment | 1000 | kg |
|  | Detergent | 482 | kg |
|  | Electricity | 22900 | MJ |
|  | Thermal energy from natural gas | 362 | MJ |
|  | Water (tap water) | 408000 | kg |
| **Outputs** | Cotton garment | 1000 | kg |
|  | Water (processed) | 204000 | kg |
|  | Water vapour | 204000 | kg |

### End-of-life

|  |  |  |  |
|---|---|---|---|
| **Inputs** | Cotton garment | 1000 | kg |
| **Outputs** | Incineration of textiles | 457 | kg |
|  | Landfill of textiles | 468 | kg |
|  | Littering/Wild Landfill | 75 | kg |

TABLE 7-2: Polo-shirt textile production, cut-and-sew, use phase and EoL input-output values

| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Knit Yarn Production** | | | 2015 |
| **Inputs** | Cotton fiber | 1700 | kg |
| | Diesel | 0.0932 | kg |
| | Electricity | 15500 | MJ |
| | Electricity from natural gas | 8080 | MJ |
| **Outputs** | Yarn | 1340 | kg |
| | Comber noils | 334 | kg |
| | Short fiber | 110 | kg |
| | Landfill of ferro metals | 0.252 | kg |
| | Plant bark and contaminants to recycling | 2.52 | kg |
| | Waste fiber to recycling | 11.4 | kg |
| | Waste fiber to landfill | 0.0632 | kg |
| | Organic waste to recycling | 1.26 | kg |
| **Knitting** | | | |
| **Inputs** | Yarn | 1340 | kg |
| | Electricity | 1260 | MJ |
| | Lubricant | 2.32 | kg |
| | Thermal energy from natural gas | 1820 | MJ |
| **Outputs** | Greige fabric | 1310 | kg |
| | Inorganic waste to landfill | 0.0226 | kg |
| | Waste lubricant for disposal | 0.0603 | kg |
| | Linty fly to recycling | 0.453 | kg |
| | Yarn waste to recycling | 3.22 | kg |
| | Fabric waste to recycling | 2.11 | kg |
| | Waste fiber to incineration | 13.4 | kg |
| **Knit Preparation** | | | |
| **Inputs** | Greige fabric | 1310 | kg |
| | Acetic acid | 3.3 | kg |
| | Calcium silicate | 10.4 | kg |
| | Electricity | 778 | MJ |
| | Enzymes | 2.03 | kg |
| | Hydrogen peroxide (50%) | 40.2 | kg |
| | Sodium hydroxide (100%; caustic soda) | 35.3 | kg |
| | Sodium sulphate | 0.0863 | kg |
| | Surfactants (tensides) | 13.6 | kg |
| | Thermal energy from LPG | 548 | MJ |
| | Thermal energy from natural gas | 2480 | MJ |
| | Water (desalinated; deionised) | 72700 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Outputs** | Prepared fabric | 1300 | kg |
| | Recycled process water | 21000 | kg |
| | Water to wastewater treatment | 27200 | kg |
| | Water vapour | 24500 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.00907 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.00479 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.00158 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.935 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.0158 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 4.99 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.00788 | kg |
| | Chromium [Heavy metals to fresh water] | 0.0171 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.000788 | kg |
| | Copper [Heavy metals to fresh water] | 0.0246 | kg |
| | Cyanide [Inorganic emissions to fresh water] | 0.00158 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.0158 | kg |
| | Iron [Heavy metals to fresh water] | 0.0236 | kg |
| | Lead [Heavy metals to fresh water] | 0.000788 | kg |
| | Manganese [Heavy metals to fresh water] | 0.0158 | kg |
| | Mercury [Heavy metals to fresh water] | 0.0000788 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0239 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.0788 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.621 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.141 | kg |
| | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.00788 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.0658 | kg |
| | Selenium [Heavy metals to fresh water] | 0.000394 | kg |
| | Solids (dissolved) [Analytical measures to fresh water] | 16.1 | kg |
| | Solids (suspended) [Particles to fresh water] | 1.03 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.0158 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.325 | kg |
| | Vanadium [Heavy metals to fresh water] | 0.00158 | kg |
| | Zinc [Heavy metals to fresh water] | 0.0402 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Batch Dyeing** | | | |
| **Inputs** | Prepared fabric | 1300 | kg |
| | Acetic acid | 7.17 | kg |
| | Disperse dye | 0.207 | kg |
| | Dispersing agent | 0.207 | kg |
| | Electricity | 1560 | MJ |
| | Enzymes, saccharification | 12.4 | kg |
| | Reactive dye | 166 | kg |
| | Sequestering agent | 0.0518 | kg |
| | Soda (sodium carbonate) | 93 | kg |
| | Sodium chloride (rock salt) | 643 | kg |
| | Sodium dithionite | 6.22 | kg |
| | Sodium hydroxide (100%; caustic soda) | 68.6 | kg |
| | Sodium sulphate | 21.4 | kg |
| | Softener | 48.9 | kg |
| | Surfactants (tensides) | 6.11 | kg |
| | Thermal energy from LPG | 1370 | MJ |
| | Thermal energy from natural gas | 7650 | MJ |
| | Water (desalinated; deionised) | 129000 | kg |
| | Steam | 8490 | kg |
| **Outputs** | Dyed fabric | 1190 | kg |
| | Fabric waste to recycling | 6.46 | kg |
| | Fabric waste to landfill | 1.33 | kg |
| | Recycled process water | 34500 | kg |
| | Water to wastewater treatment | 55800 | kg |
| | Nitrogen oxides | 0.0271 | kg |
| | Sulphur dioxide | 0.138 | kg |
| | Water vapour | 38400 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.0111 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.0115 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.00302 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 1.93 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.0302 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 9.2 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.0151 | kg |
| | Chromium [Heavy metals to fresh water] | 0.0319 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.00151 | kg |
| | Copper [Heavy metals to fresh water] | 0.0465 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Cyanide [Inorganic emissions to fresh water] | 0.00302 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.0302 | kg |
| | Iron [Heavy metals to fresh water] | 0.0453 | kg |
| | Lead [Heavy metals to fresh water] | 0.00151 | kg |
| | Manganese [Heavy metals to fresh water] | 0.0302 | kg |
| | Mercury [Heavy metals to fresh water] | 0.000151 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0457 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.151 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 1.03 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.484 | kg |
| | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.0151 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.108 | kg |
| | Selenium [Heavy metals to fresh water] | 0.000755 | kg |
| | Solids (dissolved) [Analytical measures to fresh water] | 50.3 | kg |
| | Solids (suspended) [Particles to fresh water] | 1.83 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.0302 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.4 | kg |
| | Vanadium [Heavy metals to fresh water] | 0.00302 | kg |
| | Zinc [Heavy metals to fresh water] | 0.0765 | kg |
| **Knit Finishing** | | | |
| **Inputs** | Dyed fabric | 1190 | kg |
| | Acetic acid | 0.367 | kg |
| | Antimicrobial | 0.377 | kg |
| | Diesel | 0.145 | kg |
| | Electricity | 1780 | MJ |
| | Softener | 131 | kg |
| | Soil repellant | 3.14 | kg |
| | Thermal energy from hard coal | 2250 | MJ |
| | Thermal energy from heavy fuel oil | 0.904 | MJ |
| | Thermal energy from LPG | 3030 | MJ |
| | Thermal energy from natural gas | 13000 | MJ |
| | Water (desalinated; deionised) | 19300 | kg |
| | Steam | 683 | kg |
| | Water resist | 30.8 | kg |
| | Wrinkle resist | 4.05 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Outputs** | Knit fabric | 1180 | kg |
| | Fabric waste to recycling | 6.16 | kg |
| | Recycled process water | 1190 | kg |
| | Water to wastewater treatment | 12000 | kg |
| | Water vapour | 6180 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.000525 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.00137 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.0019 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.281 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.019 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 1.84 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.00947 | kg |
| | Chromium [Heavy metals to fresh water] | 0.0191 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.000947 | kg |
| | Copper [Heavy metals to fresh water] | 0.0285 | kg |
| | Cyanide [Inorganic emissions to fresh water] | 0.0019 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.019 | kg |
| | Iron [Heavy metals to fresh water] | 0.0284 | kg |
| | Lead [Heavy metals to fresh water] | 0.000947 | kg |
| | Manganese [Heavy metals to fresh water] | 0.019 | kg |
| | Mercury [Heavy metals to fresh water] | 0.0000947 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0284 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.0947 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.486 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.119 | kg |
| | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.00947 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.0489 | kg |
| | Selenium [Heavy metals to fresh water] | 0.000473 | kg |
| | Solids (dissolved) [Analytical measures to fresh water] | 1.68 | kg |
| | Solids (suspended) [Particles to fresh water] | 1.03 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.019 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.0188 | kg |
| | Vanadium [Heavy metals to fresh water] | 0.0019 | kg |
| | Zinc [Heavy metals to fresh water] | 0.0474 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Compaction** | | | |
| **Inputs** | Knit fabric | 1180 | kg |
| | Electricity | 219 | MJ |
| | Thermal energy from LPG | 1.12 | MJ |
| | Thermal energy from heavy fuel oil | 668 | MJ |
| | Thermal energy from natural gas | 781 | MJ |
| **Outputs** | Knit fabric | 1180 | kg |
| | Steam | 32.3 | kg |
| | Fabric waste to recycling | 5.22 | kg |
| **Cut-and-sew Unit Process Data** | | | |
| **Inputs** | Knit fabric | 0 | kg |
| | Electricity | 264 | MJ |
| | Polyethylene terephthalate fibers (PET) | 1.81 | kg |
| **Outputs** | Cotton garment | 1000 | kg |
| | Waste (unspecified) | 179 | kg |
| **Use Phase Unit Process Data** | | | |
| **Inputs** | Cotton garment | 1000 | kg |
| | Detergent | 455 | kg |
| | Electricity | 23700 | MJ |
| | Thermal energy from natural gas | 644 | MJ |
| | Water (tap water) | 386000 | kg |
| **Outputs** | Cotton garment | 1000 | kg |
| | Water to wastewater treatment | 193000 | kg |
| | Water vapour | 193000 | kg |
| **End of Life** | | | |
| **Inputs** | Cotton garment | 1000 | kg |
| **Outputs** | Incineration of textiles | 457 | kg |
| | Landfill of textiles | 468 | kg |
| | Litter/Wild Landfill of textiles | 75 | kg |

TABLE 7-3: T-shirt textile production, cut-and-sew, use phase and EoL input-output values

| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Knit Yarn Production** | | | |
| **Inputs** | Cotton fiber | 1690 | Kg |
| | Diesel | 0.0931 | Kg |
| | Electricity | 15500 | MJ |
| | Electricity from natural gas | 8070 | MJ |
| **Outputs** | Yarn | 1330 | Kg |
| | Comber noils | 333 | Kg |
| | Short fiber | 110 | kg |
| | Inorganic waste to landfill | 0.252 | kg |
| | Plant bark and contaminants to recycling | 2.52 | kg |
| | Fiber waste to recycling | 11.4 | kg |
| | Fiber waste to landfill | 0.0631 | kg |
| | Organic waste to recycling | 1.26 | kg |
| **Knitting** | | | |
| **Inputs** | Yarn | 1330 | kg |
| | Electricity | 1250 | MJ |
| | Lubricant | 2.31 | kg |
| | Thermal energy from natural gas | 1820 | MJ |
| **Outputs** | Greige fabric | 1310 | kg |
| | Inorganic waste to landfill | 0.0226 | kg |
| | Waste lubricant for disposal | 0.0603 | kg |
| | Lint fly to recycling | 0.452 | kg |
| | Yarn waste to recycling | 3.22 | kg |
| | Fabric waste to recycling | 2.1 | kg |
| | Waste fiber to incineration | 13.3 | kg |
| **Knit Preparation** | | | |
| **Inputs** | Greige fabric | 1310 | kg |
| | Acetic acid | 3.3 | kg |
| | Calcium silicate | 10.4 | kg |
| | Electricity | 776 | MJ |
| | Enzymes | 2.03 | kg |
| | Hydrogen peroxide (50%) | 40.1 | kg |
| | Sodium hydroxide (100%; caustic soda) | 35.2 | kg |
| | Sodium sulphate | 0.0862 | kg |
| | Surfactants (tensides) | 13.6 | kg |
| | Thermal energy from LPG | 547 | MJ |
| | Thermal energy from natural gas | 2470 | MJ |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Water (desalinated; deionised) | 72600 | kg |
| **Outputs** | Prepared fabric | 1290 | kg |
| | Recycled process water | 21000 | kg |
| | Water to wastewater treatment | 27100 | kg |
| | Water vapour | 24500 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.00905 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.00478 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.00157 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.934 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.0157 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 4.98 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.00787 | kg |
| | Chromium [Heavy metals to fresh water] | 0.0171 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.000787 | kg |
| | Copper [Heavy metals to fresh water] | 0.0246 | kg |
| | Cyanide [Inorganic emissions to fresh water] | 0.00157 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.0157 | kg |
| | Iron [Heavy metals to fresh water] | 0.0236 | kg |
| | Lead [Heavy metals to fresh water] | 0.000787 | kg |
| | Manganese [Heavy metals to fresh water] | 0.0157 | kg |
| | Mercury [Heavy metals to fresh water] | 0.0000787 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0239 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.0787 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.62 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.141 | kg |
| | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.00787 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.0657 | kg |
| | Selenium [Heavy metals to fresh water] | 0.000393 | kg |
| | Solids (dissolved) [Analytical measures to fresh water] | 16 | kg |
| | Solids (suspended) [Particles to fresh water] | 1.03 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.0157 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.324 | kg |
| | Vanadium [Heavy metals to fresh water] | 0.00157 | kg |
| | Zinc [Heavy metals to fresh water] | 0.0402 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Batch Dyeing** | | | |
| **Inputs** | Prepared fabric | 1290 | kg |
| | Acetic acid | 7.16 | kg |
| | Disperse dye | 0.207 | kg |
| | Dispersing agent | 0.207 | kg |
| | Electricity | 1560 | MJ |
| | Enzymes | 12.3 | kg |
| | Reactive dye | 166 | kg |
| | Sequestering agent | 0.0518 | kg |
| | Soda (sodium carbonate) | 92.8 | kg |
| | Sodium chloride (rock salt) | 642 | kg |
| | Sodium dithionite | 6.21 | kg |
| | Sodium hydroxide (100%; caustic soda) | 68.5 | kg |
| | Sodium sulphate | 21.4 | kg |
| | Softener | 48.8 | kg |
| | Surfactants (tensides) | 6.1 | kg |
| | Thermal energy from LPG | 1370 | MJ |
| | Thermal energy from Nat Gas | 7630 | MJ |
| | Water (desalinated; deionised) | 129000 | kg |
| | Water (tap water) | 8480 | kg |
| **Outputs** | Dyed fabric | 1190 | kg |
| | Fabric waste to recycling | 6.45 | kg |
| | Fabric waste to landfill | 1.33 | kg |
| | Recycled process water | 34400 | kg |
| | Water to wastewater treatment | 55800 | kg |
| | Nitrogen oxides | 0.0271 | kg |
| | Sulphur dioxide | 0.138 | kg |
| | Water vapour | 38400 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.0111 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.0115 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.00302 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 1.92 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.0302 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 9.19 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.0151 | kg |
| | Chromium [Heavy metals to fresh water] | 0.0318 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.00151 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Copper [Heavy metals to fresh water] | 0.0464 | kg |
| | Cyanide [Inorganic emissions to fresh water] | 0.00302 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.0302 | kg |
| | Iron [Heavy metals to fresh water] | 0.0452 | kg |
| | Lead [Heavy metals to fresh water] | 0.00151 | kg |
| | Manganese [Heavy metals to fresh water] | 0.0302 | kg |
| | Mercury [Heavy metals to fresh water] | 0.000151 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0456 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.151 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 1.03 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.483 | kg |
| | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.0151 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.108 | kg |
| | Selenium [Heavy metals to fresh water] | 0.000754 | kg |
| | Solids (dissolved) [Analytical measures to fresh water] | 50.2 | kg |
| | Solids (suspended) [Particles to fresh water] | 1.83 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.0302 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.399 | kg |
| | Vanadium [Heavy metals to fresh water] | 0.00302 | kg |
| | Zinc [Heavy metals to fresh water] | 0.0763 | kg |
| **Knit Finishing** | | | |
| **Inputs** | Dyed fabric | 1190 | kg |
| | Acetic acid | 0.367 | kg |
| | Antimicrobial | 0.376 | kg |
| | Diesel | 0.145 | kg |
| | Electricity | 1780 | MJ |
| | Softener | 130 | kg |
| | Soil repellant | 3.14 | kg |
| | Thermal energy from hard coal | 2250 | MJ |
| | Thermal energy from heavy fuel oil | 0.903 | MJ |
| | Thermal energy from LPG | 3020 | MJ |
| | Thermal energy from natural gas | 13000 | MJ |
| | Water (desalinated; deionised) | 19300 | kg |
| | Steam | 682 | kg |
| | Water resist | 30.8 | kg |
| | Wrinkle resist | 4.04 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| **Outputs** | Knit fabric | 1180 | kg |
| | Fabric waste to recycling | 6.15 | kg |
| | Recycled process water | 1190 | kg |
| | Water to wastewater treatment | 12000 | kg |
| | Water vapour | 6170 | kg |
| | Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh water] | 0.000524 | kg |
| | Ammonia [Inorganic emissions to fresh water] | 0.00136 | kg |
| | Arsenic [Heavy metals to fresh water] | 0.00189 | kg |
| | Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.281 | kg |
| | Cadmium [Heavy metals to fresh water] | 0.0189 | kg |
| | Chemical oxygen demand (COD) [Analytical measures to fresh water] | 1.83 | kg |
| | Chlorine (dissolved) [Inorganic emissions to fresh water] | 0.00945 | kg |
| | Chromium [Heavy metals to fresh water] | 0.019 | kg |
| | Chromium (+VI) [Heavy metals to fresh water] | 0.000945 | kg |
| | Copper [Heavy metals to fresh water] | 0.0284 | kg |
| | Cyanide [Inorganic emissions to fresh water] | 0.00189 | kg |
| | Fluorine [Inorganic emissions to fresh water] | 0.0189 | kg |
| | Iron [Heavy metals to fresh water] | 0.0283 | kg |
| | Lead [Heavy metals to fresh water] | 0.000945 | kg |
| | Manganese [Heavy metals to fresh water] | 0.0189 | kg |
| | Mercury [Heavy metals to fresh water] | 0.0000945 | kg |
| | Nickel [Heavy metals to fresh water] | 0.0283 | kg |
| | Nitrate [Inorganic emissions to fresh water] | 0.0945 | kg |
| | Nitrogen (as total N) [Inorganic emissions to fresh water] | 0.485 | kg |
| | Oil (unspecified) [Hydrocarbons to fresh water] | 0.119 | kg |
| | Phenol (hydroxy benzene) [Hydrocarbons to fresh water] | 0.00945 | kg |
| | Phosphorus [Inorganic emissions to fresh water] | 0.0488 | kg |
| | Selenium [Heavy metals to fresh water] | 0.000473 | kg |
| | Solids (dissolved) [Analytical measures to fresh water] | 1.68 | kg |
| | Solids (suspended) [Particles to fresh water] | 1.03 | kg |
| | Sulphide [Inorganic emissions to fresh water] | 0.0189 | kg |
| | Total organic bounded carbon [Analytical measures to fresh water] | 0.0188 | kg |

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| Type | Flow | Magnitude | Unit |
|---|---|---|---|
| | Vanadium [Heavy metals to fresh water] | 0.00189 | kg |
| | Zinc [Heavy metals to fresh water] | 0.0474 | kg |
| **Compaction** | | | |
| **Inputs** | Knit fabric | 1180 | kg |
| | Electricity | 219 | MJ |
| | Thermal energy | 1.12 | MJ |
| | Thermal energy from heavy fuel oil | 667 | MJ |
| | Thermal energy from natural gas | 779 | MJ |
| **Outputs** | Knit fabric | 1180 | kg |
| | Steam | 32.2 | kg |
| | Fabric waste to recycling | 5.21 | kg |
| **Cut-and-sew Unit Process Data** | | | |
| **Inputs** | | | |
| | Electricity | 375 | MJ |
| | Polyester resin (unsaturated; UP) | 0.939 | kg |
| **Outputs** | Cotton garment | 1000 | kg |
| | Waste (unspecified) | 176 | kg |
| **Use Phase Unit Process Data** | | | |
| **Inputs** | Cotton garment | 1000 | kg |
| | Detergent | 373 | kg |
| | Electricity | 20000 | MJ |
| | Thermal energy | 574 | MJ |
| | Water (tap water) | 316000 | kg |
| **Outputs** | Cotton garment | 1000 | kg |
| | Water to wastewater treatment | 158000 | kg |
| | Water vapour | 158000 | kg |
| **End of Life** | | | |
| **Inputs** | Cotton garment | 1000 | kg |
| **Outputs** | Incineration of textiles | 457 | kg |
| | Landfill of textiles | 468 | kg |
| | Litter/Wild Landfill of textiles | 75 | kg |

# **7.5** ANNEX E: EVALUATION OF LAND USE (LANCA)

## Introduction

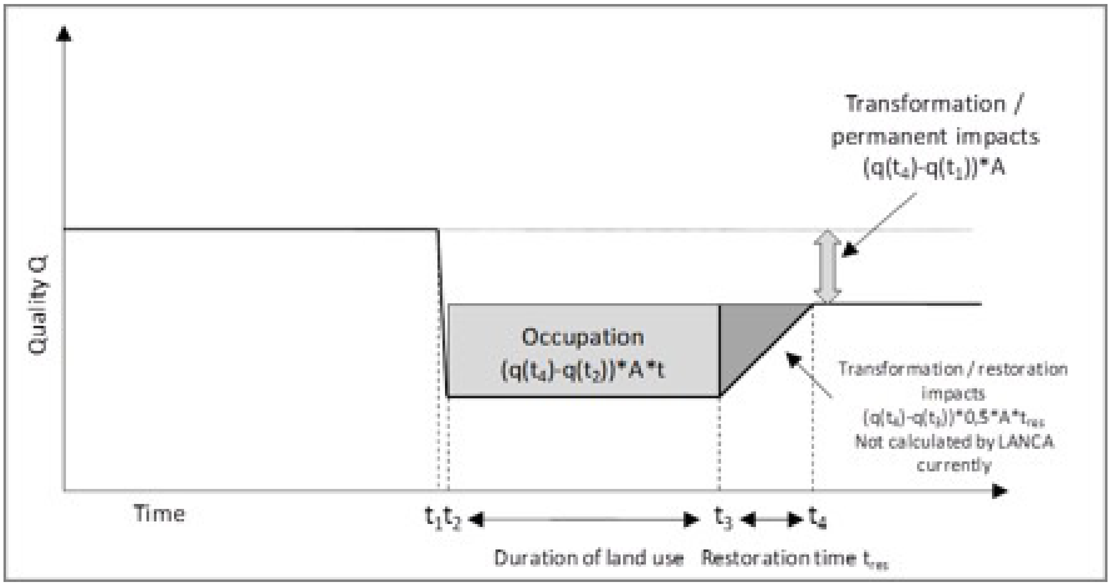
In recent years, scientists worldwide have worked on the implementation of land use aspects into life cycle assessment and are thereby continuously improving the significance and validity of LCA. The Department of Life Cycle Engineering at Fraunhofer IBP developed a method for calculating indicators for ecosystem services and for implementing these indicators into LCA studies and software systems. The objective of this method, entitled LANCA® (Land Use Indicator Value Calculation), is to provide and quantify indicator values that describe the environmental impacts of land intensive processes on ecosystem services. For a detailed description of the method please refer to Beck et al. (2010).

The evaluation of land use indicators are chosen in this study because the kind of land use has a high impact on soil functions and thereby on ecosystem services. The LANCA® calculations are based on geo-ecological classification systems (GIS based). To ensure maximum methodological consistency, the default values from the LANCA data base were used, with the same spatial resolution as the data collection described in section 3.1. However, the LANCA default data deviates from the site and project specific primary data collected in this study in some cases. This is why the results shown below should be considered as a first screening assessment and interpreted with care.

The following indicators are calculated: erosion resistance, mechanical filtration, physicochemical filtration, groundwater replenishment, and biotic production (Beck et al., 2010).

Land use Indicators are always given for "transformation" and "occupation". "Transformation" refers to the permanent impacts occurring after the regarded land use but caused by the respective land use taking into consideration the initial quality state of the land. "Occupation" impacts occur during the time of the regarded land use. The calculation scheme is demonstrated in Figure 7-1. In general, for occupation impacts the land quality after the regeneration of the land is compared to the quality during land use whereas for transformation impacts calculation, the quality before the regarded land use and after land regeneration is compared.

FIGURE 7-1: Land use calculation scheme.



## Input data

Data for calculating the land use impacts for the cotton fiber production refer to four different countries and eleven different locations. The following tables show the natural conditions of these locations and describe the reference land use type as well as the actual land use type considered.

| | China | | |
|---|---|---|---|
| | **Yangtze** | **North West** | **Yellow River** |
| **Biome** | Temperate, deciduous forest | Desert, semi desert | Temperate, deciduous forest |
| **Climate region** | Warm temperate fully humid hot summer | Arid desert cold arid | Snow winter dry hot summer |
| **Reference type tref** | Mixed tree forest, primary | Natural, non-vegetated (desert, bare rock, snow, and ice areas) | Mixed tree forest, primary |
| **Land use type $t_2$** | Arable, irrigated | Arable, irrigated, intensive | Arable, irrigated |

| | United States | | | |
|---|---|---|---|---|
| | **South East** | **Mid-South** | **South West** | **Far West** |
| **Biome** | Temperate, deciduous forest | Temperate, deciduous forest | Grassland | Desert, semi desert |
| **Climate region** | Warm temperate fully humid hot summer | Warm temperate fully humid hot summer | Warm temperate fully humid hot summer | Arid desert hot arid |
| **Reference type tref** | Mixed tree forest, primary | Mixed tree forest, primary | Grassland | Natural, non-vegetated (desert, bare rock, snow, and ice areas) |
| **Land use type $t_2$** | Arable, irrigated | Arable, irrigated | Arable, irrigated | Arable, irrigated, intensive |

| | India | | | Australia |
|---|---|---|---|---|
| | **India North** | **India Central** | **India South** | |
| **Biome** | Tropical savanna | Tropical savanna | Tropical savanna | Desert, semi desert |
| **Climate region** | Arid desert hot arid | Equatorial monsoonal | Equatorial monsoonal | Arid desert hot arid |
| **Reference type tref** | Deciduous forest, primary | Deciduous forest, primary | Deciduous forest, primary | Natural, non-vegetated (desert, bare rock, snow, and ice areas) |
| **Land use type t2** | Arable, irrigated, intensive | Arable, irrigated | Arable, irrigated | Arable, irrigated |

## Indicators

Six indicators assess land use effects incurred through the production of cotton fibers. For each indicator values for the occupation and transformation impact are calculated for the foreground and background system of the cotton fiber production process. The foreground system refers to land use impacts occurring on the field during the respective agricultural production process, whereas impacts of the background system, such as fertilizer and pesticide production or the ginning process, are listed separately.

## Occupation impacts

The following table shows the impacts of the land occupation for each indicator.

| Indicator | Unit | Foreground System | Background System |
|---|---|---|---|
| **Biotic Production** | kg biotic production per 1,000 kg fiber | 5.88E+03 | 7.38E+00 |
| **Erosion Resistance** | Kg soil per 1,000 kg fiber | 4.36E+04 | 1.50E+00 |
| **Groundwater Replenishment** | mm*m² ground water regeneration per 1,000 kg fiber | 1.09E+06 | 4.08E+02 |
| **Land Occupation** | (m²*year) per 1,000 kg fiber | 1.06E+04 | 1.07E+01 |
| **Mechanical Filtration** | (cm²*m) of water per 1,000 kg fiber | 1.60E+05 | 3.99E+03 |
| **Physicochemical Filtration** | (cmol cation exchange capacity*m²*year)/1,000 kg fiber | 1.15E+08 | 6.37E+00 |

The indicator biotic production (BP) represents the amount of biomass not produced per year taking in consideration the biomass production at the initial state before the respective land use and after land regeneration. Like most of the land use indicators, the agricultural production of cotton has significant land use impacts for the occupation phase. The values for the other contributors are comparatively small.

The indicator erosion resistance (ER) displays the capability of soil to prevent soil loss. Erosion resistance occupation impacts (expressed by kg of eroded soil) represent the kg of soil eroded in addition to naturally occurring soil erosion during the land use per functional unit regarded. The erosion resistance occupation impacts refer almost all to the occupation of land due to the cultivation of cotton. Impacts in the background system can be ignored as their values are very little.

As the name implies, the indicator groundwater replenishment (GWR) displays the capability of a soil to replenish groundwater. Groundwater replenishment occupation impacts represent the volume of groundwater that could not be replenished due to or during the land use per functional unit regarded.

The groundwater replenishment occupation impacts are highest for the cultivation of cotton. The other processes (background) show smaller values, mostly below 100 mm*m²/1,000 kg fiber.

The indicator land occupation displays the area land used for the production of the product and the duration, given in m²*a. The land occupation is also highest for the cultivation process, approximately 1 ha for one year. The other values show only small impacts.

The indicator mechanical filtration (MF) displays the capability of a soil to infiltrate water irrespective of climatic conditions. Mechanical filtration impacts represent the volume of water that could not be filtered during the land use per functional unit regarded, e.g., through surface sealing. For this indicator, cultivation has the highest occupation impacts for mechanical infiltration as well. The other factors have smaller mechanical filtration values.

The indicator physicochemical filtration (PCF) displays the ability of a soil to fix cations. Physicochemical filtration occupation impacts represent the amount of cations that could not be fixed to the soil per kg soil due to the land use per functional unit regarded. The cultivation of cotton has again the highest physicochemical filtration occupation impacts, whereas the impacts of the background system are very small.

## Transformation impacts

As it is assumed that the fields where cotton is cultivated are used as agricultural land before and after the studied cotton cultivation phase, no transformation indicator values are calculated for the foreground systems that means for the cultivation process on the field. Transformation impacts for each indicator are listed in the following table.

| Indicator | Unit | Foreground System | Background System |
|---|---|---|---|
| **Biotic Production** | (kg biotic production per year) per 1,000 kg fiber | 0 | 2.03E-02 |
| **Erosion Resistance** | (kg soil per year) per 1,000 kg fiber | 0 | 2.56E-04 |
| **Groundwater Replenishment** | (mm*m² ground water regeneration per year) per 1,000 kg fiber | 0 | 7.71E-01 |
| **Land Transformation** | m² per1,000 kg fiber | 1.06E+04 | 6.35E+00 |
| **Mechanical Filtration** | (cm²*m water per day ) per1,000 kg fiber | 0 | -2.72E-02 |
| **Physicochemical Filtration** | (cmol cation exchange capacity *m² per kg) per 1,000 kg fiber | 0 | -9.08E-03 |

Most of the transformation impacts of the background systems occur far up in the value chain or life cycle, respectively, e.g., in the production of biomass for energy generation or in mining of resources either for provision of energy or as raw materials.

## 7.6 ANNEX F: TEXTILE DATA EXAMPLE

| Material Inputs | Amount | Units | Kg/1,000kg | Notes |
|---|---|---|---|---|
| **Prepared Fabric** | 1,446,667 | Kg/yr | 1,118 | |
| **Water (specify water source, if known, under the "Notes/Comments" column. i.e. surface, municipal, well, or reclaimed)** | 309,871 | m3/yr | 239,529 | |
| **Reactive Dye** | 13,809 | Kg/yr | 11 | |
| **Direct Dye** | 0 | | | |
| **Dye Fixative** | 751 | Kg/yr | 0.58 | |
| **Pigment** | | | | |
| **Sodium Hydroxide** | 49,697 | Kg/yr | 38 | |
| **Sodium Carbonate or Soda Ash** | 42,595 | Kg/yr | 33 | |
| **Enzymes** | 9,861 | Kg/yr | 8 | |
| **Salt–Sodium Chloride** | 357,734 | Kg/yr | 277 | |
| **Salt–Sodium Sulfate** | 867 | Kg/yr | 2015 | |
| | 0.67 | | 2015 | |
| **Surfactant** | 13,395 | Kg/yr | 10 | |
| **Acid (Specify type in "Notes/ Comments" column)/Neutralizer** | 9,269 | Kg/yr | 7 | Acetic Acid |
| **Silicone Softener** | 258733 | Kg/yr | 200 | |
| **Cationic Softener** | 232860 | Kg/yr | 180 | |
| **Other Softener** | 297543 | Kg/yr | 300 | Non-ionic softener |
| **Recycled Material** | | | | |
| **Other Chemicals** | 142303 | Kg/yr | 110 | Sodium Hydrosulphite |
| **Other Inputs** | | | | |
| **Energy Inputs** | Amount | Units | MJ/1,000kg | Notes |
| **Electricity** | 6,765,764 | MJ/yr | 5230 | |
| **Heating Fuel** | | | | |
| **Fuel Oil** | | | | |
| **Natural Gas/LNG (liquid Natural Gas)** | | | | |

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| Material Inputs | Amount | Units | Kg/1,000kg | Notes |
|---|---|---|---|---|
| LPG (Liquified Petroleum Gas) | | | | |
| Propane | | | | |
| Coal | | | | |
| Diesel | | | | |
| Gasoline | | | | |
| Heavy oil | | | | |
| Wood/biomass | | | | |
| Methane | | | | |
| Imported Steam (steam you do not produce) | 36,702,835 | MJ/yr | 28,371 | |
| **Material Outputs** | Amount | Units | Kg/1,000kg | Notes |
| Dyed Fabric | 1,293,667 | Kg/yr | 1000 | |
| Fabric Waste Sent to Recycling | 136,800 | Kg/yr | 106 | |
| Fabric Waste Sent to Landfill or Incineration | 16,200 | Kg/yr | 13 | |
| Water (recycled internally) | 92,961 | m3/yr | 71,859 | |
| WasteWater (sent to onsite or shared industrial wastewater treatment plant) | 216,910 | m3/yr | 167,671 | |
| WasteWater (sent to municipal wastewater treatment plant) | | | | |
| WasteWater (discharged directly to surface water) | | | | |
| Other Outputs | 25,873 | Kg/yr | 20 | Cardboard, paper, wire, dust, scrap, pallets, glass |
| $NH_3$ | 1,300 | Kg/yr | 1 | |
| BOD | 3,600 | Kg/yr | 3 | |
| COD | 1,500 | Kg/yr | 1 | |
| Total Dissolved Solids (TDS) or Salt | 4,300 | Kg/yr | 3 | |
| Total Suspended Solids (TSS) or Turbidity | 1,100 | Kg/yr | 0.85 | |
| Other Wastes or Emissions | | | | |

# **7.7** ANNEX G: ASSESSMENT OF WATER USE–TERMINOLOGY AND METHOD

## Introduction

Freshwater scarcity is recognized as one of the most pressing environmental issues today and in the future. There is an increasing interest in the LCA community to assess water use from a LCA perspective.

In August 2014, a new standard under the 14000 series (environmental management) was released by the ISO (International Organization for Standardization): ISO 14046 on Water Footprint (ISO, 2014). The standard specifies principles, requirements, and guidelines related to water footprint assessment of products, processes, and organizations based on life cycle assessment (LCA). A water footprint assessment conducted according to this international standard:

- is based on a life cycle assessment (according to ISO 14044);
- is modular (i.e. the water footprint of different life cycle stages can be summed to represent the water footprint);
- identifies potential environmental impacts related to water;
- includes relevant geographical and temporal dimensions;
- identifies quantity of water use and changes in water quality; and
- utilizes hydrological knowledge.

The ISO 14046 does not specify particular methods or impact assessment categories that need to be applied or considered to meet the above stated requirements.

This study follows the terminology and principles outlined in ISO 14046, and uses methods that are aligned to this standard.

## Terminology

According to these publications, the following terms are used:

- **Water use:** Use of water by human activity: Use includes, but is not limited to, any water withdrawal, water release, or other human activities within the drainage basin impacting water flows and quality.
- **Water consumption:** Water removed from, but not returned to, the same drainage basin. Water consumption can be because of evaporation, transpiration, product integration, or release into a different drainage basin or the sea. Evaporation from reservoirs is considered water consumption.
- **Surface water:** Water in overland flow and storage, such as rivers and lakes, excluding seawater.
- **Groundwater:** Water which is being held in, and can be recovered from, an underground formation.
- **Green water:** Refers to the precipitation on land that does not run off or recharges the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Green water can be made productive for crop growth.
- **Blue water:** Refers to water withdrawn from ground water or surface water bodies. The blue water inventory of a process includes all freshwater inputs but excludes rainwater.
- **Fresh water and sea water:** "Fresh water" is defined as water having a low concentration of dissolved solids (ISO 14046)[3]. This term specifically excludes sea water and brackish water.

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[3] Freshwater typically contains less than 1 000 mg/l of dissolved solids and is generally accepted as suitable for withdrawal and conventional treatment to produce potable water (ISO 14046).

[4] Note: Typically, only water from irrigation is considered in the impact assessment of agricultural processes and the consumption of rain water is neglected. The rationale behind this approach is the assumption that there is no environmental impact of green water (i.e. rain water) consumption. Such an effect would only exist if crop cultivation results in alterations in water evapotranspiration, runoff and infiltration compared to natural vegetation. Additionally it remains arguable whether or not such changes (if they occur) should be covered by assessment of land use changes rather than in water inventories. However, rain water use is sometimes assessed in different methodological approaches or can be used for specific analyses.

### Consumptive and Degradative Use

“Fresh water use” is differentiated into
“fresh water consumption” and
“degradative water use”:

- “Fresh water consumption” describes all freshwater losses on watershed level which are caused by evaporation, evapotranspiration from plants[4], freshwater integration into products, and release of freshwater into sea (e.g., from wastewater treatment plants located on the coast line). Note that only “Fresh water consumption”, not sea water, is relevant from an impact assessment perspective because fresh water is a limited natural resource.
- “Degradative water use”, in contrast, denotes the use of water with associated quality alterations and describes the pollution of water (e.g., if tap water is transformed to wastewater during use). These alterations in quality are not considered to be water consumption.

### Water Scarcity Footprint

Water consumption is considered to have a direct impact on the environment (e.g., freshwater depletion and impacts to biodiversity). The blue water consumption can be derived directly from the LCA inventories (water use/input minus water released back into the watershed, excluding rain water).

In the assessment of water consumption it is crucial where the water consumption takes place. In water abundant areas the effects of water consumption will have a very low impact, while in dry areas the effects will be large. In this study, this difference is addressed by applying the “water stress index” (WSI) developed by Pfister 2009. The water stress index is based on a withdrawal to availability ratio and takes into account temporal variability of water availability. WSI values between 0 and 0.1 are classified as “no water stress”. Values between 0.1 and 0.5 indicate “moderate water stress”. Values from 0.5 to 0.9 stand for “severe water stress” and values >0.9 indicate “extreme water stress”. The global average WSI value is 0.602, indicating that the world as a whole is already under severe water stress.

The water stress index is used to characterize water consumption according to regional availability. Then normalization is applied by using the global average water stress index (Pfister 2009). The resulting unit is kg of water equivalents (kg water eq.)

$$WSF = \sum_i \frac{CWU_i \times WSI_i}{WSI_{global}}$$

WSF: water stress footprint of the product

$CWU_i$: consumptive water use–regional

$WSI_i$: water stress index–regional

$WSI_{global}$: global average water stress index (value: 0.602)

# 7.8 ANNEX H: COTTON INCORPORATED CONTRIBUTORS

## Cotton Production

**Barnes, Ed**[5]–Agricultural Engineer

**Hake, Kater**–Cotton Physiologist

**Kurtz, Ryan**–Entomologist

## Textile Production

**Ankeny, Mary Ann**–Dyeing and Finishing

**Cagle, Christine**[6]–Textile Supply Chain

**Clapp, David**–Fiber Processing

**Ekizceleroglu, Recep**–Turkish Mill Contacts

**Flores, Jaime**–Latin American Mill Contacts

**Johnson, Yvonne**–Fabric Production

**Kwan, Bonny**–Asia Mill Contacts

**Lin, Jerry**–Asia Mill Contacts

**Ngai, Spike**–Asia Mill Contacts

**O'Regan, Jan**–Nonwovens

**Tyndall, R. Michael**–Dyeing and Finishing

**Wallace, Michele**[7]–Life Cycle Assessment Certified Professional

## Consumer End-Use

**Bastos, Melissa**–Consumer Market Research

**Martin, Vikki**–Laundering

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[5] Contributions extend to overall management of the project throughout the supply chain

[6] Contributions extend to overall management of the project throughout the supply chain

[7] Contributions extend to overall management of the project throughout the supply chain

Final data analysis and results interpretation lead by Dr. Jesse Daystar, consultant for Cotton Incorporated and Assistant Director at the Duke University Center for Sustainability and Commerce.

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