CASE STUDY

A spatially explicit life cycle inventory of the global textile chain

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Abstract

Background, aim, and scope Life cycle analyses (LCA) approaches require adaptation to reflect the increasing delocalization of production to emerging countries. This work addresses this challenge by establishing a country-level, spatially explicit life cycle inventory (LCI). This study comprises three separate dimensions. The first dimension is spatial: processes and emissions are allocated to the country in which they take place and modeled to take into account local factors. Emerging economies China and India are the location of production, the consumption occurs in Germany, an Organisation for Economic Cooperation and Development country. The second dimension is the product level: we consider two distinct textile garments, a cotton T-shirt and a polyester jacket, in order to highlight potential differences in the production and use phases. The third dimension is the inventory composition: we track CO_2, SO_2, NO_x, and particulates, four major atmospheric pollutants, as well as energy use. This third dimension enriches the analysis of the spatial differentiation (first dimension) and distinct products (second dimension).

Materials and methods We describe the textile production and use processes and define a functional unit for a garment. We then model important processes using a hierarchy of preferential data sources. We place special emphasis on the modeling of the principal local energy processes: electricity and transport in emerging countries.

Results The spatially explicit inventory is disaggregated by country of location of the emissions and analyzed according to the dimensions of the study: location, product, and pollutant. The inventory shows striking differences between the two products considered as well as between the different pollutants considered. For the T-shirt, over 70% of the energy use and CO_2 emissions occur in the consuming country, whereas for the jacket, more than 70% occur in the producing country. This reversal of proportions is due to differences in the use phase of the garments. For SO_2, in contrast, over two thirds of the emissions occur in the country of production for both T-shirt and jacket. The difference in emission patterns between CO_2 and SO_2 is due to local electricity processes, justifying our emphasis on local energy infrastructure.

Discussion The complexity of considering differences in location, product, and pollutant is rewarded by a much richer understanding of a global production–consumption

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chain. The inclusion of two different products in the LCI highlights the importance of the definition of a product's functional unit in the analysis and implications of results. Several use-phase scenarios demonstrate the importance of consumer behavior over equipment efficiency. The spatial emission patterns of the different pollutants allow us to understand the role of various energy infrastructure elements. The emission patterns furthermore inform the debate on the Environmental Kuznets Curve, which applies only to pollutants which can be easily filtered and does not take into account the effects of production displacement. We also discuss the appropriateness and limitations of applying the LCA methodology in a global context, especially in developing countries.

Conclusions Our spatial LCI method yields important insights in the quantity and pattern of emissions due to different product life cycle stages, dependent on the local technology, emphasizing the importance of consumer behavior. From a life cycle perspective, consumer education promoting air-drying and cool washing is more important than efficient appliances.

Recommendations and perspectives Spatial LCI with country-specific data is a promising method, necessary for the challenges of globalized production–consumption chains. We recommend inventory reporting of final energy forms, such as electricity, and modular LCA databases, which would allow the easy modification of underlying energy infrastructure.

Keywords Atmospheric emissions · Carbon dioxide · China · Electricity · Energy · Environmental Kuznets Curve · India · Infrastructure · Nitrogen oxides · Particulates · Spatial LCI · Sulfur dioxide · Textile · Transport

1 Introduction

Life Cycle Analysis (LCA) of a product can serve as a guide to decision-making, identifying key processes and environmentally preferable alternatives. A full-product life cycle allows the answer to the question: should the environmental focus be on the production phase (cleaner production) or at the consumption phase (cleaner consumption)? In this work, we create a life cycle inventory (LCI) of the globalized textile chain, disaggregated along three separate dimensions: (1) spatially explicit at the country level, (2) applied to two distinct products, and (3) encompassing four major atmospheric pollutants and energy use. The three dimensions inform and enrich the analysis, enabling us to address the issues of cleaner production and consumption from different perspectives, with different answers depending on the product and the pollutant considered.

1.1 The textile sector in global trade

LCA approaches require adaptation to reflect the increasing delocalization of manufacturing in emerging countries. This work addresses this need by establishing a spatially explicit LCI. Our goal is to analyze the spatial pattern of pollutant emissions and illustrate the potential displacement of pollution in a globalized economy. For our case study, we choose the production and use of two representative products of the globalized textile industry: a cotton T-shirt from India and a polyester jacket from China, both consumed in Germany. The producing countries are representative of the global textile production chains, which have been expanding and changing in composition, moving to developing and emerging countries on the textile production and processing side, as well as shifting from natural to synthetic fibers (Baffes 2004). Although previous life cycle analyses of textile products have been performed (Jödicke 2001; Pulli 1997), they often do not take into account the global nature of the production–consumption chain or the entirety of the production–consumption processes (Dahllöf 2004)

1.2 The Tracking Environmental Impacts of Consumption project

This work is part of the "Tracking Environmental Impacts of Consumption" (TREI-C) research project (www.trei-c.org). The goal of TREI-C is the development of tools to assess the environmental impacts of globalized production and consumption through one detailed product life cycle assessment and more encompassing Multi-Region Input-Output modeling. A third component maps the location of emissions and impacts depending on global transfers of atmospheric pollutants and appropriate local impact factors.

Within the TREI-C project, the textile case study serves to highlight the complexity of following a production consumption chain in detail, compared to the more aggregate and comprehensive Input–Output approach. It also serves as the basis for calculations of spatially explicit country-level impact factors along a production–consumption chain. Indeed, human health impact factors are higher in China and India, due to higher population densities than in Europe or the USA, so the same quantity of emissions will have more important health consequences. This is to be added to the health vulnerability resulting from lack of public health infrastructure.

In accordance with the ultimate goals of the TREI-C project—the quantification of trade exchanges of embodied pollutants and their parallel atmospheric transport—the LCI focuses on atmospheric emissions of four common pollutants (CO_2, SO_2, NO_x, particulates). These pollutants are of significant environmental and human health relevance: CO_2

is the primary contributor to anthropogenic global warming, NO_x and SO_2 are acidifying and have already been targeted through environmental policies in Europe and the USA, and particulates cause or aggravate respiratory diseases. They are also chosen because of their data availability and because they are emitted in conjunction with fossil energy use, which arises in most industrial processes, as opposed to other pollutants, whose emission inventories are lacking or related to very specific industrial processes. Despite the inventory focus on specific atmospheric emissions, sources of aquatic pollution are also surveyed.

In the frame of this project, the present paper specifically aims to:

– Develop a hierarchical strategy for establishing the life cycle inventory of products from developing countries
– Model processes and allocate emissions in a spatially explicit manner, at the country level
– Determine the respective share of emissions and energy needs for two types of garments produced in developing countries and consumed in developed countries
– Discuss the appropriateness and limitations of applying the LCA methodology in a global context, especially in developing countries

The structure of this article relates to the spatial, product, and pollutant dimensions of the study. First, the system boundaries and functional unit for two products are described (Section 3). The data gathering strategy and the inventory data sources are outlined in Section 4. The spatial inventory results are then analyzed, and their implications are discussed in Section 5, including the particularities of different types of pollutants, use-phase scenarios, and the challenge of linking inventory and impacts in this LCI. Section 5 summarizes our conclusions, along with suggestions for building modular LCIs to accommodate global production–consumption processes.

2 System boundaries and functional unit description

This LCI is composed of two distinct product chains: a cotton T-shirt produced in India and a polyester jacket manufactured in China, both consumed in Germany. The treatment of the two is not strictly parallel, since the cotton chain in India is much better characterized than the polyester in China.

The processes considered in the cotton chain are the following (Fig. 1): (1) agriculture, including direct and indirect energy inputs, irrigation, commercial fertilizers, and pesticides, ginning (separation of seed and fiber); (2) textile processes, including spinning, knitting, bleaching, dyeing, apparel confection, with packaging, direct and indirect energy use, chemicals, and water use; (3) transport stages in India, Germany, and intercontinental; (4) retail in
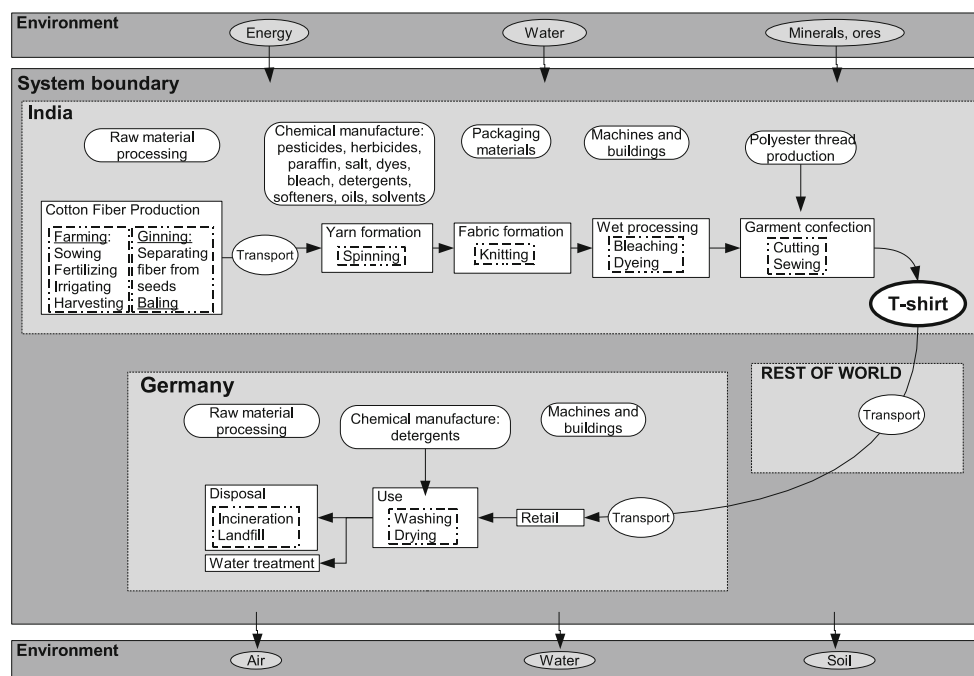
Fig. 1 System boundary and processes considered for the cotton T-shirt production–consumption chain. The system is divided into three boxes: India (producing country), Germany (consuming country), and Rest of World. The differences with the polyester jacket chain are explained in the text

Germany; (5) use phase, washing, and drying, taking into account electricity, detergent manufacturing, and water treatment; (6) disposal through landfill and incineration.

The processes considered in the polyester chain are the following: (1) resin production, including the production of base ingredients; (2) textile processes, spinning, knitting, apparel confection, considering only direct and indirect energy use, without chemicals, packaging, or water use; (3) transport in China, Germany, and intercontinental. The retail, use, and disposal processes are the same as those for the cotton chain although adapted to the polyester product.

The functional unit is "100 days of a garment being worn," with 100 days, or once a week for 2 years, or every 2 days for two seasons, estimated to be a reasonable lifetime for a garment. Although the functional unit is the same for both jacket and T-shirt, the secondary functions are very different, and no comparative assertion can be issued between these two products. However, contrasting the life cycle emissions of these products is highly interesting since there are significant differences in the use phase: the T-shirt is estimated to be washed once every two wearings, 50 times total during its lifetime, and the jacket washed three times a season or six times during its lifetime.

If a garment has a lifetime longer than 100 days, the relative contribution of the use phase to the total environmental impacts increases; however, the environmental burden per day of a garment being worn decreases, since the production and disposal contributions are distributed over a larger number of days. Conversely, a garment which is worn a few times, then almost immediately discarded, will have a much lower environmental impact from its use phase, although its impact per day of being worn will be much larger.

3 Data basis of the spatially explicit life cycle inventory

3.1 Method

This in-depth life cycle inventory including processes in both developed and developing countries is based on publicly available data sources, with a specific emphasis on gathering and adapting representative data for emerging countries. In industrialized countries, significant efforts have been made to compile and update inventories for product and process life cycle analysis: in Switzerland EcoInvent (Frischknecht and Rebitzer 2005); in Germany, Gemis (Fritsche and Schmidt 2007) or GaBi (GaBi 2008); Environmental Input–Output for the USA (Suh 2003), Denmark (Weidema et al. 2005), and others (Curran et al. 2006). This work, however, remains to be performed for emerging/developing countries where data availability is a basic problem for establishing LCIs. As a consequence, the United Nations Environment Programme-Society of Envi-

ronmental Toxicology and Chemistry Life Cycle Initiative has highlighted capacity building for LCA in developing countries as a work area for its second phase in 2007–2010. The ongoing EU 6th framework project Exiopol (2008) will contribute international Input-Output data for many pollutants and economic sectors.

In some cases, the use of the existing life cycle databases for industrialized countries may be applied to emerging/developing countries with little risk of error. However, the potential of large differences even in fairly standard industrial processes should not be underestimated (Berrah et al. 2007). In our study, we systematically prioritize local data. We find large differences between industrialized country processes and emerging country ones and thus demonstrate the need for detailed local data, especially for, but not limited to, energy infrastructure.

In this research, we use a combination of approaches to create life cycle inventories for agricultural and industrial processes in India and China. We use data following a preference hierarchy of three broad categories. The first category consists of detailed *local* data, from our industry partner Switcher, publicly available sources, either LCA or other approaches. This is fortunately the case for most of the Indian and European data, as well as most energy processes. The second category is detailed process data, adapted to regional infrastructure. This is the case for the Chinese polyester part of the study, where we use Indian data if no Chinese data is available, and European or USA studies otherwise. The last category is an existing LCA database: EcoInvent (Frischknecht and Rebitzer 2005), when no detailed process data exists. This is the case for specialty and basic chemical manufacturing, as well as infrastructure (buildings and machines). For these, we adapt standard LCA processes to account for the local electricity production.

We also choose our data sources to be as close to the year 2000 as possible, although some exceptions are inevitable.

3.2 Summary of the inventory data

The inventory focuses on four common atmospheric pollutants: carbon dioxide (CO_2), nitrogen oxides (NO_x), particulates (PMs), and sulfur dioxide (SO_2) as well as primary nonrenewable energy. The particulate diameter is not specified in many of our sources, so no size information is available, and all PM emissions are reported as total PM.

Since the full details of the inventory are lengthy, the following is a bullet-point summary of the full inventory data basis, which is completed in the Electronic supplementary material. The only stage described in full here is the electricity modeling for China and India. Some of our most important references appear only in the Electronic supplementary material but can be found in the full bibliography.

1. *Cotton Agriculture in India:* is surprisingly energy-intensive, due to decentralized and poorly regulated groundwater irrigation. Primary energy per cotton yield is even higher than in the USA. This argues against using a standard "developing country" cotton process as done in Wiegmann (2002).

2. *Textile manufacture in India:* we use a combination of regional material flow analysis (Erkman and Ramaswamy 2003) and an industry energy study (Lehmann Pollheimer 2006). The most energy-intensive process is dyeing, which uses wood-based heat. The CO_2 emissions and energy from the wood do not appear in our inventory, since they are considered to be from renewable biomass; however, the NO_x emissions are included. Power from diesel generators is included, necessary because of frequent power outages in India.

3. *Textile manufacture in China:* due to lack of local data, we rely principally on a USA polyester study (Franklin 1993), resulting in high uncertainty for this phase, since the Chinese energy use may be much higher (Berrah et al. 2007).

4. *Electricity emissions in China and India:* both Chinese and Indian electricity comes predominantly from coal-fired thermal power plants: 78% and 69%, respectively (IEA 2004). They are also over 99% self-sufficient in electricity production. The emissions from the coal-based electricity of India and China are thus the focus of our inventory efforts, and the results are summarized in Table 1.

   The CO_2 emissions for India are determined from the Central Electricity Authority (CEA) database for the Kyoto Clean Development Mechanism (CEA 2007). The Chinese CO_2 emissions are estimated from a combination of the China Energy Databook (Sinton et al. 2004), International Energy Agency (IEA) data (IEA 2007) and the Carbon Dioxide Information Analysis Center (Marland et al. 2007).

   The China Energy Databook (Sinton et al. 2004) provides Chinese SO_2 and particulate emissions for the entire electric sector but no information on NO_x emissions. For Chinese NO_x, we use the Indian value. Indian NO_x, particulate, and SO_2 emissions are found in

Mittal and Sharma (2004) and Mittal (2006). These are overall consistent with the EcoInvent process emissions for Polish coal electric production, which we adapt to account for the differences in CO_2 emissions.

   Data on transmission and distribution losses are available from China (Sinton et al. 2004) but include losses due to theft for India (TERI 2006). From an LCA perspective, stolen electricity is not lost. The Chinese 8% transmission and distribution loss to light industry is thus used for both India and China.

5. *Transport stages:* the transport stages include national and international freight, as well as international personnel transport. Consumer transport to and from the retail location is excluded, as it may be on the same order of magnitude as the entire production–consumption chain (Browne et al. 2005).

6. *Freight in India:* the long distances of truck freight transport in India warrant a dedicated process model. This is based on the Euro 0 emissions standard (a conservative estimate). The loading factor for India is almost the double (Reddy et al. 2000) of what is typically used in European LCAs. The results are shown in Table 1.

7. *Retail in Germany:* this process is taken from Environmentally Extended Input–Output analysis, with the difficulty of the determination of the appropriate monetary amount to apply to the emission factors. In fact, we keep this component separate from the total of all other emissions, due to its large estimated error margin.

8. *Use phase in Germany:* the use phase is explored in some detail, including detergent composition, water treatment, number of washings and dryings, loading factor, temperature of washing, and efficiency rating of equipment. Due to its importance, various use-phase scenarios are analyzed in the discussion.

9. *Disposal in landfill and incineration:* a disposal phase combining standard landfill and incineration processes is given; no recycling is considered. The CO_2 emissions from the cotton are considered to be renewable and are not included in the total, in contrast to the fossil polyester emissions.

Table 1 Emissions of CO_2, NO_x, particulates, and SO_2 for key energy processes in China, India, and Germany

Emissions from energy	China 1kWh	India 1kWh	Germany 1kWh	Heat 1MJ	India transport 1 ton-km
Coal fraction (%)	78	69	51		
Fossil fraction (%)	84	82	63		
Carbon dioxide (kg)	0.87	0.88	0.62	0.090	0.31
NO_x (kg)	0.0055	0.0036	0.0006	0.00014	0.0048
PM (kg)	0.0027	0.0020	0.0007	0.00006	0.0004
SO_2 (kg)	0.0060	0.0057	0.0005	0.00047	0.0003

4 Results, implications and scenarios

4.1 Spatial LCI results

Our results confirm the need for using spatially explicit data at the national level, for any process which requires energy. For example, the surprisingly energy-intensive Indian cotton cultivation cannot be modeled assuming either US or Chinese cultivation processes. Local data are especially important for the electricity-related emissions shown in Table 1. In this case, the inclusion of a variety of pollutants in the LCI is enlightening. Indeed, simply substituting European electricity processes into the Chinese and Indian mixes would not change the CO_2 emissions much but would result in massive underestimates of NO_x (a factor 4 to 6), particulates (a factor of 2 to 3), and SO_2 (a factor of 8 to 9).

The overall results for the four atmospheric pollutants, as well as nonrenewable primary energy, are summarized in Table 2 for a cotton T-shirt weighing 0.25 kg and in Table 3 a polyester jacket weighing 0.5 kg, weights purposefully chosen for easy scaling. The country of location of the emissions is indicated in each case. The emissions due to international transport occur in the Rest of World compartment. The percentage of emissions in the producing and consuming countries, as well as internationally, is also given. The origin of electricity is the most crucial factor driving the atmospheric emissions in this study. Despite the global nature of the chain, transportation is much less significant, accounting for 4% of CO_2 emissions and 14% for NO_x (due to local transport in India for the T-shirt).

Nonrenewable primary energy consists of fossil fuels and nuclear energy. The only process stage where renewable primary energy plays a significant role is the cotton dyeing, where 72% of the total primary energy is from wood.

The uncertainties given with the data stage in the Electronic supplementary material correspond to primary energy and CO_2 and are assumed to be larger for the other pollutants. The aggregate uncertainties are calculated assuming the error is normally distributed (except for production in China, where it is more likely to be systematic).

4.2 Production or consumption? Insights from studying two garments

A cotton T-shirt and a polyester jacket cannot be compared as substitutable products but are both representative of the general apparel product category. Contrasting their lifecycle emissions showcases the variable importance of the use phase. The T-shirt requires 50% more nonrenewable primary energy than the jacket, despite being half its weight; however, the T-shirt only emits 30% more CO_2

Table 2 Spatial, non-renewable primary energy and emissions of CO_2, NO_x, total particulates, and SO_2 for 100 days of garment use for T-shirt

Cotton T-shirt (0.25kg) Units	Primary energy MJ	CO2 kg	Uncertainty	NO_x g	PMs g	SO2 g	Uncertainty
Total	240.11	14.00	10%	48.98	32.70	32.03	20%
Production: India	26%	29%	15%	76%	43%	67%	25%
Cotton fiber	28.30	1.82	30%	17.11	5.43	9.83	50%
Yarn	13.07	0.96	10%	4.93	2.75	6.06	20%
Fabric	2.56	0.16	10%	0.96	0.46	0.99	20%
Colored fabric	10.37	0.63	10%	8.06	4.76	4.05	20%
Garment	2.23	0.08	10%	0.50	0.12	0.26	20%
Transport	6.05	0.37	20%	5.88	0.46	0.38	35%
Rest of World	0.4%	0.4%	20%	1.0%	0.1%	1.2%	20%
Transport	0.85	0.05	20%	0.51	0.05	0.38	35%
Sale and use: Germany	74%	71%	10%	23%	57%	31%	20%
Transport	0.22	0.01	20%	0.10	0.04	0.02	35%
Washing (50 times)	62.16	3.48	10%	4.25	10.89	3.87	20%
Drying (50 times)	114.23	6.44	10%	6.60	7.70	6.18	20%
Disposal	0.06	0.00	20%	0.08	0.04	0.00	35%
Retail (5 USD)	–	0.91	100%	2.12	1.21	0.72	100%

Data are shown separately for each process stage and summed up for each location, showing distinction between the behavior of energy and CO_2, on the one hand, and NO_x, particulates, and SO_2 on the other. The retail stage is kept separate from the total, as explained in the text. The uncertainties for the location totals and total emissions are estimated assuming normal distributions, except for the Chinese polyester production, where we expect the error to be systematic

than the jacket. On the whole, the total lifecycle emissions for the T-shirt and the jacket are on the same order of magnitude, with the cotton T-shirt emissions 30% higher than for the polyester jacket, except for SO_2, where the proportion is reversed.

This similarity in emission quantities ends as soon as the contributions of each location of emission and product stages are examined. For the T-shirt, roughly two thirds of the CO_2 and particulate emissions occur in the consuming country, with that proportion reversed for NO_x and SO_2. In the case of the jacket, all the pollutants have the vast majority (70–90%) of their emissions in the producing country. In the case of the T-shirt, reducing the lifecycle energy use and CO_2 emissions is best addressed by a focus on the consumption phase, but for the jacket, the production phase is the most crucial.

The striking difference in the location of energy use and CO_2 emissions—over two thirds in the consuming country for the T-shirt, less than one third for the jacket—are due to differences in their use phase: the T-shirt is washed and dried 50 times, compared to six times for the jacket. This can be clearly seen in Fig. 2. The importance of the use phase in apparel for CO_2 emissions is widely known; however, as our results make clear, it should not be taken as universal for all apparel types. Indeed, because of the usual underestimate of the emissions of cotton agriculture and processing stages, the proportion is often assumed to be much higher than two thirds. Moreover, this proportion is not true of all pollutant types, as reversed proportions for NO_x and SO_2 demonstrate, shown for SO_2 in Fig. 3.

For both the T-shirt and the jacket, NO_x and SO_2 emissions are larger in the production country than the share of energy use would warrant, by a factor of more than 4. Fossil fuel combustion accounts for the majority of the

NO_x emissions for cotton, the totality for polyester, and all the SO_2 emissions. The higher proportion in the production country is thus due to the lack of emission standards and filtration implementation. The nonfossil NO_x emissions of cotton have several origins. NO_x is emitted in the agricultural process, through the production and use of N fertilizers, at the level of 10% of the total. It is also emitted in the cotton dyeing process because of the large quantity of wood burned to produce heat. Since the wood is considered to be renewable biomass, the biogenic CO_2 emissions from the wood combustion are not included in our inventory; however, the corresponding NO_x emissions contribute to almost 10% of the total. To address life cycle NO_x and SO_2 emissions, the production phase is the most important for both products.

The particulate emissions are also predominantly due to electricity use but also have contributions from material production phases: steel and concrete (used for machinery and buildings) and laundry detergent. These non-energy contributions cause the higher-than-expected emissions in the consumption phase. Moreover, the difference in emission factors between Germany, China, and India is smaller for particulates (factor of 3–4) than for NO_x or SO_2 (factors of 6–12) as can be seen in Table 1.

4.3 Use-phase scenarios

Because of the importance of the use phase for energy and CO_2 for the T-shirt product and the availability of use-phase alternatives, we present four scenarios showing the relative impact of (1) machine and air drying, (2) washing temperature choice, and (3) machine efficiency rating. The results are shown in Fig. 2 and Table 4. These scenarios allow us to define hierarchies of consumer behavior

Fig. 2 Carbon dioxide emissions per 100 days of garment use for the cotton T-shirt (considering different use scenarios) and for the polyester jacket. The relative impacts of use phase are clear: air vs. machine drying is the most important, followed by the temperature of washing, with the machine efficiency rating coming last. A similar plot for energy is in the article's Electronic supplementary material, Figure SM-1
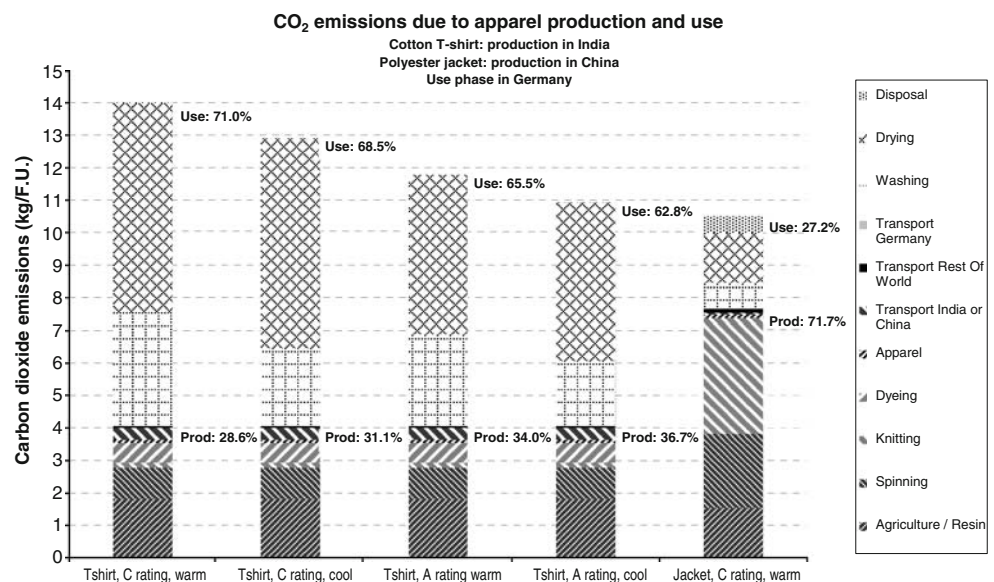
Fig. 3 Sulfur dioxide emissions per 100 days of garment use for the cotton T-shirt (considering different use scenarios) and for the polyester jacket. Note the difference in the production-use distribution of the T-shirt and jacket
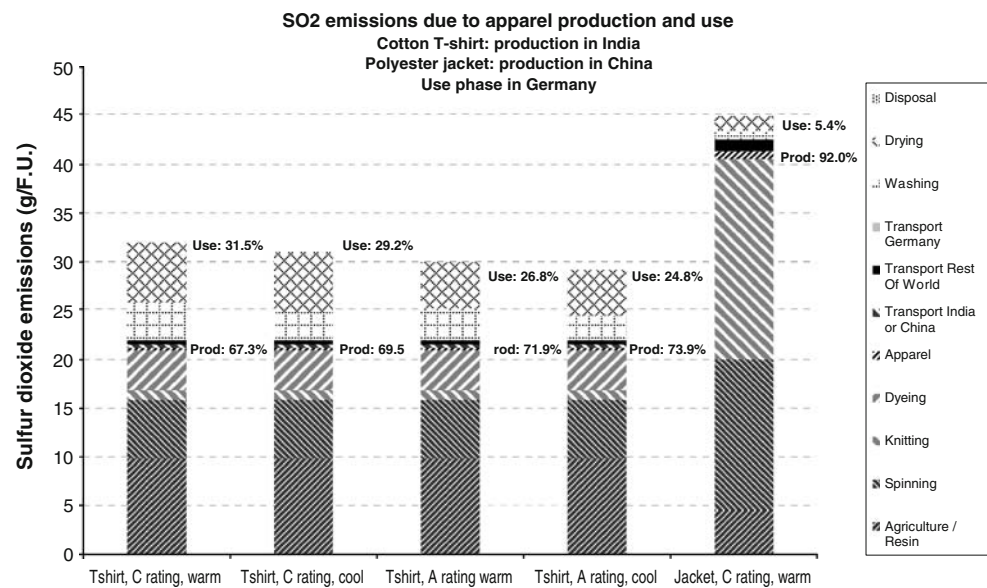
choices, an approach encouraged in sustainable consumption (Kaenzig and Jolliet 2006; Bilharz et al. 2008).

The most important choice a consumer can make is that of machine or air drying (reductions of more than 60% in the use-phase emissions with air drying), followed by temperature of washing (30% reduction of the washing phase emissions at 40°C compared to 60°C), with appliance efficiency rating being the least important (20% reduction with A rating appliances compared to C rating, other parameters held constant). In this case, the use-phase behavior of the consumer is much more important than the appliance chosen for the use phase: by switching to air drying and cooler washing, the total lifecycle product emissions are halved.

Table 3 Spatial, non-renewable primary energy and emissions of CO_2, NO_x, total particulates and SO_2 for 100 days of garment use for polyester jacket

Polyester jacket (0.5kg) Units Total	Primary energy MJ 156.39	CO2 kg 10.52	Uncertainty 35%	NO$_x$ g 35.97	PMs g 21.50	SO2 g 45.00	Uncertainty 75%
Production: China	71%	72%	50%	88%	85%	92%	80%
Resin	26.82	1.55	50%	4.14	2.38	4.48	80%
Yarn	29.23	2.28	50%	14.16	8.76	15.53	80%
Fabric	52.92	3.54	50%	11.82	6.55	20.54	80%
Colored fabric	–	–	–	–	–	–	–
Garment	1.46	0.11	50%	0.73	0.46	0.77	50%
Transport	0.82	0.05	50%	0.80	0.06	0.05	80%
Rest of World	1.2%	1.1%	50%	3.8%	0.7%	2.6%	50%
Transport	1.84	0.11	50%	1.36	0.15	1.18	80%
Sale and use: Germany	28%	27%	10%	8%	15%	5%	20%
Transport	0.82	0.02	20%	0.19	0.07	0.05	35%
Washing (6 times)	14.92	0.78	10%	0.98	1.19	0.90	20%
Drying (6 times)	27.41	1.55	10%	1.58	1.85	1.48	20%
Disposal	0.14	0.51	20%	0.20	0.03	0.01	35%
Retail (10 USD)	–	1.83	100%	4.23	2.43	1.44	100%

Data are shown separately for each process stage and summed up for each location, showing distinction between the behavior of energy and CO_2, on the one hand, and NO_x, particulates, and SO_2 on the other. The retail stage is kept separate from the total, as explained in the text. The uncertainties for the location totals and total emissions are estimated assuming normal distributions, except for the Chinese polyester production, where we expect the error to be systematic

Table 4 Details of the cotton T-shirt use-phase scenarios shown in Fig. 2, along with the use-phase CO_2 emissions of each

Scenario	Function	Weight (kg)	Appliance rating	Washing temperature (°C)	Number of washings and dryings	CO_2 emissions: washing and drying (kg)	CO_2 emissions: washing only (kg)
A	T-shirt	0.25	C	60	50	9.9	3.5
B	T-shirt	0.25	C	40	50	8.8	2.4
C	T-shirt	0.25	A	60	50	7.7	2.8
D	T-shirt	0.25	A	40	50	6.9	2.0

A five-fold difference exists between the most energy-intensive scenario (machine drying, warm washing, inefficient machines) and the most energy sparing (air drying, cool washing, efficient machine)

This result also highlights the importance of developing detergents which are effective at lower temperatures. Another consideration is the necessity of frequent washings. If a garment requires fewer washings (for example, through resistance to stains or sweat), the use-phase impacts will be correspondingly lowered.

In contrast, the SO_2 emissions are much less affected by changes in the use phase, as can be seen in Fig. 3, since 67% and 92% are emitted in the production phase for the T-shirt and jacket, respectively.

4.4 Evidences for Kuznets and non-Kuznets emissions

The CO_2 emissions in Tables 2 and 3 are proportional to energy use, mostly electricity. Since fossils represent 80% of technical primary energy worldwide, the CO_2–energy proportionality is the rule rather than the exception. CO_2 thus indicates the location of the largest energy use. In the absence of carbon capture technology, CO_2 is found and emitted in comparable quantities per megajoule, in all fossil-fuel energy-intensive processes, no matter where they are located.

In contrast, the emission of NO_x, particulates, and SO_2, although also mostly due to fossil fuel combustion, is not proportional to the energy use, since it can be mitigated by filtration technology. The energy and emissions required by the filtration are included in the inventory. In the following discussion, we focus on CO_2, NO_x, and SO_2, leaving aside particulates, since their larger contribution from material production complicates their behavior.

The reduction in NO_x and SO_2 emissions in Germany is due to the existence of effective filtration technologies and the implementation of environmental policies limiting acidifying emissions. Indeed, a similar study done in the early 1980s, before these policies were implemented, would show the NO_x and SO_2 fractions to be closely aligned with CO_2. The reduction of NO_x and SO_2 emissions in many developed countries is put forward as an example of the Environmental Kuznets Curve (EKC) conjecture: where environmental impacts first rise with economic growth but eventually decrease as increased prosperity allows the environment to become a higher priority and generates the revenue necessary for impact mitigation (Dinda 2004; Stern 2004).

The EKC is widely acknowledged to be a limited phenomenon, applying to a small subset of impacts: those with (1) local, immediate effects and/or (2) convenient technological means of abatement or substitution (De Bruyn et al. 1998). Acidifying emissions NO_x and SO_2 fulfill both these conditions; ozone depleting emissions fulfill the second. CO_2 emissions fulfill neither condition: they have global and deferred impacts, and no convenient carbon-capture technology exists to date.

In our spatial LCI, we find evidence for both EKC (NO_x and SO_2) and non-EKC (CO_2) emission behavior in the context of a global production–consumption chain. The EKC emissions are relatively smaller in the higher-income consuming country; the non-EKC emissions are high in both the high-income consuming country and the lower-income producing country (see Figures SM-2 and SM-3 in the Electronic supplementary material for CO_2 and SO_2, respectively). The difference between EKC and non-EKC emissions is clear in our data, despite the evidence that developing and emerging countries may be adopting some abatement technologies faster than expected, given their income level (Dasgupta et al. 2002).

Our results provide support for an interpretation of the EKC as a displacement of local environmental impacts, rather than global reduction. The reduction in NO_x and SO_2 emissions in Germany happened as large sectors of European industry (including textile) moved overseas. The lifecycle profile of these products benefits from the environmental abatement policies only during the use phase—the production phase may have worse impacts than before its displacement, depending on the conditions in the new country of production. The total product lifecycle emissions may not be absolutely reduced.

4.5 Linking impacts and inventories in the textile industry

Major caveats apply to our LCI for both water-borne pollution and specialty chemicals. Severe water pollution is

a consequence of the production and use of textile products: at the production stage, dye-laden effluents require treatment (lacking in India and in China); at the consumption stage, eutrophication results from discharge of laundry detergent.

The textile industry uses many specialty chemicals. Pesticides are massively used in cotton cultivation, and reactive dyes are used for dyeing. The exact quantities and formulations are not publicly available, but the resulting severe health damage is documented (Mancini et al. 2005; CSA and MARI 2005; Bhalli et al. 2006; Prithiviraj 2002; Govindarajalu 2003; Michaels 1988). Previous LCA work has attempted to understand the production phase of such specialty chemicals (Geisler et al. 2004; Dahllöf and Steen 2005) and their fate in a river system (Beck et al. 2000) but unfortunately does not address the topic of fate and impact when these chemicals are massively discharged into the environment with no or little dilution. So far, the most comprehensive effort at modeling pesticide impacts through a product LCA was done on bananas in Costa Rica (Humbert et al. 2007). This work relies on detailed data, in the absence of which a life cycle approach cannot be expected to produce reliable health and ecosystem results.

In India and China, workplace safety is much lower than in Europe or the USA. Worker exposure to dangerous chemicals and emissions is thus much more prevalent. The dyes used in the cotton industry are often azo dyes, which are currently regulated and tested for in the EU, as they emit harmful and even cancer-causing chemicals during the use phase (European Parliament and EC 2002; Robins and Humphrey 2000). Indeed, many dyes banned in Europe are now manufactured in India and are present in imported textiles. The health impact of these chemicals on the textile and chemical workers must be even more severe than on the European consumer. Another health effect within the cotton workplace is byssinosis (Mishra et al. 2003; Laraqui et al. 2002), a respiratory disease due to exposure to cotton fibers. An LCA assessing damage beyond the factory walls or outside the crop field will thus miss significant human health impacts. In these cases, health studies of affected populations are necessary to complement the LCA findings.

Salt is used in the reactive dyeing of cotton textile. Despite some efforts at salt recovery, large quantities are discharged in the wastewater: 20,000 tons per year (Erkman and Ramaswamy 2003). This has led to the salinization of local drinking and agricultural water (Kurian 2005) with health and ecosystem impacts. However, salinization is not a traditional impact category of LCA, despite being a severe problem in many emerging/developing countries. The volume of water used for textile is an environmental concern of its own. One of the largest scale environmental disasters, the drying up of Aral Sea, is a direct result of cotton irrigation in Central Asia. However, for such an impact to be brought to light

by an LCA, the water usage of a process must be related to the local hydrological cycle (including factors such as downstream water uses).

5 Conclusion and recommendations

In this article, we presented a spatial LCI, based on local process data whenever available, for the global production–consumption chains of two textile products. Our conclusions are presented along the three dimensions of our LCI: spatial, product, and pollutant. Finally, the lessons from this study regarding cleaner production or consumption are summarized.

5.1 Recommendations for local, modular process-based LCI databases

For energy-intensive processes, this work demonstrates that the use of local and detailed data is necessary to assess the environmental impact of the production and consumption phases of a product. However, existing LCI databases are not designed to allow the easy modification of underlying energy infrastructures, since they focus on primary energy carriers. To remedy this design flaw, we recommend that inventories report intermediate energy flows (electricity, heat and transportation) as well as primary energy flows. Then the underlying energy infrastructure can be modeled separately and adapted for different countries and conditions. This is necessary for the applicability of LCA approaches to globally produced goods. Even when the result wanted is a global average product, the range of local production technologies is necessary to understand how meaningful this global average is.

Another challenge for a spatial LCI is the disaggregation of emissions by their location. For a given product, some components may be produced in country A, have a processing step in country B, with final consumption in country C, and disposal in country D. In order for the analysis to follow this complexity, the end result should be expressed not only as total emissions but as emissions in each location (as we have done in Tables 2 and 3). This is a significant book-keeping challenge for LCI databases and their modeling software, but this is a necessary step for the subsequent pollutant transport and impact analysis stages. This is especially true since human health impact factors are strongly dependent on population density, which is much higher in China and India than in Europe or the USA.

5.2 Conclusions from studying different products

Our results showcase the importance of the choice of product, T-shirt or jacket, even for the same functional unit

defined as "100 days of wearing a garment." The production/consumption insights gained for one product and one pollutant (say CO_2 and a T-shirt) cannot be applied more generally (to a jacket or SO_2, for instance). The biggest difference between the two products demonstrates the relative importance of the use phase, since the jacket requires fewer washings and dryings than the T-shirt. Moreover, the use phase itself is highly variable, depending on user behavior and equipment choices. From our use-phase scenarios, we find the hierarchy of user choice impacts to be the following: (1) air vs. machine drying, (2) temperature of washing, (3) equipment efficiency.

5.3 Conclusions from accounting for different pollutants

In our inventory of four pollutants, CO_2 is approximately proportional to fossil fuel combustion (with differences between coal, oil, and natural gas), particulates have mixed fossil fuel and material contributions, and NO_x and SO_2 are caused by, but not proportional to, total fossil fuel combustion. NO_x and SO_2 follow the Environmental Kuznets Curve (EKC): their emissions tend to decrease with higher income in a country. We can thus classify these pollutants non-EKC (CO_2) and EKC (NO_x and SO_2). The displacement of manufacturing to developing countries may result in higher emissions of the EKC pollutants than if the manufacturing had remained in the industrialized country.

This analysis demonstrates the power of spatial LCA for global environmental analysis. If the LCI could be extended over time (at decadal intervals for example, taking into account technological change and trade flow modifications), it could serve as a tool to assess the environmental impact of globalization from a product or functional unit perspective.

For many of the pollutants involved in the textile product chain, a full LCA is extremely challenging, due to the lack of impact information for many specialty chemicals: pesticides, dyes, detergent ingredients. Even the impact of salt used in the cotton dyeing process is not included in traditional LCA impact categories. This is a major research need for the increasing number of goods involving a globalized life cycle.

5.4 Cleaner production or cleaner consumption?

What are the most important conclusions from this work regarding cleaner production and cleaner consumption?

For the T-shirt, the predominance of the use phase for energy and CO_2 emphasizes cleaner consumption, with equipment efficiency coming last in the hierarchy of consumer choices and air vs. machine drying and washing temperature coming first. In this case, consumer behavior is more important than equipment rating in terms of energy use, a result with interesting implications for energy policy and the rebound effect. The rebound effect occurs when energy savings following efficiency measures are not as large as expected or even negative (Hertwich 2005; Herring and Roy 2007). Our use-phase scenarios show that an emphasis on equipment efficiency may lead to a rebound effect in cases where the consumer behavior is more important than the efficiency rating. Once in possession of an A-rated appliance, the consumer may switch to more frequent or wasteful use (for example using warmer washing temperatures) in the mistaken belief that the equipment is so efficient that the energy use will in any case be lower than with a B- or C-rated appliance. Environmentally conscious appliance and apparel companies should therefore include consumer education as part of their efforts, emphasizing air-drying and cool washing.

Textile firms, of course, exert more control on the production phase of their garments. In a cleaner production perspective, the two priorities are a clean (or cleaner) electricity supply and water treatment. The electricity issue can be addressed by financing renewable technologies (Switcher, for example, funds wind electricity in India) but also by supporting regulatory improvements of the existing electricity production. Regarding water, textile firms can influence the scale of water use, the use of pesticides and harmful dyes and salt, and especially implement water treatment.

However, the question of cleaner consumption or cleaner production of one functional unit corresponding to a product evades the more important question of scale of consumption. As Schor (2005) points out, dropping textile prices have led to larger quantities consumed and consequently higher environmental burdens. Tackling the emission of non-EKC pollutants like CO_2 requires the scale of global consumption to be reduced, at least as long as electricity is produced using fossil fuels.

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