LCA of wool textiles and clothing

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10.1 Introduction

This chapter examines life cycle assessment (LCA) of wool textiles and clothing. We focus on products made from the natural fibre (wool) formed from the fleece of sheep (*Ovis aries*) and particularly on apparel, but the principles and methodology described can readily be extended to a wide range of wool textiles including not only clothing but also household fabrics and industrial products (BSI, 2014) and to products from other small ruminants producing fibre such as members of the goat and camelid families (LEAP, 2014a). We examine in more detail those aspects of the life cycle that affect the intensity of environmental impacts in a way that sets wool products apart from those made from alternative fibres. These specific life cycle features include the cradle-to-farm gate production stage, which is characterised by wide diversity and multiple products from sheep, and on the end-of-life stage where the range of options following first use of clothing by the consumer (reuse, recycling or disposal) can alter the wool supply chain impacts substantially. A case study is provided to illustrate application of LCA to quantification of environmental impacts of two items of wool apparel. This study quantifies, for the first time, the relative contributions of different stages of the complex supply chain across production, processing, manufacture and retail over multiple countries. Supply chain impact 'hotspots' are identified and the importance of considering multiple impact and resource use categories is highlighted. Finally, we discuss emerging research to resolve data and methodology challenges and future prospects for LCA of wool products.

10.1.1 The wool textile value chain

Wool has a complex protein structure that gives it unique properties that make wool fibre suitable for a wide range of products including warm outer garments, base layer wear, fashion apparel, luxury interiors and items required to have fire-retardant properties (IWTO, 2014; CSIRO, 2008). Wool is at the high value end of fibres, and although it accounted for only 1.3% of world textile consumption in 2012 (IWTO, 2013), it holds a much higher level of importance in terms of unit price and status.

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The value of a wool fleece and its use is largely determined by the diameter of the fibre. Merino is the finest wool with grades ranging from ultrafine (<16.5 μm) to broad wool of >23 μm (Nolan et al., 2013). Other sheep species and crossbreeds have higher diameter fibres with coarser wools (up to 35−45 μm) commonly used for floor coverings. Approximately two-thirds of the global wool harvest is used in the manufacture of apparel, and about one-third in interior products such as carpets, upholstery and rugs, with a small proportion (about 5% of the total) destined for industrial uses such as insulation (IWTO, 2014).

The wool supply chain starts with sheep farming systems. Globally, production of wool involves over a billion sheep across geographically and climatically diverse regions in around 100 countries. However, the majority of 2 million tonnes total annual harvest is concentrated in relatively few countries (FAOSTAT, 2014). Table 10.1 lists the top 12 countries ranked on clean wool production. Together these countries account for over 40% of the total sheep population and close to 70% of global greasy wool production. Australia is the leading producer of clean wool and in 2012 was responsible for about half of the world export volume. Approximately half of apparel wool is supplied by Australia (FAOSTAT, 2014), while New Zealand is also a major producer of high quality fine wool for apparel as well as stronger wool suited to interior furnishings. China accounted for 27% of wool imports in 2012 and is a major centre of

Table 10.1 Top 12 individual countries ranked for clean wool produced

Country	Sheep ('000 head)	Greasy wool (t)	Clean wool equivalent (t)
Australia	74,700	374,157	245,073
China	139,600	400,057	177,697
New Zealand	31,263	167,900	127,830
Russia	20,767	51,502	28,750
Iran	48,750	61,897	27,854
Sudan	52,428	55,221	27,611
Turkey	25,032	49,542	24,771
Uruguay	7350	32,500	24,050
South Africa	24,391	40,621	24,040
Kazakhstan	15,200	39,600	23,176
Turkmenistan	14,000	38,333	22,825
United Kingdom	32,215	34,000	22,780
World total	1110.647	1,999,284	1,109,433

2012 data; sourced from FAO and AWI, October 2014.

wool processing having almost 30% of global spinning and weaving. Italy (10%), India (8%) and the United Kingdom (8%) are also significant importing countries, with Italy and the United Kingdom together representing 20% of spinning and weaving. The Asian subcontinent, predominantly India and Pakistan (14%), is also important in wool processing and manufacturing.

The major steps in the life cycle of wool textiles and apparel are illustrated in Figure 10.1. The relative contribution of each stage to the environmental impact of wool products differs for different impact or resource use categories and between diverse production systems. Supply chain efficiency also significantly affects environmental performance. LCA is further complicated because of the need to consider not only the range of intermediate products shown in the right-hand side of Figure 10.1 but also co-products such as meat, milk and lanolin (see Figure 10.2), which are allocated a

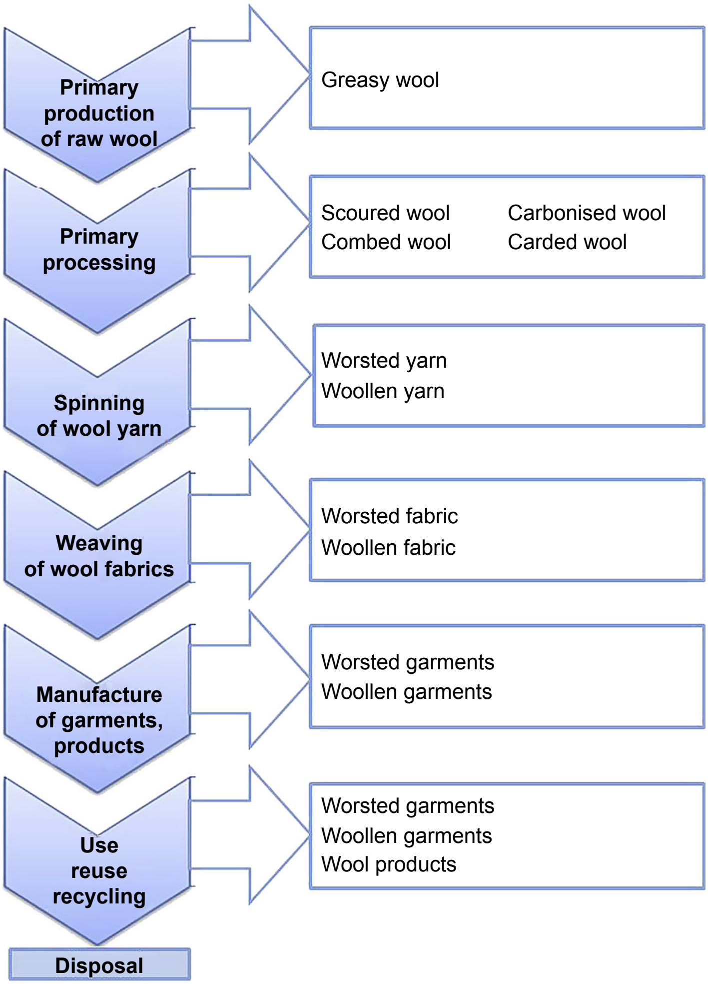

Figure 10.1 Simplified diagram of stages in the life cycle of wool apparel.

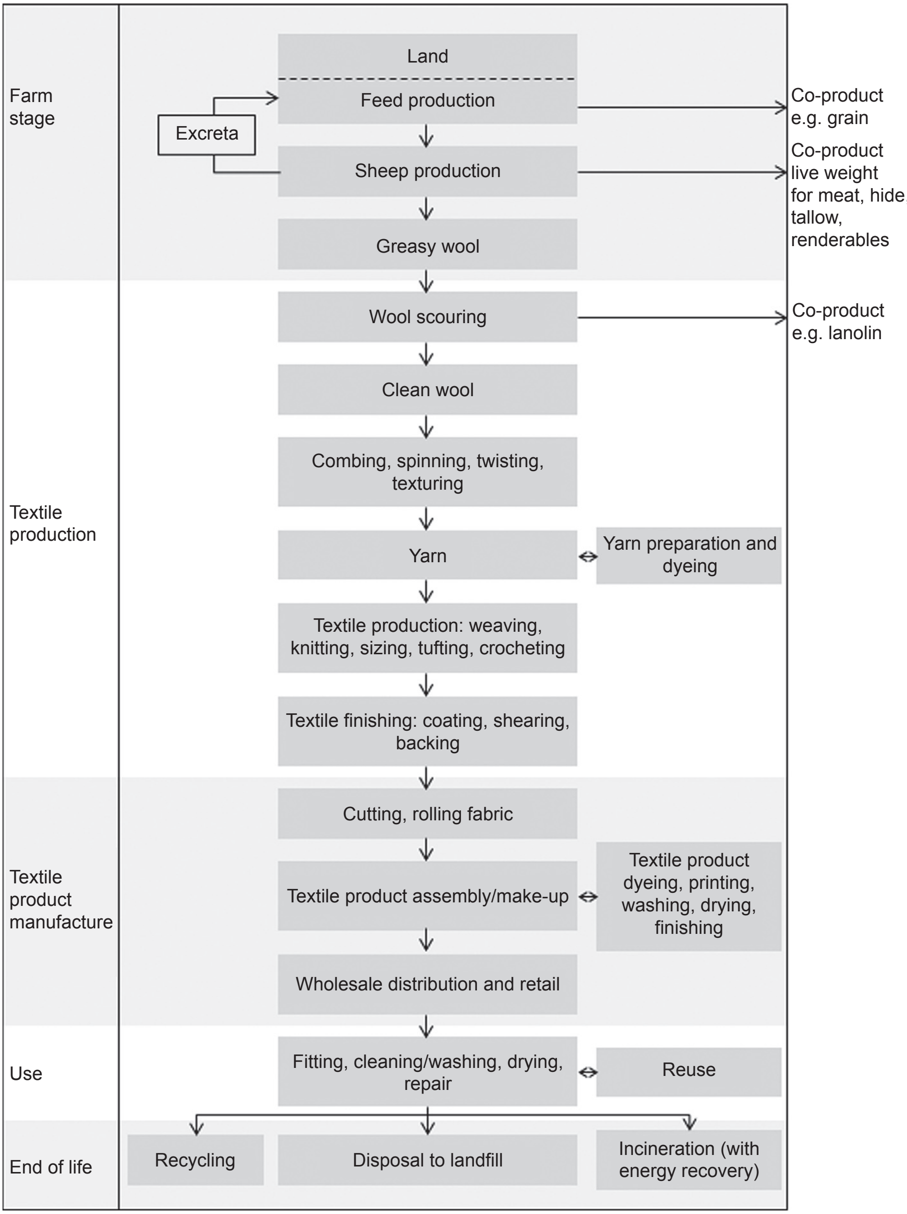

Figure 10.2 System boundary diagram for the life cycle of textile produced from wool from sheep (excluding inputs, outputs and emissions). Transportation can occur between any of the various stages outlined.
This figure is adapted with permission from BSI (2014) to account for wool production on farm.

share of the impacts in order to accurately quantify the impacts of a wool product. Wool supply chains are frequently also characterised by multiple transfers between countries and regions, and transport around the globe can involve large distances (Bevilacqua et al., 2011, Section 10.3 of this chapter). Complex social and economic interactions affect not only the volume or units of trade in wool intermediate and final products but also the quality and value of the units and how they change over time (Verikios, 2009).

The diversity and complexity of wool supply chains mean that data requirements are challenging for full LCA. For the consumer use stage, statistics on the period of garment wear and frequency and method of cleaning are known to be highly variable and are difficult to obtain. For example, average life expectancy of wool garments conservatively ranges from one or two years for items such as shirts to four years for suits and coats and 10 years for blankets (Drycleaning Institute of Australia Limited, 2014). As discussed in Section 10.2.6, information is also needed on consumer choices of 'disposal' after the period of first use – for reuse, recycling or consignment to landfill or other municipal waste streams that are recognised as significant in the full life cycle of wool products.

10.1.2 Published LCA studies of wool

There are few wool LCA studies that have attempted to quantify multiple environmental impacts across the full cradle-to-grave or cradle-to-cradle life cycle of wool textile products. Table 10.2 summarises available published LCA studies for wool. Most published studies have been restricted to primary production (cradle-to-farm gate) or to the first stage of processing to clean wool (cradle-to-primary processing). In addition, the majority of LCA studies have assessed only a single impact category, usually global warming potential (GWP), which is commonly reported as greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2e) and often called the product carbon footprint. Other impacts and resource depletion categories of environmental significance arise from the production and use of textiles and clothing, including acidification, eutrophication, human toxicity, biodiversity impact, water use and land use. A single indicator such as GHG emissions cannot be interpreted as a measure of environmental sustainability and if used to prioritise mitigation strategies may introduce risks of perverse outcomes from unidentified trade-offs (ISO, 2013).

Inconsistencies in scope, methodology and assumptions between published wool LCA studies mean that use of the results to compare products or systems and interpretation for policy or management decisions frequently carries high uncertainty. A major source of methodological inconsistency has been the handling of co-products, notably for the on-farm production of wool from sheep where co-products, particularly meat, can be economically and socially important. Eady et al. (2012) investigated GHG emissions for a mixed farming (grain, wool and meat) system in Western Australia using a cradle-to-farm gate LCA approach. Allocation between the fine wool (for textiles) and meat from merino sheep was assessed using either biophysical or economic relationships. The study estimated 36.2 or 28.7 kg CO_2e/kg greasy wool using biophysical or economic allocation methods, respectively. Brock et al. (2013) also

Table 10.2 Summary of the scope of publicly available wool LCA studies and the impact categories that were evaluated

Published LCA study	Functional unit	System boundary	Impact categories
Eady et al. (2012)	1 kg 19.5 µm greasy wool	To farm gate	GWP
Brock et al. (2013)	1 kg 19 µm greasy wool	To farm gate	GWP
Wiedemann et al. (2015)	1 kg greasy wool	To farm gate	GWP, ED, LU
Potting and Blok (1995)	1 sq m carpet	Pre-farm to disposal	Most CML[a] indicators
Barber and Pellow (2006)	1 t dry wool top	Pre-farm to wool top at spinning mill	GWP[b], ED
Brent and Hietkamp (2003)	1 kg dyed yarn	Pre-farm to dyed yarn	Most CML indicators[a], GWP[b], LU, WU
Petersen and Solberg (2004)	Wool carpet	Post-farm gate to use	GWP
Murphy and Norton (2008)	1 sq m insulation	Farm to disposal	GWP, ED, AP, EP
Bowyer (2009)	Wool broadloom carpet	Pre-farm to disposal	GWP, ED, AP, EP, HTP, ETP, WU, ODP, smog, indoor air quality, habitat alteration
Bevilacqua et al. (2011)	1 wool sweater	Pre-farm to disposal	GWP[b]

[a]**CML impact categories (LCA Institute of Environmental Sciences NL)**
GWP_{100} = global warming potential, 100-year timeframe (kg CO_2e)
AP = acidification potential (kg SO_2 eq)
EP = eutrophication potential (kg PO_4 eq)
ODP = ozone layer depletion potential (kg CFC-11 eq)
ADP = abiotic depletion potential (kg antimony eq)
HTP = human toxicity potential (kg 1,4-dichlorobenzene eq)
ETP = ecotoxicity potential (kg 1,4-dichlorobenzene eq)
POCP = photochemical oxidant creation potential (kg ethylene eq)
Resource use
ED = Fossil energy demand (MJ)
LU = Land use (ha)
WU = Water use (L).
[b]GHG emissions exclude sheep enteric CH_4 and N_2O.

conducted a cradle-to-farm gate GHG study of merino wool production, in this case from eastern Australia, and estimated emissions to be 24.9 kg CO_2e/kg greasy wool using economic allocation between wool and meat. However, GHG emissions were found to be much lower at 14.8 kg CO_2e/kg greasy wool when the farming enterprise dominance was shifted from wool to meat by introducing meat breed rams (Dorset), resulting in higher return from sheep meat. Recently, Wiedemann et al. (2015) compared several alternative allocation and system expansion methods for dealing with co-products using case-farm systems in New Zealand and the United Kingdom that produce broad wool and two systems in Australia producing fine wool. They found only small differences (<25%) in GHG emissions per kg product (i.e. wool and meat) between the four systems but large effects of methodology for handling co-products. For example, results ranged from −26 to +37 kg CO_2e/kg greasy wool for the UK system using different methods. The study examined multiple resource use categories. It showed that for all case study farms, only a small amount of arable land was used for wool products, with most land being non-arable. On these lands grazing of perennial pastures or shrubs by ruminants was often the only viable productive use.

These published studies have recognised wool and meat as the co-products for sheep production systems of interest. However, sheep systems in some regions also provide milk with high economic value for human food. It is also recognised that sheep can provide other functions that can potentially be accounted for, thereby reducing the environmental impacts allocated to wool. For example, Ripoll-Bosch et al. (2013) studied sheep systems in Spain and noted that the benefits of sheep to ecosystem services (e.g. conservation of biodiversity and landscapes) were important in extensive mid-high altitude natural/seminatural areas and allocated up to one-half of total GHG emissions to these ecosystem services based on an economic approach.

At the other end of textile supply chains, amounts of reuse and recycling of wool products are key parameters for quantification in LCA to determine the full lifetime and extent of avoidance of the production of new raw material. However, for these activities few data are available and generalisations are difficult because practices differ between countries in terms of recycling and reuse of wool products and, ultimately, in the mode of disposal. The environmental impacts associated with recycling processes as well as transport and storage of post-use products must be included in the accounting. WRAP (2012a) provided data showing that in some cases there can be a net benefit of recycling with the burdens associated with managing the waste being outweighed by the avoidance of new garment production. Woolridge et al. (2006) reported an LCA study for textile products that found that reuse and recycling of donated clothing results in a reduction in the environmental burden compared to purchasing new clothing made from virgin materials, taking into account the energy footprint of recycling and reuse and assuming the production of new apparel was avoided. In addition, diverting clothing from landfills is economically as well as environmentally beneficial in terms of promoting material security, reducing raw material costs and creating employment and economic growth.

The dearth of full supply chain, multi-impact LCA studies for wool textiles was noted in a review of published wool LCA studies (Henry, 2011), which also identified significant data gaps and research needs for more meaningful assessment of the environmental performance of wool supply chains. A subsequent LCA study (Bevilacqua et al., 2011) sought to quantify the GHG emissions (carbon footprint) across the full value chain of a wool sweater. The estimated emissions were 1.95 kg CO_2e per sweater of median weight (estimated as 0.265 kg in the 2009 collection). This assessment of GHG emissions did not include non-CO_2 GHG emissions (sheep enteric methane and excreta nitrous oxide) and this result is consequently markedly lower than reported for cradle-to-farm gate assessments that counted all significant GHG sources (Henry, 2011). However, the strength of the study by Bevilacqua et al. (2011) was in examining a complex supply chain and covering in detail the transport structure and energy emissions across eight countries and multiple locations in Italy where the processing of the fibre occurred.

10.2 Wool LCA methodological and data challenges

The general guidelines for application of LCA were set out in ISO 14044 (ISO, 2006). Those guidelines defined the preferred process starting with the importance of defining the goal and scope of an LCA study, followed by data collection and inventory analysis and then impact assessment. More recently, LCA-based guidelines covering limited impact categories specifically for small ruminants, that is, for sheep and goats (LEAP, 2014a) and for textiles (BSI, 2014), have been published. Methodological aspects of the LCA approach are described in the following sections, with emphasis on the specific application challenges for wool fibre produced from sheep. Initially, a brief description is provided of the two distinct approaches, attributional and consequential LCA, since the fundamental choice between these has a substantial influence on methodology, results and interpretation of the study.

10.2.1 Attributional versus consequential LCA

The terms attributional LCA (ALCA) and consequential LCA (CLCA) are used (Rebitzer et al., 2004) to identify studies that aim to describe, respectively, either: (1) a static representation of an average product system and its environmental exchanges; or (2) how the environmental exchanges of the system are affected by a change in the system. The choice of which way to model product life cycle environmental impacts depends on the scope and intended goals of the research. Specific aspects of consequential modelling have been described by Ekvall and Weidema (2004), while guidelines such as those developed by LEAP (2014a) describe an attributional approach. Key differences relate to data collection and handling of multifunctionality (i.e. co-products).

Representative results in ALCA require a comprehensive dataset with respect to factors that contribute to variable efficiency and environmental impacts, while CLCA is focussed on using marginal data to assess the part of the production system most likely to change as a consequence of choices or changes, for example, in supply or demand. Hence, if studying an increase in the demand for wool, a CLCA would only study farming systems that would be expected to increase in response to market changes.

Supply chains such as those for wool textiles give a range of co-products that must be considered as part of an LCA study. In ALCA an allocation approach is commonly used to divide the environmental burden between the multiple co-products, whilst in

CLCA the system is expanded to include the consequences of a change. In contrast to allocation, system expansion includes the additional functions related to the co-products (ISO, 2006). In practice, this is frequently achieved by removing the impact of avoided processes from the system of interest, commonly termed substitution or the avoided-burden method. Within wool production systems, the substitution method has been applied to co-production of wool and meat (live weight, LW) from sheep at the farm (Wiedemann et al., 2015). In that study, applying the substitution method to two Australian farm systems gave lower estimates of emissions intensity (−3 to 12 kg CO_2e/kg wool) when increased LW from the dual purpose sheep would avoid production of LW from beef cattle or meat-only wool-shedding sheep compared to 10−37 kg CO_2e/kg wool based on allocation approaches using ALCA.

The remainder of this chapter focusses on attributional LCA, which has been most commonly applied for sheep and wool systems, often to provide benchmarking results for a given system or product and to identify 'hotspots' of environmental impacts in wool supply chains. ALCA avoids the need for some of the sensitive assumptions of CLCA (Finnveden et al., 2009) and is supported by recent development of specific guidelines to improve the consistency of application to wool apparel and textiles (LEAP, 2014a; BSI, 2014). However, the inherent limitations associated with ALCA that constrain the applicability of results for predicting the influence of a change in supply and demand should be noted.

10.2.2 Goal, scope and system boundary

The goal of a study is important in defining the methodology to be used and its level of detail. Considerations include the intended aims of the study, such as benchmarking a product, identifying hotspots through the life cycle and/or evaluating potential improvement in environmental performance. The scope defines the breadth of the study and identifies the production system, functions, functional unit, system boundaries and impact categories to be studied.

For textiles and clothing produced from natural fibres from animals, the production system and system boundaries must cover all aspects of the animal production system involved in fibre production, and this stage represents the main difference between wool and production of man-made or plant-derived fibres. An example of a system boundary diagram illustrating the various key contributors over the life cycle of an article of clothing from wool is given in Figure 10.2.

In practice, wool production systems are very diverse globally ranging from sheep-only systems where the sheep are housed for much of the year and fed brought-in crops through to very extensive grazing/browsing systems where sheep roam over large areas and feed on native or introduced pastures and/or shrubs. Additionally, the sheep may be in shared systems with other animal types (e.g. cattle, goats, and deer) or in mixed farming systems with crops for sale but where sheep feed on crop stubble and waste, unharvested grain. A further complication is the various co-production components that need to be accounted for (Figure 10.2).

A major methodological complexity associated with the farm stage is the need to account for all contributing factors associated with the sheep population required for wool production. This sheep population refers to all animal classes linked to production of the wool. Thus, for sheep it includes the breeding ewes and rams as well as all

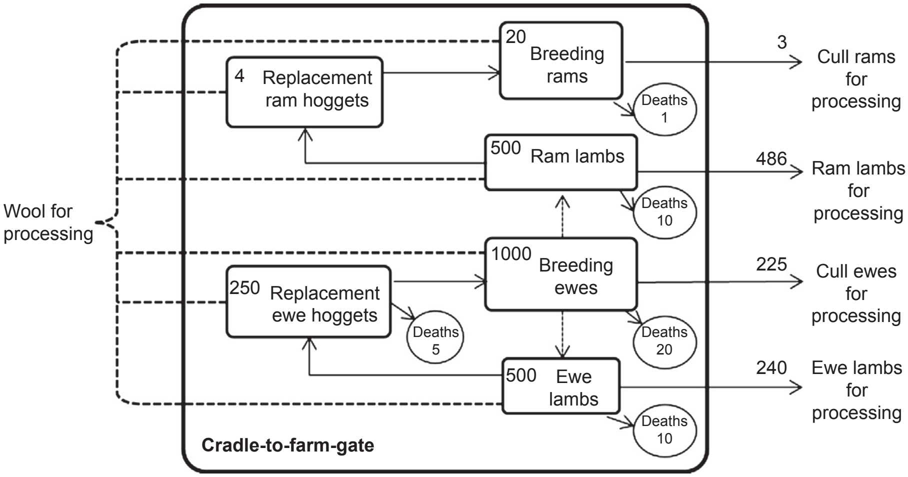

Figure 10.3 Simplified example of a sheep population illustrating relative numbers of breeding and replacement sheep on farm and surplus sheep sold for meat processing. The population is based on a breeding ewe flock of 1000, 100% lambing, 25% replacement rate, 2% death rate and first lambing at 2 years old. All sheep classes contribute to wool production, which is generally harvested by shearing sheep once or twice a year. Wool may also be harvested from hides of sheep during the meat-processing stage.
Adapted from Leap Guidelines, LEAP (2014a).

replacements required to maintain a stable population (Figure 10.3). All of these sheep produce wool, although lambs generally produce less wool of a finer fibre diameter that may have a different end use than wool from older breeding sheep.

10.2.3 Resource use and environmental impact categories

A key benefit of LCA is that it involves determination of multiple resource use and environmental impact categories so that trade-offs and interactions can be evaluated. However, most published LCA studies of sheep to date have assessed few indicators, and often only GHG emissions. General methodology for determining GHG emissions from products was provided in ISO/TS 14067 (ISO, 2013), PAS 2050 (BSI, 2011) and the GHG Protocol *Product Life Cycle Accounting and Reporting Standard* (WRI, 2011). The LEAP small ruminants, guidelines (LEAP, 2014a) give further details for assessing GHG emissions and fossil energy demand for sheep and goats covering the cradle-to-primary processing gate. Key factors covered in the LEAP guidelines include estimation of animal feed intake and handling fibre and non-fibre co-products (discussed in detail later). PAS 2395 (BSI, 2014) provides useful methodology guidelines for estimating GHG emissions for the full life cycle of textile products with details for fibre processing and later life cycle stages of textiles.

There is a wide range of other impact categories with varying levels of consensus on the most appropriate methodology for each category. For example, the ILCD Handbook (ILCD, 2011) describes various methods under the main impact categories of climate change, eutrophication, acidification, ozone depletion, human toxicity, respiratory inorganics, ionising radiation, photochemical ozone formation, ecotoxicity, land use and resource depletion (mainly fossil fuels and minerals). In practice, the relative significance of these different impact categories will vary with different types of textiles and clothing. However, for many impact categories, the cradle-to-farm gate stage has been identified as a dominant determinant of total impacts for livestock-based products (e.g. Basset-Mens et al., 2007; Ledgard et al., 2011). Production of wool has a relatively minor contribution to some resource use and environmental impact categories (e.g. those dominated by fossil fuels), while others are more important.

Land use, also referred to as land occupation, is a resource use category where results are highly dependent on the methodology. A simplistic metric of total land use/kg product results in a high value assigned to wool products made from the fibre of extensively grazed sheep. However, other important measures of land use may give relatively low values for wool. For example, use of arable land (i.e. land capable of growing crops) is low or zero in most extensive systems. In contrast, use by sheep of non-arable land can be high, but this category frequently has limited alternative uses and low intensity grazing may not affect competitive land use and may have a positive rather than negative impact on ecosystem services. A component of land use is biodiversity, and while crop production generally has a significant negative effect on biodiversity, extensive browse or grazing systems may help to enhance botanical and ecosystem diversity (e.g. Bretagnolle et al., 2011; Rippoll-Bosch et al., 2013). In addition, land use and land use change for sheep production may be either a source or sink of GHG emissions. For example, deforestation for improved grazing or cultivation for feed results in GHG emissions through loss of biogenic carbon while in some sheep farming systems reforestation and improvement of land condition may enhance carbon sequestration in vegetation and soils (e.g. LEAP, 2014b).

Freshwater consumption is another resource use of global concern. The World Health Organisation has estimated that early in the twenty-first century, 1.1 billion people do not have access to water supply sources of adequate quality (WHO, 2009), and with a growing human population, stress on water reserves will increase dramatically in the next 30–40 years (Rockström et al., 2007). Globally, agriculture is estimated to account for 85% of freshwater consumption (Shiklomanov, 2000), with the majority being for irrigation of crops. However, livestock have been identified as contributing substantially to water use (Steinfeld et al., 2006). General methodology for determining water use in LCA is provided by ISO 14046 (ISO, 2014). Water use in wool systems will require assessment of water consumption at the sheep farm for livestock drinking, irrigation and other uses, and must include assessment of water losses that occur with water supply. Water is also an important aspect in the post-farm-gate supply chain for wool processing and textiles manufacture. As specified by ISO 14046, assessment of water use must also take into account water used for the dilution of pollutants released to waterways. Best practice water assessment will apply water balance modelling throughout the supply chain to determine total use, including losses.

10.2.4 Handling multifunctional processes and co-products

Sheep can produce a range of co-products (Figure 10.2). At the farm level, this may include wool and live weight (for meat), and in some systems milk can be an important co-product. During initial processing of wool, there can also be clean wool and lanolin produced, with the latter having uses for cosmetics, skin treatment products and lubricants. Application of LCA requires that total resource use and environmental emissions are allocated between the various co-products and results can be highly dependent on the methodology selected. The ISO 14044 (ISO, 2006) guidelines provided a generic allocation procedure hierarchy and LEAP (2014a) and BSI (2014) provided further guidance for sheep production systems and products. For allocation between wool and LW, a biophysical allocation method is recommended based on the protein requirements for various animal processes including fibre production and animal growth. Fibre production is mainly determined by requirements for protein (CSIRO, 2007). Wiedemann et al. (2015) applied this approach to different sheep production systems and obtained similar results when they applied a simpler approach based on protein mass (i.e. the mass of protein in wool relative to that in LW) and suggested that it may also be a suitable alternative to biophysical allocation based on protein requirements. Studies across contrasting sheep production systems resulted in values for biophysical allocation to wool of 19−40%, whereas for economic allocation it was 1−52% (Wiedemann et al., 2015). There has been little research in this area and consequently it is recommended that sensitivity analysis is carried out using several methods. This may include the use of system expansion to understand the implications of choosing alternative products or systems, and where system change or mitigation strategies are discussed.

Where scouring of greasy wool to produce clean wool also gives lanolin co-products, LEAP (2014a) recommends the use of economic allocation since these products have greatly different end uses. In practice, the recovery of lanolin from greasy wool is relatively small and usually amounts to less than 10% by value (being higher for finer wool than coarser wool), and therefore most of the resource use and GHG emissions will be allocated to the wool.

10.2.5 Inventory data challenges

General data requirements have been described (ISO, 2006; LEAP, 2014a). However, for fibre derived from animals there is a unique requirement to fully account for resource use and environmental emissions directly from all animals associated with the production of fibre. This may require accounting for multiple farms, for example, some breeding animals reared on a different farm than the main production farm or surplus animals raised off farm and shorn before being sold for meat processing.

The key requirement is that all inputs and emissions associated with an equilibrium animal population (including all classes and ages of breeding animals) are accounted for. The most complex aspect of this is obtaining an accurate estimate of the feed consumed by the animals since this determines the production of wool (and some co-products) and environmental impacts, most directly GHG emissions. The actual amount of feed provided to animals is not often measured (except where animals are confined and feed is brought to them). Since most sheep feed outdoors on pastures or browse plants, it is necessary to estimate the feed energy and protein intake indirectly using a model. The model must be scientifically based, internationally accepted and preferably a 'tier 2' model, that is, a model that accounts for animal functions including growth, maintenance, reproduction, activity (e.g. grazing and walking) and wool production. Such models require input data on the animal population and productivity. LEAP (2014a) provided a hierarchy of acceptable models in order of preference: (1) country-specific models used in a country's national GHG inventory; (2) other peer-reviewed published models applicable to the region and country; and (3) the NRC (2007) model. The models must be supported by defensible representative data on energy and protein concentrations of the different feeds consumed.

Animals excrete urine and dung directly to land or it may be collected as manure and recycled. These different forms of excreta need to be estimated since they can be significant contributors to GHG emissions and to nutrient losses to waterways that affect eutrophication potential. For feed production, data are required on land used and external inputs, such as fertiliser and resources, for example, irrigation water. Emissions generated in feed production need to be accounted for (e.g. LEAP, 2014b) in wool LCA studies.

Most other inputs will be in common with those for other fibres used for production of textiles and clothing (BSI, 2014). An important input is energy such as fuels and electricity and their related emissions across all life cycle stages (including transportation). The scouring or cleaning process for wool can potentially use significant quantities of water and generate wastewater that must be processed to minimise impacts on eutrophication.

The functional unit (e.g. 1 m^2 of textile or an article of clothing for the lifetime of the product) includes the use, recycling and end-of-life stages of the life cycle. Methods for accounting for reuse and recycling are included in PAS 2395 (BSI, 2014). An important consideration for the use stage is the longevity or product life and its care (e.g. laundry). The relative impact of the production stage for a defined period of life of a product will vary with different lifespans, that is, there will be a higher multiplier for the production stages for shorter-lasting products. Similarly, the resource use and environmental emissions of a product are reduced where there is reuse of a product. Recycling provides a mechanism of introducing material inputs to the supply chain with lower environmental burden than virgin raw materials, for example new wool. The data challenges associated with assessing the impact of recycling and reuse of textile products have been discussed by Wolf et al. (2014). Although virgin wool accounts for about 1.5% of global fibre production, recent surveys in more economically developed countries (MEDCs) indicate that wool accounts for about 5% by weight of post-consumer clothing collected for recycling and reuse (Ward et al., 2013).

10.2.6 Consideration of the reuse and recycling phases

10.2.6.1 Overview

The majority of virgin wool-rich clothing is consumed by industrialised nations and has a relatively high selling price. Wool textiles are comparatively durable products with an intended service life of 2–10 years depending upon the type (Drycleaning Institute of Australia, 2014). Not only is wool a relatively high value material, but large quantities of post-consumer 'waste' containing the fibre, notably clothing, are collected at the end of the first-use phase, for reuse. If not suitable for reuse, collected wool clothing is recycled to manufacture other commercially valuable items. In MEDCs the recycling and reuse infrastructure is well established and is responsible for diverting large volumes of wool waste from landfill disposal or incineration such that the useful life of the fibre is many years longer than might otherwise be expected. As noted in Section 10.1.2, few studies have attempted to quantify the end-of-life treatment of wool garments, and the purpose of this section is to briefly review the flows and commercial uses of post-consumer products containing wool, particularly clothing, at the end of the first-use phase. This understanding is necessary to more accurately account for the post-first-use phase in future LCA studies.

10.2.6.2 Data

The amount of wool that is recycled and reused depends upon how much can be collected and diverted from the municipal waste stream. In practice, consumers making donations to clothing banks, take-back schemes, kerbside collections and community reuse initiatives divert used clothing from normal household waste, reducing the possibility of it being landfilled or incinerated. In Europe about 35% of textile waste is collected and diverted from landfills, which is higher than in the United States and in China. Typical pathways for used clothing composed of wool at the end of life are illustrated in Figure 10.4, which is based on a detailed study conducted in the United Kingdom (WRAP, 2012b).

For the pathways shown in Figure 10.4, GHG emissions will vary according to each particular end-of-life destination. For example, substantial GHG emissions will be associated with long-distance transportation of waste clothing to lower cost countries for sorting and recycling operations, as well as incineration and fibre decomposition in landfills. This transport also contributes to fossil fuel demand in wool LCA studies. Balanced accounting will ensure that offsets in such impacts include estimate of displacement of manufacture of the same products using entirely virgin materials. The reuse of wool-containing clothing might be expected to displace at least some purchases of new clothing, and use of recycled wool fibre as an input displaces a proportion of the virgin fibre used in certain products, albeit most likely as a blend component. This displacement is included in the accounting guidelines in PAS 2395 (BSI, 2014, p. 6). The substitution ratio between new and used garments can only be assumed because it is extremely difficult to measure.

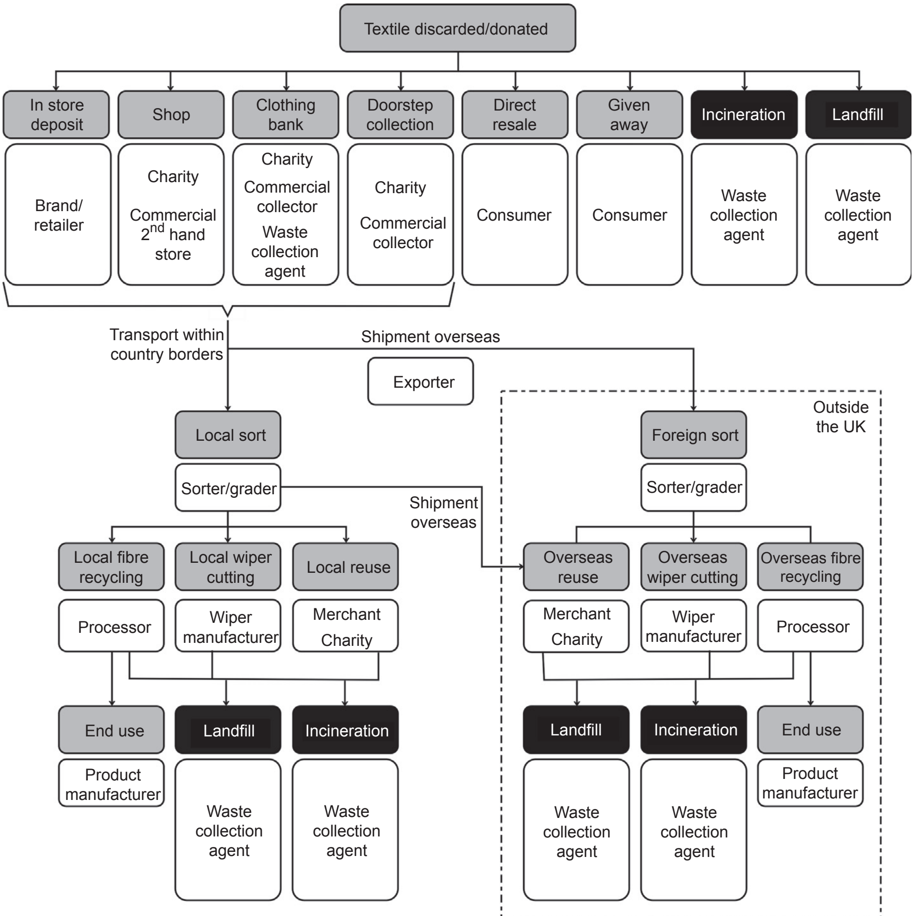

Figure 10.4 Schematic of pathways for post-consumer textiles.
This material is adapted from the Website www.wrap.org.uk of 'The Waste and Resources Action Programme', WRAP (2012b).

10.2.6.3 Reuse and recycling processes for wool textiles

Once collected, post-consumer wool products are sorted to identify what can be reused, recycled or remanufactured. Usually only a small amount is discarded for disposal after sorting. The different routes available from collection of waste textile products to recycling and reuse, together with the second-use products, are summarised in Figure 10.5 (WRAP, 2014). Note that this refers to materials other than just wool and pelletisation, polymerisation and extrusion relate specifically to recycling of man-made fibres. Although semi-automated systems have been developed, sorting is normally a manual process and takes place either in the same country as the items are collected or more commonly in lower labour cost countries. This means, for example, that items collected in Western Europe may be exported to Eastern Europe or other

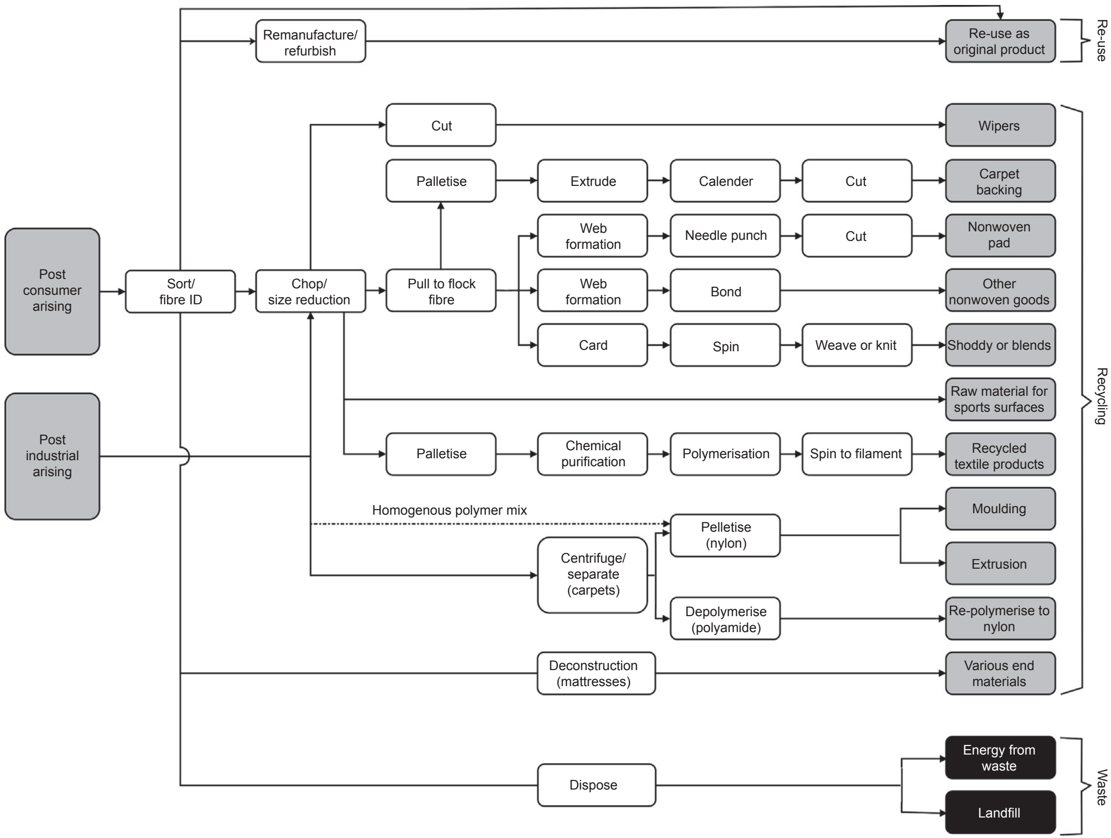

Figure 10.5 Stages involved from the collection of waste textiles to recycling and reuse.
This material is adapted from the website www.wrap.org.uk of 'The Waste and Resources Action Programme', WRAP (2014).

geographical locations for sorting, increasing the environmental impacts associated with long-distance transport. It can also have a negative economic impact on recycling companies in developed countries that may need to import sorted items that in some cases may have originally been collected in the same country.

Reuse grades containing clothing that is still wearable normally have higher resale value than the recycling grades. Wool-rich knitwear is amongst the most commercially valuable grades. Some of the clothing that is not wearable is mechanically cut up into large pieces and sold to other sectors of industry for use as wiper cloths for cleaning. The majority of the rest is mechanically recycled. Removal of wool garments for higher value reuse decreases the amount available to recyclers, and this becomes problematic when there is dependency on the supply of recycled wool to meet product performance requirements in the second-use phase product. Mechanical recycling of wool has been in commercial operation for over 200 years. Markets for recycled post-consumer clothing containing wool are therefore well established and mostly rely on open-loop recycling. Recycling involves taking wool products that are at end of life and transforming them into either the same product (closed-loop recycling) or a secondary product (open-loop recycling). Closed-loop recycling of wool is possible, but because of a reduction in the fibre length during mechanical recycling, the resulting product may require blending with at least 5−30% virgin fibre.

Post-consumer wool-rich knitwear is particularly suited to the shoddy process in which used wool clothing is mechanically pulled back into fibre using machines operating with a series of closely set rotating rollers covered in metal teeth or hooks before being converted back into yarn. The low-density yarns and loose-knitted fabric structure help to minimise the degree of fibre breakage that takes place during pulling, enabling the recovered fibre to be blended with virgin wool and spun into new yarns. Although notionally of lower grade than wool yarns made entirely from virgin fibres, shoddy yarns containing wool recyclate can still be used to make high value clothing such as wool-rich jackets and coats as well as blankets, shawls and scarves. Such consumer products frequently have a life expectancy of three to five years or more depending on frequency of use (Russell et al., 2015). One of the challenges in retrieving wool from used garment recyclate is that it may be co-mixed with other fibres that originally comprised the linings or sewing threads. In addition to manual dismantling of the garment components, carbonisation has also been used to chemically remove some cellulosic polymer components such as cotton. One of the major traditional centres for wool recycling and the production of yarns and fabrics based upon the shoddy process is the Prato district of Italy. In recent years, production of garments using the shoddy process has been to some extent rediscovered by brand owners as a possible way of reducing the overall carbon footprint and environmental impact of products containing wool (e.g. M&S, 2014; Patagonia, 2014).

Mechanical pulling of clothing containing wool can also produce fibre recyclate of short length suitable for filling cushions and soft furnishings as well as for making nonwoven insulator pads that are placed directly over the spring units in mattresses. Traditionally, when this recycled fibre material, which is known as flock or flocking, contains 40−80% wool it may be used to confer flame retardancy on mattress insulator pads. Mattresses are durable products with an expected life expectancy of five to seven years. Nonwoven fabric production is less sensitive to fibre length, and therefore wool recyclate that may be too short to convert into twisted yarns for conversion into knitted or woven structures can still be made into useful fabrics. Post-consumer wool usually forms a blend component with other fibres, a large proportion of which may also be recycled. Commercial nonwoven products containing post-consumer wool also include thermal insulation, building and construction boards, horticultural basket liners and carpet underlay. The potential use of nonwovens comprising recycled wool as sorbents for dealing with pollutants and spillages of oils or diesel fuel have also been experimentally evaluated (Radetić et al., 2003, 2008).

A relatively small proportion of post-consumer wool garments is used to make high value products for resale using the woven or knitted fabrics as component parts rather than pulling them back into fibre first. Examples include new fashion garments, accessories, bags and soft toys. These products are frequently sold at high prices because of the substantial labour and design input as well as the fact that they can be marketed as unique items.

Non-textile secondary products from wool recycling include use of wool fibre waste to enrich soil. In a closed-loop wool carpet recycling study, McNeil et al. (2007) reported that when ground-up wool carpets were used as fertiliser, elevated levels of essential elements such as nitrogen (19%), sulphur (19%) and magnesium (7%) were observed in the grass grown on it compared to the control sample. Wool-rich waste carpet is also used as mulch matting and for insulating compost heaps.

In summary, the reuse and recycling of wool products have the potential to substantially reduce environmental impacts by significantly extending material lifetime and by replacing production of new garments as well as other industrial products (Chapman, 2010). However, significant challenges have existed in modelling these impacts because of limitations in LCA methodology as well as the data gaps that exist in many countries associated with textile product waste management. Guidance for more consistent consideration of reuse and recycling in LCA GHG emissions of textiles is now available in PAS 2395 (BSI, 2014). For open-loop recycling, the GHG benefits of recycling result from the avoided emissions associated with the virgin manufacture of the secondary products that the material is recycled into (EPA, 2014). Open-loop recycling does not account for avoided emissions from manufacturing the primary material since recycling this material does not displace manufacturing of the primary material. It only displaces manufacturing of the secondary product (EPA, 2014). The potential environmental benefits associated with the shoddy process of using post-consumer recycled wool as a raw material to make new garments are particularly noteworthy. This results from sorting wool garments based on colour prior to mechanical recycling and then blending the resulting fibre recyclate appropriately prior to spinning, thus avoiding the need for a dyeing process, eliminating water usage, dyestuffs and auxiliary chemicals and wastewater effluent. LCA of building insulation products containing recycled wool has also been reported (Schmidt et al., 2004).

National campaigns aimed at improving resource efficiency, retailer-backed and incentivised take-back schemes, as well as growing consumer awareness particularly amongst the Lifestyles of Health and Sustainability (LOHAS) demographic, that encourage consumers to donate more clothing, have led to collection rates of over 40% in certain European countries. However, collection rates between individual countries vary considerably, and there is significant scope to substantially increase rates of collection in those MEDCs where most new wool garments are consumed and reduce the amount entering the municipal waste stream for landfill and incineration. Other current and emerging data challenges include storage by consumers of wool clothing without wear, which may result in overestimation of cleaning, expanded lifetimes of some high value used garments sale via the Internet and passing of wool apparel between family and friends for reuse, sometimes as valuable ‘heirlooms’.

10.3 LCA case study for wool apparel

An LCA of two merino apparel products, a pair of socks and a garment, which are sold in Europe (EU) and the United States (US), is presented to illustrate the importance of key methodological issues in wool LCA and, in particular, choices for co-product allocation. This study was commissioned by the New Zealand Merino Company, Wool Research Organisation of New Zealand and an industry partner in 2014 and was conducted following ISO 14040:2006, ISO 14044:2006 and PAS 2395:2014 guidelines. The description of the case study follows the steps of defining the goal and scope of the study, important methodological choices, the life cycle inventory (LCI), life cycle impact assessment (LCIA) and, finally, interpretation of results and conclusions.

10.3.1 Goal, scope and systems boundary of the case study

The goals of the study were to:

1. Evaluate hotspots across the full life cycle of two merino outdoor apparel products (Table 10.3):
   a. A pair of socks (‘Socks’), 72% merino wool, 21% nylon, 2% spandex; and
   b. A men’s long-sleeved garment (‘Garment’), 100% merino wool.
2. Assess the sensitivity of results to allocation methods at the farm gate where several allocation methods were applicable.

The scope of the study included all relevant processes from cradle to grave. The intended audience for the initial study was the NZ Merino Company and its industry

Table 10.3 Declared unit for the LCA

Declared unit	Mass excluding packaging	Mass including packaging
1 pair of socks (medium size)	0.0817 kg	0.122 kg
1 garment (men’s long-sleeved base layer crew neck shirt, 250 g)	0.250 kg	0.255 kg

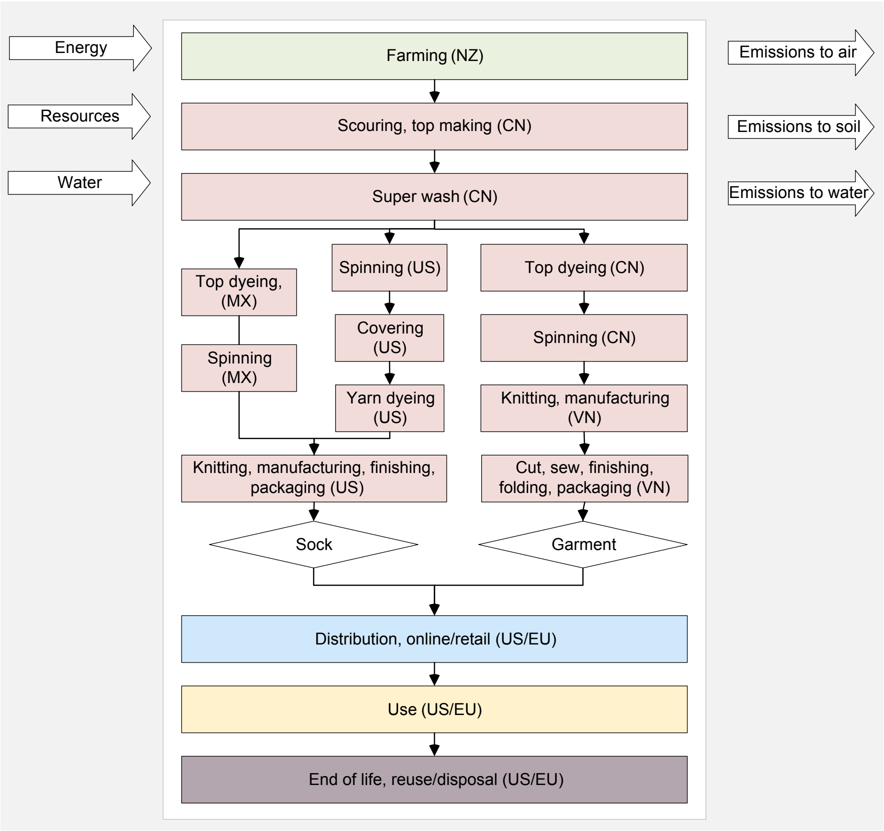

Figure 10.6 Production system and system boundaries for socks and garment (NZ = New Zealand; MX = Mexico; CN = China; VN = Vietnam; EU = Europe; US = United States).

partners. As such, no external critical review outside of the review process for this book chapter was undertaken. It was assumed that each product was washed once per week and used for one year before being discarded.

The study considered all relevant unit processes, inputs and outputs from cradle to grave, as illustrated in Figure 10.6. Inputs and outputs related to the retail location were excluded due to a lack of available data. Two scenarios were used (North American and European) to account for regional differences once the products leave the manufacturing site.

10.3.2 Data requirements and limitations

Primary data were collected for all foreground processes (e.g. farm, processing, transport, warehousing and distribution). The use phase was modelled based on literature data and background processes such as input materials, electricity, fuels, fuel combustion and end-of-life process were taken from GaBi LCA databases (PE, 2013).

The distribution information for the EU distribution centre was adapted from the primary data collected in the US. This could, in future, be improved by using primary data from a European distribution centre.

Data requirements: Production and packaging of the Garment and Socks were based on primary data. Distribution, use and end of life were modelled based on secondary data and scenarios for the US and EU.

Selected environmental indicators: This study assessed global warming potential (GWP) and two additional indicators: primary energy demand (PED) and freshwater consumption (Table 10.4). Other indicators were not included due to limitations on availability of inventory data.

Co-product allocation: As one of the goals of this case study was to understand the impacts of different product types, it was necessary to apportion environmental burdens to the relevant co-products. The stages in the wool life cycle where allocation was most relevant were:

- Farm, which produced both meat and fibre as economically significant products from sheep
- Processing, producing wool top (used in the further production stages), lanolin, noils and sweepings
- Warehousing and logistics, which were typically shared with many different product types.

For the sheep production phase, four co-product allocation methods were applied in order to test the sensitivity of the final results to the choice of method:

1. Protein required for wool and meat based on the methods of CSIRO (2007) and following the protocols of LEAP (2014a) and Wiedemann et al. (2015) for biophysical allocation from sheep (the base case) as described in Section 10.2.3
2. Mass of protein
3. Mass
4. Economic.

Modelling of biogenic carbon: Biogenic carbon stored in wool fibres was directly accounted for in the inventory as a removal of CO_2 from the atmosphere. However, the carbon sequestered in wool eventually returns to the air, and all CO_2 sequestered during growth was modelled as a release at end of life.

Table 10.4 Environmental indicators included within this study

Impact category	Impact assessment model	Unit	References
Climate change	Global warming potential (GWP) over a 100-year time horizon	kg CO_2 equivalent	IPCC (2007)
Consumption of primary energy	MJ (net calorific value) from nonrenewable energy sources	MJ	PE (2013)
Water consumption	Consumptive use of freshwater	kg	PE (2013)

10.3.3 Life cycle inventory

The steps in Figure 10.6 are described in further detail below.

10.3.3.1 Production

Farm production (Socks/Garment): Primary data from 27 merino farms based in New Zealand were collated, including 13 extensive farms (average stocking rate of 1.3 stock units (SU, equivalent to one 55 kg ewe rearing one lamb) per hectare), 7 medium intensive farms (average stocking rate of 3.3 SU/ha) and 7 intensive farms (average stocking rate of 9.3 SU/ha). The OVERSEER model, a tool to estimate nutrient flows and GHG emissions of farm systems (Wheeler et al., 2007), was used to calculate on-farm emissions. The three farm intensities were weighted according to their national production quantity to be representative of average New Zealand merino wool.

Scouring and top making (Socks/Garment): The input for this process was raw wool after shearing and the functional output 'wool top' was a semi-processed product of fibres in a form ready for spinning. There were five co-products considered: wool top, burrs, noils, sweepings and lanolin. Economic allocation in line with LEAP (2014a) was applied to divide the burdens between these co-products, which allocated 96.8% of burdens to wool tops.

The remaining textile manufacturing processes had only one economically valuable output and, therefore, required no allocation. These processes included:

- Super wash (Socks/Garment), a process that removed the cuticle scales from the combed fibre before applying a resin to prevent felting, imparting shrink resistance to the product to enable machine washability
- Top dyeing and spinning (Socks), in which the wool top was dyed and spun into yarn
- Spinning (Socks/Garment), in which the wool top was spun into yarn
- Covering (Socks), in which the wool was wrapped in nylon yarn
- Yarn dyeing (Socks/Garment)
- Knitting/manufacturing (Socks/Garment) in which the dyed yarn was knitted into fabric
- Cut and sew, finishing (Garment)
- Packaging (Socks/Garment) after which the finished product was packed ready for distribution
- Waste disposal and wastewater treatment was included in the production steps.

10.3.3.2 Distribution

Transport distances to warehouses and distribution centres were based on primary data collected at the production sites. Inputs and outputs were only available for the whole site and were allocated based on the total mass of apparel stored in the warehouse.

The following two distribution scenarios to the end user were included in the study:

1. Online distribution whereby the product was delivered directly to the customer; and
2. Retail distribution involving transport of the product to a retail store for pick-up by the customer. Inputs and outputs of the retail store were not available and were excluded from the study. For the shopping trip, it was assumed that the consumer bought only one item and drove 5 km each way in a medium-sized petrol car (10 km return trip).

Two location scenarios were included in the study:

1. US scenario: Based on the actual location of the warehouse/distribution centre
2. EU scenario: No data for the EU warehouse were available, and US foreground data were assumed with European background datasets.

10.3.3.3 Use

The use phase in US or EU considered a lifetime of 1 year and 52 washing cycles per year/lifetime. It was assumed that the washing and drying machines ran fully loaded. Energy, water and detergent use were allocated based on mass. As an example, given that a conventional US washing machine uses 0.21 kWh per load and one load equals 3.7 kg (equivalent to 14 garments or 45 pair of socks), 0.015 kWh would be allocated to one garment and 0.00467 kWh to one pair of socks per washing cycle.

Since the energy and water use for washing can dominate the life cycle impacts of apparel, three use-phase scenarios were applied: best case, average and worst case (Table 10.5). The average use case was created by rolling together consumer behaviour into a statistical average of reported behaviour (Cotton Inc. 2014). It is important to note that these scenarios do not directly consider different washing patterns for different fabric types (cotton vs wool). However, the best case scenario represented cold wash only and the recommended washing temperature for the analysed products was 40 °C. Energy and water use for the scenarios is summarised in Table 10.6.

Following Goodall (2012) it was assumed that a 40 °C cycle used 30% less energy than a 60 °C cycle, and from Josephy (2010) it was assumed that a 20 °C (cold wash cycle) reduced the energy use by 70% compared to a 60 °C cycle. US energy and water

Table 10.5 Description of use scenarios

	Best case		Average		Worst case	
	US	EU	US	EU	US	EU
Wash temperature	Cold wash	20 °C	54% Cold, 46% Heated	40 °C	Heated wash	40 °C
Washer efficiency	Energy star	A	70% Conv, 30% Energy star	B	Conventional	G
Water heater type	Nat. gas	Electric	50% Nat. gas	Electric	Electric	Electric
Drying method	Air dry	Air dry	16% Air dry, 84% Dryer	16% Air dry, 84% Dryer	Dryer	Dryer
Dryer efficiency	N/A	N/A	70% Conv, 30% Energy Star	B	Conventional	G
Air heater type	N/A	N/A	50% Nat. gas	N/A	N/A	N/A

Table 10.6 Use scenarios: energy and water use of washer/dryer per kg of product

	Best case		Average		Worst case	
	US	EU	US	EU	US	EU
Washing						
Water (l/kg)	14.71	8.33	26.66	8.33	31.79	10.00
Electricity (kWh/kg)	0.04	0.06	0.05	0.16	0.06	0.27
Nat. gas hot water (MJ/kg)	0.57	–	0.48	–	–	–
Electricity pre-heated water (kWh/kg)	–	–	0.07	–	0.17	–
Drying						
Electricity use (kWh/kg)	Air dry	Air dry	0.13	0.59	0.28	0.91
Natural gas use (MJ/kg)	–	–	0.53	–	–	–

demand for washer and dryer cycles was taken from the Department of Energy (DOE), the 'Energy Star Savings Calculator' (USEPA and DOE, 2010) and supplemented with data from the 2010 DOE Energy Conservation Program for Consumer Products (USA, 2010) and AATCC standards (AATCC, 2011).

10.3.3.4 End of life

For the end-of-life phase of the product, two scenarios were analysed within the scope of this study. The best case assumed direct release of the carbon sequestered in the product. Regardless of whether the product had one or more users, if the use phase was 10 years or less, all GHG emissions were treated as if they occurred at the beginning of the assessment period (i.e. in the first year). This approach was consistent with that recommended in ISO 14067 (ISO, 2013). A worst case scenario assumed that the products were landfilled. In this case, anaerobic decomposition of wool occurred, producing methane as well as CO_2. Methane has 25 times the GWP of CO_2 (IPCC, 2007) and landfill disposal produced a higher climate change impact as modelled based on a textile landfill dataset (PE, 2013).

10.3.3.5 Background data

Upstream processes were modelled using secondary data from the GaBi Databases 2013 (PE, 2013).

10.3.4 Case study results

For Socks, 42–55% of the total GWP was due to the farm stage and one-third due to the processing stage (Table 10.7). The use stage (average EU and average US scenario)

Table 10.7 Global warming potential, socks (CO_2e as a percentage of total life cycle emissions)

	EU scenario for socks				US scenario for socks			
Distribution	**Online**		**Retail**		**Online**		**Retail**	
End of life	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**
Farm	52%	53%	42%	42%	54%	55%	43%	43%
Processing	25%	25%	20%	20%	25%	26%	20%	20%
Warehouse and distribution	0%	0%	0%	0%	0%	0%	0%	0%
Pick-up at retailer	0%	0%	20%	20%	0%	0%	21%	21%
Use	19%	20%	15%	16%	17%	18%	14%	14%
End of life	3%	2%	3%	1%	4%	2%	3%	1%
Total[a]	100%	100%	100%	100%	100%	100%	100%	100%

[a]The total may not be exactly 100% due to rounding errors.

contributed 14–20%. The US had slightly lower impacts due to a lower electricity consumption as most (54%) laundry was assumed to be washed cold while in the average EU scenario the washing temperature was 40 °C.

For the Garment, more than 54% of the GWP originated from the farm stage and approximately 30% from the processing stage (see Table 10.8). It should be noted that LCA impact indicators such as GWP are relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

The primary energy demand was dominated for both the Socks (Table 10.9) and the Garment (Table 10.10) by the use and the processing phases. For the distribution scenario through a retail store, about one-quarter was associated with the pick-up at the store.

Water consumption quantified fresh water (from lakes, rivers or groundwater), that is, water that leaves a watershed and is lost to ecosystems and for downstream users. Most of the water was consumed during the use phase (Socks: 58–74%; Garment: 44–60%) (Tables 10.11 and 10.12). Due to the different washing machines used in the US and EU (top loader vs front loader), water consumption in the average US use scenario was substantially higher than in the average EU scenario. The estimates for the use phase have a high uncertainty relating to both data and methodology limitations relating to frequency and type of cleaning and to the water consumed during washing. The estimates of water consumption assume that all water input to washing machines is consumed, that is,100% is lost from the watershed. This depends on the water supply and wastewater system in which the washing occurs. Some cities and regional centres have water collection and infrastructure systems that facilitate return of household wastewater to watersheds, but any returns during the use phase could not be quantified due to lack of data on the proportion returned for locations of use of the two apparel products in this case study. The assumption that 100% of the water use in washing was consumed gives a high estimate, and future calculations of consumptive water use may be lower with availability of more accurate data on frequency of cleaning, lifetime of product use, and supply, management and treatment of household cleaning water.

10.3.4.1 Sensitivity of results to allocation method

As described in Section 10.3.1, four methods for co-product allocation at the cradle-to-farm gate were applied: a baseline case of biophysical allocation (protein required) and three alternative scenarios. Results for both products were found to be highly dependent on the applied allocation method. Figure 10.7 shows the GWP of the finished Socks (a) and Garment (b) for the finished product ready to be transported to a distribution centre. The cradle-to-farm gate phase contributed up to half of the total life cycle emissions, and the method of co-product allocation to the farm gate was a critical factor in the estimated environmental footprint of merino products. For example, using economic allocation for the sheep production phase resulted in estimated GHG emissions for the Socks and Garment that were, respectively, 18% and 21% higher than using the biophysical causality method based on protein required for wool and live weight (see Section 10.2.4).

Table 10.8 **Global warming potential, garment (CO_2e as a percentage of total life cycle emissions)**

	EU scenario for garment				US scenario for garment			
Distribution	**Online**		**Retail**		**Online**		**Retail**	
End of life	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**
Farm	57%	57%	54%	54%	57%	58%	55%	55%
Processing	29%	30%	28%	28%	30%	30%	28%	29%
Warehouse and distribution	0%	0%	0%	0%	0%	0%	0%	0%
Pick-up at retailer	0%	0%	5%	5%	0%	0%	5%	5%
Use	11%	12%	11%	11%	10%	10%	10%	10%
End of life	2%	1%	2%	1%	2%	1%	2%	1%
Total[a]	100%	100%	100%	100%	100%	100%	100%	100%

[a]The total may not be exactly 100% due to rounding errors.

Table 10.9 **Primary energy demand, socks (MJ as a percentage of total life cycle energy demand)**

	EU scenario for socks				US scenario for socks			
Distribution	**Online**		**Retail**		**Online**		**Retail**	
End of life	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**
Farm	5%	5%	3%	3%	6%	6%	4%	4%
Processing	44%	45%	31%	31%	54%	54%	35%	35%
Warehouse and distribution	1%	1%	1%	1%	1%	1%	1%	1%
Pick-up at retailer	0%	0%	31%	31%	0%	0%	36%	36%
Use	50%	50%	35%	35%	40%	40%	25%	25%
End of life	0%	0%	0%	0%	0%	0%	0%	0%
Total[a]	100%	100%	100%	100%	100%	100%	100%	100%

[a]The total may not be exactly 100% due to rounding errors.

Table 10.10 **Primary energy demand, garment (MJ as a percentage of total life cycle energy demand)**

	EU scenario for garment				US scenario for garment			
Distribution	**Online**		**Retail**		**Online**		**Retail**	
End of life	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**
Farm	7%	7%	6%	6%	8%	8%	7%	7%
Processing	54%	54%	48%	48%	62%	62%	55%	55%
Warehouse and distribution	1%	1%	1%	1%	1%	1%	1%	1%
Pick-up at retailer	0%	0%	10%	10%	0%	0%	12%	12%
Use	39%	39%	35%	35%	29%	29%	26%	26%
End of life	0%	0%	0%	0%	0%	0%	0%	0%
Total[a]	100%	100%	100%	100%	100%	100%	100%	100%

[a]The total may not be exactly 100% due to rounding errors.

Table 10.11 **Water consumption, socks (L as a percentage of total life cycle consumption)**

	EU scenario for socks				US scenario for socks			
Distribution	**Online**		**Retail**		**Online**		**Retail**	
End of life	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**
Farm	28%	28%	27%	27%	18%	18%	16%	16%
Processing	12%	12%	11%	11%	8%	8%	7%	7%
Warehouse and distribution	0%	0%	0%	0%	0%	0%	0%	0%
Pick-up at retailer	0%	0%	3%	3%	0%	0%	13%	13%
Use	60%	60%	59%	58%	74%	74%	64%	64%
End of life	0%	0%	0%	0%	0%	0%	0%	0%
Total[a]	100%	100%	100%	100%	100%	100%	100%	100%

[a]The total may not be exactly 100% due to rounding errors.

Table 10.12 **Water consumption, garment (L as a percentage of total life cycle consumption)**

	EU scenario for garment				US scenario for garment			
Distribution	**Online**		**Retail**		**Online**		**Retail**	
End of life	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**	**Landfill**	**Reuse**
Farm	38%	38%	37%	37%	27%	27%	26%	26%
Processing	18%	18%	18%	18%	13%	13%	12%	12%
Warehouse and distribution	0%	0%	0%	0%	0%	0%	0%	0%
Pick-up at retailer	0%	0%	1%	1%	0%	0%	4%	4%
Use	44%	44%	44%	44%	60%	60%	58%	58%
End of life	0%	0%	0%	0%	0%	0%	0%	0%
Total[a]	100%	100%	100%	100%	100%	100%	100%	100%

[a]The total may not be exactly 100% due to rounding errors.

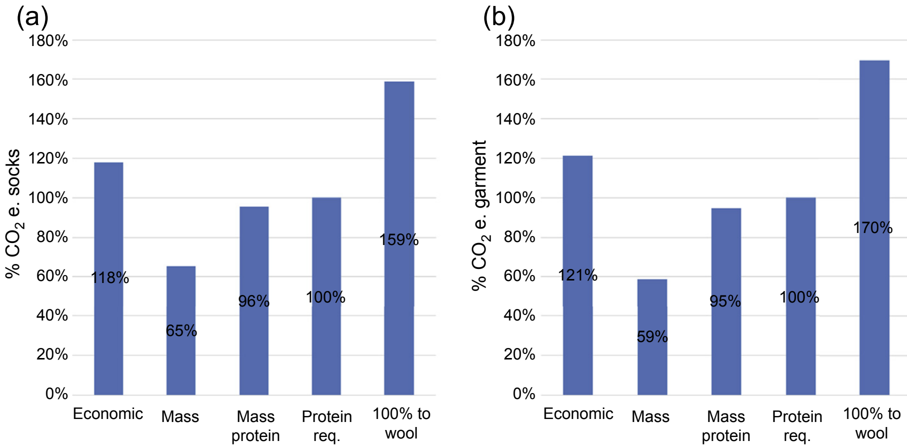

Figure 10.7 Impact of allocation method for the cradle-to-farm gate phase on GWP relative to biophysical allocation (protein required), shown as 100%. Results are for the products ((a) Socks and (b) Garment) at the point of a distribution centre.

10.3.5 Interpretation and conclusions

The following conclusions were drawn from the case study for each major life cycle phase.

10.3.5.1 Merino sheep farming

- Methane emissions from enteric fermentation and nitrous oxide emissions from soils were the main drivers of GWP.
- Primary energy demand was predominantly associated with fertiliser supply and water use.
- Water consumption was driven by on-farm water sources used as livestock drinking water.
- The choice of co-product allocation method significantly affected the results.

10.3.5.2 Apparel processing

- GWP and PED were predominantly associated with energy use.
- Water consumption was predominantly associated with water used for cooling systems and dyeing processes.

10.3.5.3 Warehousing and distribution

- The impacts were minimal for some aspects of this phase. However, online and retail scenarios showed a significant difference in impacts with retail having a higher impact than online distribution.

10.3.5.4 Use phase

- Washing and drying caused approximately half of the water consumption with the conservative assumptions applied here and one-third of the primary energy consumption during the life cycle of the product. Considering the uncertainty regarding consumptive water use in this phase, further research of water system supply and wastewater treatment is required to refine this estimate.

10.3.5.5 End of life

- The end-of-life scenario contributed 1–4% of the GWP of the Socks and Garment. Breakdown in anaerobic landfill resulted in higher emissions due to some carbon being released as methane.

10.3.5.6 Limitations of the study

- The cradle-to-grave results are very sensitive to assumptions in the use phase since the number of lifetime washes, the impacts of those washes and the background water systems can vary widely in practice. More consumer behaviour data, information from appliance manufacturers and information regarding background water systems could improve the accuracy of the use phase model, but the range of consumer behaviour (and therefore large variations in use phase burdens) would likely remain.

10.4 Summary and future developments in wool LCA studies

Apparel and textiles made from the natural fibre, wool, have characteristics throughout their life cycle from farming of sheep to the end-of-life stage that are both highly diverse and complex. Quantification of the environmental performance of wool textiles using a LCA approach can only be interpreted in the context of this complexity and the resultant methodological challenges. Substantial challenges relate to choice of the method of allocation of impacts and resource use between co-products of sheep production, notably meat and fibre, but also other economically and socially significant products or services. Sensitivity analysis in the case study presented in Section 10.3 demonstrates the sensitivity of results to the choice of allocation method and the importance of recent research that has provided greater consensus on methods for handling co-products of wool supply chains. The relatively large contribution from the cradle-to-farm gate stage indicates potential for increased sheep production efficiency and the importance of research on options for improving resource use efficiency and reduced environmental emissions. LCA studies can help to define the magnitude of benefits from these farm system options and encourage their adoption.

The case study for two merino wool apparel items showed for the first time the relative contributions of each phase in the full life cycle across multiple impact or resource use categories. In this assessment, socks and a long-sleeved T-shirt garment were produced from NZ merino wool, with processing and manufacture involving facilities in China, Mexico, Vietnam and the US for retail in the US or Europe. For the GWP impact using biophysical allocation, production on farm represented one-third to half of the life cycle GHG emissions, while processing was 30–35% of the total.

The majority of published wool LCA studies have assessed only GHG emissions, but the case study presented here showed that the relative contribution of life cycle stages can vary between resource or impact categories. For primary energy demand, the processing and use phases contributed most, and for consumptive water use, the use phase had the highest contribution. Understanding these differences in 'hotspots' and potential for trade-offs between environmental categories is important in targeting mitigation actions but also in conclusions on overall environmental performance as stress and priorities vary regionally. The case study results for the post-use or end-of-life phase showed a small contribution to the primary apparel products (1–4%) that use 100% virgin wool. However, the analysis of reuse and recycling showed the importance of these processes through effects on inputs to secondary products. The use of recyclate as an input has generally not been quantified but is being recognised as a knowledge gap in assessment of environmental impacts of wool textiles (BSI, 2014).

For a balanced perspective of the environmental impacts of any textile product, including those composed of wool, cradle-to-cradle thinking is required. Hence, studies should take account of the durability of different textile products, the frequency of use versus storage time, as well as the specific route that might be adopted for reuse and recycling (e.g. Laitala and Boks, 2012). These processes cannot be easily generalized and more accurate quantification of the environmental impacts and resource use of wool textiles and clothing using LCA requires new data across full, representative value chains.

References

AATCC (American Association of Textile Chemists and Colorists, 2011. Technical Manual, TM150-2010, p. 255. Standardization of Home Laundry Test Conditions, p. 402. Reference Liquid Laundry Detergent, "2003 detergent", p. 396.

Barber, A., Pellow, G., 2006. Life Cycle Assessment: New Zealand Merino Industry, Merino Wool Total Energy Use and Carbon Dioxide Emissions. Report by The Agribusiness Group, New Zealand.

Basset-Mens, C., Rankin, D.A., Boyes, M., Ledgard, S., 2007. Life Cycle Assessment of New Zealand Wool Carpet – Preliminary Study. Report by AgResearch, Hamilton, New Zealand.

Bevilacqua, M., Ciarapica, F.E., Giacchetta, G., Marchetti, B., 2011. A carbon footprint analysis in the textile supply chain. International Journal of Sustainable Engineering 4, 24–36.

Bowyer, J.L., 2009. Life Cycle Assessment of Flooring Materials: A Guide to Intelligent Selection. Dovetail Partners. Incorporated. http://www.dovetailinc.org.

Brent, A.C., Hietkamp, S., 2003. Comparative evaluation of life cycle impact assessment methods with a South African case study. International Journal of Life Cycle Assessment 8, 27–38.

Bretagnolle, V., Gauffre, B., Meiss, H., Badenhausser, I., 2011. The role of grassland areas within arable cropping systems for the conservation of biodiversity at the regional level. In: Lemaire, G., Hodgson, J., Chabbi, A. (Eds.), Grassland Productivity and Ecosystem Services. CABI International, Wallingford, UK, pp. 251–260.

Brock, P.M., Graham, P., Madden, P., Alcock, D.J., 2013. Greenhouse gas emissions profile for 1 kg of wool produced in the Yass Region, New South Wales: a life cycle assessment approach. Animal Production Science 53, 495–508.

BSI, 2011. PAS 2050:2011—Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. BSI, London, UK.

BSI, 2014. PAS 2395:2014—Specification for the Assessment of the Life Cycle Greenhouse Gas (GHG) Emissions from the Whole Life Cycle of Textile Products. BSI Standards Limited, London, UK, 42 pp.

Chapman, A., July 2010. Review of Life Cycle Assessments of Clothing. Oakdene Hollins, 32 pp.

Cotton Inc, 2014. Life Cycle Assessment of Cotton Fiber & Fabric. Full Report. Prepared for VISION 21. Carz, NC, United States of America.

CSIRO, 2007. In: Freer, M., Dove, H., Nolan, J.V. (Eds.), Nutrient Requirements of Domesticated Ruminants. CSIRO Publishing, Clayton South, Australia.

CSIRO, 2008. Flame Resistance of Wool. http://www.csiro.au/Outcomes/Food-and-Agriculture/WoolFlameResistance.aspx.

Drycleaning Institute of Australia Ltd 2014. http://www.drycleanersweb.com.au/sites/default/files/user-content/resources/file/fair_claims_guide_0.pdf.

Eady, S., Carre, A., Grant, T., 2012. Life cycle assessment modelling of complex agricultural systems with multiple food and fibre co-products. Journal of Cleaner Production 28, 143—149.

Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. International Journal of Life Cycle Assessment 9, 161—171.

EPA, 2014. Recycling. http://www.epa.gov/climatechange/wycd/waste/downloads/recycling-chapter10-28-10.pdf (accessed 21.10.14.).

FAOSTAT, 2014. Food and Agriculture Organisation of the United Nations: Statistics. FAO. http://faostat.fao.org/site/613/default.aspx; http://faostat.fao.org/site/613/default.aspx#ancor (accessed 06.10.2014).

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. Journal of Environmental Management 91, 1—21.

Goodall, C., 2012. How to Live a Low-carbon Life: The Individual's Guide to Stopping Climate Change. Routledge.

Henry, B.K., 2011. Understanding the Environmental Impacts of Wool: A Review of Life Cycle Assessment Studies. http://www.iwto.org/uploaded/publications/Understanding_Wool_LCA2_20120513.pdf.

ILCD, 2011. ILCD Handbook. Recommendations for Life Cycle Impact Assessment in the European Context. European Commission — Joint Research Centre. EUR 24571 EN. Publications Office of the European Union, Luxemburg, 159 pp.

IPCC, 2007. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Climate Change 2007: Synthesis Report: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 104 pp.

ISO, 2006. ISO 14044. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. International Organisation for Standardisation, Geneva, Switzerland.

ISO, 2013. ISO/TS 14067. Carbon Footprint of Products — Requirements and Guidelines for Quantification and Communication. ISO/TC 207/SC 7. International Organization for Standardization, 52 pp.

ISO, 2014. Environmental Management — Water Footprint — Principles, Requirements and Guidelines. International Organisation for Standardisation, Geneva, Switzerland.

IWTO, 2013. IWTO Wool Market Information 2013 Edition: Statistics for the Global Wool Production and Textile Industry.

IWTO, 2014. Wool Fact Sheets. http://www.iwto.org/wool/factsheet/ (Accessed October 2014).
Josephy, 2010. Cold Wash Do Prejudices Impede High Energy Savings? Topten International Services TIS. Mibelle Group, Federation of Migros Cooperatives.
Laitala, K., Boks, C., 2012. Sustainable clothing design: use matters. Journal of Design Research 10, 121–139.
LEAP, 2014a. Greenhouse Gas Emissions and Fossil Energy Demand from Small Ruminant Supply Chains: Guidelines for Quantification. LEAP, FAO, Rome, Italy. http://www.fao.org/fileadmin/user_upload/benchmarking/docs/LEAP_Small_Ruminants_DRAFT.pdf.
LEAP, 2014b. Environmental Performance of Animal Feeds Supply Chains. LEAP, FAO, Rome, Italy. http://www.fao.org/fileadmin/user_upload/benchmarking/docs/LEAP_Anima_feeds_DRAFT.pdf.
Ledgard, S.F., Lieffering, M., Coup, D., O'Brien, B., 2011. Carbon footprinting of New Zealand lamb from an exporting nations perspective. Animal Frontiers 1, 27–32.
M&S (Marks and Spencer), 2014. Shwopping. Available from: http://www.ecouterre.com/ms-to-sell-first-shwop-coat-made-from-secondhand-garments/ http://corporate.marksandspencer.com/plan-a/about-plan-a/shwopping (cited 21.10.14.).
McNeil, S.J., Sunderland, M.R., Zaitseva, L.I., 2007. Closed-loop wool carpet recycling. Resources Conservation and Recycling 51, 220–224.
Murphy, Norton, 2008. Life Cycle Assessment of Natural Fibre Insulation Materials. Final report Imperial College London, Prepared for the NNFCC. http://eiha.org/media/attach/372/lca_fibre.pdf.
Nolan, E., Farrell, T., Ryan, M., Gibbon, C., Ahmadi-Esfahani, F.Z., 2013. Valuing quality attributes of Australian merino wool. Australian Journal of Agricultural and Resource Economics 58, 314–335.
NRC, 2007. Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids. National Research Council. The National Academies Press, Washington, USA, 362 pp.
Patagonia, 2014. Recycled Wool. Available at: http://www.patagonia.com/us/patagonia.go?assetid=93863 (cited 21.10.14.).
PE (PE International), November 2013. GaBi Database & Modelling Principles 2013. Version 6.0. http://documentation.gabi-software.com.
Petersen, A.K., Solberg, B., 2004. Greenhouse gas emissions and costs over the life cycle of wood and alternative flooring materials. Climatic Change 64, 143–167.
Potting, L., Blok, K., 1995. Life-cycle assessment of four types of floor covering. Journal of Cleaner Production 3, 201–213.
Radetić, M.M., Jocić, D.M., Jovančić, P.M., Petrović, Z.L., Thomas, H.F., 2003. Recycled wool-based nonwoven material as an oil sorbent. Environmental Science and Technology 37, 1008–1012.
Radetić, M., Ilic, V., Radojevic, D., Miladinovic, R., Jocić, D., Jovancic, P., 2008. Efficiency of recycled wool-based nonwoven material for the removal of oils from water. Chemosphere 70, 525–530.
Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment: Part 1: framework, goal and scope definition, inventory analysis, and applications. Environment International 30, 701–720.
Ripoll-Bosch, R., de Boer, I.J.M., Bernués, A., Vellinga, T.V., 2013. Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: a comparison of three contrasting mediterranean systems. Agricultural Systems 116, 60–68.

Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. Proceedings of the National Academy of Sciences 104, 6253–6260.

Russell, S.J., Swan, P., Trebowicz, M., Ireland, A., 2015. Review of wool recycling and reuse. Proceedings of the 2nd International Conference on Natural Fibres. Azores Portugal, 27th–29th April 2015. http://www.icnf2015.fibrenamics.com.

Schmidt, A.C., Jensen, A.A., Clausen, A.U., Kamstrup, O., Postlethwaite, D., 2004. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. The International Journal of Life Cycle Assessment 9, 53–66.

Shiklomanov, I.A., 2000. Appraisal and assessment of world water resources. Water International 25, 11–32.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., de Haan, C., 2006. Livestock's Long Shadow: Environmental Issues and Options. Food and Agriculture Organisation of the United Nations, Rome.

USA, 2010. Energy Conservation Program for Consumer Products: Test Procedure for Residential Clothes Washers. Department of Energy. Notice of Proposed Rulemaking, 75 Federal Register 182 (21 September 2010), pp. 57556–57595.

US Environmental Protection Agency (EPA) and Department of Energy (DOE). (2010) USEPA, DOE, 2010. Life Cycle Cost Estimate for 1 Energy Star Qualified Residential Clothes Washer(s). Retrieved from: http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroupandpgw_code=CW.

Verikios, G., 2009. Modelling the world wool market: a hybrid approach. Economic Modelling 26, 418–431.

Ward, G.D., Hewitt, A.D., Russell, S.J., 2013. Fibre composition of donated post-consumer clothing in the UK. Proceedings of the ICE-Waste and Resource Management 166, 29–37.

Wheeler, D.M., Ledgard, S.F., de Klein, C.A.M., 2007. Using the OVERSEER nutrient budget model to estimate on-farm greenhouse gas emissions. Australian Journal of Experimental Agriculture 48 (2), 99–103.

WHO, 2009. Water Sanitation and Health. World Health Organisation. http://www.who.int/water_sanitation_health/hygiene/en (accessed 1.03.09.).

Wiedemann, S.G., Ledgard, S.F., Henry, B.K., Yan, M-J., Mao, N., Russell, S.J., 2015. Application of life cycle assessment to sheep production systems: Investigating co-production of wool and meat using case studies from major global producers. The International Journal of Life Cycle Assessment 20, 463–476.

Report EUR 26316 EN. In: Wolf, O., Kougoulis, J., Cordella, M., Dodd, N. (Eds.), January 2014. Environmental Improvement Potential of Textiles (IMPRO Textile). European Commission, Joint Research Centre, Institute for Prospective Technological Studies (IPTS).

Woolridge, A.C., Ward, G.D., Phillips, P.S., Collins, M., Gandy, S., 2006. Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective. Resources Conservation and Recycling 46, 94–103.

WRAP (Waste & Resources Action Programme), 2012a. A Carbon Footprint for UK Clothing and Opportunities for Saving. http://www.wrap.org.uk/sites/files/wrap/Appendix%20IV%20-%20Carbon%20footprint%20report.pdf.

WRAP (Waste & Resources Action Programme), 2012b. Textiles Flow and Market Development Opportunities in the UK.

WRAP (Waste & Resources Action Programme), 2014. Textiles Collection Guide. Available at: http://www.wrap.org.uk/content/textile-collection-guide (cited 21.10.14.).
WRI, 2011. Greenhouse Gas Protocol − Product Life Cycle Accounting and Reporting Standard, 2011. World Resources Institute and World Business Council for Sustainable Development, Washington DC, USA.