The need to decelerate fast fashion in a hot climate - A global sustainability perspective on the garment industry

Citation for the original published paper (version of record):
Peters, G., Li, M., Lenzen, M. (2021). The need to decelerate fast fashion in a hot climate - A global sustainability perspective on
the garment industry. Journal of Cleaner Production, 295.
http://dx.doi.org/10.1016/j.jclepro.2021.126390

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Journal of Cleaner Production 295 (2021) 126390

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The need to decelerate fast fashion in a hot climate - A global sustainability perspective on the garment industry

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ARTICLE INFO

Article history:
Received 21 August 2020
Received in revised form
11 February 2021
Accepted 12 February 2021
Available online 14 February 2021

Handling editor: Dr Sandra Caeiro

Keywords:
Fast fashion
Clothing
Multi-region input-output model (MRIO model)
Environmentally extended input-output analysis (EEIOA)
Energy
Greenhouse effect

ABSTRACT

Controversy exists regarding the scale of the impacts caused by fast fashion. This article aims to provide a robust basis for discussion about the geography, the scale and the temporal trends in the impacts of fast fashion because the globalisation of the fashion industry means original, peer-reviewed, quantitative assessments of the total impacts are relatively rare and difficult to compare. This article presents the first application of Eora, a multiregional environmentally extended input output model, to the assessment of the impacts of clothing and footwear value chain. We focus on the key environmental indicators of energy consumption, climate and water resources impacts, and social indicators of wages and employment.

The results of the analysis indicate that the climate impact of clothing and footwear consumption rose from 1.0 to 1.3 Gt carbon dioxide equivalent over the 15 years to 2015. China, India, the USA and Brazil dominate these figures. The trends identified in this and the other indicators represent small increases over the study period compared to the 75% increase in textile production, meaning that the impacts per garment have improved considerably. On the other hand, the climate and water use impacts are larger as a proportion of global figures than the benefits provided via employment and wages. Our analysis of energy consumption suggests most of the per-garment improvement in emissions is the result of increased fashion-industrial efficiency, with a lesser role being played by falling carbon intensity among energy suppliers. While both the social benefits and environmental impacts per mass of garment appear to have decreased in recent times, much greater improvements in the absolute carbon footprint of the fashion industry are attainable by eliminating fossil-fueled electricity supplies, and by eliminating fast fashion as a business model.

1. Introduction

1.1. Fast fashion

The impacts of the clothing industry have only recently become a focus of media scrutiny, and accurate data on it remains difficult to obtain. Even critics of the industry complain that the current public debate is confounded with unreliable and exaggerated claims and a lack of academic research (e.g. Wicker, 2020). This is a consequence of the globalisation of fashion supply chains and the historically scant attention paid to life-cycle sustainability issues in this industry compared with many other industries (Peters et al., 2015).

In its current predominant form, the industry represents the opposite of what Korhonen et al. (2018) defined as a “circular economy”, in that it does not maximise the service which its material and energy flows provide, nor does it limit these flows to what nature tolerates.

On the contrary, the rapid growth in the production of clothing and footwear, driven by rising wealth and consumption in developing nations, is a consequence of its conscious adoption of “fast fashion”, which has been defined as “a business model based on offering consumers frequent novelty in the form of low-priced, trend-led products” (Niinimäki et al., 2020). By accelerating the

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https://doi.org/10.1016/j.jclepro.2021.126390

rate at which new collections are designed and produced, and by constructing cheap and fragile garments, fast fashion makes clothing repair unnecessary (because garments are discarded before they get damaged), uneconomical (because new garments are so cheap) or impossible (because the garments are too flimsy) (Middleton, 2015). Barely used garments are soon thrown away or accumulate in wardrobes in wealthy countries (Roos et al., 2019).

Led by retailers like Zara in the late 1990s, many European and American companies leapt at the opportunity to outsource production to low-wage countries in Asia, enabling the fast-fashion model. This has separated the consumer and producer countries and in practice concealed actors in the workforce via nested subcontractor relationships, so the geographic locations where a garment causes environmental and social impacts may not be obvious even to the retailer. In addition to this geographical separation, fast fashion has provided a reason for total fiber production to approximately double from 2000 to 2018 and thus also created a dramatic disconnection from the amount of fiber used to serve people in the previous century (see Fig. 1). On a per capita basis, this means while 7.6 kg fibers/person was produced in 1995, that figure rose to 13.8 kg/person in 2018, an 82% increase (47% from 2000 to 2015).

1.2. Sustainability aspects

The focus on cheap and speedy delivery has coexisted with a lack of focus on social impacts in the supply chain, contributing to disasters like the 2013 Rana Plaza collapse in Bangladesh. It should also be acknowledged that the disconnection visible in Fig. 1 has had important economic and employment benefits for the countries that have increased production (Soligno et al. 2019), but also significant additional impacts in terms of resource consumption and emissions.

This is because the clothing and footwear industries (or "sectors of the economy") which we will call the "fashion industry" in this article, are resource-intensive. In fact, most of the resources demanded by fashion consumption are used before consumers obtain their clothing. Fig. 2 is based on the total consumption of clothing in Sweden (Sandin et al., 2019), and since that country relies on globalized supply chains, the relative proportions are likely to be broadly representative of consumption in other high-wage countries where fast fashion is popular. It indicates that about 75% of the energy demand over the garment life cycle occurs prior to retail sale. Transportation of garments is relatively insignificant compared to processes that organize physical materials (fiber manufacturing, yarn spinning, textile weaving) and those which reflect the heat capacity or the enthalpy of vaporization of

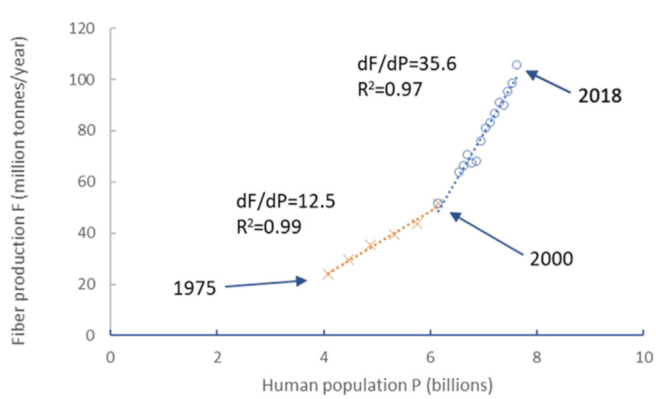

Fig. 1. The global rate of fibre production compared with human population, indicating the effect of fast fashion (data: IC, 2019).

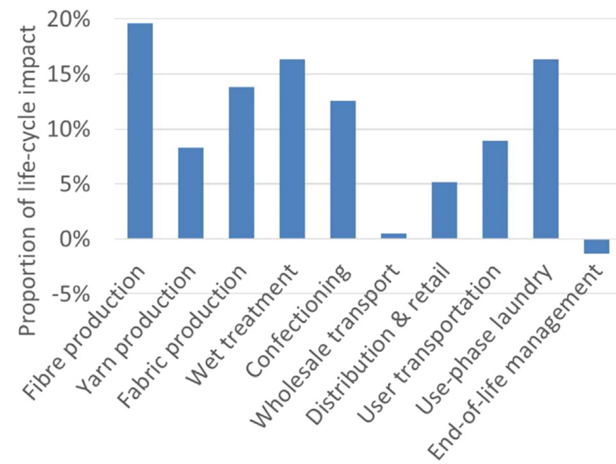

Fig. 2. Energy consumption during garment life cycles (data from Sandin et al., 2019).

water (wet treatment processes such as bleaching and dyeing). The greenhouse gas emissions of the life cycle reflect a similar pattern of relative distribution, moderated by the greenhouse intensity of the energy supplies in the producing and consuming countries (Sandin et al., 2019). The distribution of water scarcity impacts is even more extreme since cotton is grown by irrigation of arid land, so the production of fiber (merely the first life cycle step shown in Fig. 2) can represent over 88% of the total water scarcity impacts of a typical garment over its whole life cycle (Sandin et al., 2019). Analysis of this kind suggests that most of the impacts of current fashion consumption occur prior to sale, that rejecting fast fashion can be an effective environmental intervention for consumers, and that we should analyse the supply chain upstream from the consumer to address key impacts of the textile and clothing industry (Roos et al., 2016).

1.3. Aims

As stated earlier, there is a distinct lack of empirical information about the impacts of the global fashion industry. New consumer and industrial interest in sustainability manifested itself a decade ago with the proliferation of textile ecolabelling initiatives and detailed academic supply-chain analysis funded by industry (Clancy et al., 2015; Peters et al., 2015). The industrial interest has resulted in some worthwhile resource efficiency initiatives, and academic engagement has begun to deliver data on the impacts of fashion, but the available reports are often piecemeal, being for example life cycle assessement (LCA) of a particular product or an assessment of only one kind of impact. Few assessments of the key impacts of the global fashion industry have been published using LCA. Environmentally extended input-output analysis (EEIOA) is an ideal tool for this kind of work but has also rarely been applied to the global fashion industry. Some notable exceptions include the EEIOA work driven by the Carbon Trust (2011), the LCAs of the Ellen MacArthur Foundation (2017) and Quantis (2018) and some other EEIOA publications with a broader ambit than just this sector (e.g.: Wood et al., 2018; Eurostat (2019)).

Therefore, the overall aim of this article is to address the uncertainty around the global impacts of fast fashion. In particular we aim to examine the questions of: (1) the question of where the impacts of the fashion industry arise; (2) the scale of the total energy, water, climate and employment impacts of the clothing and footwear industry compared to global impacts; and (3) whether the trends in EEIOA results indicate that resource efficiency initiatives having the desired effect or being overtaken by expanding consumption.

2. Method

2.1. Mathematical approach

Environmental and social footprints of the global fashion industry can be enumerated using environmentally-extended multi-region input-output (MRIO) analysis. MRIO analysis was conceived by Nobel Prize laureate Wassily Leontief Leontief and Strout (1963). Since then its ability to comprehensively map supply-chain networks has been applied in numerous studies, for example on economic impact analysis, using Computable General Equilibrium models. Drawing confidence from existing comprehensive global standards UN (1999) and worldwide data sources (see SI of Lenzen et al. 2012), MRIO analysis has recently been used to map the relationships along supply chains where physical flows do not exist, identifying associations between consumption and production for various indicators ranging from physical resources like energy and water (e.g. Tukker et al., 2016; Lenzen et al., 2013; Soligno et al., 2019), to environmental indicators like mercury (Hui et al., 2017) or greenhouse emissions (Wiedmann 2009). It has even been used to investigate more abstract ideas like negative social impacts and corruption. Some examples of this include Simas et al. (2014); Zamani et al. (2018); McBain and Alsamawi (2014); Xiao et al. (2017); Xiao et al. (2017). (See Wiedmann and Lenzen (2018) for a longer summary of applications.)

By following financial flows at the national scale, EEIOA enables analysts to model international value chains where commercial confidentiality or non-existent data hampers other approaches. EEIOA is less specific than traditional environmental LCA, and therefore unless EEIOA is hybridized with traditional LCA, it less suited to the assessment and comparison of engineering processes with the life cycle of a particular product. However, for the purposes of this paper, EEIOA can provide a usefully rich dataset for the assessment of the global fashion industry. Here, we use MRIO analysis to establish the environmental and social footprints of global fashion consumption, covering its entire supply-chain network, including transportation of goods, power generation, manufacture of equipment, and extraction of raw ores, coal, oil and gas.

The environmental and social footprints F of textiles can be defined as the matrix product $F = \mathbf{qLy}^*$, where the $N\times 1$ vector $\mathbf{y}^*$ is the global final demand of textiles in current US\$, the $N\times N$ matrix $\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is Leontief's inverse (the hat ^ symbol denotes vector diagonalisation), and the $G\times N$ matrix $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$ holds so-called satellite coefficients describing environmental and social impacts per unit of monetary output for all N sectors in the global economy. Here, $\mathbf{x} = \mathbf{T1} + \mathbf{y}$ is $N\times 1$ total output that, because of the national accounting identity, is equal to the sum of $N\times N$ intermediate demand $\mathbf{T}$ and $N\times 1$ final demand $\mathbf{y}$, with $\mathbf{I}$ and $\mathbf{1} = \{1,\ldots,1\}$ being the $N\times N$ identity matrix and an $N\times 1$ summation operator, respectively.

To see how this calculus covers international supply chains, call $\mathbf{A} := \mathbf{T}\hat{\mathbf{x}}^{-1}$ the direct requirements matrix, and consider the series expansion of the Leontief inverse (Waugh 1950): $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots$. Writing the environmental and social footprints F of textiles as a summation $F = \mathbf{qLy}^* = \sum_{im,rv} q_i^r L_{im}^{rv} y_m^{*v}$, and unravelling the Leontief inverse as a series $F = q_{\text{tex}}^u y_{\text{tex}}^{*u} + \sum_{k,t} q_k^t A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u} + \sum_{jk,st} q_j^s A_{jk}^{st} A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u} + \sum_{ijk,rst} q_i^r A_{i,j}^{rs} A_{i,k}^{st} A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u} + \ldots$, we can show how the textile demand y_{tex}^{*v} in region v sets in motion a complex cascade of supply chains: the term $q_{\text{tex}}^u y_{\text{tex}}^{*u}$ represents the impact exerted by textile retailers in region u. $q_k^t A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u}$ is the impact of supplying industries k resident in regions t, and the summation involves all industries in all regions. Similarly, $q_j^s A_{jk}^{st} A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u}$ describes a two-node supply chain, where the impacts stems from industries j in regions s, but the supply chain involves an intermediate step via product k made in region t, and so on. To illustrate: Assume that u is Italy, then $q_{\text{tex}}^u y_{\text{tex}}^{*u}$ includes the emissions from company cars belonging to Italian clothing retailers. Assume that t is Vietnam, and k is clothing manufacturing. Then, $q_k^t A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u}$ is the energy used in Vietnamese workshops supplying Italian retailers with the realisations of their designs. The sum then means that all such 1st-order connections are agglomerated into the footprint of clothing bought in Italy. Further up the supply chain, assume that s is Pakistan, and j are yarn and fabrics from cotton. Then, $q_j^s A_{jk}^{st} A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u}$ is the family income for Pakistani workers spinning cotton yarn destined for Vietnamese textiles for Italian suits. The sum also includes other supply chains such as emissions from Vietnamese power plants supplying Vietnamese workshops, or energy for Turkish yarn from combed wool for Vietnamese textiles for Italian suits. $q_i^r A_{i,j}^{rs} A_{i,k}^{st} A_{k,\text{tex}}^{tu} y_{\text{tex}}^{*u}$ are three-node chains, for example water used for growing Uzbek cotton supplied to Pakistan, to make yarn for Vietnamese workshops supplying Italian clothing retailers. And so on. This serves to demonstrate that with increasing order, the textiles' supply chain becomes ever more complex, and also that the Leontief inverse elegantly captures impacts up to infinite orders.

2.2. Data sources

For this study, data for $\mathbf{x}, \mathbf{T}$, and $\mathbf{y}$ are taken from the Eora MRIO database because of its high sector resolution, adherence to original data sources, and high country detail. The Eora database has been applied to a number of high-impact footprint studies such as on biodiversity (Lenzen et al., 2012a,b), nitrogen emissions (Oita et al., 2016), and carbon emissions from global tourism (Lenzen et al., 2018). The construction principles and data sources for the Eora database have been described in detail (Lenzen et al., 2013a). Data $\mathbf{y}^*$ on the final demand for textiles stem from the Eora database and the World Bank's household consumption database World Bank (2017), with adjustments using UN household expenditure data United Nations Statistics Division (2019). $\mathbf{Q}$ is a so-called satellite account ($G\times N$), including the following environmental, social and energy indicators:

- Global greenhouse gas emissions and their Global Warming Potentials: CO_2 ($GWP = 1$), CH_4 ($GWP = 28$), N_2O ($GWP = 265$), CFCs ($GWP = 8925$), HFCs ($GWP = 3772$), SF_6 ($GWP = 23500$), NF_3 ($GWP = 16100$) were taken from the EDGAR database (Janssens-Maenhout et al., 2017a,b).
- Unscaled water use was based on the AQUASTAT database (Lenzen et al., 2013b; Janssens-Maenhout et al., 2017; AQUASTAT, 2019), with scaling factors taken from the lastest consensus-based "available water remaining" (AWARE) factor for waster scarcity impacts (Boulay et al., 2018).
- Employment was based on data published by the International Labor Organization (Alsamawi et al. 2014; ILO 2015).
- Wages and income data were taken from the Eora MRIO database (Lenzen et al., 2013a).
- Energy consumption data came from the International Energy Agency (IEA 2015; Lan et al., 2016).

It would be interesting to assess the use of chemicals in parallel with the other indicators in this work. Unfortunately, the extensive data necessary for this kind of assessment is unavailable and is generally very poor even in detailed product or process LCAs (see Table 1 in Roos et al., 2015).

2.3. Selecting industry segments

Detailed assessment of the industry sector list for each country in the Eora model was used to focus on the sectors connected with clothing and footwear consumption, so for example “Textiles and wearing apparel” in Zimbabwe was included but “Carpets and floor mats” in Japan was not. Additionally, a simple scenario was analysed to address the third aim of this study, in which all electricity production sectors were eliminated to provide a rough indication of the extent of the potential reduction in climate impact which might result from eliminating greenhouse emissions from the fashion industry’s electricity supply by purchasing renewable energy.

3. Results and discussion

3.1. Where the impacts arise

Here we address the first research question and discuss the results of this work from a geographical perspective. The data in Fig. 3 is on an absolute basis and shows a simplified structural path analysis of the eight indicators except for the graph of total national expenditure in the clothing and footwear sectors. These figures show China’s dominance of all the indicators in absolute terms, except in relation to total expenditure, where the USA makes the largest national contribution to the global industry. China’s significance is most apparent when it comes to the employment generated by the clothing industry. In these graphs, “direct” impacts refers to those caused by these sectors, while the “first order” and higher order “supply chain” segments of the graphs indicate the impacts associated with the direct suppliers to these sectors (e.g. direct electricity purchases) and indirect suppliers (e.g. electricity purchases by suppliers of materials to the clothing sector) respectively. (Note that these are not the same as “scopes 1, 2 and 3” under the WBCSD/WRI reporting guidelines – the second order includes more than scope 2 energy suppliers.) The selection of the ten most significant countries is based on inspection of the country rankings, selecting the country with the highest result for each of the 8 indicators and continuing down the ranking lists until ten top countries were identified.

Given the dominant role played by China in Fig. 3, it is worthwhile examining the value chains in China in more detail for some key indicators. The structure of Fig. 4 indicates the 25 most important sectors connected with energy use and greenhouse emissions of global household consumption in 2015. The figures are arranged in rows by order (or “trophic level”). Note that figures connected vertically are not cumulative, so for example, the contribution of the “Knitted mills” sector shown in the figure does not include those of the “Cotton textiles” sector nor “Electricity” production. The latter dominates the overall data, representing 46% of the energy consumption and 15% of the greenhouse gas emissions in this subset of the data. The difference in these percentages is a reflection of several factors including the importance of the water-using processes mentioned in the introduction, which may involve local fuel combustion rather than (potentially more expensive) purchases of electricity, and also the large contribution of livestock (12%) to the greenhouse gas emissions shown in the figure on account of relationship between livestock production and enteric methanogenesis.

The indicators computed via the Eora MRIO database are shown cartographically in Fig. 5. They indicate where in the world the consumption occurs that causes the impacts, on a per capita (i.e.: per consumer) basis. The influence of the expenditure on clothing and footwear (Fig. 5(e)) is apparent in all the maps and clearly reflects the effect of wealth – there is a correlation between wealth and textile consumption in which a citizen of western Europe, North America and Australasia consumes over an order of magnitude more fashion products (measured by their economic value) than a person living in Africa. This is not surprising but worth bearing in mind when considering other parts of the figure as it points to the inequitable distribution of the benefits and downsides of the fashion industry. In the maps other than Fig. 5(e) the distribution of impact intensities is modulated by the presence of significant textile manufacturing (e.g.: Uzbekistan and Turkmenistan) or clothing production (e.g.: Estonia) and local dominance of those products among local consumers.

3.2. The scale of fashion industrial impacts in the global context

Regarding our second question, the overall results drawn from the EEIOA model show that the clothing and footwear sector of the global economy represent about 2% of the resource use and environmental indicators considered in this study (Table 1). On the other hand, the wages and income generated by the sector are somewhat lower. It is notable that the total energy consumption of the sector has increased by 29% over the study period while greenhouse emissions have increased by only 23%, suggesting an improvement in the carbon intensity of the energy supplies it obtains has been a factor constraining the sector’s climate impact. The water data suggests total water consumption has increased more than the proportion of it which is drawn from overutilised freshwater environments. This may be a consequence of the expansion of polyester production and a relative reduction in the role played by cotton irrigation in dry landscapes. The effect of inflation on wages and income is considerable and suggests that while average annual earnings per employee have risen from 4400 USD in the year 2000 to 9500 USD in 2015, more than doubling in nominal terms, this actually represents an increase of 22% in inflation-

Table 1
Overview of the sector’s importance in the global context.

Industry sector	all (2000)	clothing and footwear (2000)		all (2015)	clothing and footwear (2015)	
Energy (PJ/year)	397178	7589	1.9%	548361	9838	1.8%
Greenhouse emissions (Gt CO_2-e/year)	40	1.03	2.6%	53	1.27	2.4%
Water use (TL/year)	2215	45	2.0%	2531	51	2.0%
Water scarcity impact (TL-e/year)	81074	1857	2.3%	84372	1886	2.2%
Wages & income (nominal, trillion USD)	16	0.21	1.3%	35	0.49	1.4%
Wages and income (2015, trillion USD)	29	0.37	1.3%	35	0.49	1.4%
Employment (million)	2471	48	1.9%	2906	51	1.8%

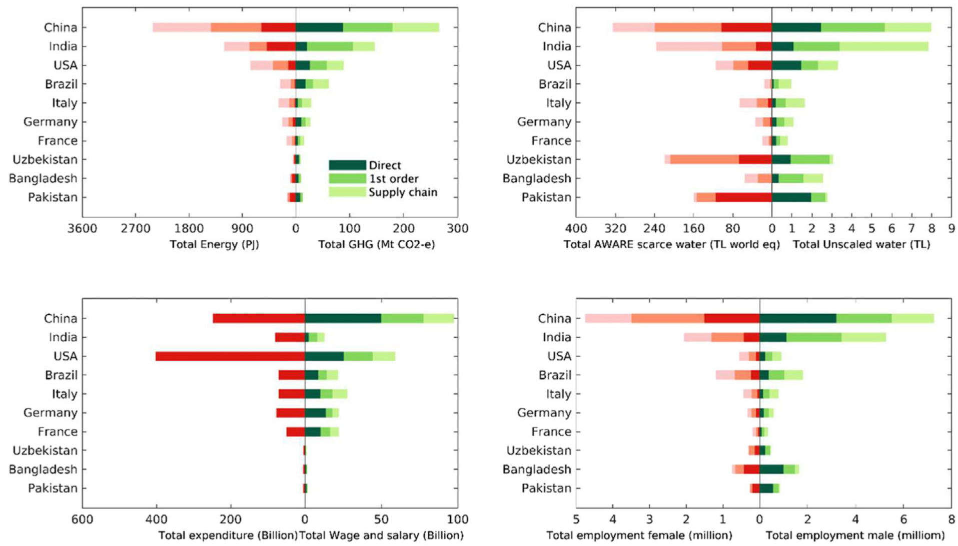

Fig. 3. Top 10 countries by textiles related total energy, GHG, AWARE-scaled water scarcity impacts, (unscaled) water use, expenditure, wage, female employment and male employment.

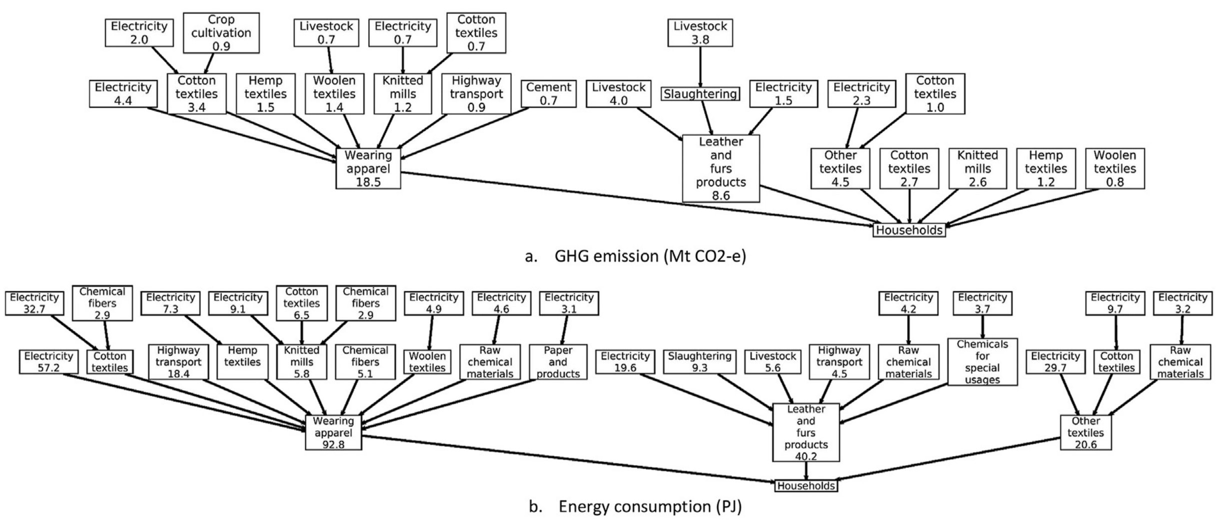

Fig. 4. Top 30 1st-to 3rd-order supply-chain contributions to the GHG and energy consumption footprint of China's fashion industry.

adjusted terms. This modest improvement is nevertheless interesting in the context of the overall reduction in employment in this sector in high salary regions such as the EU and USA and the increase in sector employment in developing countries over this 15 year period (Kucera and Mattos, 2020).

Across LCA and EEIOA methods, the results of previous attempts to estimate the scale of the environmental impacts of the global fashion industry vary widely. Examples of estimates of annual climate changing emissions, in descending order of scale, include: 4 Gt CO_2-e (in 2016; Quantis 2018); 2.9 Gt CO_2-e (in 2018; Niinimaki et al., 2020); 1.2 Gt CO_2-e (in 2015; Ellen MacArthur Foundation, 2017); 1 Gt CO_2-e (in 2011; Wood et al., 2018) and 0.3 Gt CO_2-e (Carbon Trust, 2011). The latter report focusses on results rather than methods, so aspects of the scope are uncertain, but since it was based on the GTAP7 IOA model we assume the results refer to the year 2004. This order of magnitude range among the previous EEIOA estimates seems impossible to explain by a mere 7 years of industrial growth, a period during which global fiber production increased by about 32% (IC, 2019). It is also puzzling that the both the older and more recent estimates derived from environmentally extended input-output analysis (EEIOA) (Carbon Trust, 2011; Wood et al., 2018) are lower than the estimates based on traditional life-cycle assessment (LCA) process analysis (Ellen MacArthur Foundation, 2017; Niinimaki et al., 2020; Quantis, 2018). Typically, an analyst would expect the opposite, that EEIOA would generate higher estimates of environmental impacts than process analysis, on account of the elimination of truncation errors in the construction of models of the value chain. For example, in an assessment of the carbon footprint of beef production systems, which are dominated by enteric methanogenesis that process LCA clearly identifies, EEIOA nevertheless estimated results that were 4% higher than the process LCA (Peters et al., 2010), while the greenhouse gas emissions caused by the production of bulk chemicals estimated by EEIOA were 76% higher on average when compared with process LCA (Alvarez-Gaitan et al., 2013). Some of the factors contributing to the relative scale of the estimates of the fashion industry's emissions may be to do with the system boundaries of the analyses, or the way in which EEIOA databases

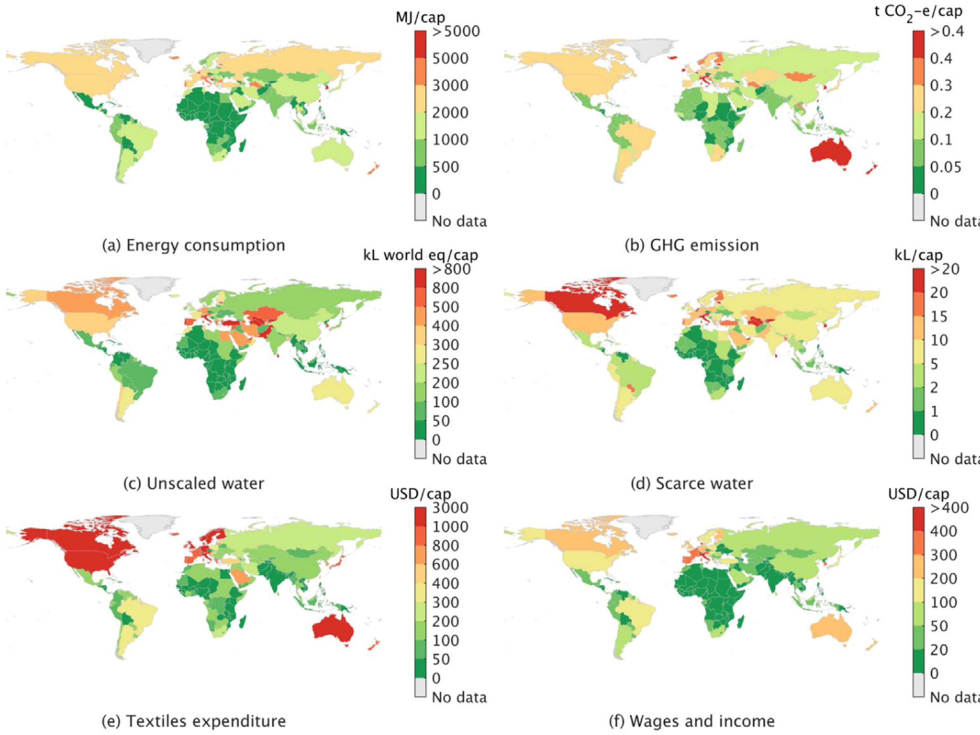

Fig. 5. Per capita footprints of 189 countries for the clothing and footwear sector in 2015. (a) Energy (b) Carbon, (c) (unscaled) water use, (d) AWARE-scaled water scarcity impacts, (e) expenditure on the sector, (f) wages and income.

are constructed using balancing algorithms. The latter have the capacity to create errors in the scale of the emissions of individual industries, while preserving the accuracy of the overall national emission budgets. It is interesting that the EEIOA results we present are at the high end of the range of published estimates of greenhouse gas emissions (i.e. beyond the 1 Gt CO_2-e of Wood et al., 2018) while just above the lowest published LCA estimate (1.2 Gt CO_2-e from Ellen MacArthur Foundation, 2017). While this gives us some confidence regarding the veracity of our result, it would be worthwhile to perform new analysis using other EEIOA models to confirm this result.

Fig. 6 shows the trends over time for the key indicators examined in this work. For many of these graphs the influence of the global financial crisis in 2008 is seen to have rippled through the fashion supply chain, temporarily arresting the growth in several of these indicators after the steady growth from the start of the millennium. In most cases the growth recovers but is tempered over the last four years of the data, as expenditure on the sector levelled off (Fig. 6(e)). The water indicators are relatively unchanged over the period, which reflect the fact that the annual rate of cotton production has remained relatively constant over most of the period, compared to the doubling of the rate of polyester production. The water scarcity impact results also reflect the use of static AWARE scaling factors, as a multiannual series of such factors was not available.

Fig. 6 also shows the increasing dominance of east Asia and south-east Asia as regions spending money on fashion and causing the impacts of the sector. Although in per capita terms Fig. 5 indicates the significance of Europe and North America, in absolute terms the impacts of these regions does not account for most of the growth in the impacts of the sector. The European greenhouse gas footprint actually decreased in absolute terms over the period. Wood et al. (2018) suggest the global clothing sector increased its total greenhouse emissions by 20% in the period 1995 to 2011, which is compatible with our result.

3.3. Trends in resource efficiency versus fashion consumption

In Fig. 7, the data from Fig. 6 is presented in terms of the total mass of textile produced in each year instead of absolute terms. This presentation indicates that fashion companies have reduced their resource impacts per mass of textile product. Fiber production rose continuously (from 51 million tonnes) from the start of the time period to its 2007 peak (71 million tonnes). It fell back the subsequent two years on account of the global financial crisis but the difference was made up by 2010 and output continued to grow towards 2015 (90 million tonnes). Note that this data has not been adjusted in terms of the mass of textiles produced for applications other than clothing and footwear manufacturing. We do not know if this proportion has changed over time, but it was recently estimated to be 16% of global textile production (Quantis, 2018). If textile production for other purposes is held constant in absolute terms over the period, the ultimate position of the trends is 16% lower. If it is assumed to be constant in relative terms over the 15 year time period, it does not affect the normalised indicators as shown in the figure. In any case, the observation that material use has been rising faster than greenhouse gas emissions, energy consumption and water use is consistent with Wood et al. (2018) despite the use of a different EEIOA model for that study.

The only indicator that has increased per mass of product is the indicator of wages in nominal terms. In inflation-adjusted terms, wages per mass of product have fallen along with the other indicators. The consumption of energy per mass of product fell by 26% over the period to 2015. This suggests that industry has engaged with efficiency measures and/or that economies of scale have played a role as Asian production systems expanded. This has been a major cost-management focus in the industry - a landmark study by Laurence Berkeley National Laboratory (Hasanbeigi and Price,

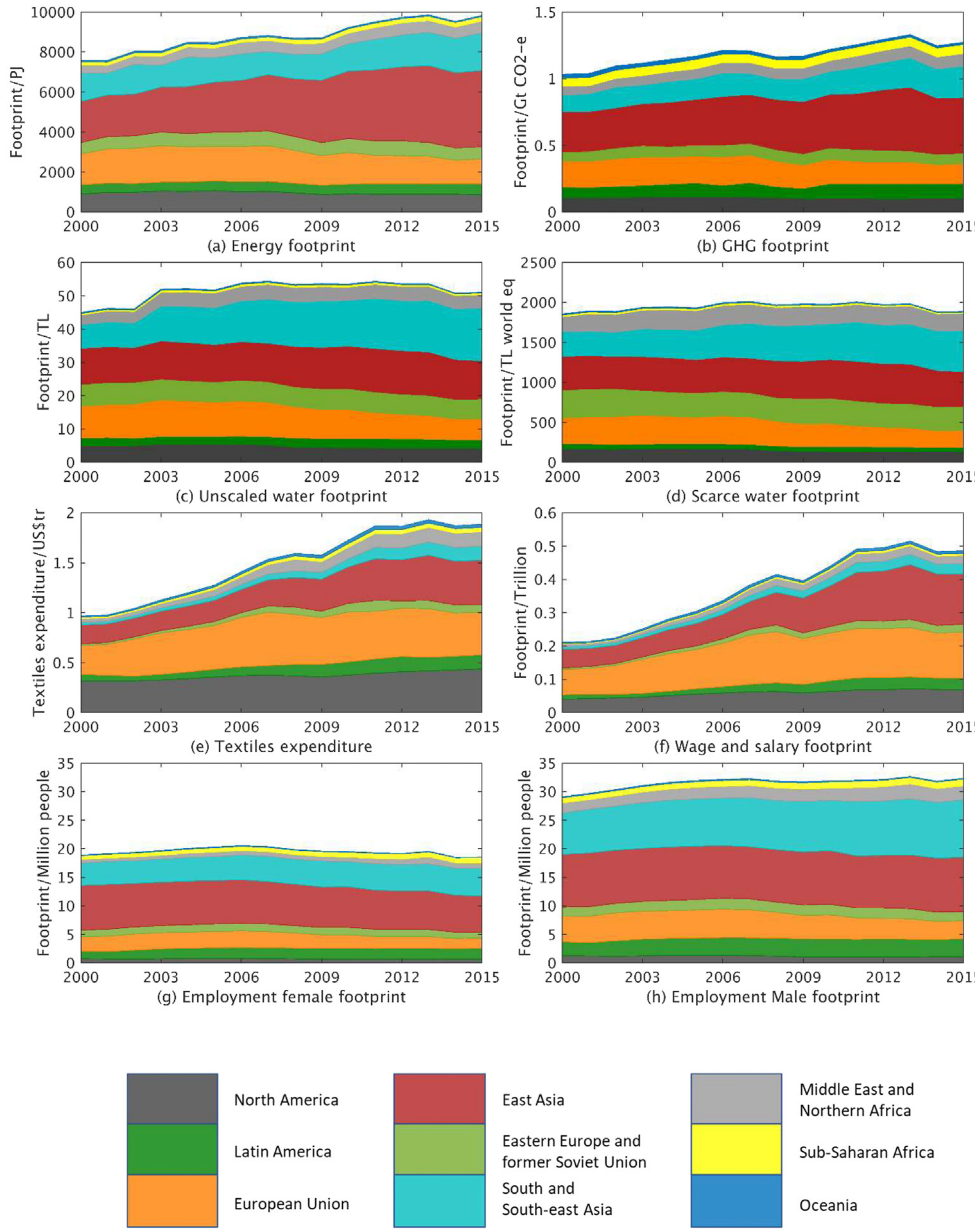

Fig. 6. Trends in the footprint of textile related expenditure, energy, GHG, AWARE scarce water, unscaled water, expenditure, wage, female employment and male employment (2000–2015).

2012), identified 184 recent efficiency initiatives, many of which saved large proportions of the energy previously used for the textile processes, and mostly with short financial payback periods (0.5–3 years). For example, better process control in dryers saved 22% of previous energy consumption, and heat recovery equipment saved 30% of energy use (Hasanbeigi and Price, 2012). Financial benefits such as these and increased emphasis on environmental management systems and ecolabelling requirements (e.g. Bluesign) from western buyers have led to increased interest in eco-efficient processes in textile manufacturing countries (e.g. Turkey - see Alkaya and Demirer, 2015).

Energy efficiency would be expected to result in greenhouse gas efficiency. The results presented in this paper show that there is a marginally larger improvement in the climate impact of the industry per mass of product, which becomes apparent midway through the time series and results in a 29% reduction over the time period. Given the small difference between this and the energy trends, it appears that the improvement in climate impacts is primarily due to a reduction in the energy intensity of garment production, rather than the carbon intensity of the energy supplied to the industry. The data suggests fashion industry leaders may be switching energy purchases from fossil to renewable, as recommended by previous LCA work (Sandin et al., 2019). In our simple scenario analysis, we examined the outcome of continuing this trend by completely eliminating emissions associated with electricity production from the MRIO table. The calculations indicated that fossil fuel combustion equivalent to 8400 PJ would be eliminated, with 1400 PJ remaining. This corresponded to a reduction of the global carbon footprint of the fashion industry from 1.3 to 0.2 Gt CO_2-e. The remaining emissions are associated with the consumption of fossil energy for the production of heat for wet processes and emissions of greenhouse gases like methane and nitrous

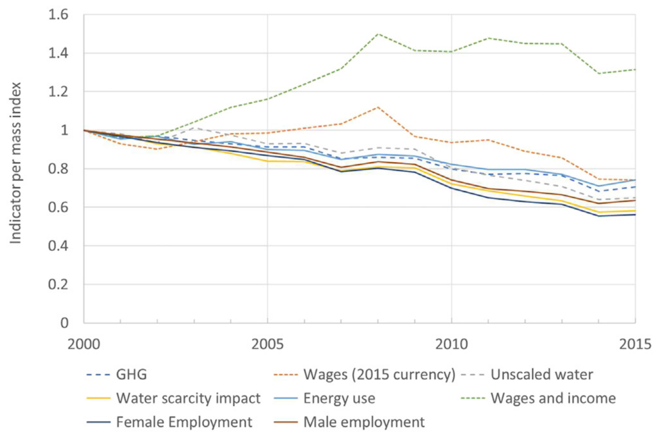

Fig. 7. Indicator trends on a mass basis (2000–2015).

oxide associated with agricultural feedstocks.

The water efficiency gains shown in Fig. 7 are being achieved in many ways (Nieminen et al., 2007). For example, Nike and other major brands have started investing in supercritical CO_2 dyeing systems which almost eliminate water use for this unit operation (Hepburn, 2015). But since as indicated in the introduction the dominant water use in the industry is for cotton irrigation, we hypothesise that the decrease in the (unscaled) water use indicator is primarily the result of an increased proportion of polyester in the total global production of textiles, which would be expected to cause the average water intensity of the textile to fall over the period. The slower decrease in the AWARE-scaled water scarcity impact is probably primarily associated with the production of cotton but should be treated with caution because it is based on national rather than catchment-scale water scarcity factors, for example the USA has a lower factor (34 kL world equivalent per kL) than China or Egypt (42 and 98 kL world equivalent per kL, respectively). The shifting dominance of major cotton producers over the period may be reflected in the divergence of the water indicators but the scaled indicator only roughly represents the degree of water stress in the catchments within each country.

On a positive note, the impacts of fast fashion have not grown as fast as the industry's output. Our results are reasonably consistent with other published work on this point. Eurostat (2020) indicates that European the energy consumption and greenhouse gas emissions associated with the final consumption of textiles and leather products have fallen by 17% in the 10 years to 2018, despite total energy consumption for the region having only fallen by 2% for the same period. The underlying assumption regarding imported materials in that database is that they were produced using technology as carbon-efficient as European norms. In addition to the different time period, this factor adds some uncertainty to the comparison but is broadly consistent with our observation of falling climate impacts for the sector in Europe.

3.4. Limitations

As with any static input-output exercise, our analysis comes with shortcomings. First, whilst it comes with advantages such as high regional and sectoral resolution, the input-output framework assumes linearity between final demand and total input requirements, treats products as homogeneous within one sector, and assumes one single output price for all (intermediate and final) demanders. Second, as a result of the set of limitations just explained, our results are to be interpreted strictly *ex-post*, that is they indicate past associations of actors in supply chains, resource use and pollution, but do not permit causal inference let alone future predictions. If anything, these *ex-post* associations can indicate an *implication* of consumers (Alsamawi et al., 2014a,b) in the adverse consequences of fast-fashion production. Finally, the compilation of large, global MRIO databases is fraught with both missing and conflicting primary data. Reconciling large MRIO tables with available data is a severly underdetermined optimisation problem, that in general does not have a unique solution, and in which small and unsupported MRIO elements may be associated with large uncertainties (Lenzen et al. (2012a,b). Nevertheless, research (Inomata and Owen, 2014) has shown that for high-level global findings, available MRIO frameworks that even use different input data (Owen et al., 2014) converge sufficiently well (Moran and Wood, 2014).

It would be worthwhile to extend the EORA database from 2015 to the present day to examine the gyrations caused by the covid-19 epidemic and suggestions that consumer demand has been dampened by social distancing and interruptions to supply chains. The period covered by this data is nevertheless interesting because it begins just after companies like Zara began driving the fast fashion business model, straddles the global financial crisis and extends beyond the point at which the rate of publication of critiques of fast fashion clothing life cycles started to grow exponentially (Peters et al., 2015).

4. Conclusions

At 1.3 Gt/year, our estimate of the greenhouse gas emissions of the fashion industry are at the high end of the range in published EEIOA studies but the low end of LCA-based studies. China, India, the USA and Brazil dominate these greenhouse results and the other indicators calculated in this work. The results of our calculations indicate that the impacts of fast fashion are a small part of the global impacts of human activity. Happily, they also indicate that the impact per garment has fallen over the study period. Nevertheless, the per capita consumption statistics driving these impacts are in excess of the values which prevailed until the end of the last century and from this point of view at least, the impacts are hard to justify. Fast fashion helps to explain why consumers used 47% more clothing per capita in 2015 compared with the year 2000. Simply put, that increase suggests the clothing and textile industry is overdimensioned and obese. In a climate emergency, this excessive use of materials must be quickly curtailed (Ripple et al., 2019).

Driving down the impacts of clothing life cycles is a multifaceted problem but as quantified in this article, most of the impacts arise pre-consumer, in the producing countries, so strategies to reduce impacts will most efficiently intervene somewhere in the garment life cycle in way that influences pre-consumer activities. This can mean interventions to use garments at their end-of-life to replace feedstock, efforts to improve the efficiency of industrial processes and efforts to reduce consumption. Fast fashion has liberated or disconnected consumers' buying habits from their physical needs. Eliminating the unnecessary size of the fashion industry will require engagement from industry, governments and the non-government sector to try and influence consumers to buy fewer but better clothes. A reduction in consumption does not necessarily have a linear relationship with profits, if the industry can justify higher prices for some garments by returning to the better quality and durability of garments made before the era of fast fashion, but a partial redirection of the workforce to less damaging and better paid employment should be contemplated. It would be worthwhile to examine the social impacts of eliminating fast fashion in greater depth to better understand how the transition can be implemented without degrading the social conditions for workers in the industry, and to study how to quantitatively model such a downsizing process.

CRediT authorship contribution statement

Greg Peters: Conceptualization, Methodology, Resources, Formal analysis, Writing - original draft, Project administration, Funding acquisition. **Mengyu Li:** Data curation, Investigation, Methodology, Software, Validation, Formal analysis, Writing - review & editing, Visualization. **Manfred Lenzen:** Conceptualization, Validation, Formal analysis, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by a grant from the Energy Area of Advance at Chalmers University of Technology.

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