Sustainable Apparel Materials

An overview of what we know and what could be done about the impact of four major apparel materials: Cotton, Polyester, Leather, & Rubber[1]

Randolph Kirchain, Elsa Olivetti, T Reed Miller and Suzanne Greene

Materials Systems Laboratory
Massachusetts Institute of Technology
Cambridge, MA

September 22, 2015

---

[1] This document does not represent original scholarly research. It was created to catalyze a dialogue on the challenges surrounding sustainable materials production and use. The authors hope that this document inspires some within the materials community to begin to understand and act upon those challenges.

Sustainable Apparel Materials

An overview of what we know and what could be done about the impact of four major apparel materials: Cotton, Polyester, Leather, & Rubber

Randolph Kirchain, Elsa Olivetti, T Reed Miller and Suzanne Greene

Materials Systems Laboratory | Massachusetts Institute of Technology | Cambridge, MA

Material Patterns

An Introduction to the Economic, Environmental, and Social Impacts of the Global Textiles Industry by Randolph Kirchain and Elsa Olivetti

Around 2010, global extraction of non-fossil resources[2] exceeded 60 billion tonnes, or nearly 10 tonnes per person per year. (SERI 2013) In aggregate, the burden of extracting, winning, and fashioning those materials accounts for over one third of global anthropogenic carbon emissions (Sassoon, Hermann et al. 2009), not to mention their corresponding impacts on land use and the release of water and air toxics and solid waste. The magnitude of these impacts conclusively shows that materials are one core driver of the environmental challenge facing the world in the twenty-first century.

This challenge puts the materials community – that is, the industries and individuals who work with or make decisions around materials – in a unique position to enable sustainable patterns of consumption. Materials are not simply a bundle of physical properties; materials influence the manner in which a product is fashioned, the form of that product, and, ultimately, its performance while in use. As a result, manipulating materials can revolutionize the nature of commerce, its interaction with the environment, and the character of resource use. Materials can change the rules of the game and no industry is better positioned to address the world's sustainability challenges.

Few industries provide a more immediate image of the pervasive impact of materials than those we turn to on a daily basis to clothe us. The textiles and apparel industry and the materials on which they rely all have important economic, environmental and social impacts throughout the globe.

Economic

In 2010, the global apparel industry produced more than 150 billion garments, enough to provide more than twenty new articles of clothing to every person on the planet. At that scale, it is not surprising that the market for textiles is critical to the world economy. In fact, it is estimated that in 2010 the textiles and apparel market had revenues in excess of $1.8 trillion dollars (AM Mindpower 2010).

Within this market, one of the best-documented sectors is apparel production. These data reveal the global nature of the textiles trade and, in particular, the uneven distribution of production and consumption across the planet. More than two-thirds of revenue for apparel producers derives from export trade. Unsurprisingly, this means that garment manufacturing is geographically removed from major garment markets. As Figure 1 shows, more than 60% of production is carried out in East Asia, while about 60% of consumption occurs in the EU, the US, and Japan (with China rapidly becoming a large consumer as well). (Gugnami and Mishra 2012)

---

[2] The SERI analysis includes extraction of metal ores, industrial and construction minerals, and biomass (from agriculture, forestry and fishery). Resources 2014, 3, 319-339; doi:10.3390/resources3010319

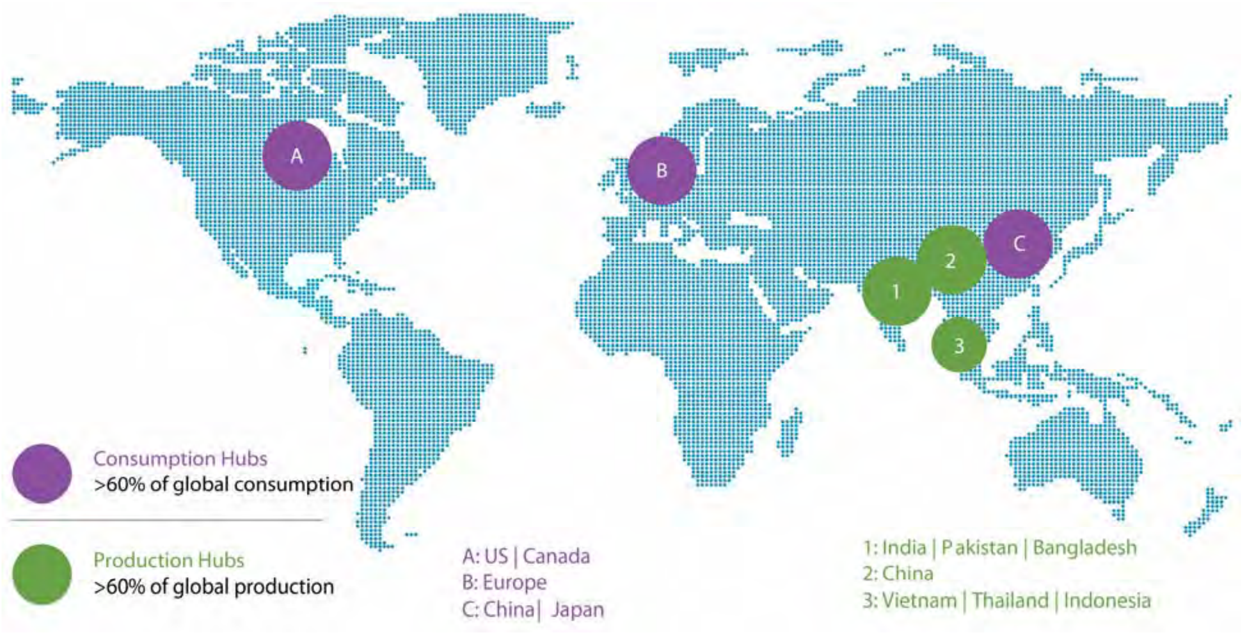


Figure 1. Concentration of global production and global markets for apparel. (Figure from Gugnami and Mishra 2012: pg 5)

Environment

"A single mill can use 200 tons of water for each ton of fabric it dyes. And rivers run red--or chartreuse, or teal, depending on what color is in fashion that season--with untreated toxic dyes washing off from mills."(NRDC 2011)

By 2015, the global apparel industry is expected to produce more than 400 billion square meters of fabric per year, representing nearly enough material to cover the state of California annually. These fabrics will be produced from nearly 100 million tonnes of fiber and filament yarns, about 40% of which are agriculturally derived (i.e., cotton, wool, …) and 60% synthetic (i.e., polyester, nylon, …). (Gugnami and Mishra 2012)

This scale of production directly establishes the scale of the industry's environmental impact. Although much work still needs to be done to fully characterize the magnitude of the burden, and there is a great range in terms of practices, including firms that are quite responsible. A rough analysis from 2009 estimates that the global industry consumes nearly 1 billion kWh of electricity or 130 million tonnes of coal, making the apparel industry a significant contributor to global greenhouse emissions. (O Ecotextiles 2009)

One key resource utilized by the textiles industry is water. In 2009, the *New York Times* (reporting on a California study) revealed that several dozen gallons (or more than 400 pounds) of water were required to process one pound of textiles. (Peters 2009) Mapping this consumption rate onto the countries where production is concentrated shows that the industry's use and discharge rates constitute a significant fraction of available water resources. As an example, in 2009, textile production ranked third among major industries in China in terms of total wastewater discharge, emitting over 2.5 billion tonnes, primarily from the dyeing and finishing steps of manufacture. (IPE 2012)

Social

"Apparel production is a springboard for national development, and often is the typical starter industry for countries engaged in export-oriented industrialization."(Gereffi and Frederick 2010)

The low barriers to entry that make textile and apparel production so pervasive also make scoping and quantifying its full social impact nearly impossible. However, even conservative estimates suggest that this industry directly employs more than 40 million people worldwide. In some developing countries, the textiles and apparel industries are a particularly important source of manufacturing employment, which is often associated with lifting individuals out of poverty. Key examples of this include Cambodia (80.1%), Mauritius (72.8%), Sri Lanka (49.2%), Bangladesh (35%), Pakistan (42.9%), and Madagascar (45%). (McNamara 2008) The derivative effects of this scale of employment are clearly immense. The government of India has estimated that every direct textile industry job means another 1.2 jobs in allied industries (e.g., machinery, design, transport). (Gugnami and Mishra 2012)

The societal impact of this kind of work cannot be understated. In a detailed study of the textiles industry in Madagascar, Alessandro Nicita and Susan Razzaz (World Bank) found that moving from inconsistent, subsistence, or marginal employment to a job within the textiles and apparel production industry would increase an individual's purchasing power by 24% on average – a change sufficient to lift them out of poverty. (Nicita and Razzaz 2004; Nicita 2008)

Digging deeper

The next sections of this document take a more detailed look at four major materials employed in the apparel industry today. These are

- Cotton
- Polyester
- Leather
- Rubber

Specifically, each of the following sections explores one particular issue of environmental sustainability – greenhouse gas (GHG) emissions – for each of these materials. For GHG emissions, each section identifies the environmental hotspots within production supply chain, the drivers of those hotspots, and a sense of how these numbers could shift in coming years. Finally, each section provides recommendations for mitigating current and future impacts.

AM Mindpower (2010). Global Apparel and Textile Industry, AM Mindpower Solutions.

Gereffi, G. and S. Frederick (2010). "The global apparel value chain, trade and the crisis: challenges and opportunities for developing countries." World Bank Policy Research Working Paper Series, Vol.

Gugnami, A. and A. Mishra (2012). Textile & Apparel Compendium 2012, Technopak.

IPE (2012). Cleaning up the Fashion Industry. Beijing, Institue of Public and Environmental Affairs.

McNamara, K. (2008). The Global Textile and Garments Industry: The Role of Informati on and Communic ati on Technologies (ICTs) in Exploiting the Value Chain, infoDev.

Nicita, A. (2008). "Who Benefits from Export-led Growth? Evidence from Madagascar's Textile and Apparel Industry†." Journal of African Economies **17**(3): 465-489.

Nicita, A. and S. Razzaz (2004). "Who benefits and how much? How gender affects welfare impacts of a booming textile industry." How Gender Affects Welfare Impacts of a Booming Textile Industry (April 15, 2003). World Bank Policy Research Working Paper(3029).

NRDC (2011) "Green Fashion: Beautiful on the Inside." Smarter Living.

O Ecotextiles (2009). Carbon footprint of the textile industry. O ECOTEXTILES: Indulgent Yet Responsible.

Peters, S. (2009). Cutting Water Use in the Textile Industry. New York Times.

Sassoon, R. E., W. A. Hermann, et al. (2009). "Quantifying the Flow of Exergy and Carbon through the Natural and Human Systems." MRS Online Proceedings Library **1170**(1170-R01-03).

SERI (2013). Global resource extraction by material category. materialflows.net.

Cotton

Global Climate Impacts of the Apparel Supply-chain

Summary

How clean is your cotton t-shirt? As with most things, the answer is *it depends* – on geography, scope of what you consider, energy source, and so on. Taking these factors into account, we found that across many studies the most significant environmental impacts of cotton reported were greenhouse gases emitted during the manufacturing phase, water use within agriculture and manufacturing, and fertilizer/pesticide use within agriculture. Although all of these issues are important, this document explores, in detail, the magnitude and nature of the climate change burden of cotton.

On average, the climate impact of one t-shirt is roughly equal to the carbon footprint of driving a passenger car for 10 miles. However, the level of impacts varies significantly based on the region where the production activities occurred. For example, cotton produced in a factory powered by an old, inefficient coal boiler will have a higher impact on climate change than cotton produced in a factory powered by renewables. (Notably, only a small fraction of production facilities receive their power from renewables.)[3]

While one t-shirt may seem insignificant, the scale of the use of cotton in the apparel industry as a whole is certainly not. Industry-wide, greenhouse gas emissions in one year are equivalent to driving to the sun and back more than 1,000 times or taking nearly 10% of the US's cars and light trucks off the road. With demand expected to grow in the coming years, and production expected to shift to less energy efficient regions, cotton's impact could grow by more than 50%.

This report focuses on the greenhouse gas emission hotspots within cotton production, the drivers of those hotspots, and a sense of how these numbers could shift in coming years. Recommendations for mitigation are suggested, according to leading practitioners that could harness innovative technology and sustainable agriculture in an effort to reduce the burden of cotton on our environment.

Snapshot: Cotton Life Cycle

Grown on farms in China, India, U.S., and beyond, cotton comes a long way before it hits the shelves. To understand the environmental impact of a product with a long and complex supply chain, like cotton, scientists turn to a method called life-cycle assessment (LCA). LCA attempts to

---

[3] http://www.unido.org/fileadmin/user_media/Services/Energy_and_Climate_Change/Energy_Efficiency/Renewables_%20Industrial_%20Applications.pdf"

Figure 2 The primary life cycle stages of cotton.

capture the entirety of a product's impact by tracking the impacts associated with every activity needed to create, use, and dispose of the product, demonstrated in Figure 2. To trace cotton's life cycle, studies have collected data on each activity along the chain of production, from the farm to the recycling bin. Most studies highlight greenhouse gas emissions in the manufacturing stage, the focus of this report, as a hotspot, or activity with relatively higher impact. However, water use in agriculture, land management practices, including pesticides, fertilizers, and, land degradation, as well as manufacturing chemicals are also relevant issues to consider in some contexts.

To identify the environmental hotspots for cotton, we first explore the cradle-to-gate impact of producing a single cotton t-shirt.[4] To understand the global implication of those impacts, we then scale the impact of the t-shirt to the volume of the apparel industry both as it is today and as it is expected to be in the future, as illustrated by (Figure 3). Market data are used to make projections in order to see what the impacts might look like in the future. Understanding impacts within a global context provides an important perspective when trying to understand the relative impact of one's role within the industry as a whole, as consumer or as company.

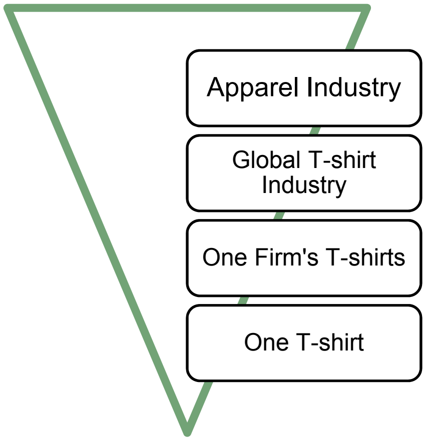


Figure 3 The scale of impacts from one t-shirt to the cotton industry as a whole.

Greenhouse Gas Emissions

Life Cycle Assessment

To understand the global warming potential (GWP) of a cotton t-shirt, the greenhouse gas (GHG) emissions of all climate change relevant gases for all life cycle activities are estimated then expressed in terms of CO_2 equivalents (CO_2-eq). A recent life cycle assessment by Cotton Inc.(Cotton Incorporated 2012) considered the greenhouse gas emissions during three primary phases of cotton production.[5]

Cotton Inc. estimated the GWP of one kilogram of manufactured dyed knit or woven cotton fabric to be 10.8 kg CO_2-eq, which translates into 4.3kg CO_2-eq per t-shirt. (A t-shirt weighs approximately 0.4 kg(Knowledge Cotton Apparel).)

Hotspots

Cotton's cradle-to-gate GHG emissions are concentrated within the manufacturing stage (more than 80% of total emissions). In particular, the process by which raw cotton is transformed into yarn, open-end spinning, as well as the dyeing and weaving processes, consume relatively high amounts of energy – this energy consumption generates 60% of the total manufacturing emissions. Of course, the exact carbon emissions for a particular factory depends on the local energy source, i.e. a factory running on coal would have a higher impact than one running on wind energy. Error bars in Figure 4 account for this type of uncertainty within the results.

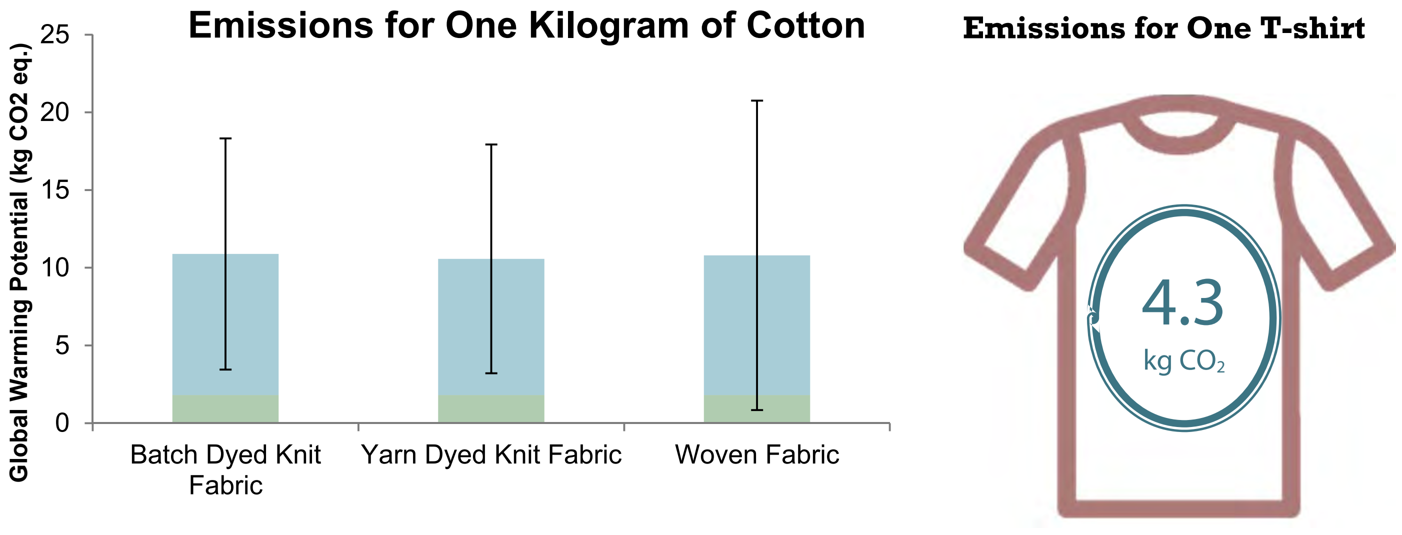
The Cotton Inc. study considered the end-of-life of cotton simply in terms of its eventual release of biogenic carbon[6] from landfilling or incineration, not potentially recycling or other forms of reuse. The remainder of the impact is made of up the emissions related to agricultural production, such as operating farm machinery or producing fertilizer.

---

[4] Cradle-to-gate refers to the life cycle steps between the farm and the factory.

[5] In this case, the manufacturing phase does not include the actual cutting and sewing of fabric, so these results are "cradle-to-factory gate".

[6] Biogenic carbon is that sequestered into the cotton fiber as it grows is considered equal to and offsets the eventual carbon released at the end-of-life.



****Assuming roughly 2.5 t-shirts to 1 kg cotton***

Figure 4 Greenhouse gas emissions are the most significant during the manufacturing phase (Own analysis, based on [1]).

So What?

So the GHG emissions are 4.3 kg CO_2 per t-shirt, but what does it all mean? How does your t-shirt measure up? To get an idea of the scale of the impact of one t-shirt, Figure 5 shows its equivalent in terms of other common impacts, based on the EPA's GHG Equivalencies Calculator (US EPA 2014). From this we can see that the burden of the cotton in one shirt is equivalent to driving a passenger car more than 10 miles.

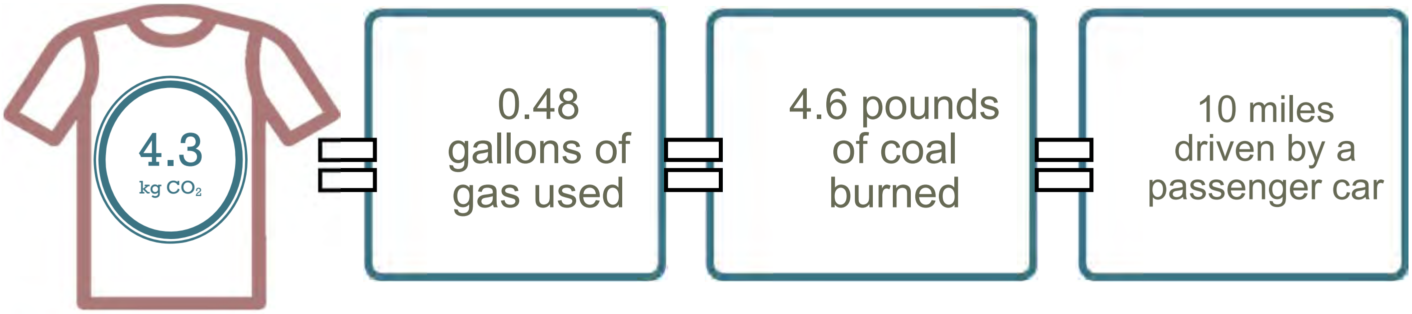


Figure 5 Equivalent impacts to the cradle-to-gate impact of one t-shirt's worth of cotton.

Cotton's Present and Future Impact

So far, we have considered the impact of cotton in terms of the production of one t-shirt. With more than 150 billion garments produced each year, it's helpful to scale the t-shirt's impact to the cumulative results for the apparel industry as a whole to put that figure in perspective.

Global Emissions

In 2013, 25 billion kilograms of cotton was produced worldwide. Approximately 40% of that, or about 10 billion kilograms, was used in making apparel. At that scale, the estimated cradle-to-gate impact of cotton used within the global apparel industry is 107.5 million tons of CO_2-eq. While the impact of one t-shirt may have seemed small, the combined impact of cotton in the apparel industry is much more significant. Figure 6 helps to put these large numbers into perspective. For instance, this annual figure of over 100 Mt CO_2-eq represents the same climate-related burden as about 25 coal fired power plants or the electricity to power nearly 12% of American homes. Compared to transportation related activities, that burden is equivalent to more than 250 billion miles driven by the average car, enough to drive to the sun and back more than 1,000 times. From a more grounded perspective, that level of driving is double the burden of all passenger cars in New York State. No matter what we compare it to, more than 100 million tons of CO_2 burden is significant.

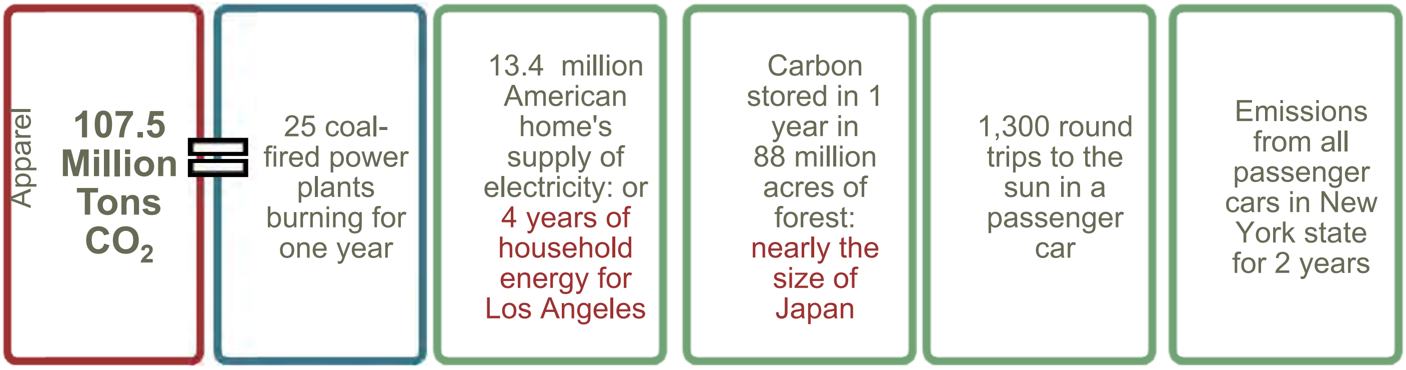


Figure 6 Equivalent greenhouse gas impacts of cotton's use in the global apparel industry

Future Projections

Considering expected increases in demand for apparel, Figure 7 projects the future change in emissions for knit or woven fabric, from cradle to gate, showing a significant increase in just the next decade.(Cotton Incorporated 2012; National Cotton Council of America 2014) Given these trends, if the industry does not change practices, the use of cotton in the global apparel industry will generate nearly 160 Mt of CO2e per year by 2030. That level of emissions is equivalent to the equivalent of the annual emission of more than 40 coal-fired power plants or more than 33 million passenger cars. These figures make it clear that, as with all materials, it will be critical to develop and implement strategies to reduce the impact of this important industry.

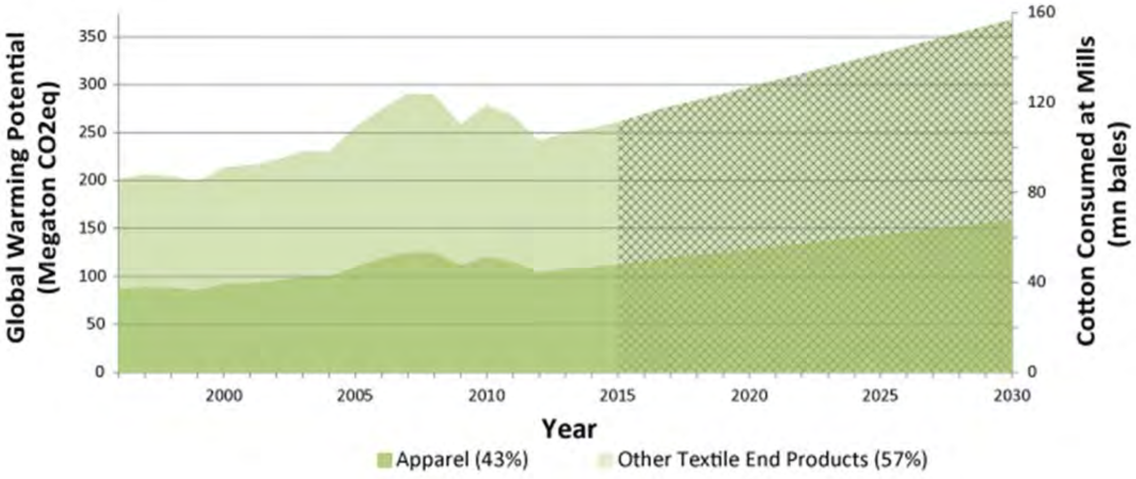


Figure 7 Historic and projected growth of cotton consumption and greenhouse gas emissions for both apparel and other

textile products.

Uncertainty from Geographical Trends

The geography of the production and consumption of cotton is both globally distributed and shifting. Perhaps the most important trend is in production location specifically, sub-Saharan Africa, Brazil, and India are expected to increase their cotton production while a significant decline is expected in industry-leader China and continued declines in Europe.(Business Monitor International 2014)

This dynamic may alter the impact of the apparel sector as time goes on. As mentioned earlier, a cotton manufacturing plant is primarily only as dirty as its energy source; a factory that runs on coal will have a much higher impact than one that runs on renewable energy. Thus as production shifts location, it also shifts from one electrical grid to another. Unfortunately, there is insufficient information at this time to quantify this impact. Nevertheless, these trends should be monitored closely.

Recommendations for Cotton Impact Reduction

Reducing the impact of cotton can be accomplished through various fronts. The hotspots highlighted in this report of manufacturing energy, manufacturing water use, and others all have possible solutions. As with any large industry, though, it will be challenging to implement meaningful changes on a global scale. Nevertheless, the first step in that journey is to identify the possibilities. This section will provide an overview of recommendation for change that were identified in the sources reviewed within this report. Clearly, these recommendations require further evaluation on their potential effectiveness and appropriateness, especially in light of the broad geographic scope of the cotton industry. They are included here in hopes of spurring further inquiry into these and other options for moving the cotton industry into a more sustainable future.

Transition to low-input organic management system cotton farms

To aid in deciding which type of agricultural production system to implement for a particular cotton farm, comparing several types on a wide variety of environmental metrics shows that low-input organic management systems (sustainable water sources such as rain, optimum yields, sophisticated fertilizer) have a slight or negligible impact potential, while on the other extreme high-input conventional farming have highly or moderately important impact potential. As of 2006, only 0.04% of cotton farms worldwide were organic.(Kooistra, Termorshuizen et al. 2006) Encouraging the use of location appropriate water-saving measures may also help make improvements, as well as supporting NGOs and government policies that further improve sustainable agriculture.

Partner with Organizations such as Better Cotton Initiative and Textile Exchange

Existing organizations have an understanding and action plans to improve cotton production. According to the Cotton Inc. report, the largest single contributor to agricultural global warming impact (1/3 of the impact) is associated with fertilizers. Low-input organic farming utilizes sophisticated fertilizer practices, and therefore can be expected to best reduce the agricultural global warming impact. Looking at Figure 3, the manufacturing stage dominates the impact, though, so reducing energy consumption at that stage is also important. The Better Cotton Initiative includes principles that farmers minimize impact of crop protection practices, use water efficiently, care for the health of the soil, preserve the quality of the cotton fiber and promote Decent Work. Textile Exchange provides resources to promote organic cotton farming. Supporting these organizations, especially those with local contingents, could help to expand sustainability measures more quickly.

Use coarser yarns

Reducing manufacturing energy demand will reduce both the GWP and the water indirectly degraded. "Thinner yarn is related to higher energy demand per kilogram"(van der Velden 2014). "The yarn count being produced may be one of the most significant variables to consider. Production rate is directly linked to yarn count. Coarser yarns not only produce the greatest mass per unit time (or unit energy) but they are also less sensitive to [raw material choice, level of processing and technical knowledge, capital investment, and spinning system]."(Cotton Incorporated 2012)

Key Data Gaps: Cotton

This report aims to summarize the information within recent and relevant studies on cotton and to project these data into the future; however, gaps within available data should be considered when reviewing results. We first present a summary of the studies that were reviewed in presenting the conclusions shown in this report.

Reference	Scope	Data Regions	Data Years	Inclusion and Data Usage
Environmental analysis of a cotton yarn supply chain. Bevilacqua et al. 2014	Cradle-to-Grave Life Cycle Assessment indicators	Four farms with regional best practices in Egypt, China, India and the USA	2005-2012	Included Data not used since not representative
Life Cycle Assessment of Cotton Fiber & Fabric: Full Report. Cotton Inc. 2012	Cradle-to-Grave Life Cycle Assessment indicators	Global average data. China, India, US used for agricultural data.	2005-2009	Included Data used extensively since comprehensive and representative
The sustainability of cotton: Consequences for man and environment. Kooistra et al 2006	Environmental impact indicators for agricultural impact comparing cotton production systems	Global comparison	2005	Included Some data on farming systems used; little primary data
Environmental impacts of textile industries. Pavarthi et al 2009	Categorization of pollutants from textile manufacturing	Ambiguous	Ambiguous	Included Categories of pollutants mentioned
Environmental Impacts in the Fashion Industry: A Life-cycle and Stakeholder Framework. Kozlowski et al. 2012	"Conceptual and analytic framework for conflating life-cycle and stakeholder analysis to develop responses from the	n/a	n/a	Not included Conceptual, not primary data

Reference	Scope	Data Regions	Data Years	Inclusion and Data Usage
	fashion industry”			
EDIPTEX – Environmental assessment of textiles. Danish EPA 2007	Cradle-to-grave LCA of six Danish textile products	Global/regional average agriculture, manufacturing in Denmark	Ambiguous	Not included Manufacturing not globally representative; LCA data presented in relative vs absolute terms
LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. van der Velden et al. 2013	Comparison of textile life cycle data across literature and databases. Calculations output in Ecocosts, CO2, CED, and ReCiPe.	Global data comparison. European electricity used for calculations.	Sources from 1980s to present	Included Insights from global data related to global warming and yarn thickness
The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Chapagain et al 2006	Water footprint analysis of cotton agriculture based on rainfall and water consumption using FAO’s CropWat model	Global with country-specific averages	1997-2001	Included Data used for country-specific water and fertilizer estimates
Life-cycle assessment of continuous pad-dyeing technology for cotton fabrics. Yuan et al 2013	LCA of dyeing cotton fabric. Thorough life cycle data preparation	Jiangsu Province, China	Recent years assumed	Not included Only normalized results presented
Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester. Cherrett et al 2005	Energy, global warming, and ecological footprint cradle-to-gate comparisons for several textiles,	Case studies from around the world	Before 2005	Not included Data outdated and case-study specific
A spatially explicit life cycle inventory of the global textile chain. Steingereger et al 2008	Compares impact of production phase to use phase using existing impact data.	Production in China and India, use in Germany	2000-2007	Not included Outdated secondary data
Moving down the cause-effect chain of water and land use	Two cotton production systems are compared to	Northwest China	Ambiguous	Not included Case-study

Reference	Scope	Data Regions	Data Years	Inclusion and Data Usage
impacts: An LCA case study of textile fibres. Sandin et al 2012	wood systems. Compares consequential and attributional LCA approach.			specific results
Textiles industrial water footprint: methodology and study. Wang et al 2013	Case study of industrial water footprint of cotton & poly/cotton shirts	Case study of large knitwear manufacturer	Recent years assumed	Not included Case-study specific results
The Deadly Chemicals in Cotton. Environmental Justice Foundation 2007	Description and history of pesticide use and impacts in cotton agriculture	Focus on West Africa, Uzbekistan, and India	n/a	Not focused on climate-related impacts

Understanding the relative consumption of cotton across major consuming industries was a challenge. While one can examine the exports and imports by product category, much of the textile produced in Asian countries is consumed domestically, and thus isn't reflected in the trade statistics. Further, there is not a specific trade category for cotton footwear, though there is a category for footwear with "other" textile uppers. Also, while there is not a single high-level cotton garment trade category, there are a few dozen subcategories that specify cotton content, so those can be summed. Secondly, in order to estimate water and fertilizer use more accurately, more updated estimates of country-level water consumption for cotton are needed. Finally, the predictions for global warming potential would be more accurate if the predicted shifts in production location were included.

References

AM Mindpower (2010). Global Apparel and Textile Industry, AM Mindpower Solutions.

Business Monitor International (2014). "Global: Cotton: Shifting Order to Create Opportunities."

Cotton Incorporated (2012). Life Cycle Assessment of Cotton Fiber & Fabric: Full Report.

Gereffi, G. and S. Frederick (2010). "The global apparel value chain, trade and the crisis: challenges and opportunities for developing countries." World Bank Policy Research Working Paper Series, Vol.

Gugnami, A. and A. Mishra (2012). Textile & Apparel Compendium 2012, Technopak.

IPE (2012). Cleaning up the Fashion Industry. Beijing, Institue of Public and Environmental Affairs.

Knowledge Cotton Apparel Academy: The Study of Sustainable Materials and PRocesses Used in Production by Knowledge Cotton Apparel. Herning, Denmark.

Kooistra, K., A. Termorshuizen, et al. (2006). The sustainability of cotton: Consequences for man and environment, Wageningen University.

McNamara, K. (2008). The Global Textile and Garments Industry: The Role of Informati on and Communic ati on Technologies (ICTs) in Exploiting the Value Chain, infoDev.

National Cotton Council of America. (2014). "Cotton Supply and Demand." Retrieved 7-22-2014, from https://www.cotton.org/econ/cropinfo/supply-demand.cfm.

Nicita, A. (2008). "Who Benefits from Export-led Growth? Evidence from Madagascar's Textile and Apparel Industry†." Journal of African Economies **17**(3): 465-489.

Nicita, A. and S. Razzaz (2004). "Who benefits and how much? How gender affects welfare impacts of a booming textile industry." How Gender Affects Welfare Impacts of a Booming Textile Industry (April 15, 2003). World Bank Policy Research Working Paper(3029).
NRDC (2011) "Green Fashion: Beautiful on the Inside." Smarter Living.
O Ecotextiles (2009). Carbon footprint of the textile industry. O ECOTEXTILES: Indulgent Yet Responsible.
Peters, S. (2009). Cutting Water Use in the Textile Industry. New York Times.
Sassoon, R. E., W. A. Hermann, et al. (2009). "Quantifying the Flow of Exergy and Carbon through the Natural and Human Systems." MRS Online Proceedings Library **1170**(1170-R01-03).
SERI (2013). Global resource extraction by material category. materialflows.net.
US EPA. (2014). "Greenhouse Gas Equivalencies Calculator." from http://www.epa.gov/cleanenergy/energy-resources/calculator.html#resultsepa.gov/cleanenergy/energy-resources/calculator.html.
van der Velden, N. M. P., Martin K.; Vogtlander, Joost G. (2014). "LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane." INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT **19**(2): 331-356.

Polyester

Summary

Polyester is a synthetic textile with raw materials originating from petrochemicals like oil and natural gas. The primary ingredient of polyester, PET, is manufactured into yarn that is knit or woven into textiles.

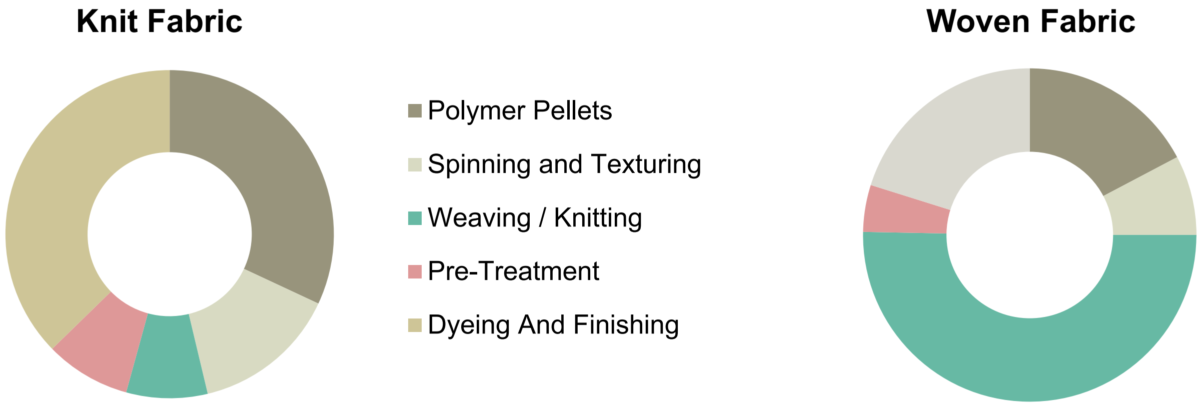


Figure 1 Average proportion of global warming impacts from cradle-to-gate manufacturing of polyester fabric.

The amount of energy used, and thus greenhouse gases emitted, is dependent on the type of fabric produced. Figure 1 demonstrates what numerous studies have shown: weaving requires more energy than knitting, resulting in woven fabric having a higher impact than knit fabrics. The average polyester t-shirt has a global warming impact of 3.8 to 7.1 kilograms of CO_2e, depending on whether it's knit or woven. Globally, production of polyester is large and growing, creating a high global impact stemming from fossil fuel based energy production. Opportunities for reduction come from transitioning to low carbon energy sources, using knit fabrics, and increasing the share of polyester sourced from recycled products.

Snapshot: Polyester Life Cycle

Polyester is a textile made from either natural or synthetic polymers, most commonly polyethylene terephthalate, or PET. PET may sound familiar from its use in plastic water bottles, shampoo containers and the like, which can be recycled to form polyester fibers. Collection of PET bottles for recycling varies widely between countries. For example, in 2009, Germany, Japan, Brazil, and the US collected 94%, 78%, 56%, and 28%, respectively (Welle 2011). In 2007, 8% of the world's polyester production was sourced from recycled PET (Shen 2011). While there is room for growth in PET collection for recycling in most countries, this also demonstrates how much polyester will continue to be manufactured from virgin (or, "first use") PET because of growth in demand.

Unlike cotton and leather, the majority of polyester textiles begin their life at an oil or natural gas well, not on a farm, as Figure 2 shows. Oil or natural gas is processed to form a variety of products, of which PET is one. Once formed, the PET pellets are heated, made into fibers and filament yarns, spun and then textured to resemble cotton or wool yarn. From there, the polyester yarns are woven or knit into textiles, then cut and sewn into the desired clothing design. Knit fabrics are commonly used in "stretchy" clothing like t-shits, sweatshirts, cardigans, and towels. Woven fabrics refer to stiffer textiles like linen, denim and tweed, which only take on stretchy qualities when mixed with more elastic (and often polyester-based) fabrics.

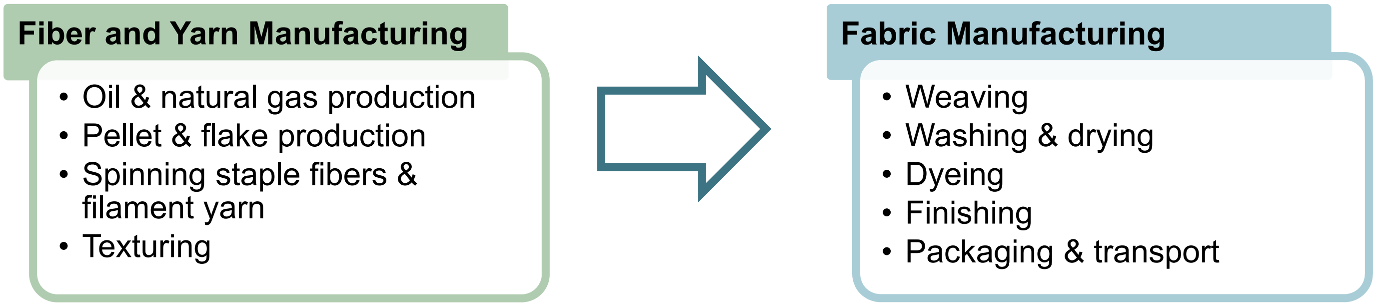


Figure 2 Steps in the polyester manufacturing process (van der Velden 2014).

Global Warming Impact

The bulk of the global warming impact derives from fossil fuels, either to create the polymer pellet feedstock or to generate electricity that runs the production machinery. The amount of electricity required depends on the manufacturing processes needed to create a desired effect in the final material. The biggest driver of this difference is whether the fabric is created by weaving or knitting the polyester fibers. In fact, woven fabric uses over three times as much electricity as knit, as shown in Figure 3 (ITMF 2012). Nearly 80% of all fabric is woven, while only 50% of apparel is woven (technopak 2012). The thickness of the yarn also has an impact. Although it takes less energy to produce a kilogram of fabric with thicker yarn, these yarns tend to be used to create heavier fabrics. Therefore, for the same sized piece of fabric, the heavier fabric with thicker yarn will have consumed more energy and create more global warming impact than the lighter fabric with thinner yarn.

However, it should be noted that the impacts listed here are based on a typical electric grid in order to represent a global average, i.e., one that is has an average mix of greenhouse gas emitting and renewable energy sources. If a manufacturing facility is on a 100% renewable grid, the greenhouse gas emissions have the potential to decrease. Thus, location of manufacturing facilities or on-site use of renewables could make a big difference in the final impact.

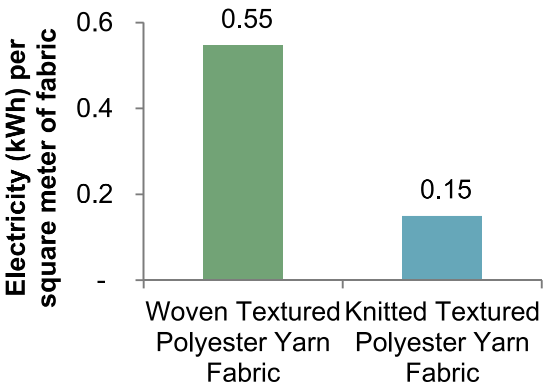


Figure 3: Difference in electricity use based on fabric type.

Polyester's Present and Future Impact

As with other materials, the production of polyester is expected to rise over time based on the popularity of polyester growth in the synthetic fiber industry. The following section describes the history of the market, and how it might grow.

Historical Polyester Production and Future Projections

Polyester is a relatively new textile. Introduced in the 1970s, production has grown steadily since then. Polyester and fiber production reached roughly 40 million tons by 2010, and is projected to nearly double by 2030, as seen in Figure 4 to about 73 million tons, weighing as much as 200 Empire State Buildings!.

Production has always been centered in Asia, with China producing the vast majority of polyester. North America and Northeast Asia once held a larger share of the market, though always under 10% of the total market share, and now reduced to a very small percentage. A rise in production in Southeast Asia can be seen in recent years, though it remains at roughly 10% of the world's production with some indication of continued growth (Tecnon OrbiChem 2014). Other key producers include India, Taiwan, South Korea, Malaysia and Japan (oerlikon 2010).

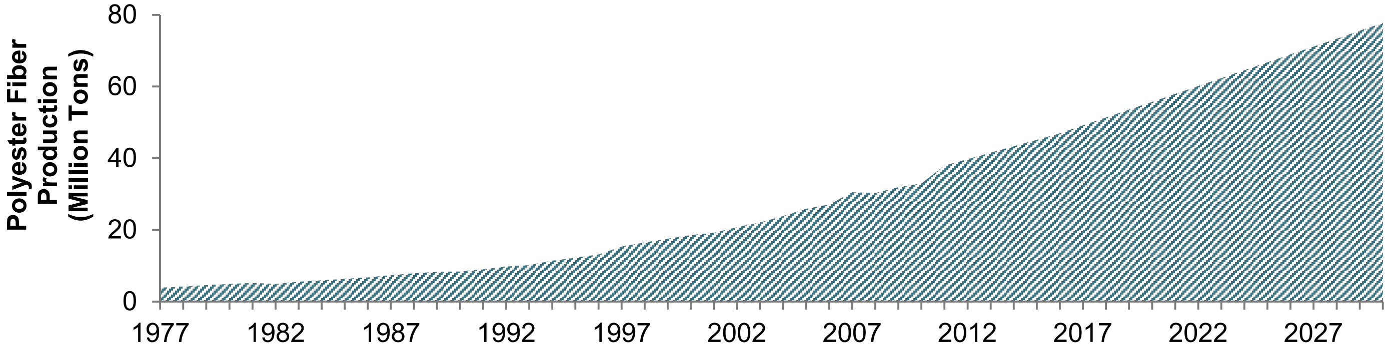


Figure 4 Projected growth in polyester fiber production based on historic trends.

Polyester Industry Today

While we have discussed the impact of polyester in terms of apparel, it has a wide range of uses throughout society. Figure 5 demonstrates the different uses of yarn and fibers, according to different sources. The figure on the left shows the amount of yarn that is used in textiles, including projections of how this might change in the future – short answer, not much will change – textiles remain the primary use of polyester. Nearly 80% of yarn goes to textile, and that number will stay relatively steady over the next ten years. On the right, the fiber market in the US is considered, showing that textile makes up roughly one-third of the market in 2014. Note that these values are not necessarily representative of global values, and that the share of textile used in apparel is not clear from existing data sources; more data from industry can help to fill this gap.

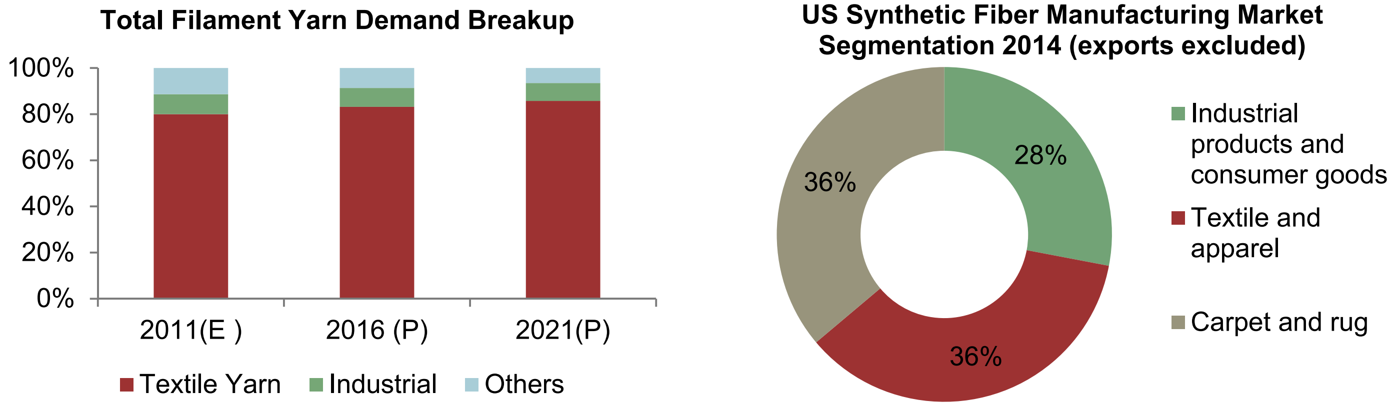


Figure 5 The market breakdown for polyester yarn and fiber. (Left) The global market breakdown, with E referring to estimated production and P referring to projected production. (Right) Market data for US polyester manufacturing.

Global Greenhouse Gas Emissions

As the polyester industry grows, so will its impact. With electricity grids under present conditions, the global impact of polyester fabric will grow from roughly 880 billion kg CO2e today to a projected 1.5 trillion kg CO2e by 2030. Figure 6 shows the historic and projected growth in emissions based on current conditions. Of course if there is a rapid growth in renewable energy in this time, emissions could decline, however projections are based on what is understood today, and will likely remain for the next 15 years.

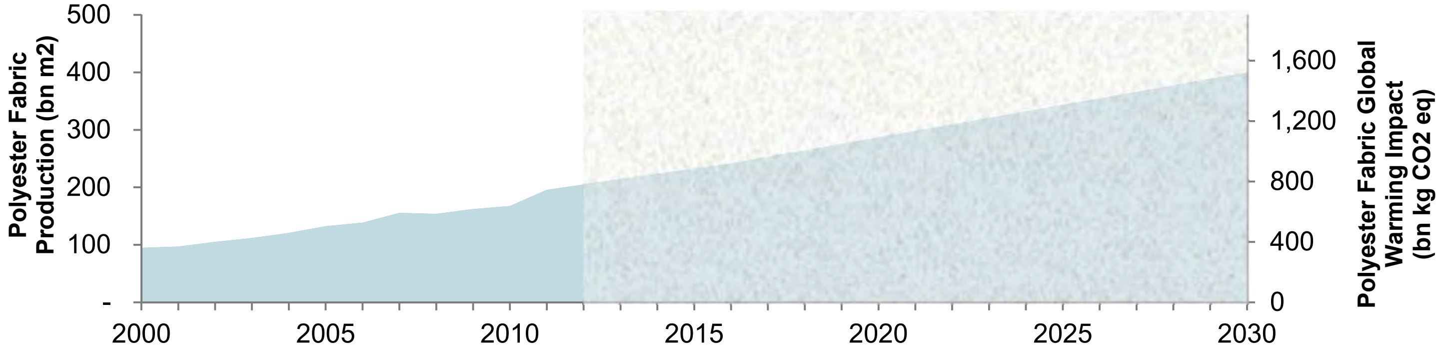


Figure 6 Projected growth in polyester fabric and associated greenhouse gas emissions until 2030. The shaded region indicates forecasted data. Note that while many fabrics are polyester blends, this is for equivalent 100% polyester fabric.

Based on the current marketplace, an estimate 80% of polyester production goes into textile. This includes both textile yarn and staple fibers, which are the primary types of polyester produced. Based on this, we can estimate that over 706 billion kilograms of greenhouse gas can be attributed to polyester production for use in textiles in 2015. As we did before, we will equate this figure to other common impacts with climate change concern, shown in Figure 7.

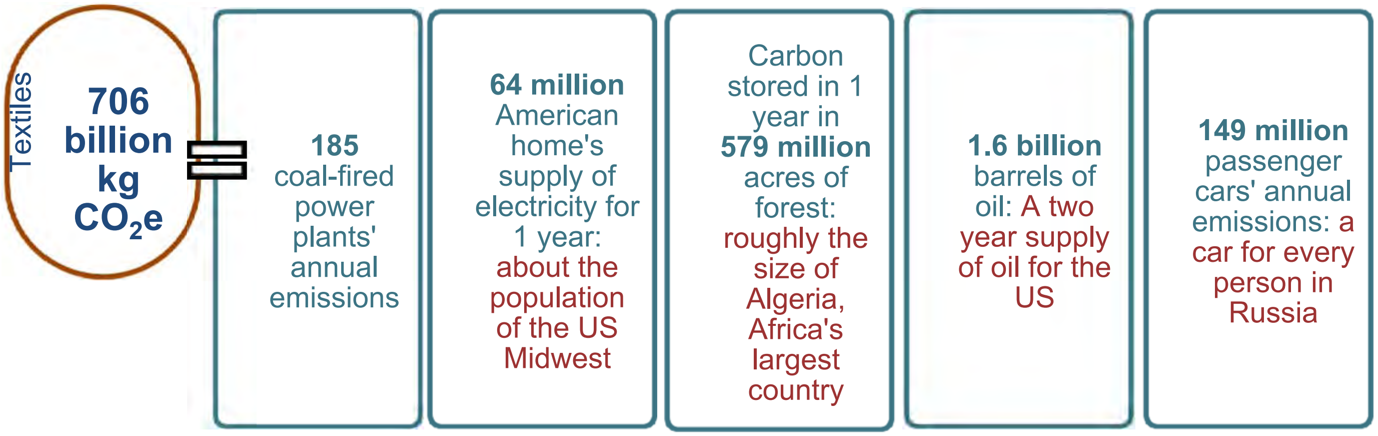


Figure 7 Total impact of polyester used in the textile industry per year.

Greenhouse Gas Emissions of a T-shirt

On average, a polyester-based t-shirt would include 1.7 square meters of polyester fabric, assuming roughly 20% of fabric ends up as scrap. As shown in Figure 8, the impact is highly dependent on whether a t-shirt was knit or woven, as well as how it is treated during the dyeing and finishing phase, then the actual use. With all of these uncertainties in mind, we can estimate the impact of one polyester t-shirt to be 3.8 kg CO_2e if the fabric is knit and 7.1 kg CO_2e if the fabric is woven.

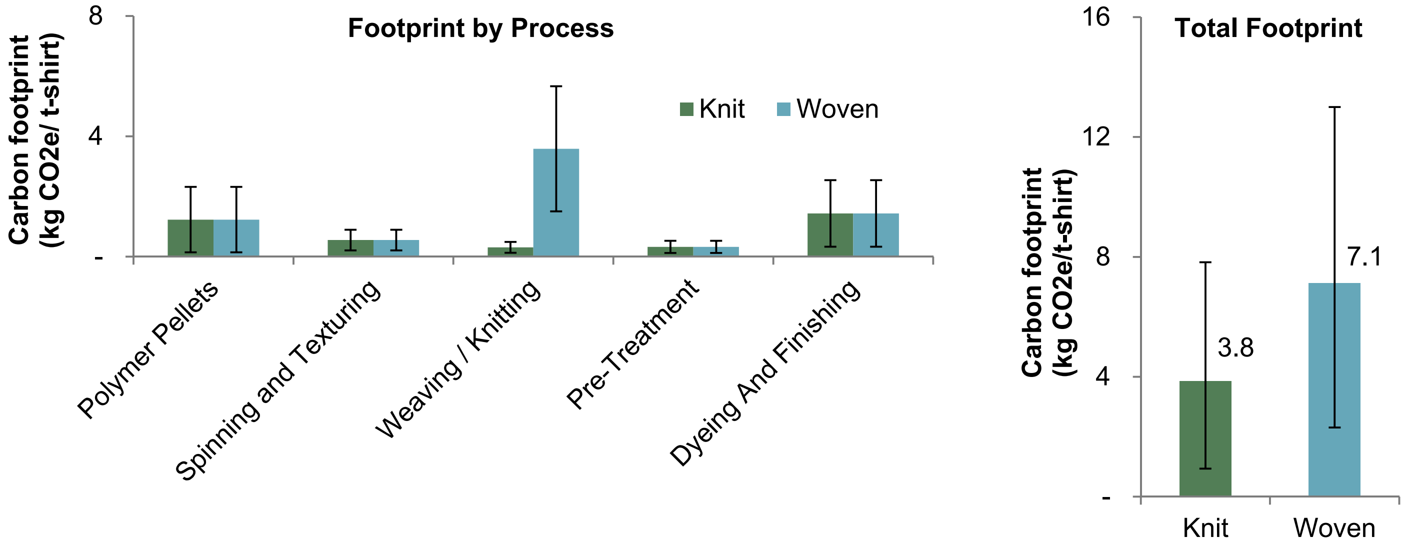


Figure 8 Estimated greenhouse gas emissions for one t-shirt's worth of polyester. The error bars show ranges of uncertainty for various thread weights and processes.

Hotspots

The most significant hotspot in greenhouse gas (GHG) emissions is related to the amount and weight of fabric used in the t-shirt. A heavy woven t-shirt has a higher impact than a light knit tee since it weaving requires more energy than knitting, and a heavy t-shirt uses more yarn than a light t-shirt.

Of course, there are impacts in polyester production beyond GHGs. For example, the production of PET is linked to potential water pollutants, in particular, antimony trioxide. Antimony trioxide is used as a catalyst in polyester production, and can be released during dyeing, distillation and other processes that require heat (Victor Innovatex 2003). The antimony ends up in wastewater, which may or may not be adequately treated, depending on the production location and local water quality guidelines. In the US, there is a limit on antimony levels in surface and drinking water supplies.

Other impacts could come from chemicals used in the dyeing process, similar to cotton textiles. Further impacts could be attributed to the oil and natural gas industry themselves, as they obtain the primary material used to make polyester. Oil and gas production can create impacts such as water pollution, soil contamination, land use change, as well as greenhouse gas emissions related to processing and transporting materials. Air pollution from coal fired power plants is also a concern since it causes acid rain, smog and respiratory health issues, particularly in China (Zhang, Zhang et al. 2015).

So What?

Compared to the emissions of a cotton t-shirt, the polyester emissions are, on average higher. A knit t-shirt emits roughly 20% more greenhouse gas, 3.8 kg CO_2e, while a woven shirt emits twice as much, 7.1 kg CO_2e, for an average of 5.5 CO_2e. To understand how this value compares to other common impacts, we will compare with other values using the EPA's GHG Equivalencies Calculator (US EPA 2014).

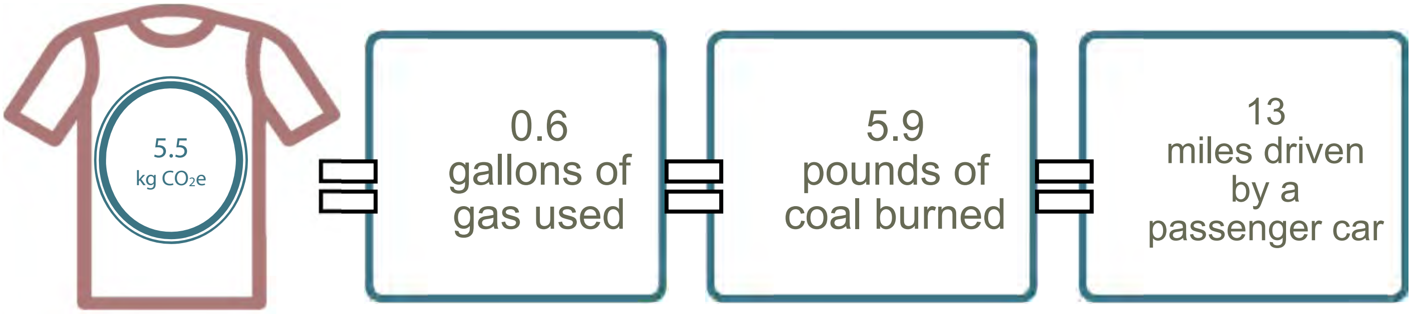


Figure 9 Equivalent impacts to cradle-to-gate impact of one t-shirt's worth of cotton

Recommendations for Polyester Impact Reduction

- Locate manufacturing facilities in areas with lower emission electricity grids, or facilitate lower emissions in existing locations. Polyester is produced in factories, thus grid emissions are the majority of the impact. Cleaner grids equals lower carbon footprint.
- Use more knit fabrics. Knit fabrics require significantly less energy to produce.
- Use lighter weight fabrics which require less energy to produce per area.
- Use all of the recycled PET available, an effort that could include expanding PET collection.
- Encourage PET recyclers to use processes that minimize electricity use (Shen 2011).

Key Data Gaps

- More information is needed on the share of textiles used in apparel.
- Uncertainty is high for the greenhouse gas emissions. To refine our estimates, more information is needed on the production and electricity grid mix, as well as the proportion of yarns at various thicknesses and textiles at various weights.

References

ITMF (2012). International production cost comparison. I. T. M. Federation. Zürich.

oerlikon (2010). The Fiber Year 2009/10: A World Survey on Textile and Nonwovens Industry.

Shen, L. (2011). Bio-based and recycled polymers for cleaner production: An assessment of plastics and fibres, Utrecht University.

technopak (2012). "Textile & Apparel Compendium 2012."

Tecnon OrbiChem (2014). Global Fibres Overview. Synthetic Fibres Raw Materials Committee Meeting at APIC 2014, Pattaya.

US EPA. (2014). "Greenhouse Gas Equivalencies Calculator." from http://www.epa.gov/cleanenergy/energy-resources/calculator.html#resultsepa.gov/cleanenergy/energy-resources/calculator.html.

van der Velden, N. M. P., Martin K.; Vogtlander, Joost G. (2014). "LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane." INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT **19**(2): 331-356.

Victor Innovatex (2003). Sustainable Textile Development at Victor Innovatex

Welle, F. (2011). "Twenty years of PET bottle to bottle recycling—An overview." Resources, Conservation and Recycling **55**(11): 865-875.

Zhang, H., B. Zhang, et al. (2015). "More efforts, more benefits: Air pollutant control of coal-fired power plants in China." Energy **80**(0): 1-9.

Leather

Summary

Leather is an integral part of many shoes, but is also found in clothing, gloves, upholstery and other goods. Leather is an agricultural product, and its environmental impact stems heavily from its production on farms. Methane, a powerful greenhouse gas, makes up the majority of the impact of leather, coming, very simply, from the gas released as part of the source animal's digestive process.

The leather industry continues to grow, alongside global meat consumption. Leather is widely used around the globe, in vehicles, as upholstery, and in consumer goods like belts, bags and shoes. Over 22 billion square feet of leather is manufactured each year, an area roughly the size of Maryland or Luxembourg, over 50% of which is used in footwear. The total global annual impact of the leather worldwide is estimated around 130 MT CO_2e, about the same as the emissions from 30 million passenger vehicles used in one year.

As the leather industry grows, so will the greenhouse gas emissions, though the location where the impact is realized may also shift. The amount of leather originating in developing countries is growing, which tends to lead to a higher impact. These animals tend to be smaller than those grown in developed countries, thus more animals are needed to obtain the same amount of leather. Further, impacts due to converting forest areas to ranches may also cause a spike in emissions, though the number is not estimated in this study due to high uncertainty around present day practices. With few solutions for controlling methane emissions from animals, these emissions are projected to grow over time, thus increasing the global impact of leather.

Leather's Present and Future Impact

The following section will explore the growth of the leather industry, and what it means in terms of global warming impact.

Global Warming Impact

We examine the environmental impact of leather primarily in terms of greenhouse gas emissions. Until it reaches the final consumer, each phase of leather's life cycle creates greenhouse gas emissions, which we will describe in more detail below.

The majority of the greenhouse gas burden comes from the upstream phase, where the animals are grown, slaughtered and the hides removed. The burden, however, differs depending on the type of animal. The United Nations Food and Agriculture Organization found that, on average, the impact for sheep and goats is about half that of cattle (FAO 2013).

The main source of greenhouse gas emissions from cattle, as well as other ruminants like sheep and goats, is the methane released during the animal's digestive process. Ruminants multi-chambered stomachs contain microorganisms that break down the grasses, releasing methane in the process. Simply put, this causes cows to belch, releasing methane into the atmosphere. Methane is a potent greenhouse gas, causing 25 times as much global warming impact compared with CO_2. This methane from animals contributes between 55% to 92% of the upstream phase burden for leather (the specific figure depends on the study).

Other upstream sources of impact include manure storage and land application, the production of feed crops, manufacture of farm equipment, fertilizers and agrochemicals, land management and land use changes (see next section) (Desjardins, Worth et al. 2012).

Snapshot: Leather Life Cycle

The leather life cycle begins on the farm, known as the upstream phase in LCA. As shown in Figure 1, the majority of leather comes from cows, followed by sheep and goats, then pigs. Growing animals require food, water and shelter, all of which come with their own share of environmental impact. For example, cattle feed requires cropland, fertilizer, pesticide, water, farming machinery running on fossil fuels, and so on. Even within bovine production, the weight of the animal as well as its hide will vary by region as shown in Figure 2. This variation is critical to understanding the overall impact of the leather industry because the products they provide and waste they generate is a function of their size. When their growth is complete, animals are transferred to a slaughterhouse, where the manufacturing and processing phase begins.

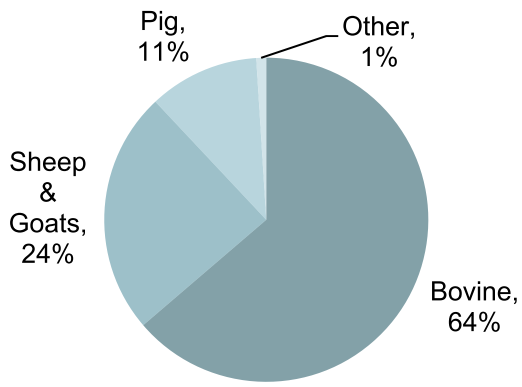


Figure 1 Breakdown of animals used to make leather.

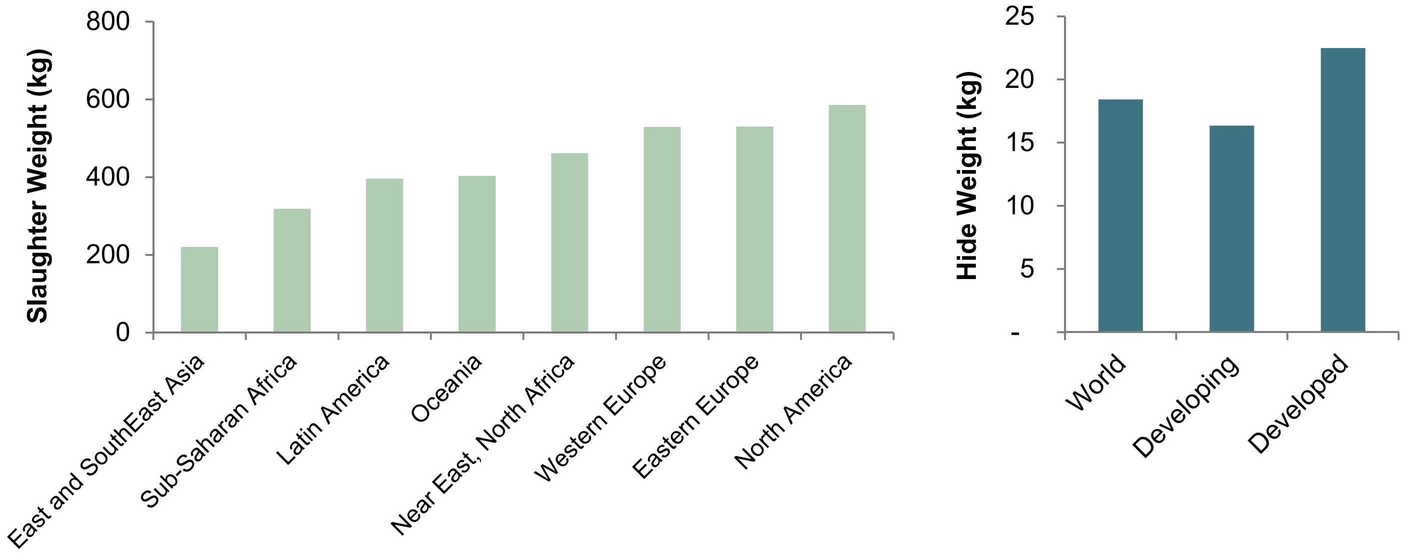


Figure 2: (Left) Average slaughter weight of beef cattle by region (FAO 2013). (Right) Comparison of the average weight (wet salted weight (kg)) per hide and skin between developed and developing countries and the global average. Calculated from (UN FAO: Trade and Markets Division 2013).

Processing can take various pathways depending on the final product. Chemicals are used to treat the animal hides, detergents are required for cleaning, machinery is used for manipulation and transformation, and packaging must be constructed. Each of these items again contains their own impact from development to application, alongside the energy used to power facilities and their machinery. Depending on the operation, the leather could be transported to various facilities throughout this process chain as well. Finally, the finished leather is transported to an additional location(s) where it is further processed to be included in shoes, bags, etc., known as the downstream phase. Manufacturing can also significantly influence total impact because much more material is processed than ends up in the final product.

Historic Variation in Leather Production

As can be seen in Figure 3, for light and heavy leather (typically used in leather shoe soles), around the early-to-mid 1990s, the production of leather in developing countries surpassed that of developed countries; the gap has since widened.

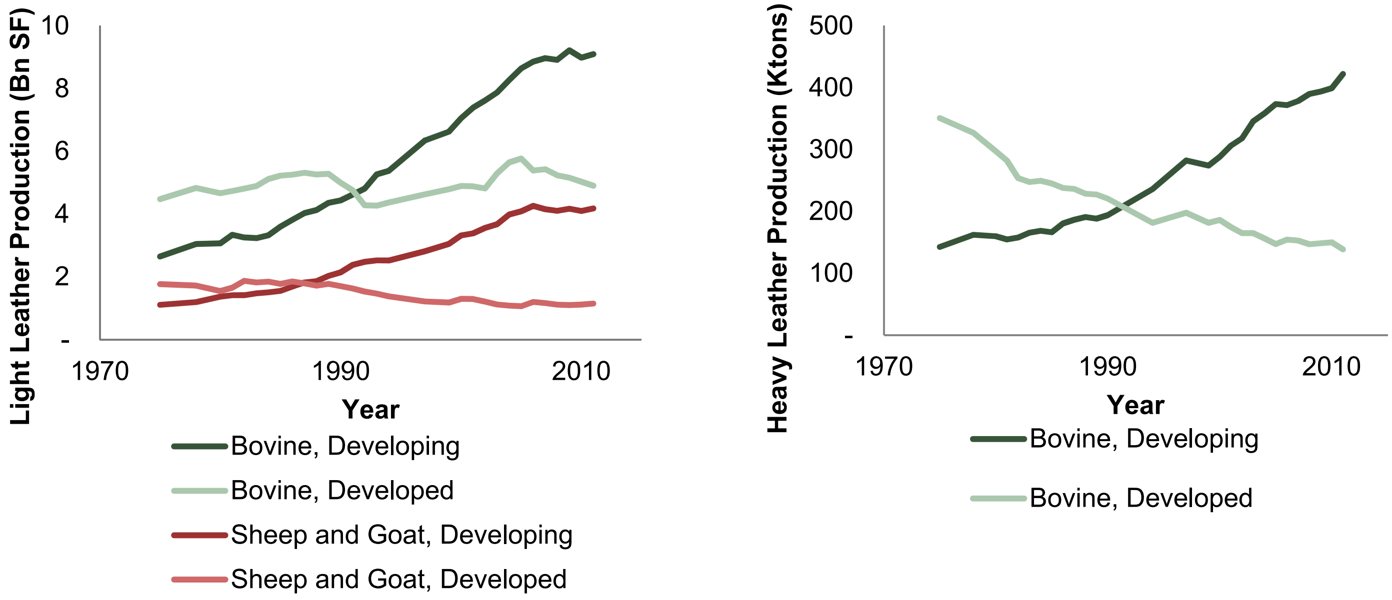


Figure 3 Production of light leather from bovine animals, sheep and goals (left); and production of heavy leather from bovine animals (right) (UN FAO: Commodities and Trade Division 1994; UN FAO: Trade and Markets Division 2013).

Future Projections

As the leather industry continues to grow, so will its environmental impact. Using publicly available data, this section looks at how the impact might change in the future. Figure 4 shows the historic market share and future projections for leather by end use. If present trends continue, the share of leather used for footwear will drop over time, as upholstery and automobile leather grows. This is because leather footwear production is declining relative to rubber and plastic footwear, down from nearly 30% of global volume in 2003 to roughly 15% of volume in 2013 (World Footwear 2014). In the year 2020, the total global light leather production is estimated to be 26.5 billion square feet, with footwear accounting for 13.2 billion square feet; in the year 2030, those estimates increase to 29.9 and 13.9 billion square feet, respectively.

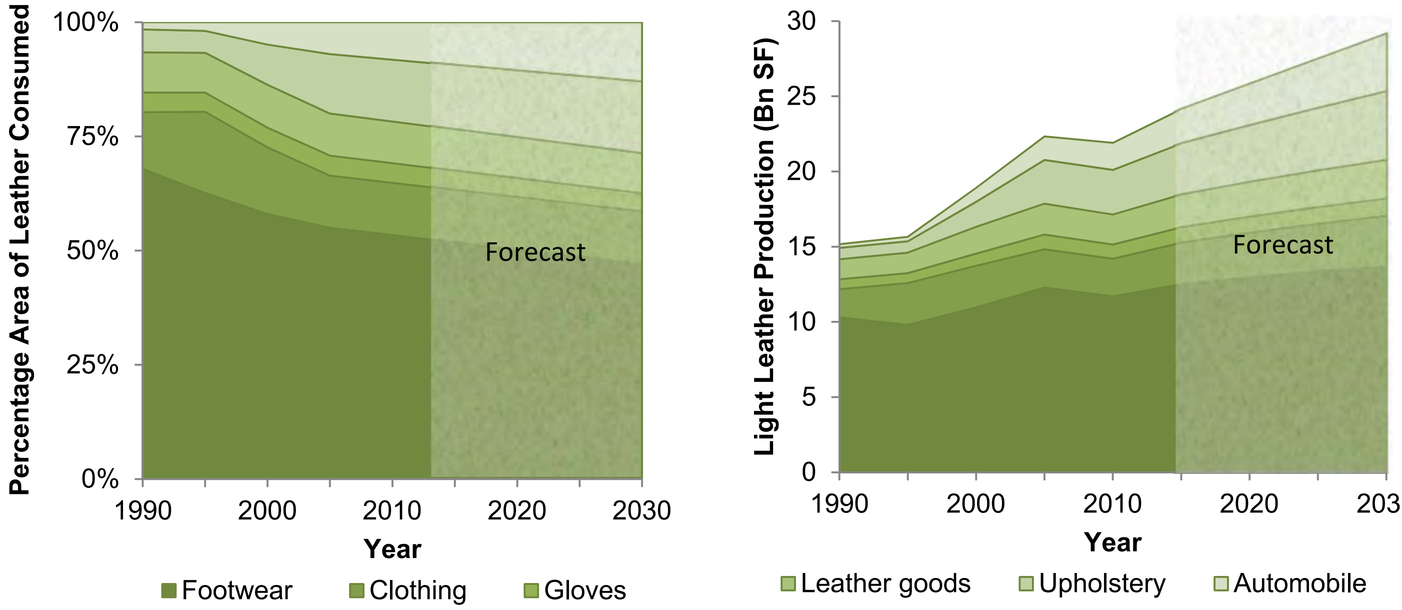


Figure 4 Market share and production projections for the leather industry based on historic market trends.

Based on this overall growth of leather use globally, Figure 5 shows that leather footwear's global warming impact will grow over time, similar to the market as a whole. Beyond simply increase in use, this growth is in part due to a shift in the geographic production of animals to developing countries, where differences in climate, husbandry and crop production practices result in different upstream agricultural emissions, shown in Figure 3, as well as different slaughter weights and hide weights, explored more in Figure 2. The global warming impact from developed countries is estimated to remain at around 35 MT CO2e per year, while the impact from developing countries is expected to grow from around 95 MT CO2e per year in 2015, to 104 MT CO2e per year in 2020 and further to 121 MT CO2e per year in 2030. Worldwide, these sum to an estimated 130, 138, and 155 MT CO2e per year in 2015, 2020 and 2030, respectively.

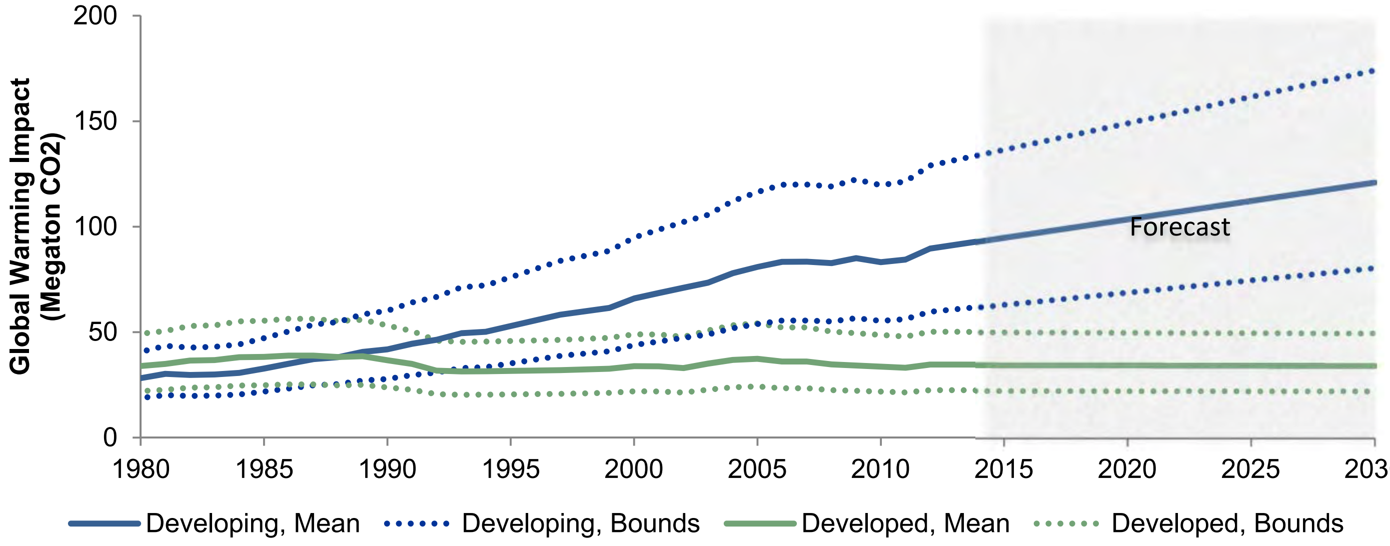


Figure 5 Estimated growth in emissions for the leather industry. Bounds represent uncertainty in the estimates.

An additional reason for this growth is based on changes in agricultural practices, the UN FAO has predicted how global emissions from bovine enteric fermentation and manure management will grow in coming decades, consistently estimating enteric fermentation to be 10 times higher than manure management. As seen in Figure 6, enteric fermentation emissions are projected to grow, while manure management remains the same.

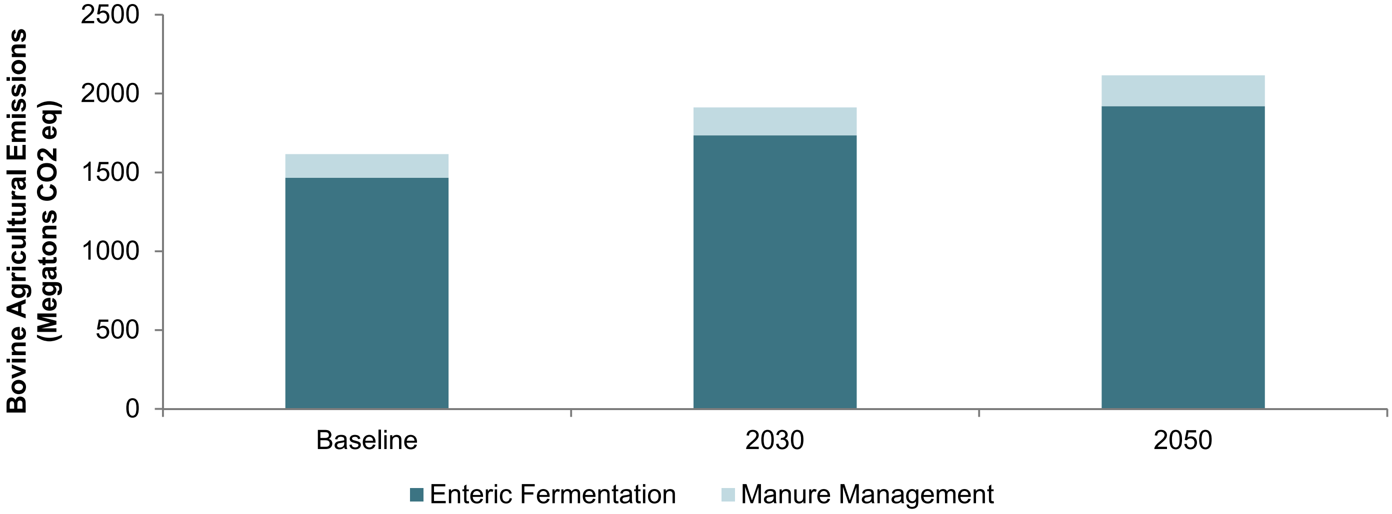


Figure 6 Projection of manure management practices compared with enteric fermentation (UN FAO 2015) .

Greenhouse Gas Emissions per Shoe

For the purposes of this report, we will consider the average emissions for the leather contained within a typical shoe, allowing us to understand the numbers from a relatable perspective. The average consumption of leather amounts to 1.7 square foot per pair of shoes. While many shoes now use leather in conjunction with synthetic materials, an average figure of 1.7 square feet per pair for all types of footwear incorporating leather provides a representative value considering variations in sizes, such as children's versus adult shoes (UNIDO 2010). However, a study of factories in India in 2004-2005 reported an average of 7 square feet per pair of leather shoes (Joseph and Nithya 2009). So, clearly this value can vary depending on the product.

As shown in Figure 7, leather within a pair of shoes has a carbon footprint of roughly 10 kg CO_2e,[1] including the upstream, manufacturing and downstream phases of leather. Because of the differences in animal weight, as well as processes, estimates were made for both developed and developing countries, with developed countries producing slightly less carbon overall. The upstream impact is higher in developing countries, contributing more to the total (90%) than in developed countries (87%).

---

[1] Note that CO2e includes greenhouse gas emissions beyond carbon dioxide.

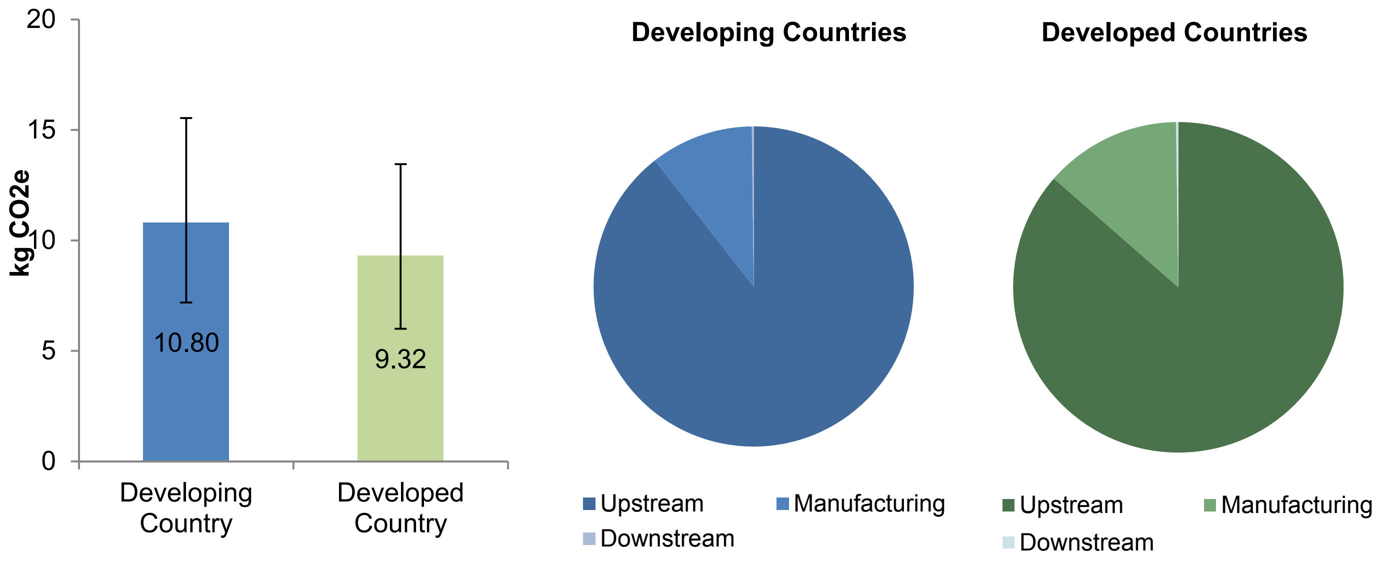


Figure 7 Estimated global warming impact (kg CO2e) per amount of leather used in a pair of shoes, 1.7 square feet.

So What?

If the GHG emissions of leather are 10 kg CO_2e per pair of shoes, how does this equate to the real word? Are leather shoes better or worse than other things? To get an idea of the scale of the impact of one pair of shoes, Figure 8 shows its equivalence in terms of other common impacts, based on the EPA's GHG Equivalencies Calculator (US EPA 2014).

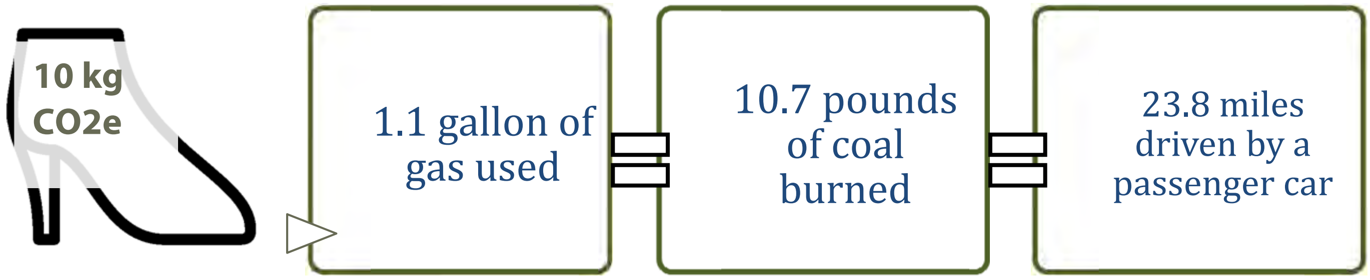


Figure 8 Equivalent impacts to cradle-to-gate impact of a pair of shoes' worth of leather.

Leather Industry Today

As mentioned above, the global footwear industry is estimated to use 13.2 billion square feet of leather in by the year 2020 translating to an estimated 8 million tons of 7.9 billion kg of CO2e emitted in one year for the global leather industry related to footwear. Figure 9 explores this figure in more detail, providing a context for the amount of greenhouse gas released globally.

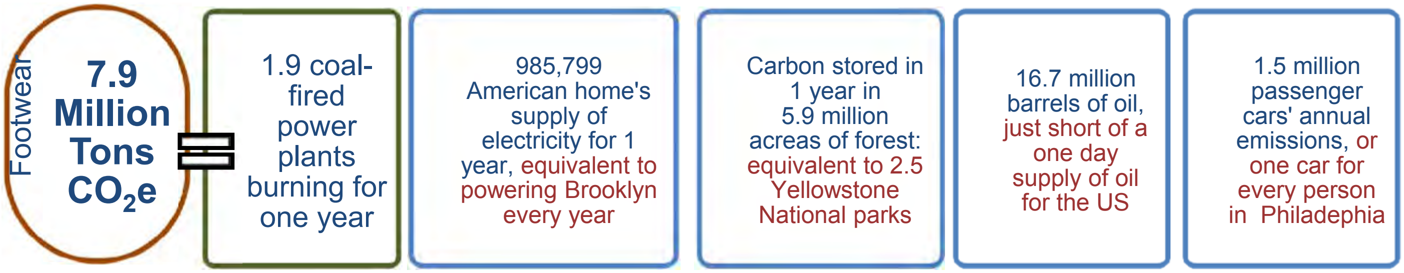


Figure 9 Equivalent greenhouse gas impacts of leather's use in the global footwear industry.

Recommendations for Leather Impact Reduction

A study of the carbon footprint of European livestock resulted in these recommend global warming mitigation options for livestock products (Hermansen and Kristensen 2014):

- better feed conversion at the system level
- use of feeds that increase soil carbon sequestration versus carbon emission
- ensure that the manure produced substitutes for synthetic fertilizer, and use manure for bio-energy production.

Considering the importance of upstream emissions due to livestock enteric fermentation, both existing strategies (e.g. choice of feed) and novel approaches toward reducing these emissions is critical. While we did not incorporate land use change estimates, it is clear that clearing a forest of any kind, an especially a rainforest, to make way for ruminant animals will result in drastic carbon storage reduction, which is equivalent to significant global warming emissions.

Other recommendations:

- Improve practices in developing countries in order to increase the size of cattle.
- Increase share of leather originating from goats.
- Discourage agricultural practices that involve slash and burn practices and/or the clearing of tropical forests.
- Encourage manure management in accordance with local best practices.

Key Assumptions: allocation & land use

A Note on Allocation

To come to a reasonable value of life cycle GHG, we must make certain assumptions; since a cow's body will eventually be used for many purposes, the impact of the leather must be separated from the impact of, say, the eventual hamburger. In LCA practice, this separation is referred to as allocation. For leather production, there are two primary methods for allocation: by mass, i.e. the weight of each component, or by economics, the final value of each component. Further complicating things, these allocation values can vary significantly by location, as seen in Table *1*. For example, a cow in India may weigh 275 kg compared with a 478 kg Italian cow, just as the price of leather or hamburger may vary just as widely by location or over time.

As a demonstration, Table *1* shows the standard mass-based allocation for the agriculture through slaughterhouse phases for a cow. The raw hide (unprocessed leather) accounts for 5-7% of the total animal weight, thus 5-7% of its environmental impact per the mass-allocation method. While it may still be worthy of debate, the mass-based impact allocation is the most widely accepted process and thus will be used in this report. The location of the activities is considered, however, providing an estimate for developed and developing countries.

Table 1 *Allocation of agriculture and slaughterhouse environmental impact for finished bovine leather (EPD 2011).*

Category	Living Weight (kg)[2]	Raw Hide	Comestible Goods	Scraps
Calf (male or female, 0-12 month)	245	**7%**	64%	29%
Bull (male, > 12 month)	680	**7%**	65%	28%
Cow (female, > 12 month)	650	**5%**	44%	51%

On Land Use

The conversion of land to agriculture or from one form of agriculture to another is an important source of greenhouse gas emissions because the conversion can release large quantities of CO_2 held in soil organic matter. This impact is especially acute for areas that were previously forested or areas containing large amounts of organic matter (i.e., peat) in the soil. For example, in Brazil (the 5th largest producer of leather over the last two decades), expanding cattle ranching operations are responsible for the majority of the continuing destruction of the Amazon rainforest (MVO Nederland 2013). However, estimates on the amount of greenhouse gas that is released due to land conversion have a very broad range and are highly uncertain thus are not included in this study. That said, it should be noted that land use change is a source of greenhouse gas emissions, and potentially a significant one depending on the geographic area. Further study is needed to accurately assess its role in leather's impact.

Key Data Gaps

This report aims to summarize the information within recent and relevant studies on leather and to project these data into the future; however, gaps within available data should be considered when reviewing results. Some key data gaps identified include:

- The steps to estimate the emissions related to cattle, and then to properly allocate them to leather, require information from each step of the cattle and leather manufacturing processes. While estimates have been gleaned from existing studies, to create a more robust estimate reflective of different practices around the world, more detailed primary data is needed. For example:
    - Total upstream emissions per kg of cow
    - Market price of hide and other cattle byproducts
    - Ratio of hide weight : slaughter weight
    - Wet salted hide weight reduction after slaughterhouse
    - Ratio of leather weight : wet salted hide weight
    - Market price of grain leather and split leather
    - Amount of grain leather versus split leather produced

- While studies have begun to estimate the impact of land use change, attributing the impact to cattle and later leather is a highly complex calculation that requires further investigation. Land use change is an additional source of emissions that will continue to grow in impact.

The studies used to understand the impact of leather are referenced below.

References

Desjardins, R. L., D. E. Worth, et al. (2012). "Carbon Footprint of Beef Cattle." Sustainability **4**: 3279-3301.
EPD (2011). Product Category Rules: CPC Class 2912, Finished Bovine Leather. Version 1.0.
FAO (2013). "Greenhouse gas emissions from ruminant supply chains: A global life cycle assessment."
Hermansen, J. E. and T. Kristensen (2014). "Management options to reduce carbon footprint of livestock products." Animal Frontiers **1**(1).
Joseph, K. and N. Nithya (2009). "Material flows in the life cycle of leather." Journal of Cleaner Production **19**: 676-682.
MVO Nederland (2013). Sustainability in the leather supply chain. E. Young.
UN FAO. (2015). "FAOSTAT: Emissions - Agriculture." from http://faostat3.fao.org/browse/G1/*/E.
UN FAO: Commodities and Trade Division (1994). World Statisical Compendium for raw hides and skins, leather and leather footwear 1974-1992.
UN FAO: Trade and Markets Division (2013). World Statisical Compendium for raw hides and skins, leather and leather footwear 1993-2012.
UNIDO (2010). Future Trends in the World Leather and Leather Products Industry and Trade.
US EPA. (2014). "Greenhouse Gas Equivalencies Calculator." from http://www.epa.gov/cleanenergy/energy-resources/calculator.html#resultsepa.gov/cleanenergy/energy-resources/calculator.html.
World Footwear (2014). "Footwear Consumer 2030: Incorporating Global Trends to Foresight Footwear Market."

Synthetic Rubber

Snapshot: Synthetic Rubber Life Cycle

Several types of synthetic rubber are utilized in footwear. The chief type is styrene ‐ butadiene rubber (SBR), along with polybutadiene (BR), nitryl (NBR), polychloroprene (CR), plastics (TR) and various other forms of latex (International Institute of Synthetic Rubber Producers Inc.). Synthetic rubber is made from petrochemicals, which are derived from natural gas and refined crude oil. "The manufacturing of rubber products involves six principal processing steps (mixing, milling, extrusion, calendering, curing, and grinding), with ancillary steps in between. Initially, the raw rubber (natural or synthetic) is mixed with several additives which are chosen based upon the desired properties of the final product"(US EPA 2009).

Figure 1 Steps in the processing of synthetic rubber for footwear (International Institute of Synthetic Rubber Producers Inc.)

Global Warming Impact

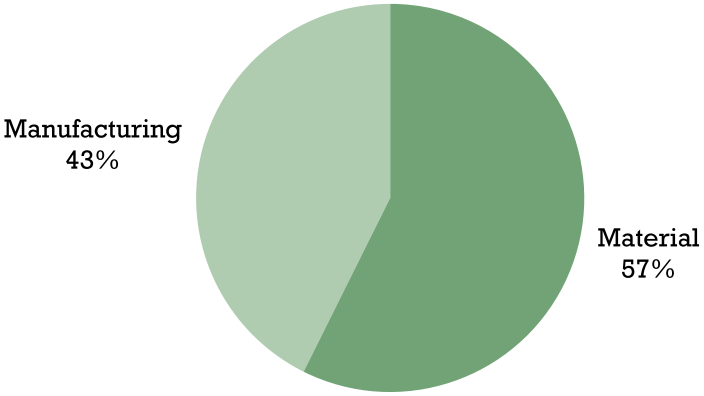


Figure 2: Comparison of Material and Manufacturing Global Warming Potential

The global warming impact of synthetic rubber soles in footwear is driven by the raw materials and transformation of those petrochemicals into a synthetic rubber compound with suitable performance characteristics. The remainder of the impact is due to the sole manufacturing stage, where the synthetic rubber is molded into the final product. A study of footwear production (Cheah, Ciceri et al. 2013) showed that the electricity consumption in injection molding is higher than the industry average. Coal is also burned to both power and heat the buildings where shoe soles are made, making the combustion of coal a primary contributor of manufacturing GHGs.

Greenhouse Gas Emissions of a Rubber-soled Shoe

In many sneakers, the outsole—the bottom layer that touches the ground—is made from rubber, whereas the midsole cushion is made from copolymers like EVA. The outsole of a sneaker weighs about 120 g, and additionally an estimated 40% of input rubber lost as scrap during injection molding, for a total requirement of 200 g (Cheah, Ciceri et al. 2013). Therefore, the outsole is estimated here to result in 1.1 kg CO_2e, about 8% of the total impact of a sneaker. This value is derived from an estimated 3.1 kg CO_2e from the production of one kg of synthetic rubber, and 0.46 kg CO_2e associated with the electricity and coal use during creation of an outsole.

Hotspots

Considering the production of synthetic rubber, fossil fuels are not sustainable resources and their use as petrochemical ingredients in products reduces the amount available for energy production. Additionally, air pollutants such as volatile organic compounds (VOCs), hazardous air pollutants (HAP) and particulate matter (PM) are released during rubber manufacturing (US EPA 2009).

The second largest source of emissions is related to the manufacture of the outsoles from synthetic rubber. The use of coal to power and heat the manufacturing facilities is the driver of this impact, followed by energy inefficient injection molding with considerable scrap.

So What?

To understand how the 1.1 kg CO_2e impact of a sneaker outsole compares to other common impacts, we will compare with other values using the EPA's GHG Equivalencies Calculator (US EPA 2014).

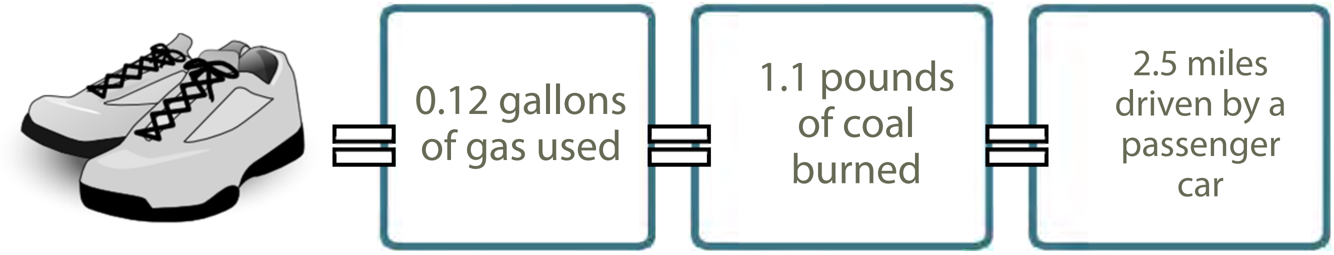


Figure 3 Equivalent impacts to cradle-to-gate impact of the rubber outsoles of one shoe.

Rubber's Present and Future Impact

Historical Rubber Production and Future Projections

The history of natural and synthetic rubber is fascinating. Synthetic rubber production was triggered during WWII in the US because the Axis powers controlled the vast majority of natural rubber production in Asia, the critical material in tires for military vehicles. Decades earlier, Britain smuggled rubber tree seeds from Brazil and transported it to Asia; the new fierce competition crippled Brazil's production (International Institute of Synthetic Rubber Producers Inc.). Synthetic rubber can now substitute natural rubber in most applications; its production surpassed natural rubber around 1960. In 2015, production grew to an estimated 16 million metric tons, and is expected to grow to 24 million metric tons in 2030.

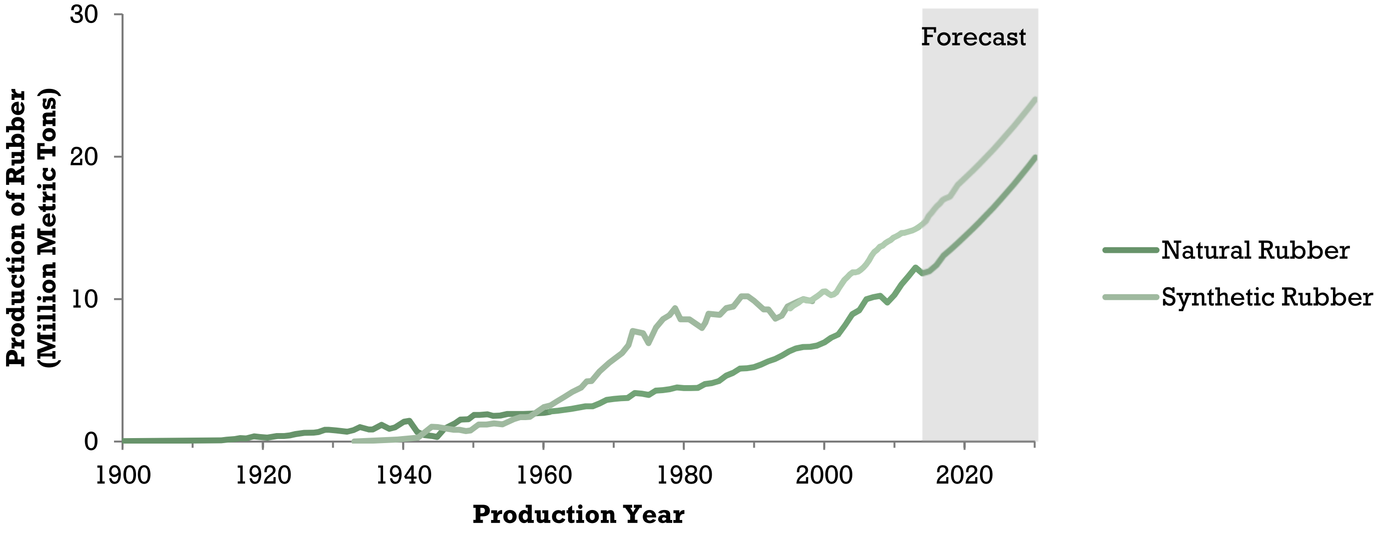


Figure 4 Production of synthetic and natural rubber. (Cornish 2001; IRSG 2009; FAO 2015)

Rubber Industry Today

As the rubber industry grows, so will its impact. In 2013, the automobile industry consumed the largest share of rubber, about 81%. Consumer goods, such as shoes, sporting goods and foodstuff/packaging, used 6% of the world's synthetic rubber supply (Accenture Strategy 2014).

Looking at SBR specifically, according to IHS:

> "Styrene-butadiene rubber is currently the largest volume synthetic rubber, which is produced by the copolymerization of styrene and butadiene by either the emulsion or solution process. Although the emulsion process is clearly the current capacity leader, the solution process has better future potential due to versatility and flexibility in imparting desired polymer structure. The current focus on high performance and "green" tires, as well as the current and upcoming government regulations regarding tire labeling, have contributed significantly to the increased popularity of the solution process" (IHS 2013).

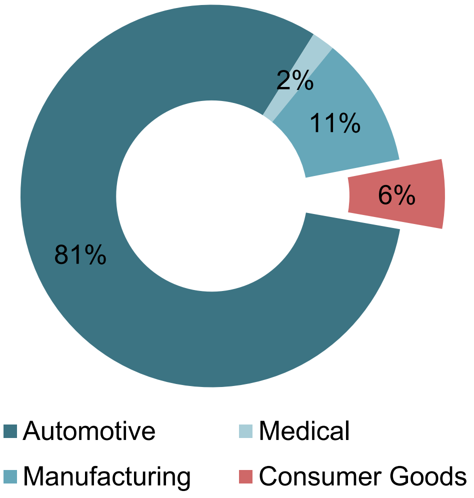


Figure 5 The share of the synthetic rubber market used for consumer goods, like shoes.

Global Greenhouse Gas Emissions

A study of the vulcanization of concentrated rubber in a tire estimated 0.11 kWh electricity per kg rubber (Bras and Cobert 2011); this rate is used to represent automotive and manufacturing end uses. The electricity related to the injection molding of rubber outsoles is about 0.78 kWh per kg rubber (including scrap); this rate is used to represent consumer goods and medical. The variation in production practices across end use markets and lack of specific data on those end uses reduces the confidence in these estimates.

In the figure below, the global warming impact of global synthetic rubber manufacturing has grown to roughly 78 million metric tons in 2015, and could grow to 117 million metric tons in 2030.

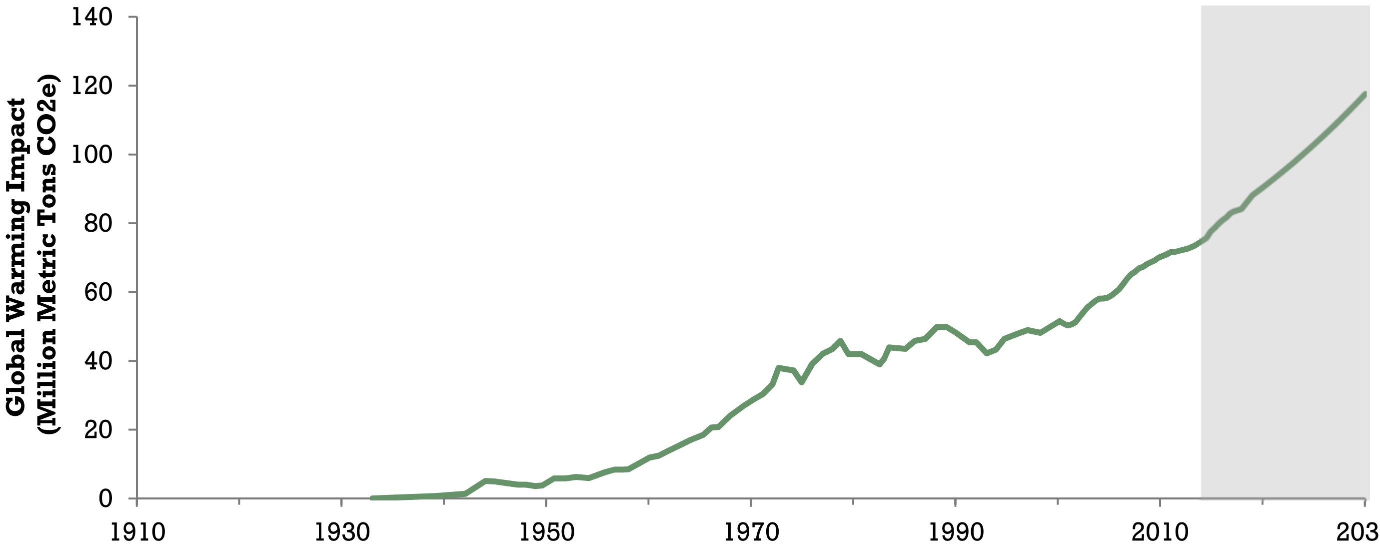


Figure 6 Projected growth in greenhouse gas emission until 2030; shaded area includes projections based on historic patterns. This plot is for all of rubber, note that only 6% of rubber is used in consumer goods.

Based on today's marketplace for rubber in the consumer goods industry, the emissions in 2015 are estimated to be 5.0 million tons of CO_2, with a similar impact to 1.8 coal-fired power plants over one year.

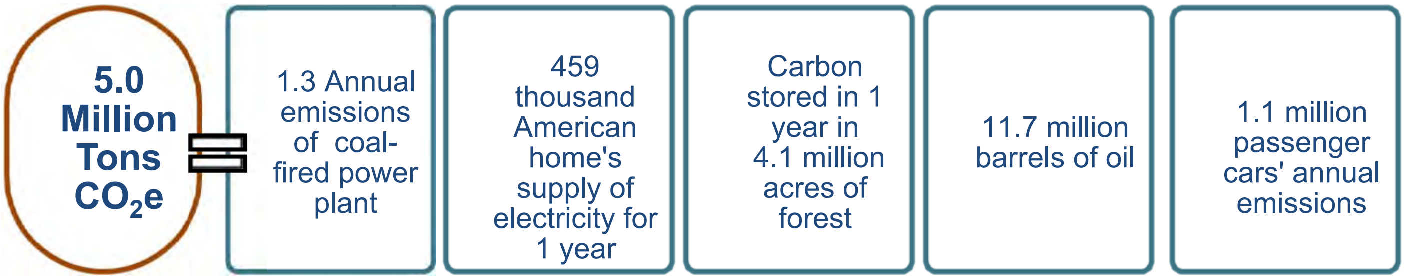


Figure 7 Estimated total impact of synthetic rubber used in the consumer goods industry.

Recommendations for Rubber Impact Reduction

- Compare the life cycle impact of synthetic rubber to natural rubber, which is a renewable resource, and if it is deemed environmentally preferable, consider whether natural rubber would be a suitable alternative in some products.
- "In terms of the manufacturing phase, finding cleaner alternatives for heating, pursuing energy-efficiency improvements related to the sole production […], and reducing machinery idle time would help to lower the GWP of the product." (Cheah, Ciceri et al. 2013)

Key Data Gaps

Compared to other materials, there are relatively few comprehensive studies on the life cycle impact of natural rubber used in footwear. Below are a few key data gaps:

- The environmental impact for is characterized by the Ecoinvent 3.0 process 'Synthetic rubber {GLO}| market for | Alloc Def, U', which was tailored to EPDM (ethylene propylene diene monomer (M-class)) rubber versus the SBR typically utilized in footwear.
- The market share of end uses of synthetic rubber could be better characterized, as well as associated manufacturing processes.
- Extended characterization of coal heating practices, electricity demand, and scrap rates of rubber injection molding facilities across the footwear industry

References

Accenture Strategy (2014). Extracting Value from Natural Rubber Trading Markets: Optimizing Marketing, Procurement and Hedging for Producers and Consumers.

Asiedu, Y. and P. Gu (1998). "Product life cycle cost analysis: state of the art review." International Journal of Production Research **36**(4): 883 - 908.

Bras, B. and A. Cobert (2011). "Life-Cycle Environmental Impact of Michelin Tweel® Tire for Passenger Vehicles." Int. J. Passeng. Cars - Mech. Syst **4**(1).

Cheah, L., N. D. Ciceri, et al. (2013). "Manufacturing-focused emissions reductions in footwear production." Journal of Cleaner Production **44**(0): 18-29.

Cornish, K. (2001). "Biochemistry of natural rubber, a vital raw material, emphasizing biosynthetic rate, molecular weight and compartmentalization, in evolutionarily divergent plant species." Natural Product Reports **18**(2): 182-189.

FAO (2015). FAOSTAT: Production.

IHS. (2013). "Process Economics Program Report 64A: Solution Styrene-Butadiene Rubber." from https://www.ihs.com/products/chemical-technology-pep-Solution-Styrene-Butadiene-Rubber-2013.html.

International Institute of Synthetic Rubber Producers Inc. "BRIEF HISTORY & INTRODUCTION OF RUBBER." from http://www.iisrp.com/WebPolymers/00Rubber_Intro.pdf.

IRSG (2009). Panel 4: Prospects. International Smallholder Rubber Conference, Cambodia.

US EPA (2009). "AP 42 Draft Section 4.12: Manufacture of Rubber Products."

US EPA. (2014). "Greenhouse Gas Equivalencies Calculator." from http://www.epa.gov/cleanenergy/energy-resources/calculator.html#resultsepa.gov/cleanenergy/energy-resources/calculator.html.

Appendices

About these Reports/Objectives/Disclaimer

This report was compiled from existing data; wherever possible, the most recent data are used. Data sources include company data, market research statistics, governmental or NGO data, and literature. When suitable data were not available, older or more general data were substituted. These instances are infrequent and clearly marked. As such, however, the results should be considered in light of the caveats listed within the report.

When evaluating the environmental impacts of a material, the result depends on what boundaries are set in the analysis. For example, if you only consider the life cycle of the cotton until it meets the store shelf as a product (cradle-to-gate, so to speak), you will find one number; however, if you consider the end-of-life of a product, its recycling or reuse, you will likely find a larger number. In the individual material reports below, the use phase is explicitly not considered. Often, the washing of clothing or textiles can have a high impact, potentially even higher than the material itself, due to energy used by hot water heaters. Because this report is meant to understand the impacts of the material, the use phase will be discussed briefly in this section across all the materials. Furthermore, end of life is only briefly considered within these reports because of the high uncertainty in how a material may be treated after use.

In the same vein, materials have multiple applications, thus the product you consider will also alter results; for example, the carbon footprint of a t-shirt will be different from a pair of pants not only because they clearly differ in design and mass, but also because of how and where they are produced. The results for one product can be grouped with a suite of products to determine the cotton impact of a particular company or industry, and could be aggregated to consider cotton production as a whole. This report aims to briefly consider each of these angles.

While these reports aim to provide a relevant and timely overview of the environmental impacts of each material, the list may not be exhaustive and only reflect the conditions at the time of drafting.