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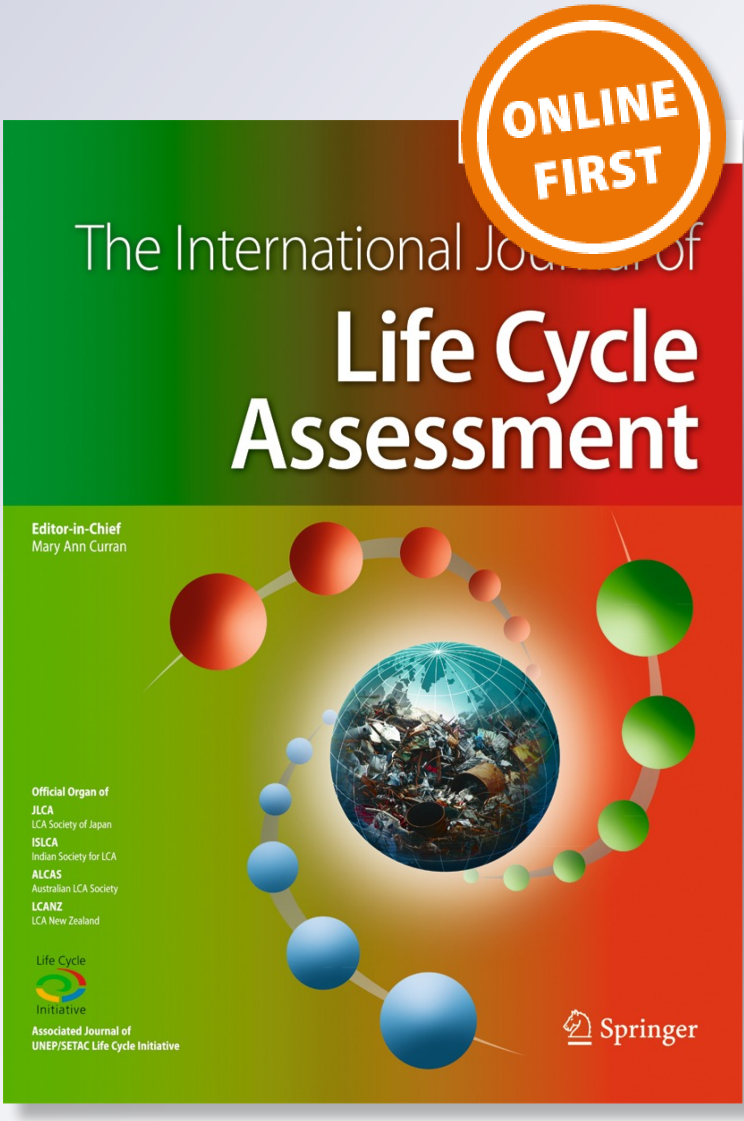

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LCI METHODOLOGY AND DATABASES

Effect of methodological choice on the estimated impacts of wool production and the significance for LCA-based rating systems

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Abstract

Purpose One aim of LCA-based rating tools developed by the apparel industry is to promote a change in demand for textiles by influencing consumer preferences based on the environmental footprint of textiles. Despite a growing consensus that footprints developed using attributional LCA (aLCA) are not suitable to inform decisions that will impact supply and demand, these tools continue to use aLCA. This paper analyses the application of the LCA methods to wool production, specifically the application of aLCA methods that provide a retrospective assessment of impacts and consequential (cLCA) methods that estimate the impacts of a change.

Methods Attributional and consequential life cycle inventories (LCIs) were developed and analysed to examine how the different methodological approaches affect the estimated environmental impacts of wool.

Results and discussion Life cycle impact assessment (LCIA) of aLCI and cLCI for wool indicates that estimated global warming and water stress impacts may be considerably lower for additional production of wool, as estimated by cLCIA, than for current production as estimated by aLCIA. However, fossil resource impacts for additional production may be greater than for current production when increased wool production was assumed to displace dedicated sheep meat production.

Conclusions This work supports the notion that the use of a retrospective assessment method (i.e. aLCA) to produce information that will guide consumer preferences may not adequately represent the impacts of a consumer's choice because the difference between aLCIA and cLCIA results may be relatively large. As such, rating tools based on attributional LCA are unlikely to be an adequate indicator of the sustainability of textiles used in the apparel industry.

Keywords Apparel · Attributional life cycle assessment · cLCA · Consequential life cycle assessment · Fabric · Wool · Higg MSI aLCA · Life cycle assessment

1 Introduction

Environmental impacts are an unavoidable effect of any industry, with many industries striving for ongoing improvement required to meet legislative requirements and consumer expectations. The global textile and apparel industry consumes significant volumes of natural resources and fossil fuels for raw material production, processing and use of apparel that generate environmental impacts across the product life cycle. The environmental impact of textiles is dependent on the type of fibre from which the apparel is made (Muthu 2015), the manufacturing and processing techniques and the length of time that apparel spend in use prior to disposal. Because of the long supply chain and its ability to provide a comprehensive view of the environmental aspects of the product and/or processes, life cycle assessment (LCA) is a useful tool for understanding and improving the sustainability of the textile and apparel supply chain. Accordingly, the LCA approach has been adopted as a primary means for determining the sustainability of apparel, with non-government organisations (e.g. Sustainable Apparel Coalition (SAC) and MADE-BY), implementing LCA as the basis for their respective rating systems. These rating systems are used to determine which textiles are environmentally 'superior' or 'inferior' fabric types based on their environmental impacts (Sustainable

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Apparel Coalition 2018b). The commendable objective of these rating systems is to improve the environmental and social impacts of the apparel industry by providing information that can guide procurement decisions of apparel manufacturers and consumers. To achieve this objective, ratings developed by these systems have been used to inform recommendations for dramatic changes in the type of fibre used in the apparel sector. For example, the ratings from the SAC Higg Materials Sustainability Index (MSI) dataset was utilised to support recommending a 30% reduction in global cotton use (Global Fashion Agenda 2017). Other programs initiated by governments (e.g. the Product Environmental Footprint (PEF)) also apply LCA to communicate environmental information about products, including apparel, to consumers (European Commission 2013). However, debate over the appropriate LCA method and data requirements to inform these systems continues.

The ratings that are produced by the systems developed by the apparel industry to determine the sustainability of a material (e.g. SAC Higg MSI) constitute a 'footprint' based on multiple environmental impacts. Footprints, using retrospective analyses based on attributional LCA (aLCA) methods, may mislead policy or procurement decisions (Perry 2014; Plevin et al. 2014; Reap et al. 2008) because they provide an estimate of the environmental impacts of the status quo as opposed to analysing the impacts of a change where a change in supply and/or demand may be expected (Brandão et al. 2014; Brander 2017; Brander et al. 2008; Plevin et al. 2014; Wardenaar et al. 2012). Rather, the impacts of a change need to be estimated using a consequential LCA (cLCA) approach. Differences between aLCA and cLCA and a review of the appropriate use and interpretation of attributional and consequential LCA can be found in existing literature (Brander et al. 2008; EU JRC 2010; Finnveden et al. 2009). Briefly, a consequential analysis estimates the consequences of a decision by considering the market effects of a decision. It seeks to include these effects by using system expansion to deal with co-production, assuming that system inputs from constrained suppliers come from marginal production systems and also assuming that where production is increased, it avoids the production of the most appropriate substitute.

Previous research has demonstrated that the results from aLCA may differ considerably to a cLCA of the same product. For example, Sheehan et al. (1998) used attributional methods to compare the benefits of replacing fossil fuel-derived diesel use in buses with soybean-derived biodiesel and concluded that the "*use of biodiesel to displace petroleum diesel in urban buses is an extremely effective strategy for reducing* CO_2 *emissions*". However, a later study by García Sánchez et al. (2012) that applied consequential methods showed that the production and use of biodiesel can have greater emissions than fossil fuel diesel when land use change associated with increased demand for biofuel feedstocks are included. Similar trends occurred when assessing the climate impacts of dairy production. Gollnow et al. (2014) concluded, using attributional methods, that increasing milk production per dairy cow reduced the GHG emission intensity of milk production, whereas a consequential analysis (Cederberg and Stadig 2003) found that increasing milk production per dairy cow had no impact on emission intensity because of induced changes in the co-production of beef. Zehetmeier et al. (2012) also found that mitigation strategies focussing on milk production using attributional methods resulted in erroneous conclusions because the method failed to consider market effects in the co-product system (i.e. red meat production). The differences between aLCA and cLCA discussed above can be attributed to cLCA including market effects of changes in production of the functional unit as well as co-products of the system. They demonstrate that the analysis of a change in a system needs to include these market effects.

This study assessed how LCA methodological choice can affect the perceived environmental sustainability of wool production. It did this by producing three life cycle inventories (one attributional life cycle inventory (LCI) and two consequential LCIs) for the production of 500 g of clean fine wool fibre produced in the NSW high rainfall zone (HRZ) and processed in Asia ready for textile production. Results from the analyses of these LCIs were then used to calculate a single score using the components of the Higg MSI methods that are publically available to assess whether single scores could change in response to the implementation of a different methodology. The results from the study are discussed in the context of using LCA to improve the sustainability of the apparel industry.

2 Materials and methods

2.1 Functional unit and boundaries

The functional unit for the study was 500 g of 100% superfine Merino wool, clean and suitable for processing into a textile. The mass was chosen to reflect wool requirements for the manufacture of an outer garment such as a sweater. The analysis boundary was cradle to mill, and included all processes and impacts associated with wool production and pre-processing (i.e. scouring). Three LCIs were developed: an aLCI and two cLCIs. Two cLCIs were developed to assess the impact of the product substituted in the system expansion process on the environmental impacts of additional wool production.

2.2 Systems description

2.2.1 Wool production

Wool was produced in a fine wool Merino production system in the high rainfall zone of NSW, as described by Wiedemann et al. (2016c). Wool was then assumed to be transported to India or China for processing after which it was ready to be formed into yarn.

2.2.2 Co-production and/or market effects

Major co-products of the wool production system are lambs and mutton (sheep meat) from the on-farm stage, and sheep meat is a major high-value co-product from sheep systems. While the Merino breed has been selected specifically for high-value wool, lamb production is a major contributor to farm revenue and on a mass basis represents a greater biological output from the system. For cLCI that represented an increase in wool production, co-production was handled by system expansion and we decided to test the sensitivity of the cLCIA to the chosen substitute by using either a dedicated cross-bred meat sheep enterprise or a beef production enterprise.

Sheep meat is a global specialty meat representing ~ 5% of global meat production (FAO 2017), and global demand is expected to either remain constant or increase (FAO 2016). It is possible that additional sheep meat produced in response to increased wool production may displace other meat products such as beef, pork or chicken. However, the strong predicted global demand, the observable market demand in Australia (Meat and Livestock Australia 2018) and the cultural preference for sheep meat indicates that an increase in sheep meat production from wool focussed Merino systems are unlikely to displace other meats. In addition, Australia is also the most affected supplier of lamb (Colby 2015), which is predominantly supplied from cross-bred sheep systems. Considering the above, the first cLCI assumed that an increase in fine wool Merino production would occur by farmers replacing their dedicated cross-bred meat sheep that produced wool unsuitable for garment production (i.e. coarse wool suitable for interior textiles) with Merino sheep (cLCI-SM). This substitution is analogous to the substitution of beef from dairy cattle systems with beef from purpose-grown beef herds in response to production changes (Cederberg and Stadig 2003; Thomassen et al. 2008; Zehetmeier et al. 2012). In addition to changes in sheep meat production, the cLCI-SM also resulted in a reduction of coarse wool produced in cross-bred meat sheep systems. This change was handled by substituting coarse wool with nylon, a substitution fibre for interior textiles (Jackman and Dixon 2003). Beef was chosen as an alternative substitute because, being a red meat, there are fewer cultural barriers than other alternative meats in key sheep meat export markets such as the Middle East. Globally, Australia and Brazil are two of the world's largest beef exporters and are reasonably chosen to be the most affected suppliers of beef by changes in the global beef market (Meat and Livestock Australia 2016). In the present analysis, we assumed that Australian beef production was the most affected supplier. Accordingly, the second LCI assumed that, on average, an increase in Merino sheep production in the NSW HRZ would displaced some of the beef cattle herd (cLCIA-BM) and meant that some regional beef herd was replaced by sheep meat and fine wool production.

The wool processing stage also results in co-production, namely lanolin from the scouring process that is primarily used for body lotions and creams. Lower grade lanolin is also used as a lubricant and corrosion inhibitor in marine, heavy industrial and commercial applications; however, this is sourced from Australian scouring operations (Lanotec 2018), and because the inventory was from Chinese and Indian processors, it was not deemed to be a relevant substitute. Co-production of lanolin was, therefore, handled by system expansion to include avoided production of raw coconut oil (on a 1:1 mass basis).

2.3 Inventory

2.3.1 Animal production data and substitutes

For the purposes of this scoping study, it was assumed that relatively small changes in wool demand were expected to influence all producers across the NSW HRZ, so inventory was based on average production of fine wool in the region as detailed in Wiedemann et al. (2016c). A dataset of the most affected producers was not available at the present time but will be investigated as part of ongoing research by the authors. For the aLCI, co-production was handled by allocating impacts on a protein mass basis as per Wiedemann et al. (2016c). System expansion was implemented for cLCI and assumed that additional fine wool Merino sheep production avoided either cross-bred meat sheep and coarse wool production or beef production, as discussed above. Data used for avoided production of cross-bred sheep meat production were taken from Wiedemann et al. (2016b), while beef production inventory data (cLCI-BM) were taken from Wiedemann et al. (2016a), with some modification of land and water supply processes to account for the likely expansion of lamb production on farms previously used for wool. In both instances, the most affected suppliers that were increasing either sheep meat or beef were expected to have performance levels similar to the regional average. The increase in nylon associated with the reduction in the supply of coarse wool to the market was represented by the relevant Ecoinvent v3.0 (Weidema et al. 2013) inventory for global production on a 1:1 mass basis.

2.3.2 Wool processing data and substitutes

Wool processing data were taken from the wool industry LCI database (unpublished data), and included average data from eight wool scouring plants, predominantly in China and India. Primary data were collected over a 12-month period in 2016 and 2017. Data were averaged across all processing plants without selecting the most affected suppliers in this scoping level research (Table 1) and may be expected to be a conservative approach. This is not taking into account that improvement in water and energy use in the processing sector is ongoing and more modern, cost-competitive processors are expected to have lower energy and water requirements (Blackburn 2009; Kocabas 2008; Muthu 2015). Throughout the processing, inputs with inventories available in Ecoinvent v3.0 (i.e. LPG, diesel, sodium chloride, electricity, heat) used the respective attributional (i.e. APOS) or consequential (i.e. Conseq) inventory. Where Ecoinvent inventories were not available, inventories from AusLCI (Grant et al. 2017) were used. Ecoinvent consequential LCI that represented global demand of coconut oil was used to represent production avoided by the co-production of lanolin.

Table 1 Inventory for the scouring and combing of 1 kg of wool (see Section 2.3.2 for source)

	Material/process	Amount	Unit
Input	Australian greasy wool	1.390	kg
	Water	17.843	l
	Diesel	0.00021	kg
	Liquid petroleum gas	0.00051	kg
	Detergent	0.00425	kg
	Surfactant	0.00130	kg
	Flocculent	0.00039	kg
	Sodium bicarbonate	0.00509	kg
	Sodium chloride	0.00384	kg
	Metal salt	0.00374	kg
	Nylon packaging	0.00063	kg
	Steel strap packaging	0.00068	kg
	Polyethelene packaging (plastic bags)	0.00198	kg
	Articulated truck B-double transport	0.834	tkm
	Freight ship transport	11.775	tkm
	Articulated truck (urban freight)	0.274	tkm
	Electricity—high voltage	0.209	kWh
	Energy from natural gas	6.266	MJ
	Process steam from light fuel oil	0.013	MJ
Output	Clean wool (scoured)	1.000	kg
	Lanolin	0.077	kg
	Wool for recovery[a]	0.004	kg
	Water lost to evaporation	2.399	l
	Solid waste treatment (municipal)	0.310	kg
	Scouring wastewater treatment	15.444	l

[a] Wool for recovery was treated as a residual (primary data)

2.3.3 Land transformation

Land transformation was not required to be included in foreground processes because all production changes occurred within existing enterprises. Land transformation impacts in background Ecoinvent processes used were included in the assessment.

2.3.4 Emission calculations

Emission calculations built into the inventory were consistent with those described by in previous research (Wiedemann et al. 2016a, b, c).

2.4 Impact assessment

All LCIs were developed and analysed in SimaPro (PRé Sustainability 2016). Impact assessments were global warming using the IPCC GWP 100a v 1.3 indicator set based on the AR5 report (IPCC 2013). Fossil energy demand was assessed using a modified ReCiPe midpoint (H) indicator set v 1.13 (Goedkoop et al. 2009) that removed normalisation to provide raw estimates. Estimates were converted from kilogram oil equivalent to megajoules (MJ) with lower heating values (LHV). Stress-weighted water use was assessed using the water stress index (WSI) of Pfister et al. (2009) and reported in water equivalents (H_2O-e) after Ridoutt and Pfister (2010).

2.5 Calculation of impacts using Higg MSI methodology

The Higg MSI methodology calculates a single score with which to compare the relative impacts of fabrics used in the apparel industry (Sustainable Apparel Coalition 2016). The single score is developed by weighting and normalising global warming, water scarcity, eutrophication, abiotic (fossil fuel) depletion and chemistry impacts. The present study used the methods of the Higg MSI to calculate a single score based on global warming, fossil fuel depletion and water scarcity impacts for aLCIA, cLCIA-SM and cLCIA-BM. Results from each LCIA were weighted and normalised using the same values for each impact category presented in the Higg MSI methodology (Sustainable Apparel Coalition 2018a) to a value that represented the global warming, fossil fuel depletion and water scarcity impacts. These values were then normalised and summed to calculate a single score. It should be noted that, although the Higg MSI score includes eutrophication impacts, we were unable to include eutrophication impacts in our calculations because of a lack of suitable inventory data.

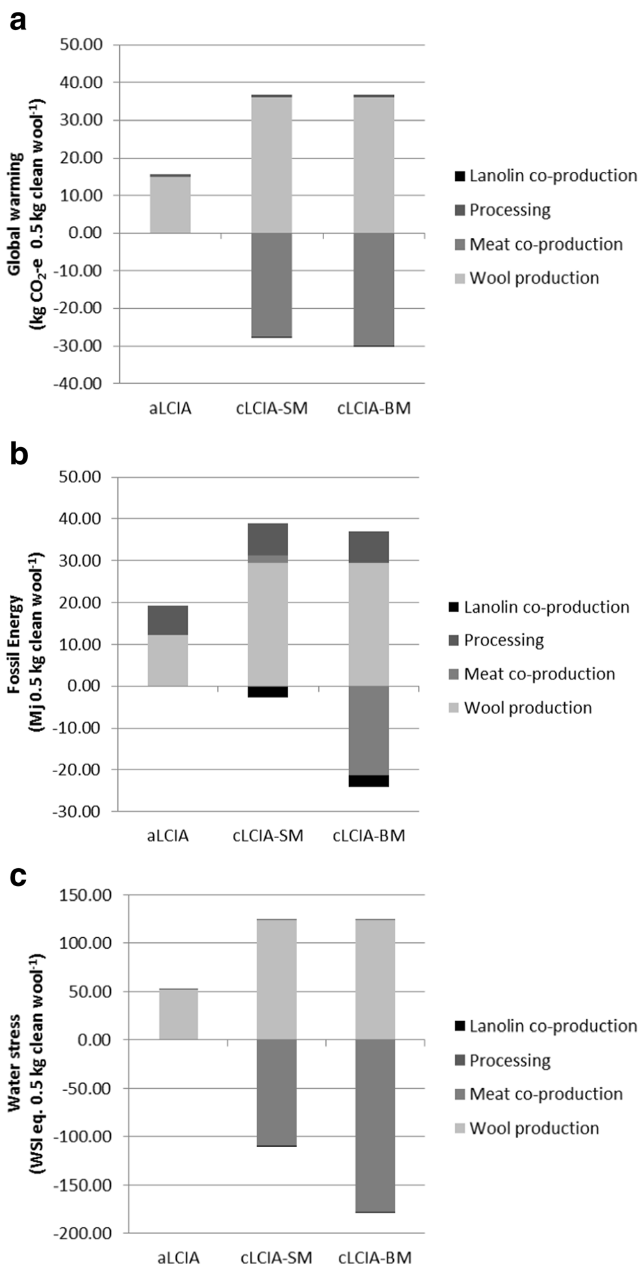

Fig. 1 Global warming (**a**), fossil energy demand (**b**) and water stress (**c**) impacts for the production of 500 g of clean, Merino wool when estimated using cLCI with the system expanded using sheep meat (cLCI-SM) or beef (cLCI-BM), or when estimated using aLCI

3 Results

3.1 LCIA

The impacts associated with the production of 500 g of clean fine Merino wool ready for textile processing differed between cLCIA-SM, cLCIA-BM and aLCIA scenarios. GHG emissions were 9.11 and 6.82 kg CO_2-e for the production of an additional 500 g wool under the cLCIA-SM and cLCIA-BM scenarios, respectively. The estimated impacts of wool production using aLCIA were 15.75 kg CO_2-e for 500 g of clean wool. Figure 1 shows the contribution that expanding the system to include avoided sheep meat or beef production made to the total emissions for cLCIA scenarios. It also shows that the emissions for avoided coconut oil production (to handle additional co-production of lanolin, where relevant) and emissions associated with wool processing contributed very little to the overall emission profile for wool.

Fossil energy requirements for the production of an additional 500 g of clean fine Merino wool were 36.15 and 13.13 MJ for the cLCIA-SM and cLCIA-BM, respectively, and that the energy requirements for the production of 500 g of clean wool assessed by aLCIA were 19.32 MJ. Energy use for the processing phase made a greater contribution to total energy use than for global warming impacts, and the contribution that avoided emissions associated with co-production in cLCIA scenarios made also varied considerably.

Total water stress associated with the production of an additional 500 g of clean fine Merino wool was 14.64 and − 52.90 water stress index equivalents (WSI-e) for cLCIA-SM and cLCIA-BM, respectively, and the water stress associated with existing production of 500 g of wool was 52.12 WSI-e. Wool production made the greatest contribution to the total water stress impacts for wool regardless of the methodological choice and co-production of lanolin, and wool processing made only minor contributions to total water stress impacts.

Using consequential Ecoinvent v3.0 inventories to represent marginal producers in cLCI resulted in a 0.4 and 2% decrease in global warming and fossil energy impacts, respectively, and a 0.7% reduction in water stress impacts (data not shown).

3.2 Higg MSI score

Global warming, fossil resource use and water scarcity impacts as calculated by the Higg MSI methodology for each LCIA are presented in Table 2. Global warming and fossil resource use impacts of wool production were greatest for the aLCI. In contrast, water scarcity impacts were greatest for cLCIA-BM. The single scores as calculated by the

Table 2 Single scores for global warming, fossil energy and water scarcity impacts for the production of 500 g of clean fine Merino wool ready for textile production as calculated using the methods of the Higg MSI (Sustainable Apparel Coalition 2016)

	LCIA		
	aLCIA	cLCIA-SM	cLCIA-BM
Global warming	15.1	8.7	6.5
Fossil energy	1.4	2.7	1.0
Water scarcity	1.0	0.3	− 1.0

modified Higg MSI methodology were 39, 27 and 21 for the aLCIA, cLCIA-SM and cLCIA-BM, respectively.

4 Discussion

This study is the first to show that the impacts of producing additional fine Merino wool production used in the apparel industry in response to additional demand were lower than those for current wool production (Fig. 1). This was evident in results from LCIA and also when those results were used to calculate individual impacts using the Higg MSI methodology (Table 2). Calculating single scores using the available Higg MSI methodology showed that single scores from cLCIA results were 31 and 47% lower than those calculated using aLCIA results. Differences between aLCIA and cLCIA were primarily related to the displaced product system, rather than the impacts of marginal inputs (where used). These results demonstrate that, in addition to aLCA being a technically incorrect methodology to use where there is an inherent drive to alter fibre choices and thereby influence supply and demand (Brander et al. 2008; Plevin et al. 2014), the use of aLCA by the Higg MSI is likely to have overestimated the perceived impacts of apparel made with fine Merino wool. Previous research has also shown that the results of aLCIA and cLCIA can differ substantially. For example, a comparison between cLCI and aLCI from Ecoinvent v3.0 found that over 66% of the LCIs deviate by more than 10% (Weidema and Moreno 2013). This means that it is quite likely that other Higg MSI scores, and the perceived sustainability of all materials rated by the MSI, would change if a consequential approach was systematically applied to calculate scores. The differences reported here for wool between methodological approaches provide a strong justification for the implementation of a consequential method in rating systems and strongly suggest that the Higg MSI scores and other apparel sustainability indicators (e.g. MADE-BY) that currently use aLCA in their assessment cannot be considered a reliable indicator of the sustainability of materials used in the apparel industry.

In addition to differences in results between attributional and consequential approaches, results for impacts assessed by cLCIA were sensitive to choice of substitute (Fig. 1). Similar results have been found in other studies (Fig. 1; Cederberg and Stadig 2003; Flysjö et al. 2011; Zehetmeier et al. 2012), and the sensitivity reported here is similar to the range in values shown between different allocation methods for wool (see Wiedemann et al. 2015). Importantly, this sensitivity is not a justification for not using a consequential approach in rating systems because sensitivity to co-production is already an issue in aLCA. For example, McGeough et al. (2012) reported that, depending on the allocation method used, the global warming impacts for a kilogram of fat and protein corrected milk ranged from 0.67 to 0.92 kg CO_2-e. Research has also examined the allocation issue in the context of bioenergy production. Wardenaar et al. (2012) reported that when physical allocation was used instead of economic allocation to handle co-production associated with the production of bioelectricity from rapeseed oil, the global warming impacts decreased from 0.604 to 0.477 kg CO_2-e kWh. Further, Luo et al. (2009) also showed that the estimated environmental impacts of corn stover-based ethanol were highly dependent on whether mass or economic allocation was used. There were a number of reasons for differences between the results of cLCIA-SM and cLCIA-BM. cLCIA-SM had greater global warming impacts than cLCIA-BM because, even though cLCIA-SM displaced the production of sheep, it also displaced the production of coarse wool that needed to be substituted with nylon. Similarly, the production of additional nylon was responsible for the high fossil energy demand for cLCIA-SM relative to cLCIA-BM. In contrast, water stress impacts for cLCIA-BM were greater than for cLCIA-SM. This was the result of lower on-farm water demand for sheep production compared to cattle, an established difference between the species (Zonderland-Thomassen et al. 2014), so avoiding beef production results in a much lower water stress. These results demonstrate that differences in cLCIs developed for wool are likely to occur due to market effects associated with the co-products. Many other textiles are also produced from fibres that are produced with a co-product. For example, cotton fibres are co-produced with cotton seed, and petroleum-based polyester is also co-produced with many other petroleum products so the sensitivity of choice of substitute is unlikely to be limited to materials made from wool. Sensitivity of results to substitution products means that selecting the most appropriate substitute when implementing a consequential approach requires careful consideration by the apparel industry. A proposed resolution to this issue is that rating tools ensure that a consistent approach to determining the most appropriate substitute for use in system expansion is implemented based on the available guidance (EU JRC 2010).

5 Conclusions

Improved sustainability is a priority for the apparel sector, and considerable effort has been placed on the development of tools and rating systems to quantify impacts and enable improvements to be made. The results of this study indicate that using aLCI to assess the impacts of a preference for woollen materials by consumers may lead to an incorrect estimate of these impacts. The potential for rating tools that use an attributional approach to incorrectly estimate the impacts of a fibre is not solely limited to wool production. Considering that the purpose of these rating tools is to influence the demand for different textiles based on perceived sustainability, it is clear that a consequential approach is most appropriate. The implementation of a consequential approach to developing LCI for assessing impacts would require a consistent approach to determining the most appropriate substitute for use in the system expansion process and identifying marginal suppliers. The impacts of co-production demonstrated by this study suggest that other animal or plant-based fibres for which co-production occurs (e.g. cotton, flax, coir, kenaf, kapok and leather) are also likely to change if assessed using cLCIA.

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References

Blackburn R (2009) Sustainable textiles: life cycle and environmental impact. Elsevier

Brandão M, Clift R, Cowie A, Greenhalgh S (2014) The use of life cycle assessment in the support of robust (climate) policy making: comment on "using attributional life cycle assessment to estimate climate-change mitigation…". J Ind Ecol 18:461–463

Brander M (2017) Comparative analysis of attributional corporate greenhouse gas accounting, consequential life cycle assessment, and project/policy level accounting: a bioenergy case study. J Clean Prod 167:1401–1414

Brander M, Tipper R, Hutchison C, Davis G (2008) Technical paper: consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels. Econometrica press

Cederberg C, Stadig M (2003) System expansion and allocation in life cycle assessment of milk and beef production. Int J Life Cycle Assess 8:350–356

Colby L (2015) World sheep meat market to 2025. AHDB Beef & Lamb

EU JRC (2010) ILCD handbook: general guide for life cycle assessment: detailed guidance. Publications Office of the European Union

European Commission (2013) Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase European Commission

FAO (2016) OECD-FAO Agricultural Outlook 2016-2025, Commodity snapshots: Meat. United Nations Food and Agriculture Organisation

FAO (2017) Meat consumption. United Nations Food and Agriculture Organisation

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manag 91:1–21

Flysjö A, Henriksson M, Cederberg C, Ledgard S, Englund J-E (2011) The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. Agric Syst 104:459–469

García Sánchez JA, López Martínez JM, Lumbreras Martín J, Flores Holgado MN (2012) Comparison of life cycle energy consumption and GHG emissions of natural gas, biodiesel and diesel buses of the Madrid transportation system. Energy 47:174–198

Global Fashion Agenda (2017) Pulse of the Fasion industry. Global Fashion Agenda and Boston Consulting Group

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level—report I: characterisation Den Haag

Gollnow S, Lundie S, Moore AD, McLaren J, van Buuren N, Stahle P, Christie K, Thylmann D, Rehl T (2014) Carbon footprint of milk production from dairy cows in Australia. Int Dairy J 37:31–38

Grant T, Eady S, Cruypenninck H, Simmons A (2017) AusLCI methodology for developing life cycle inventory for Australian agriculture. Lifecycle Strategies Pty Ltd, Electronic

IPCC (2013) Climate change 2013: the physical science basis. Intergovernmental panel on climate change, working group I contribution to the IPCC fifth assessment report (AR5). IPCC

Jackman DR, Dixon MK (2003) The guide to textiles for interiors. Portage & Main Press

Kocabas A (2008) Improvements in energy and water consumption performances of a textile mill after BAT applications Middle East Technical University, Ankara, Turkey

Lanotec (2018) Heavy duty liquid lanolin. http://lanotec.com.au/product/heavy-duty-liquid-lanolin/

Luo L, van der Voet E, Huppes G, de Haes HAU (2009) Allocation issues in LCA methodology: a case study of corn Stover-based fuel ethanol. Int J Life Cycle Assess 14:529–539

McGeough E, Little S, Janzen H, McAllister T, McGinn S, Beauchemin K (2012) Life-cycle assessment of greenhouse gas emissions from dairy production in eastern Canada: a case study. J Dairy Sci 95:5164–5175

Meat and Livestock Australia (2016) Fast facts 2016: Australia's beef industry. Meat and Livestock Australia

Meat and Livestock Australia (2018) Industry projections 2018: Australian sheep. Meat and Livestock Australia

Muthu SS (2015) Handbook of sustainable apparel production. CRC Press

Perry C (2014) Water footprints: path to enlightenment, or false trail? Agric Water Manag 134:119–125

Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 43:4098–4104

Plevin RJ, Delucchi MA, Creutzig F (2014) Using attributional life cycle assessment to estimate climate change mitigation benefits misleads policy makers. J Ind Ecol 18:73–83

PRé Sustainability (2016) Simapro v8.3.0, 8.3.0 edn

Reap J, Roman F, Duncan S, Bras B (2008) A survey of unresolved problems in life cycle assessment. Int J Life Cycle Assess 13:374–388

Ridoutt BG, Pfister S (2010) A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob Environ Chang 20:113–120

Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H (1998) Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Final report. National Renewable Energy Lab., Golden

Sustainable Apparel Coalition (2016) Higg materials sustainability index (MSI) methodology. Sustainable apparel coalition, online, Accessed 30/11/2017

Sustainable Apparel Coalition (2018a) Learn more about the Higg MSI. http://msi.higg.org/page/learn-more. Accessed 26th Feb 2018

Sustainable Apparel Coalition (2018b) Sustainable Apparel Coalition. www.apparelcoalition.org. Accessed 19th Feb 2018

Thomassen MA, Dalgaard R, Heijungs R, de Boer I (2008) Attributional and consequential LCA of milk production. Int J Life Cycle Assess 13:339–349

Wardenaar T, Van Ruijven T, Beltran AM, Vad K, Guinée J, Heijungs R (2012) Differences between LCA for analysis and LCA for policy: a case study on the consequences of allocation choices in bio-energy policies. Int J Life Cycle Assess 17:1059–1067

Weidema BP, Moreno E (2013) Presentation to EcoInvent user meeting

Weidema BP et al. (2013) Overview and methodology: data quality guideline for the ecoinvent database version 3. Swiss centre for life cycle inventories

Wiedemann SG, Ledgard SF, Henry BK, Yan M-J, Mao N, Russell SJ (2015) Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers. Int J Life Cycle Assess 20: 463–476

Wiedemann S, McGahan E, Murphy C, Yan M (2016a) Resource use and environmental impacts from beef production in eastern Australia investigated using life cycle assessment. Anim Prod Sci 56:882–894

Wiedemann S, Yan M-J, Murphy C (2016b) Resource use and environmental impacts from Australian export lamb production: a life cycle assessment. Anim Prod Sci 56:1070–1080

Wiedemann SG, Yan MJ, Henry BK, Murphy CM (2016c) Resource use and greenhouse gas emissions from three wool production regions in Australia. J Clean Prod 122:121–132

Zehetmeier M, Gandorfer M, Heibenhuber A, de Boer I (2012) Modelling GHG emissions of dairy cow production systems differing in milk yield and breed-the impact of uncertainty. In: 8th International Conference on Life Cycle Assessment in the Agri-Food Sector, 2012

Zonderland-Thomassen MA, Lieffering M, Ledgard SF (2014) Water footprint of beef cattle and sheep produced in New Zealand: water scarcity and eutrophication impacts. J Clean Prod 73:253–262