Life Cycle Assessment of Four Different Sweaters

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ABSTRACT

Life cycle assessment (LCA) is a methodological tool to describe the impacts of a product over its lifetime, from 'cradle to grave.' Despite increased employment of LCA, textile LCA studies are often private, outdated, not transparent, or lack accurate data. Further, we know of no LCA study specific to sweaters. This screening LCA combines published literature and data from OpenLCA databases (Ecoinvent 3.3 and GaBi Professional) to create a LCA comparison for four sweaters. To determine the composition of these sweaters, we massed and assessed the material composition of 117 sweaters in October 2015. Based on results, our study compares one sweater of 100% cotton (21% of total sweaters), one of 100% wool (0.08% of total sweaters), and one of 100% acrylic (11% of total sweaters). Additionally, 21% of all sweaters were cotton-polyester blends. For the sake of simplicity, we analyzed the most common make-up, 60% cotton and 40% polyester (4% of all sweaters, 21% of cotton-polyester blends.) As previous studies on textiles have focused on either material production or the use phase of textiles, we assess a more complete product life cycle for the consumer in the United States. We quantified the environmental burden of fiber production, sweater creation, and use in terms of TRACI impact categories that include global warming potential (GWP) and eutrophication. Although the use phase had the largest global warming potential for each sweater, the use phase did not have the highest impact in all categories. In all ten TRACI categories, the wool sweater had the least impact. Information for all stages of the life cycle in all impact categories is presented except for the acrylic sweater, for which limited information exists.

INTRODUCTION

Life cycle assessment (LCA) is a methodological tool to describe the effects of a product over its lifetime, from raw material extraction to disposal. It is a relatively new methodology, its earliest form dating back only to 1966. The process involves four steps: first, the goal and scope of the study are defined. Second is an inventory analysis that evaluates the inputs and outputs of each of a product's stage of production. Third, an impact analysis assesses how the inputs and outputs found in the inventory analysis affect the environment. This is a way of comparing each input and output into common, equivalent units. For example, the release of methane, twenty-five times more potent per molecule emitted than carbon dioxide, is reported as a carbon dioxide release equivalent, and presented as 'global warming potential'. The final step is the improvement analysis that locates where in the supply chain improvements can occur, and how they can occur. While previous studies on textiles have focused on either material production (van der Velden et. al 2014, Laursen et. al 2007, Beton et. al 2014, Cardoso 2013) or the use phase of textiles (Steinberger et. al 2009), I assess a more complete sweater life cycle for a typical consumer in the United States. This project is also unique in that it assesses and compares sweaters made of a variety of fiber materials, including a blend. Information provided in this study has the potential to influence consumers, designers, and other stakeholders in decisions and behaviors to lessen environmental impacts of their products at purchase and throughout the lifetime of the sweaters.

Existing LCA textiles often exclude or hardly include the consumer as a stakeholder (van der Velden et. al 2014, Beton et. al 2014, Laursen et. al 2007) and only assess one or two fabric types, completely excluding blends (van der Velden et. al 2014, Cardoso 2013, Steinberger et. al 2009). Several LCA studies also focus on just one step in production, such as acrylic fiber production (Yacout et. al 2016) or cotton yarn production (Bevilacqua et. al 2014); these limited studies have the benefit of in-depth and precise information that assesses more variables than larger-scale LCA studies. However, all LCA studies take a unique approach to constructing the functional unit and the system boundaries. For example, van der Velden (2014) has a declared unit of 1 kg of fabric. While their study covers extensive possibilities in the manufacturing phase, little consideration is put into the use phase due to the variations in consumer behavior. Information like this may not be able to give insight into a impact throughout its full life cycle.

This study seeks to fill the gaps in apparel life cycle assessments by utilizing the best available data and applying it to real-world, tangible sweaters. The scope of this study is the immediate supply chain of four different sweaters: fiber production, garment creation, and use (Figure 1). Thus, inputs like farm machinery construction or truck construction are excluded in the final results. This study is consumer-focused, in that its goal is to provide consumers with information they may use to alter their habits. Because of this focus, several stages of the sweater's life like spinning to yarn and weaving are included together in a category called 'garment creation.' I hypothesized that the use phase would have the largest environmental burden of all processes in the life cycle of a sweater, with the exception of wool, which is not meant to be tumble-dried. This is based in large part on the findings of Steinberger et. al (2009). In the case of wool, it is hypothesized that the first stage, fiber creation, will cause the largest environmental burden, due to animal agriculture.

METHODS

Overview

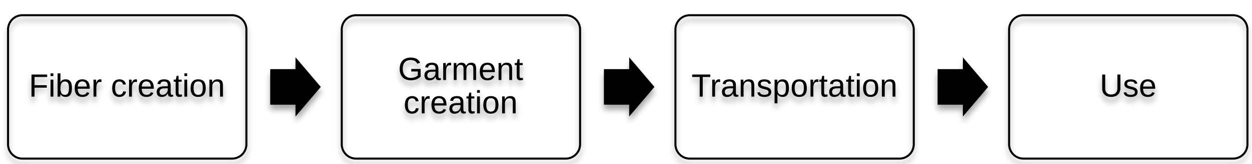


Figure 1. General process flow diagram of sweaters.

All data has been run through a TRACI analysis in openLCA. When available, information for a stage in production is directly from the Ecoinvent or GaBi Professional databases. When unavailable, literature was consulted, typically for energy values that were then run through a database to obtain the impacts associated with electricity use in the country of production via TRACI analysis. Much of the highly-cited literature does not report global warming potential or other impact categories, instead reporting energy usage in MJ or kWh (Steinberger et. al 2009, van der Velden 2014, Laursen et. al 2007). The indirect method of only energy inputs to obtain output values comes with a potential loss of information, and consequentially may not be accurate. However, using the energy consumption of machinery allows the machine itself to be located in different regions, thus capturing the reality of a globally diverse energy mixture (and consequentially diverse environmental impacts).

Locations for each stage in production were determined by locating the highest-producing region of raw materials in the world, then the highest-producing region of textiles in the same country, then the highest-trafficked port in that country. Distances between these locations were determined using Google Maps, which provides a realistic route that a cargo vehicle may take. The size of the truck used was the average of a 48’ cargo truck and a 53’ cargo truck, and its impact is from NREL. The distance from the port of production to the US port (Long Beach, CA in all cases) (AAPA World Port Rankings 2015) was determined using searoutes.com. 40’ intermodal containers were used for sea transportation (Rodrigue and Slack 2017), and data for the impact of transoceanic transportation is from Ecoinvent. From the port to the retailer, Mathews et. al (2002) determined 1825 km from Long Beach to Ann Arbor, MI, and this distance was selected for this study as well.

To determine the impact of one sweater during the transportation stage, it was necessary to know the amount of sweaters in a truck or an intercontinental box. Truck dimensions were found on a truck rental website, and the intercontinental box dimensions were found on searoutes.com. Retailers were called in April 2017 and asked about the dimensions of a typical box and the amount of sweaters within it; answers varied, but the most common answer was a 16*16*16 in box filled with 30 to 50 sweaters (this study assumes 40 sweaters in a 16*16*16 in box are shipped from the factory). No corrugated cardboard boxes were used for the transportation of raw materials, for example cotton or greasy wool, and the amount of (soon-to-be) sweaters is determined by the weight capacity of the truck. Data on the corrugated cardboard box itself (‘packaging’) is directly from Ecoinvent and is included in this study. The impact of a consumer’s travel to obtain the sweater is omitted.

Use phase information is from Steinberger et. al (2009), which assumes a 3.9 kg load and assumes 50 washes for a T-Shirt and 6 washes for a jacket. A sweater’s function seemed to be in the middle of a T-shirt and jacket, so 28 laundry cycles are assumed. From Steinberger et. al’s (2009) data, use information for 1 kg of fabric in a 3.9 kg load was calculated and used a multiplier for all sweaters.

Sweater selection

117 sweaters were measured for their mass and material-make up in October and November of 2015. The most common sweaters were selected for analysis: 100% cotton (21% of all sweaters), 100% acrylic (11% of all sweaters), and a cotton-polyester blend (21% of all sweaters). 60% cotton-40% polyester was the most frequent cotton-polyester blend (21% of all cotton-polyester sweaters, 4% of total sweaters). The 100% wool sweater was selected based on the curiosity of the authors (0.08% of all sweaters). Sweater mass was determined by the average of each sweater material.

Notes on the 100% cotton sweater

a. Sweater specification
   The cotton sweater represents the average mass of all measured 100% cotton sweaters, 441 g.
b. Cotton production
   Data for the production of cotton is directly from Ecoinvent.
c. Sweater creation

Data for the creation stage is from Seinberger et. al (2009) and is summed in this study.

d. Transportation

Steinberger et. al (2009) sources its cotton apparel from India. Because their data was utilized in the creation stage, their location is also utilized for the transportation stage. Cotton production is assumed to be in Mashrata, and textile manufacturing is assumed to be in Tirapur. Mumbai is the port from which the completed sweater is shipped, and it arrives in Long Beach, CA and is retailed in Ann Arbor, MI.

e. End-of-life/disposal

Notes on the 100% wool sweater

a. Sweater specification

The sweater mass in this study is that of the single measured 100% wool sweater, 350 g.

b. Wool production

Data for the production of wool (sheep farming) is directly from Ecoinvent.

c. Sweater creation

Data for the creation of wool sweaters is from Albino-Cardoso (2013). The energy inputs discovered in their study were recreated (averaged in cases of ranges of energy use) using a TRACI analysis.

d. Transportation

The inner Mongolia region of China is the world's top wool producing region (Longworth et. al 2005) and the garment is assumed to be created in Zhejiang, one of China's top garment producing provinces (EU SME Centre 2011).

e. Use

Wool sweaters are often not meant to be tumbler-dried in heat. Therefore, this sweater is assumed to be air-dried, thus excluding it from a part of the use phase.

Notes on the 60% cotton, 40% polyester sweater

a. Sweater specification

The sweater is the average of all measured 60% cotton/40% polyester sweaters, 545 g.

b. Fiber production

Data for the production of cotton is from the Ecoinvent database. Polyester fiber creation is from Steinberger et. al (2009).

c. Sweater creation

Data for polyester fiber creation and sweater creation from Steinberger et. al (2009). Impacts for this sweater were allocated by percentage; therefore, 40% of the impact of a 545 g polyester sweater was added to 60% of the impact of a 545 g sweater.

d. Transportation

The cotton for this sweater is sourced from Xiajang, the region that produces the most cotton in China (Clever and Xinping 2016). There was no reliable source for the raw material source for polyester, or the method of transportation. This stage in transportation has been omitted.

Notes on the 100% acrylic sweater

a. Sweater specification

The average 100% acrylic sweater measured 445 g.

b. Acrylic fiber creation and sweater creation

The data for the fiber and sweater creation are from Beton et. al (2014) and could not be disaggregated. Further, Beton et. al (2014) used the ReCiPe analysis method to assess environmental impacts. In an attempt to convert ReCiPe results for climate change to TRACI results, 5 random products, analyzed with both the TRACI and ReCiPe (E-Egalitarian) methods, were compared in OpenLCA in search of a common conversion. None existed, and conversion factors ranged from 1.07 to 2.2. An average comparison factor was used to convert the Beton et. al (2014) climate change value to what a TRACI analysis of the same inputs may yield.

c. Transportation
No reliable data was found for the raw material source for acrylic, or the method of transportation. This stage in transportation has been omitted.

RESULTS

Results for all collected impact categories for each of the four sweaters are presented in Tables 1, 2, 3, and 4. "NA" signifies that data was not available either in the literature or in OpenLCA. For the acrylic sweater's fiber creation and sweater manufacture, only data on Global Warming Potential was collected due to availability (Beton et. al 2014). Graphs 1 and 2 show comparisons of all sweaters and their respective life cycle stages in the selected category Global Warming Potential. These graphs show the Global Warming potential in kg CO^2 equivalency (Graph 1) and each life cycle stage's contribution as a percentage of the whole sweater's Global Warming Potential (Graph 2). Graphs 3 and 4 show comparisons of Ecotoxicity contributions of each process in each sweater, in CTUe (Graph 3) and CTUe as a percentage of the whole sweater (Graph 4). Acrylic sweaters have been omitted from Graphs 3 and 4 due to insufficient information for comparison.

Acidification

Acidification is the increasing concentration of hydrogen ions within a media (air and water). The sweater creation had the largest acidification in the 100% cotton and 100% wool sweaters, while the cotton/polyester blend's and acrylic's largest source of acidification was in the use phase.

Ecotoxicity

Ecotoxicity uses chemical inputs known to cause harm to environments and is a more general health measurement than the Carcinogenics and Non-carcinogenics categories. Cotton was the large contributor to Ecotoxicity. Wool creation was less impactful but still the largest contributor of the wool sweater. The use phase was the acrylic sweater's biggest Ecotoxicity contributor.

Eutrophication

Eutrophication is an excess of algae due to the enrichment of an aquatic ecosystem with unnecessary nutrients, and threatens the health of the ecosystem. The highest eutrophication value is due to transportation in the cotton and wool sweaters, and use in the cotton/polyeter and acrylic sweaters.

Global Warming

Global warming potentials are calculated by measuring outputs like methane relative to carbon dioxide (for example, 1 kg methane is equal to 4 kg carbon dioxide due to its potency). TRACI calculates global warming potentials of a 100-year horizon. The use phase dominates the global waming potential of a sweater except for when it is not tumble-dried (the wool sweater).

The acrylic sweater presents unclear results due to the combination of the fiber and sweater creation stages.

Ozone depletion

Measuring ozone depletion uses a similar potency-equivalence as calculations for global warming potential. Ozone depletion was small for all impact categories, with fiber creation being the biggest contributor for cotton and cotton/polyester sweaters, and the sweater creation stage being the largest contributor for the wool sweater.

Photochemical oxidation

Photochemical oxidation is the creation of smog, caused by nitrogen oxides and volatile organic compounds reacting in sunlight. The transportation stage created the most smog in all sweaters except the cotton/polyester blend, where the use phase was the larger contributor.

Carcinogenics & Non-carcinogenics

These measures of human health effects are based on chemical inputs that are known to cause harm to human health, either by cancer or otherwise. The transportation stage had the largest effect on human health in both categories in all sweaters.

Human health- respiratory effect, average

Respiratory effects refer to the health effects of inhaling particulate matters. In the case of the wool and acrylic sweaters, the use phase caused the most particulate matters, 100% cotton sweaters released most particulate matter in the transportation phase, and the sweater blend released most particulate matters in the sweater creation stage.

100% Cotton sweater			Acidification	Ecotoxicity	Eutrophication	Global warming	Ozone depletion	Photochemical oxidation	Carcinogenics	Non-carcinogenics	human health - respiratory effects, average
		Units	kg SO2 eq	CTUe	kg N eq	kg CO2 eq	kg CFC-11 eq	kg O3 eq	CTUh	CTUh	kg PM2.5 eq
Cotton production	0.412	kg	0.011893465	17.9842308	0.009806597	1.58071408	1.50776E-07	0.104077306	7.08898E-08	2.24038E-07	0.002190975
Sweater creation	0.412	kg	0.197075878	0.2089035	0.004343953	18.5546765	4.01468E-10	1.154307652	3.36353E-09	1.29314E-07	0.031552233
Packaging	0.018	kg/sweater	2.23378E-06	0.00264602	2.41291E-06	0.00069165	NA	2.40745E-05	2.43683E-11	1.02973E-10	4.75363E-07
Transportation	1	sweater	0.15384317	0.01668519	0.014152963	1.45144453	1.87751E-08	1.258409033	0.000158211	0.264120878	0.033743683
Use	28	cycles	0.082982286	0.70913954	0.003466088	28.8175439	1.09063E-08	0.490951378	2.58818E-09	8.71061E-08	0.005123574
Total	1	sweater	0.445797033	18.921605	0.031772013	50.4050707	1.80859E-07	3.007769444	0.000158288	0.264121319	0.072610941

Table 1. TRACI results of a 100% cotton sweater.

100% Wool		Impact category	Acidification	Ecotoxicity	Eutrophication	Global warming	Ozone depletion	Photochemical oxidation	Carcinogenics	Non-carcinogenics	human health - respiratory effects, average
		Units	kg SO2 eq	CTUe	kg N eq	kg CO2 eq	kg CFC-11 eq	kg O3 eq	CTUh	CTUh	kg PM2.5 eq
Wool production	0.35	kg	0.016097868	0.21053017	0.005461359	1.34429385	1.09922E-08	0.034202835	3.40223E-09	1.22455E-10	0.00062393
Sweater creation	0.35	kg	0.038220021	2.07848591	0.003227367	10.9976185	8.68688E-07	0.336782419	3.2875E-08	1.45E-07	0.018233912
Packaging	0.018	kg/sweater	2.23378E-06	0.00264602	2.41291E-06	0.00069165	NA	2.40745E-05	2.43683E-11	1.02973E-10	4.75363E-07
Transportation	1	sweater	0.0097704	0.00842914	0.002451954	1.14785327	9.48493E-09	0.344147985	7.99264E-05	0.133430472	0.000885565
Use	28	Washes	0.024842384	0.21229491	0.001037642	8.62710011	3.265E-09	0.146975978	7.74822E-10	2.60769E-08	0.001533843
Total	1	sweater	0.088932906	2.51238616	0.012180734	22.1175574	8.92431E-07	0.862133291	7.99635E-05	0.133430643	0.021277724

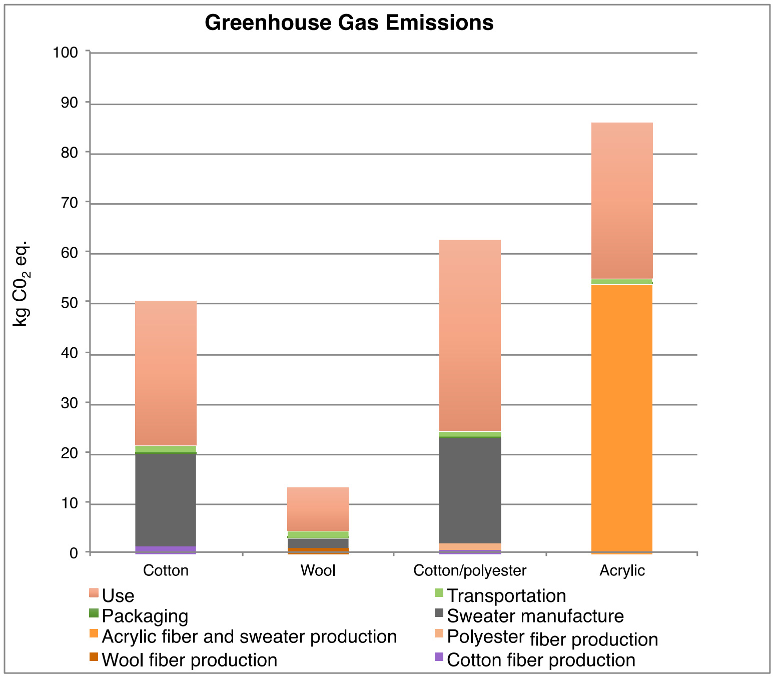
Table 2. TRACI results of a 100% wool sweater.

60% cotton/40% polyester		Impact category	Acidification	Ecotoxicity	Eutrophication	Global warming	Ozone depletion	Photochemical oxidation	Carcinogenics	Non-carcinogenics	human health - respiratory effects, average
		Units	kg SO2 eq	CTUe	kg N eq	kg CO2 eq	kg CFC-11 eq	kg O3 eq	CTUh	CTUh	kg PM2.5 eq
PET production	0.218	kg	0.009439716	0.04662264	0.007783392	1.25459588	1.18669E-07	0.082605046	5.62645E-08	1.77816E-07	0.001738953
Cotton production	0.327	kg	0.001381318	14.2738919	0.000135395	1.08076083	2.59339E-11	0.016025586	3.11545E-10	1.61005E-08	6.82895E-05
Sweater creation	0.545	kg	0.084927692	0.57328064	0.003056221	20.9102653	7.50886E-12	0.741901317	8.50846E-09	1.8383E-07	0.049127441
Packaging	0.018	kg/sweater	2.23378E-06	0.00264602	2.41291E-06	0.00069165	NA	2.40745E-05	2.43683E-11	1.02973E-10	4.75363E-07
Transportation	1	sweater	0.00918275	0.0086144	0.003814613	1.07134654	9.69339E-09	0.319492029	8.1683E-05	0.136363049	0.000845877
Use	28	cycles	0.109770257	0.93806079	0.004584994	38.1202948	1.4427E-08	0.649438109	3.42368E-09	1.15225E-07	0.006777744
Total	1	sweater	0.214703967	15.8431164	0.019377028	62.437955	1.43823E-07	1.809486163	8.17516E-05	0.136363542	0.058558579

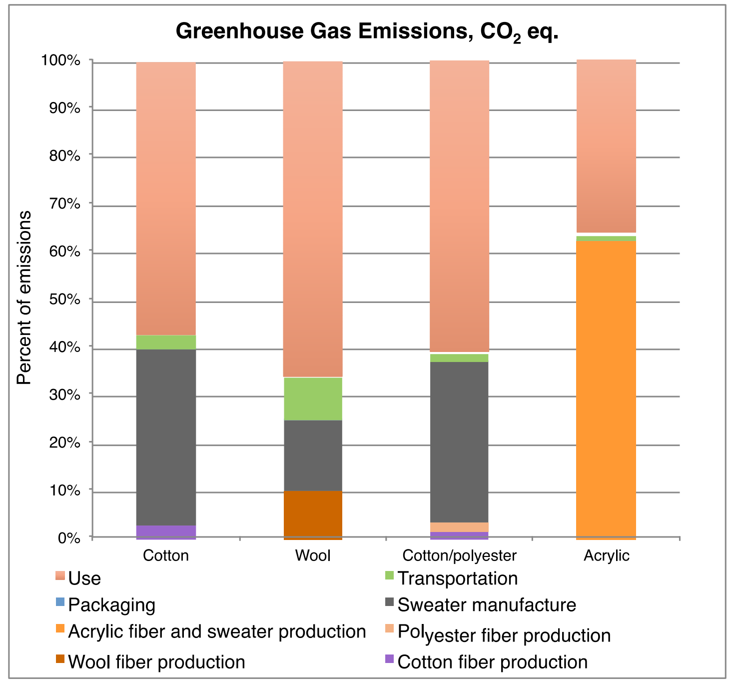
Table 3. TRACI results of a 60% cotton, 40% polyester blended sweater.

100% acrylic		Impact category	Acidification	Ecotoxicity	Eutrophication	Global warming	Ozone depletion	Photochemical oxidation	Carcinogenics	Non-carcinogenics	human health - respiratory effects, average
		Units	kg SO2 eq	CTUe	kg N eq	kg CO2 eq	kg CFC-11 eq	kg O3 eq	CTUh	CTUh	kg PM2.5 eq
Acrylic fiber and sweater creation	0.445	kg	NA	NA	NA	53.8983426	NA	NA	NA	NA	NA
Packaging	0.018	kg/sweater	2.23378E-06	0.00264602	2.41291E-06	0.00069165	NA	2.40745E-05	2.43683E-11	1.02973E-10	4.75363E-07
Use	28	cycles	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total	1	sweater	0.171754022	0.77860381	0.00645421	85.807465	2.30529E-08	0.75610194	0.158585338	0.000301686	0.005947276

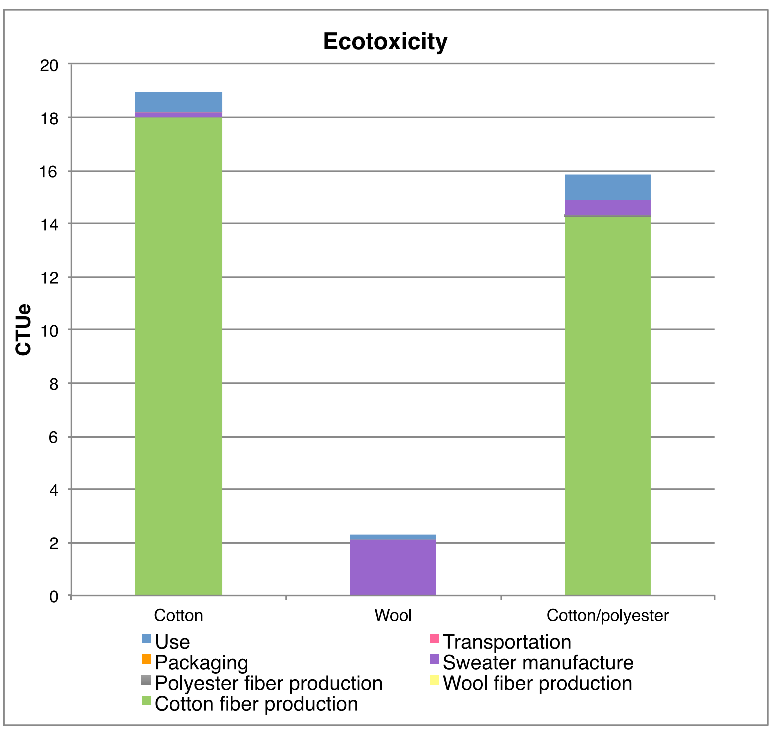
Table 4. TRACI results of a 100% acrylic sweater.



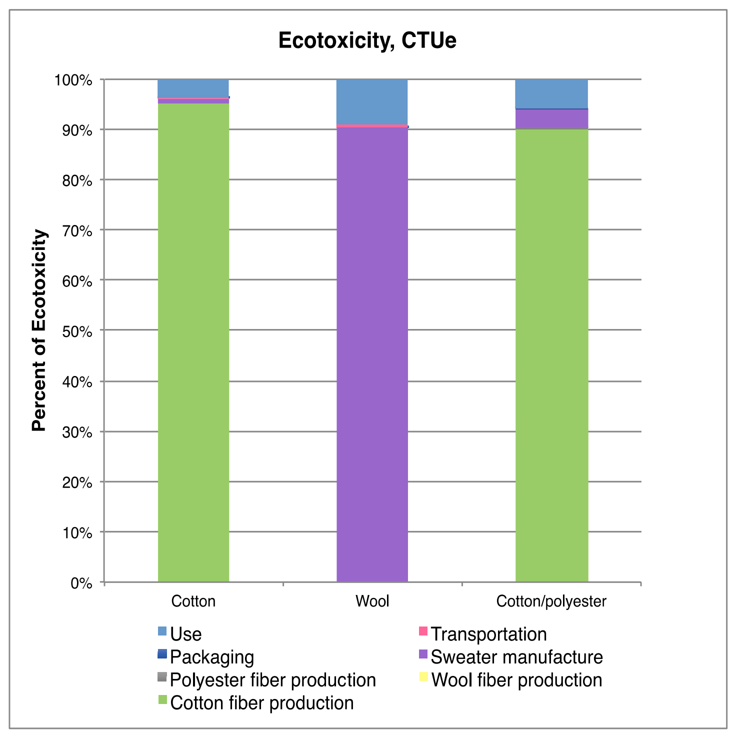
Graph 1. Greenhouse gas emissions in kg CO[2] equivalence.



Graph 2. Greenhouse gas emissions as a percentage of the whole sweater's emissions.



Graph 3. Ecotoxicity in CTUe.



Graph 4. Ecotoxicity as a percentage of the whole sweater's Ecotoxicity.

DISCUSSION

In agreement with other studies (van der Velden et. al 2014, Steinberger et. al 2009) the use phase is a large contributor to the environmental impact of a sweater, particularly in the global warming potential and photochemical oxidation categories. This was expected due to the continuous use of the sweater; while it is only created once, it is washed (in this case) 28 times. The use phase did not contribute most in all impact categories for various reasons. One of the highlights is the high ecotoxicity of cotton (graphs 3 and 4). High ecotoxicity values of cotton are most likely due to extensive fertilizer use in the fiber creation phase (Steinberger 2009, Cardoso 2013). Synthetic sweaters did have high contributions to global warming potential due to their high energy requirements in fiber and sweater creation processes, though it was not comparatively as high as has been suggested by Beton et. al (2014), which attributes high global warming potentials to synthetic fibers due to the combustion energy required for their finishing and electricity demand for their formation, printing, and dyeing.

Notably, my hypothesis that the fiber creation would have the highest impact where usage behaviors were different (i.e. the wool sweater) was not true for any impact category. In general, fiber creation stages were low-impact in all categories. This is likely due to by-products associated with a fiber's creation. Ecoinvent data for cotton fibers also represent the by-product of cottonseed, used to make oil and stock feed. Impacts for cotton growth are allocated to both products, and as there is a larger mass of cottonseed than cotton fiber, more impacts are allocated to cottonseed. Similarly, Ecoinvent data for wool also represents sheep raised for meat. Thus, the true impacts of 'fiber creation' are not, nor should they be, fully represented. Allocations for polyester and acrylic fiber creations in the utilized data are unknown, but are unlikely.

Wool is the only sweater that was the least impactful in all ten impact categories. However, with the considerable gap in knowledge of the acrylic sweater's fiber and sweater creation impacts, further research would be necessary to verify wool being the most environmentally-friendly fabric. At this time, consumers may not be fully informed enough to be able to purchase the absolute least impactful sweater type, but they can modify their use behavior to significantly reduce their sweater's global warming potential (and any other impact category). Using a drying machine uses almost twice (wash: 4.9 MJ/kg, drier: 9.1 MJ/kg) as much energy as the washing machine, thus line-drying can make a considerable change in a sweater's impact and energy consumption.

While geography was carefully considered in this project, it is unlikely that locality matters much in transportation. However, regions often have their own energy mixes that would make a sweater life stage process more or less impactful. Some areas may have cleaner energies than developing countries due to the local natural resource availability. For example, a sweater made in California, USA would likely have a smaller impact than one made in West Virginia, USA, especially in terms of global warming potential, because the energy supplied to the factory is cleaner and not necessarily because it is being made closer to the consumer (Shehabi et. al 2014).

Textile LCA studies have a lot to consider due to high variance in every process in its lifetime. Even the most comprehensive LCA studies only measure specific scenarios. Further textile LCA research should aim to best represent actual textiles and practices used to create them, especially in regards to geographically-specific methods and resources. But even before more accurate models of the textile supply chain are studied, baseline data should be improved, and be made transparent, particularly in regards to synthetic fibers.

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