3
Sustainable wool production and processing

I. M. RUSSELL, CSIRO Division of Materials Science and Engineering, Australia

Abstract: This chapter reviews the history and development of wool as a modern textile fibre and describes the systems that have been developed to overcome the inherent variability in the fibre production process. Wool is a natural and renewable protein fibre, with a complex physical micro- and nano-structure and a complex chemistry. Together these allow development of textile garments with unique comfort, performance and appearance characteristics. However, 'natural' does not automatically equate to 'sustainable' and the wool industry, like most other mainstream textile fibre industries, is examining its environmental performance. For Australian Merino wool, this is not being done as a marketing tool, but as a means to identify and confront the main environmental challenges and to direct future research. Three main production, processing and garment scenarios representative of Australian wool supply chains have been chosen for examination using life cycle assessment (LCA). Overall conclusions from the current study are that: biogenic methane is the major contributor to the carbon footprint, and the Australian industry is intensively developing tools to reduce enteric emissions; garment laundering accounts for most water consumption, and much energy (heating water and electrical drying); more research is needed to address the gaps in our background environmental knowledge, especially for electricity and energy production in Asia where the bulk of textile processing is currently performed.

Key words: wool, production, processing, EU eco-label, life cycle assessment (LCA), energy, CO_2-e.

3.1 Introduction

Wool is defined by the *Shorter Oxford English Dictionary* as the 'fine soft curly hair forming the fleecy coat of the domesticated sheep (and similar animals)'. While several animals produce similar protein-based fibres – such as mohair and cashmere (from goats), alpaca and angora – wool obtained from sheep is by far the main protein fibre in common use. Historically, wool is one of mankind's oldest fibres, valued for its natural warmth and water repellence. Sheep were one of the first animals to be domesticated by man around 10000 BC (International Wool Textile Organisation, 2009), and they were mainly valued for their meat and for their milk (for immediate drinking or for storage as cheese). The sheep skins were converted to leathers, often with the fleece preserved to increase warmth. The wool from these early sheep was poor, often coarse and uneven, although there were some finer fibres that were suitable for spinning. The proportion of spinnable fibres was increased over the next several thousand years by selective breeding and this led to the development of manufactured clothing. With its longer fibre length and residual wax, wool was easier to spin than vegetable fibres, and could be more readily dyed. One report suggests that the tribes of northern Europe were spinning and weaving animal fibres before 10 000 BC (International Wool Textile Organisation, 2009).

The process of selective breeding of sheep to increase the value of the wool continues to the present time, driven by the value of the wool fibre in international trade. Wool and cotton were important raw materials that drove the industrial revolution in the eighteenth century in England. Various breeds of sheep were exported from Spain and other European countries from around 1800 to what were to become the major wool-producing countries: Australia, New Zealand, South Africa, China, Uruguay and Argentina. Selective breeding continued to develop animals that were adapted to the new climates and conditions and to optimise the production and quality of the fibre and the meat. As an example, the first Merino sheep that were introduced to Australia in 1797 (11 years after the first settlement) for wool production produced a fleece weighing just 1.5–2 kg each year. The current average cut of greasy wool is almost 5 kg. Sheep are able to thrive in rough, barren and arid regions, or in high altitudes or high temperatures where other animals can not survive. Sheep can utilise weeds and vegetation that other animals will not eat and can tolerate quite high salt concentrations in their drinking water.

There are around 40 different breeds of sheep in the world producing around 200 wool types of varying standards and end uses. An important requirement within the breeding programs was to develop sheep with a uniform fibre diameter over the whole body of the sheep so that all of the wool could be harvested and processed uniformly. Cashmere remains an exception where a dual-layer coat persists; however, specialised equipment has been developed to separate the coarse hair from the ultra-fine and highly valued cashmere fibre.

3.2 Wool uses

It is largely the fibre diameter of the wool that determines the value and the end uses of the harvested fleece. British breeds produce mostly coarser quality wool (fibres are around 30 micrometres (or microns) in diameter or more). This wool is highly suited for products such as carpets, blankets and hand-knitting yarns. Finer wools (with fibres of 20 microns in diameter or less) produce soft and luxurious fabrics that are highly suited to next-to-skin wear, and that can be used for applications that range from active sportswear to elegant evening wear. For fine wool garments it is important that wool is uniformly white and contains no dark fibres that would limit the range of garment colours that can be produced. This is less important for the coarser fibres where naturally coloured fibres can be tolerated or may even enhance the 'natural' character of the products.

Different countries have tended to specialise in different sheep types and different wool fibre diameters. Australia has specialised in finer wools produced mainly by Merino sheep (in June 2002 the Australian flock was composed of 85.1% Merino, 10.4% crossbred and 4.5% other breeds) (Australian Wool Testing Authority, 2009). In fact the Australian Merino is not a single homogeneous breed. Four main strains of sheep have been developed in response to the environment and the need to optimise both wool and meat production. Australia is increasing its relative production of finer wools. In 1993/1994, only 8.8% of the wool clip was finer than 19 micron, compared with 30% in 2003/2004. In 2002/2003, Australian wool accounted for 48.5% of the global total of wool used in apparel (Australian Wool Testing Authority, 2009). A recent estimate is that Australia dominates the luxury apparel end of global production – producing 85% of the world's apparel wool and 95% of the world's wool of <19.5 microns (Gray, 2009; Lyons, 2008). Even though consumers invest US$80 billion per annum in wool apparel in the OECD (Organisation for Economic Co-operation and Development) countries alone (Lyons, 2008), wool remains a minority fibre in a textile world dominated by synthetics and cotton.

As the economic returns from both meat and wool can vary annually, a significant number of Merino ewes are mated with rams from English breeds of sheep such as Border Leicester to produce offspring with good meat characteristics, i.e. good carcass, high fertility, robust constitution and good milk production (important for rapid lamb growth). These sheep produce crossbred wool, coarser than Merino wool, but still valuable. This strategy provides farmers with the option to rapidly shift their farm output from wool to lamb meat in response to economic and climatic factors, especially with further breeding of the 'Border/Merino' ewes with 'Downs' breed rams to improve meat production. Sheep can therefore be seen as dual-purpose animals and this complicates any environmental assessment of wool production owing to the fact that the environmental inputs (land, water, fuel, fertiliser) and environmental outputs (methane, urine, faeces) need to be allocated between the products from the animal (meat, wool, skin). In addition, few farms produce sheep as a sole product. Most produce some beef and a variety of crops, and many use the crop stubbles as a food resource for sheep and other animals (Australian Wool Testing Authority, 2009).

3.3 Consumer trends and environmental impacts

There is little doubt that consumers in Northern Hemisphere countries are developing a strong preference for sustainable and ethical textiles. There is growing awareness that all manufactured goods have an environmental impact and that the textile industry has a disproportionate effect. Cooper (2007) demonstrates that the chemical and textile industries are large users of water and large emitters of contaminated process waters. Of these two industries, most of the water used in the chemical industry is for cooling, while, in textiles, most water usage is process water which is discharged with processing contaminants.

This will become more important in a future dominated by global warming, water shortages and peak oil, and by environmentally aware retailers and consumers. AWI (Australian Wool Innovation) Consumer Insights research shows a mass trend toward a lifestyle of health and sustainability – and this extends to apparel (Lyons, 2008). The LOHAS (lifestyles of health and sustainability) market represents 'one-in-three' Americans (Karp, 2008) and is expanding. The LOHAS consumers are seeking goods and services that support their desire for health, environment protection, social justice, personal development and sustainable living.

Europe is exerting increased pressure on global supply chains, initially because it is collectively the world's largest market, but more recently because of its environmental leadership. Kanwar (2008) noted that 'If you manufacture globally, it is clearly simpler to be bound by the toughest regulatory standard in the supply chain. As China and other sourcing countries lean towards the European approach, US companies are also beginning to work to EU rules.' REACh legislation (Registration, Evaluation, Authorisation and Restriction of Chemical substances; EU Regulation, 2006) and other EU standards will continue to have an impact on global supply chains that seek access to the European Union. The EU eco-label for textiles is a powerful standard for environmental good practice in the production of textiles although it is poorly understood by industry and remains a poor marketing tool.

It has already been noted that the wool and cotton industries led the way into the industrial revolution and the modern textile industry was among the first to adopt globalisation. Through the 1990s there was progressive movement of the textile factories from traditional processing countries to less developed countries, attracted by lower wage rates, progressive assistance packages and by less stringent (or less monitored) environmental standards. Unfortunately, the sheer size and pollution loads from areas where the textile wet processing mills are concentrated have led to new pollution events (Reuters, 2008). China is responding to recent high-profile pollution incidents with stricter controls on effluent volume and pollution loads, with increased pollution monitoring and plant closures. It is reported that 10 000 factories across all sectors have been closed (Woo, 2008).

Retailers are also responding to consumer pressures. Retail giant Wal-Mart has signalled that by 2009, factories where their goods are manufactured should be identified, and by 2012, 95% of all products should be sourced from factories with highest rankings for environmental and social standards (Anon., 2008a). Buyers are increasingly seeking supply chain transparency and hard evidence to support environmental claims. There is increasing awareness of 'Greenwash' both by consumers and regulators (Greenwash is the practice whereby disinformation is disseminated by an organisation with the intent to present an environmentally responsible public image). Regulators are increasingly insisting that environmental claims should be accurate, verifiable and in context, and that the basic information to support the claims should be easily accessible. In general, vague and non-specific claims that are too general in nature to be of any use to consumers should be avoided and this includes terms such as 'environmentally friendly', 'green', 'non-polluting' and even 'sustainable' (ACCC, 2008; Defra, 2000; Mohr, 2005).

Global consumption of textiles is large. The textile industry has grown, not only in line with global human growth, but also as a result of per capita consumption. Around 1900, humans used around 2 kg of textiles per head, whereas by 2010 consumption will exceed 10 kg per head (Bide, 2008; Lenzing Group, 2008). As with most other consumable goods, per capita consumption is weighted to the wealthiest countries, with the USA and UK consuming as much as 10 times the quantity of textiles per head as in developing countries.

The environmental problems are associated not only with resources used in the initial manufacture of the textiles but also in the use of resources to clean and dispose of the garments. Most textile garments finish their life in landfill, a diminishing resource in most developed countries. It has been estimated that 1.2 million tonnes/year of textiles are sent to landfill in the UK (Draper *et al.*, 2007), while two million tonnes/year are sent in Japan (Akihiro, 2008). This mass is split evenly between clothing and other textile products. There are increasing calls for greater recycling of textiles as this consumes much less energy than the manufacture of new textiles; however, problems with identifying useful end products for all of this recycled material remain difficult. Even in the UK which has reasonably well developed recycling systems, only around 25% of garments are recycled (Waste Online, 2004).

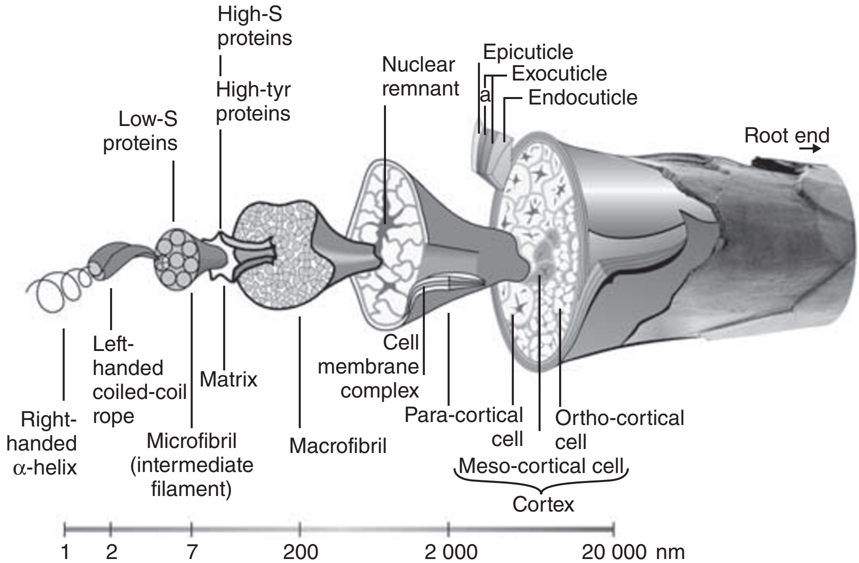
A second estimate for the combined waste from clothing and textiles in the UK is about 2.35 million tonnes (38 kg/person). Of the 330 000 tonnes of recovered textiles, 200 000 tonnes are exported while 100 000 tonnes are recycled within the UK. These recovered clothes are given to the homeless, sold in charity shops or sold in developing countries in Africa, the Indian sub-continent and parts of Eastern Europe. Over 70% of the world's population use second-hand clothes. Incineration is used for 10% of clothing while 60% is sent to landfill (Alford *et al.*, 2006). The EU has indicated that there is likely to be legislation to encourage greater recycling of textiles, initially in the UK and France, but then across the EU (Anon., 2008b; Defra, 2008; Paillat, 2008).

Because wool is a relatively expensive fibre, there is higher demand for discarded wool garments and processing wastes which are sold to specialist firms for fibre reclamation to make yarn or fabric. Incoming material is sorted into type and colour to minimise re-dyeing. The material is shredded into 'shoddy' (fibres). Depending on the end uses of the yarn, other fibres are chosen to be blended with the shoddy by carding before spinning. Products may be garments, felt and blankets. In anaerobic landfills, wool, cotton and other natural fibres degrade rapidly while oil-based textiles degrade extremely slowly, but all potentially produce methane. Methane is a potent greenhouse gas and unless it is recovered, the global warming potential is greater than from incineration.

3.4 Wool fibre: structure and properties

Wool is a naturally produced protein, biodegradable and renewable, and is therefore well placed to take advantage of the emerging 'green' trend for textiles. Wool has a number of advantages as a textile fibre and these arise as a result of its complex chemical and physical structure. The wool fibre forms in follicles in the sheep's skin, initially as a structure of elongated living cells, but these cells dry and harden (keratinise) as the fibre emerges. An outer layer of overlapping, flattened cuticle cells provides a tough water-resistant coating to encase spindle-like cortical cells that contain a nano-structure of crystalline, water-insensitive filaments within a high-cystine, water-sensitive matrix (Fig. 3.1). This complex histology provides a fibre with unique properties. While the surface is water-, dirt- and stain-repellent, the fibre interior is highly moisture absorbent (higher than all other common fibres) and this provides good wear comfort. The fibre is breathable and fabric structures can be engineered so that garments can be either warm or cool. The filament/matrix structure ensures that, when moisture is absorbed, the fibre diameter increases but the length and strength are less affected. The crystalline filaments also ensure that the fibre is highly elastic so that it does not wrinkle under most wear conditions and garments have excellent drape and shape retention. Garments can be formed and permanently set under the influence of heat, moisture and if needed, reducing agents.

The internal chemistry of the fibre is complex as it is based on a protein structure with more than 20 amino acids. This ensures that the fibre is



3.1 Expanded schematic of wool fibre structure (© CSIRO Materials Science & Engineering Textile and Fibre Technology Program Graphics by H.Z. Roe, 1992 & B. Lipson 2008, based on a drawing by R.D.B. Fraser, 1972).

readily dyed, that it absorbs odours, and that it is naturally fire-resistant and anti-static. The overlapping scales on the surface of the fibre provide a differential friction effect that allows fabrics to compact or felt in water. This can be desirable to achieve effects in finishing, but it can lead to garment shrinkage if uncontrolled. A variety of shrink-resist finishes have been developed that can be applied at loose fibre or at garment stages so that machine-washable, easy-care garments can be produced.

3.5 Wool and ecolabels

While wool is natural, it is important to note that 'natural' does not automatically mean environmentally friendly. Wool, like all other textiles, needs to develop a defendable environmental profile in response to the growing environmental awareness of consumers in developed countries. Of course, only the hardest 'green' consumers are prepared to purchase garments purely on their environmental profile, to achieve body covering with minimum environmental cost. For the vast majority of consumers, purchasing decisions are made on appearance, functionality, fashion, quality, performance and price. Of these, price seems to be the single item where consumers seem most prepared to compromise. Surveys in Europe and the USA show a progressive increase in the numbers of consumers prepared to pay more for ethical and sustainable textile goods (Anon., 2008c). Some commentators believe that good environmental credentials are now a 'given', however the problem remains that it is still very difficult to identify goods manufactured using good environmental practices in the market place. Ecolabels are important in this area, however not all textile ecolabels identify environmentally preferred goods. Some textile ecolabels might deal only with labour issues, while some, such as the 'human ecology' labels, deal only with the absence of toxic chemicals in the final manufactured product. These types of ecolabels are silent on environmental practices through the supply chain. This is often not understood well by either consumers or, unfortunately, many retailers and textile processors. The International Wool Textile Organisation (IWTO) has recently defined 'eco-wool' textiles as goods that meet the EU eco-label criteria at all stages of the supply chain, from raw wool to finished product (deBoos, 2008).

The EU eco-label is an important textile processing standard that covers all stages of textile manufacturing, from raw fibre to finished product. It contains criteria that exceed 'environmental best practice' for textile processing as defined in the EU BREF document (EIPPCB, 2002) and the Integrated Pollution Prevention and Control legislation (IPPC, 96/61/EC). The EU eco-label is a Type 1 ecolabel (as described by Internation Standard ISO 14024). These labels are based on criteria independently established across the life cycle of a product and certified or audited by an independent third party. The criteria in Type 1 ecolabels are set and assessed independently, they are readily available and they cover the total processing sequence. Specific criteria are applied to those processing stages with the greatest environmental impact. Type 1 ecolabels provide the greatest degree of transparency and the greatest assurance that the product has been manufactured with minimum environmental impact.

Other international Type 1 textile ecolabels have usually taken their criteria from the EU eco-label. Some of these derived Type 1 standards (but not the EU eco-label itself) may add some social elements (fair pay, safety, child labour, etc.). Type 1 ecolabels adopt a supply chain approach where information on all processing additives is available to downstream processors. This information flow is often missing in textile supply chains. A British Government report has identified the EU eco-label as the most robust measure of textile sustainability after considering 207 other standards, databases and product lists globally (Anon., 2008d), and the UN Environmental Programme (UNEP) is advocating its use in South Africa and India (Ferratini, 2008/2009).

There is increasing awareness that environmental discharges from a wet textile process such as dyeing arise from two sources:

(a) the compounds deliberately added to the process by the dyer;
(b) the materials already present on the fibre when it is received. The identity of these materials is often outside the control or knowledge of the processor receiving the fibre and they may contribute a greater pollution load than the process additives. They may be difficult to remove and they may be toxic or poorly biodegradable.

The general issue of supply chain communication has been raised as an important element of good environmental practice in the EU BREF document (EIPPCB, 2002) and by Cooper (2007). The problems are most severe at dyeing since dye liquors are difficult and costly to treat because of their volume and temperature. Wool has a long supply chain compared with most other fibres and the fibre may change ownership several times as it progresses from farm to garment. Because the manufacture of EU eco-label garments begins with identifying compliant batches of raw wool, garment manufacturers have been deterred by the task of identifying and then commissioning the processing of the specific wool lots. An important development has been the opening of a database in the EU eco-label website that allows late-stage manufacturers to find partially processed fibres, tops or yarns that have been manufactured in compliance with the EU eco-label (EU, 2007). At least one supply chain has moved in this direction. It is also expected that the adoption of the EU eco-label by the international wool industry as its definition of eco-wool will also assist this process within wool supply chains.

3.6 Life cycle assessment (LCA) studies

In 2006, the Commonwealth Scientific and Research Organization (CSIRO) and the Australian wool industry began a small project to perform a preliminary LCA on Australian wool. Other wool-producing countries are performing partial studies (Barber and Pellow, 2006; Kelly, 2008). Australian wool is used for the production of many types of garments and processing occurs in many different countries. In order to simplify the study and to allow identification of the major environmental pressure points, three typical Australian wool supply chains manufacturing common apparel products were selected:

- fine wool grown in a high-rainfall climate by a specialist producer, processed in Italy into lightweight next-to-skin knitted garments;
- medium-micron wool produced on mixed enterprise farms, processed in Asia into men's suits;
- slightly coarser wool, produced in Australia's arid pastoral zone, processed in Asia into an outerwear knit.

All garments were assumed to be sold and used in Europe.

The study covered the total production, transport, processing, garment care and garment disposal sequences. The project adopted the ISO 14040 as a framework, and the main environmental impacts focused on the usage of water and fossil fuels and on emissions of greenhouse gases. The project was conducted in order to identify and rank the main environmental challenges – were the major emissions of greenhouse gases and usages of water associated with on-farm fibre production (methane emissions from sheep, CO_2 emissions from trucks and tractors, N_2O emissions from fertiliser), with transport, with processing, or with garment care?

The aim of the study was not for tactical marketing or inter-fibre comparisons; it is acknowledged that all fibres have their own unique pressure points. Rather the study was conducted as a strategic planning tool, to ensure that future investments by the Australian wool industry in the environmental area addressed the major issues. Comprehensive modelling of all inputs and outputs associated with the provision of a product or service is potentially extremely complex. The task is simplified considerably by the availability of calculation and database software that includes much of the 'background' data on environmental impacts associated with the provision of general services such as transport, electricity (in various countries) and fertiliser manufacture.

This study was conducted with the SimaPro software package (Pré Consultants bv, The Netherlands) to perform overall calculations and to provide the background LCA data through its associated databases. The most comprehensive resources are available for services provided in Europe through the EcoInvent 2.0 database (May 2008 version). The Australian distributor of the SimaPro software (Life Cycle Strategies, Victoria, Australia) has modified some of the European data with assumptions appropriate to Australia and has provided a reasonably comprehensive Australian database.

3.6.1 On-farm production of wool fibre

The process of LCA is generally poorly developed for agriculture, especially as it applies in the arid Australian environment. The most detailed studies and methodologies have been developed for European farming but these are often poorly applicable to Australia. As an example, in European agriculture, water is generally plentiful and soils are often wet. This has an impact on such factors as emissions of nitrous oxide (N_2O) from animal urine and from use of nitrogenous fertilisers. In Australia, water is a scarce resource and access to water is highly contested. At present there is no means to value the scarcity of water in an LCA study, however tentative steps are underway.

In this study we only considered drinking water supplied to the sheep from contestable sources such as dams (holding stored run-off water captured from the property in wet seasons and prevented from draining to a waterway) and underground bore water, with associated overheads (evaporation and transport losses). Other brief LCA studies also adopted this approach (Laursen *et al.*, 1997). Consistent with many other agricultural LCA studies, rainwater landing on the property (an important resource for plant/fodder production) and dew condensation were not considered, even though the water in and on plant matter are an important water resource for sheep. Water stored in the soil ('green water') is a valuable resource for the production of plants and for retaining carbon and nitrogen in the soil; Australian farmers actively manage this resource (where possible). The estimates of the volumes of drinking water depend on climate (mainly temperature), food intake (quality and quantity), animal size, distance to water and factors such as lactation. Sheep are extremely hardy animals and in temperate climates they can survive for prolonged periods on dew and plant moisture alone. However, this study assumed a plentiful drinking water supply and, as a result, estimated values of water usage probably erred on the high side. The volume of urinary water returned to the soil was subtracted from the total water consumed on the basis that N_2O was generated when the urine reached the soil, and that the urinary water (with nutrients) was retained on the farm and contributed to plant growth. Sheep respire large volumes of moisture but this can not be captured on the farm and is regarded as lost to the system. Unfortunately there are no agreed protocols.

The estimates of water use obtained in this way were more than two orders of magnitude lower than worst-case estimates previously made. These previous calculations were based on the assumption that sheep were raised solely for wool production on irrigated pastures (Meyer, 1997). In fact it is now extremely rare for sheep to be run on irrigated pastures in Australia, and, when it is done, it is invariably for meat production (fattening of lambs).

The methodology for carbon accounting in sheep production is well developed because of Australia's international greenhouse gas reporting commitments. A small part of the carbon emissions on farm are as CO_2 itself, from use of farm equipment, electricity, transport and, indirectly, for production and transport of fertilisers. A very small adjustment in the carbon balance included the carbon fixed in the wool fibre product from the farm.

A larger proportion of on-farm carbon emissions arise from the production of the potent greenhouse gases, methane and N_2O. On a mass basis, both are many times more potent than CO_2 itself. Total emissions of greenhouse gases are usually expressed as CO_2 equivalents (or CO_2-e), where the mass emissions of other gases are multiplied by factors according to their global warming potential. The principal emissions of methane from sheep production are from enteric digestion processes. It is possible that methane could be produced from faeces, but this is regarded as negligible under Australia's dry farmland conditions. The volumes of methane from sheep depend on the size of the animal, the diet (poor diets produce more methane), lactation and numerous other factors. The principal sources of N_2O production are from urine when it is deposited on soil (along with other nutrients), as well as from the use of nitrogenous fertilisers in crop production. In general, superphosphate is the only fertiliser used on high-rainfall pastures in Australia for intensive sheep production, and no fertilisers are used in the arid pastoral zones. Nitrogenous fertilisers are not used directly on pastures for sheep (they are too expensive), however they are used on grain crops in mixed farming enterprises and farm animals are allowed to graze on the stubbles once the grains have been harvested. Again the emissions of N_2O from nitrogenous fertilisers depend on rainfall. In the dryland farms used for wheat production in Australia, emissions are lower than in Europe and other wet climates. The current study allocated some of the N_2O emissions from grain production to the sheep according to the protein value of the residual grain and stubble. Nitrogenous fertilisers are often used in the production of fodder used to supplement the feed of sheep in drought periods and again the associated N_2O was assigned to the sheep (as well as transport and energy used to produce the fertiliser) based on the farm expenditures on fodder.

Sequestration of carbon on the farm was not included although many Australian farmers plant trees to fix carbon and to lower the water table to reduce soil salinification. Agricultural soils are capable of sequestering large amounts of carbon and nitrogen. While this was considered in this study, no allowance was made as:

- under the greenhouse gas accounting rules, sequestered carbon must be 'additional, permanent and verifiable', and these conditions are not yet met;
- these activities are not relevant to the product's carbon footprint.

Generally the allocation of environmental inputs and emissions to the sheep was made on economic factors based on overall farm expenditure and receipts, as it is economic returns that decide whether the land is used for animal production or for cropping. An initial economic allocation was based on the overall farm receipts for all farm products to obtain a 'per sheep' share of inputs and impacts. A number of other environmental inputs and outputs (such as drinking water and methane emissions) were already available on a 'per sheep' basis. A second economic allocation was performed based on farm receipts for sheep meat and for wool to divide the 'per sheep' inputs between the meat and the wool products. Again it is the economic returns that decide whether the sheep is produced for either wool or meat. While ISO 14040 regards economic allocation as a poorly preferred option, with a product such as wool, the price per kilogramme of wool varies more than tenfold depending on the micron of the wool. Crossbred sheep are usually produced for their meat and often lead short lives; sheep with fine wool are often retained for several productive years, by which time the meat has relatively poor value. It is only economic allocation that reflects these differences.

3.6.2 Early-stage wool fibre processing

In comparison with cotton and synthetic fibres, wool undergoes several processing stages before it can be effectively used in a textile factory as combed, aligned fibres for blending or for production of yarns. The wool is manually shorn from the sheep and the main fleece wool from the back, sides and chest of the sheep is then separated (or skirted) to remove the stained and burr-contaminated wools from the rear and underside of the animal. This poorer wool still finds valuable uses in wool supply chains. The fleece wools are then sorted into consistent lines of wool (similar micron, fibre length, appearance and style) by wool classers before the wool is baled and transported to a central store. These lines of wool (weighing around 1 tonne on average) are then sampled and objectively tested (for yield, micron, vegetable matter, etc.) as these factors determine the amount of clean wool in the sales consignment, its value and its likely processing characteristics. These presale evaluations are necessary to counter the fleece-to-fleece and flock-to-flock variability in a natural product. In Australia most of the wool is sold at 'open cry' auctions mainly on the basis of the objective measurements. The wool is purchased by buyers whose job is to acquire (at minimum cost) the wools that will allow a processing lot (20–50 tonnes) to be compiled and that will, after initial processing, meet specifications for fineness, variation in fineness, fibre length, variation in fibre length, colour, etc. in the combed tops. Predictive computer programs are available to assist this process.

It is only when the wool is ready to be washed or 'scoured' (either in Australia or overseas) that the specific lines of wool that were purchased are retrieved from their original place of storage. Wool to be shipped overseas may be 'dumped' (three bales are highly compressed together) to increase the packing density in shipping containers. This reduces the energy overheads in shipping the container as well as the wool. Transport is by truck and ship to the overseas seaport (China or Italy) and then by truck to the mill.

The total consignment is mixed in a variety of ways to ensure that the finished consignment is consistent from start to finish. Scouring of the wool is performed at 60–70°C in a continuous counter-current operation in a scouring line usually with six scouring bowls. In a typical scouring operation, non-ionic detergent is used and around 10 L of water are used per kilogramme of greasy wool. The most energy-efficient scours use covered scouring bowls, heat the water using direct gas firing of the bowls and recover heat from the discharged liquors; however practices vary widely. Steam is a less efficient heating medium but unfortunately in some countries, such as China, where coal-fired boilers are common, it may be the only option. It is reported that 90% of industrial boilers in China are coal fired, many of which operate at less than design efficiency (Li and Sun, 2007).

The scouring operation is designed to remove contaminants from the wool. A typical bale of Australian wool may contain only 65% of wool, the remainder is wool wax (around 30% of this is recovered from the scour and sold to be refined into lanolin), dirt, sheep sweat salts and other skin contaminants. Effluents from the wool scour are therefore highly contaminated. While there are high-energy methods such as evaporation that can be used to clean these effluents, in fact there are lower energy options that can remove most of the contaminants in-line and recover valuable by-products (compostable organic material, potassium fertilisers) (Bateup *et al.*, 1996). Within any supply chain there will be environmentally good operators and there will be environmentally poor operators and this complicates the comparison of generic textile supply chains. The uniform and cleaned mat of wool from the scour is squeezed to remove excess water and dried in efficient drum driers usually fitted with moisture meters to ensure that the wool is not over-dried and damaged (but also to save energy).

There are two main streams in wool processing. The woollen system uses short wool fibres and the wool passes through a woollen card where a series of wire-coated rotating drums align the fibres. A final set of rubbing tapes split the fibre web into 'slubbings' that are subsequently spun into yarns with little further drafting. These yarns are typically coarse and hairy and are used for tweed-type fabrics and hand-knitting yarns. The worsted system is used for fine woven and fine knitted fabrics. Scoured wools with long fibre lengths pass though a shorter worsted card where rotating wire-covered cylinders begin to align the fibres. The wool scouring process unfortunately entangles some of the wool and there is significant fibre breakage in the worsted card. This reduces the average fibre length. Most of the vegetable matter is also removed. The carded web emerging from the card is further blended and gilled (combed) with steel combs in four or five stages. The shortest of the broken fibres in the now well-aligned wool are removed in a rotary comb, a process that separates the long fibres from the short broken fibres ('noil') that may comprise 6–8% of the incoming fibre. This fibre is lost to the worsted process but finds ready use in the woollen system. The highly aligned long fibres are given a final gilling before typically being rolled into large balls ('tops') ready for blending or spinning.

These early processing stages are functionally equivalent to the extrusion (primary spinning) processes used with synthetic fibres. As with synthetic fibres, various lubricating oils are added on the fibre to minimise fibre breakage in mechanical processing. While the operations in the woollen and worsted processing sequences are complex and specialised, the fibre throughputs are high and the energies required per kilogramme of fibre are generally lower than the energies for the synthetic fibres, even when the on-farm energies and transport are considered.

3.6.3 Fabric production

All textile fibres, once in the mill in the form of clean, aligned staples, are typically spun, woven or knitted, dyed, finished and made up into garments. There are environmental similarities in all of these sequences for all fibres. The differences between mills are probably greater than the differences between fibres. There will be modern mills that use state of the art, efficient, low liquor ratio equipment and there will be mills that use greater resources. As an example, a Finnish study found that the water usage across six large textile mills dyeing and finishing mainly synthetics and cotton ranged from 140 to 370 L/kg of fabric. Energy uses ranged from 55 to 124 MJ/kg. The mill with the highest water usage also consumed the most energy. Discharges of COD (chemical oxygen demand, a measure of oxygen depletion in water) ranged from 61 to 393 g/kg of fibre (Kalliala and Talvenmaa, 2000). In general, the main factors that differentiate the environmental footprints of different fibres are the energy, water and resource usages to produce the combed, aligned fibres.

There are a few studies that provide processing data (energy and water use) for processing operations, but most show that between-mill resource usage varies over large ranges. It is difficult to combine much of this data into a coherent processing sequence because of the high variability within the individual processing stages. As an example, British Textile Technology Group (BTTG) (1999a) cites an energy use for winch dyeing of 5.7–16.9 MJ/kg and a water use of 28–293 L/kg. Additionally, it is often difficult to know specifically what is included and excluded in the data that are available. As an example, is the energy for air conditioning or effluent treatment included in the mill operations? A streamlined LCA for selected cotton and polyester garments (Collins and Aumônier, 2002) performed for Marks and Spencer solved the problem with the range of data by using the best environmental data for each stage, effectively assuming environmental best practice for all processing stages.

The current study used specific process stage data from specific early-stage wool processing mills, including data from a South African study evaluating life cycle impact assessment methods for the production of twofold wool yarns (Brent and Hietkamp, 2003). For wool dyeing and finishing, because of the variety of processes encountered and the associated uncertainties, overall mill data were used. These data were poorly available and the results from only a single woven fabric mill and from a single knitted fabric mill were used. However, for the woven fabric mill, all activities were captured including air conditioning, effluent treatment and operation of staff canteen and toilets. The fact that the mill had achieved EMAS (Eco-Management and Audit Scheme) certification probably meant that it was among the better environmental operators.

Another major difficulty was the lack of background data available within LCA software packages for operations in Asian processing countries. While most of the standard packages include a wide choice of operational sequences in Europe (for example, country-specific data for supply of electricity), there are few corresponding sources for Asia. The LCA practitioner may be forced to select electricity data from another country where coal-fired power generation is predominantly used, but that may poorly reflect the coal mining, transport and air quality impacts in China. The men's suit and outer knitwear scenarios assumed garment manufacture in China, necessitating transport of the garments to Europe by container ship and surface transport.

3.6.4 Environmental impacts in use and on disposal

The Marks and Spencer streamlined LCA study demonstrated that the water and energy resources required to clean and maintain a garment in wear can exceed the resources required to manufacture the garment initially. In fact, for the polyester trousers and the men's cotton briefs, the garment washing and care phase consumed 76% and 80%, respectively, of the total energy in the garment life cycles. The main contributors to energy use were high-temperature washing, garment drying and ironing. The Marks and Spencer study demonstrated the environmental benefits of lowering the wash temperature. While some modern wool garments are capable of withstanding hot washing and tumble drying, most consumers are not prepared to take the risk, even if there are assurances on the care labels. This current study assumed that consumers would use a gentle warm wash cycle and air-dry the wool garments. This had the effect of substantially reducing the in-use care resource usage for the knitted garments.

This study found little information on the lifetime of wool garments or on the number of cleaning cycles. Wool has good odour absorbing properties and this reduces the frequency of laundering. A garment lifetime of 20 washes was assumed. The men's suits were assumed to be dry cleaned four times per year for three years or 12 dry cleanings with the energy and resource usages taken from the Marks and Spencer streamlined LCA report

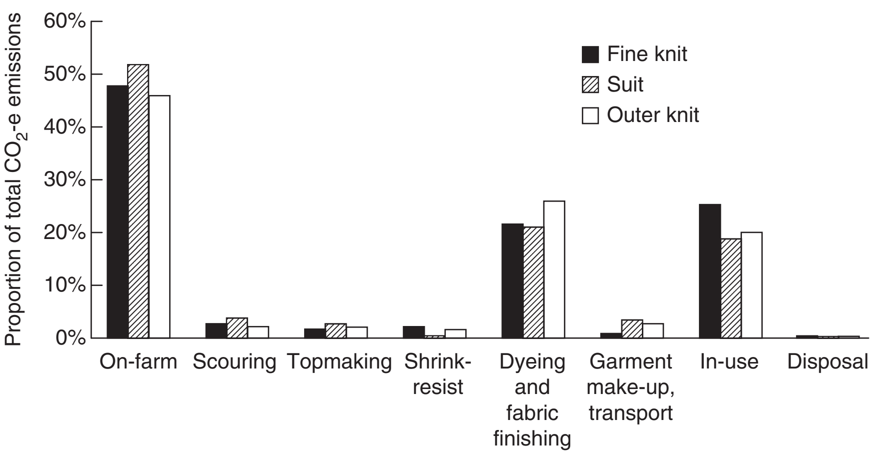
(Collins and Aumônier, 2002) and from BTTG reports (British Textile Technology Group, 1999b).

UK default figures for disposal of garments were essentially used, however wool is a relatively expensive fibre and in Japan and in the UK schemes have been developed to recycle the fibre. For the purposes of this study, 40% of wool garments were assumed to be recovered/recycled (slightly higher than for other fibres), with 7% incinerated and 53% disposed to landfill (Alford *et al.*, 2006).

SimaPro models for incineration of combustible wastes and for disposable of degradable materials such as paper and cardboard to European landfills were used to model the end-of-life behaviours of these wool garments. In fact the end-of-life disposal caused very little change in the overall picture for these wool garments. The recovered/recycled fibre and garments were assumed to be environmentally neutral as substitution of recovered fibre to replace new garments manufactured from virgin fibre cannot be demonstrated.

3.6.5 Overall results

Figure 3.2 shows the relative proportion of CO_2-e for the three wool production and use scenarios as calculated by SimaPro. These emissions are calculated per kilogramme of garment and therefore take account of mass losses through the processing chain. For each supply chain, around 2 kg of greasy wool is required to produce 1 kg of garment and this increases the apparent contribution of on-farm emissions. The main mass loss is at scouring where wool wax, dirt and sheep sweat salts are washed from the wool.



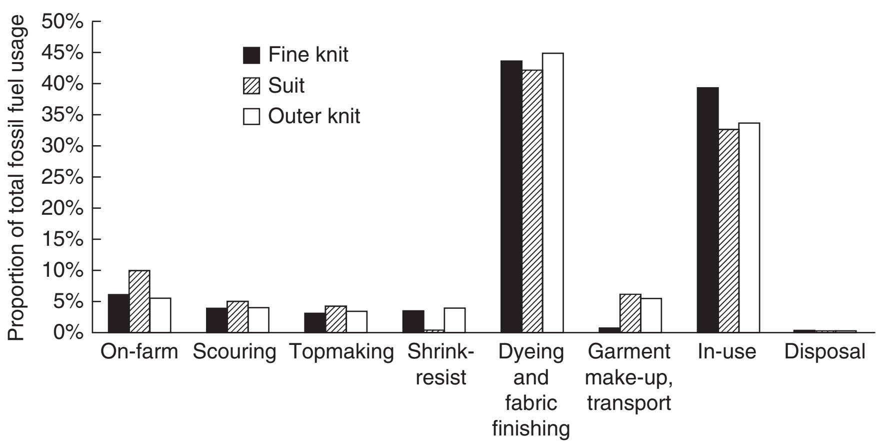
3.2 Emissions of CO_2-e through the wool garment life cycle.

In this simple model, losses through processing have been considered as lost to the specific supply chain, but in fact fabric losses are usually valuable clean fibre which is sought after as raw material for other wool products. Examples are losses of noils in topmaking (these are used in the woollen system for manufacture of knitwear) and fabric offcuts in suit manufacture and in cut-and-sew garments.

The on-farm emissions of CO_2-e form around half of the total emissions and include biogenic methane (the largest contribution) as well as N_2O from urine and, for the sheep/wheat-zone farm, N_2O emissions from the use of nitrogenous fertiliser on crops. Energy used on the property as well as in production and transport of fertilisers (for the high-rainfall zone and sheep/wheat-zone farms) and fodder are also included.

The other major stages for emission of CO_2-e are in dyeing and finishing and in garment care (washing and dry cleaning). The emissions from dyeing and finishing will be roughly similar for all fibres, however the laundry operations for the knitted wool garments in the model are low-energy scenarios (warm wash, air dry). For other fibres, the CO_2-e emissions from garment care would probably be higher. Emissions in sea and land transport are relatively low and are included in the scouring and garment make-up components.

In order to more clearly show the relative contributions of animal-related emissions from fuel, electricity and fertiliser production, SimaPro is able to estimate usages of fossil fuels through the supply chain. Figure 3.3 shows that the energy used on-farm and in the early stages of fibre preparation is low in comparison with the fossil fuels used in dyeing and finishing and in garment care. The higher energy use on-farm for the men's suit scenario in



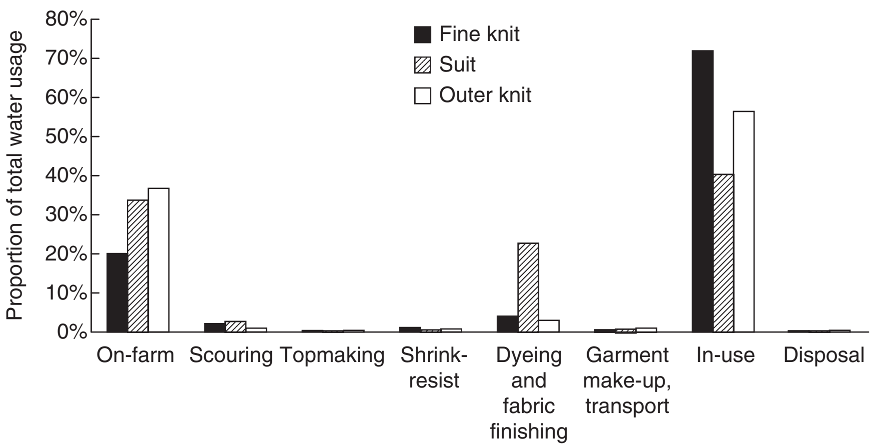
3.3 Fossil fuel usages through the wool garment life cycle.

the mixed farming scenario is largely associated with manufacture (in Australia) of nitrogenous fertiliser used on the crops. Again surface transport is a minor component of fossil fuel use.

This study has clearly shown the relative importance of enteric methane in contributing to the carbon footprint of Australian wool. The problem is not unique to sheep but is common to all ruminant animals including cattle. There is substantial scope to reduce livestock emissions and research is underway both in Australia and internationally (Trivedi, 2008). It has been found, for instance, that substantial differences exist within breeds of cattle in the amounts of emissions, independent of diet.

While researchers have developed methods to achieve small reductions, it is hoped that genetic and management tools being developed by sheep, beef and dairy industries and by researchers sponsored by the Australian and New Zealand governments will yield larger reductions. Researchers have recently found that kangaroos in Australia produce very little methane, yet are a ruminant. The differences relate to the gut microorganisms, but translation of this observation into practice is likely to be difficult.

Figure 3.4 shows the relative water consumption through the three wool production and processing supply chains. The major water usage is at the garment laundry stage. While the men's suit is assumed to be dry cleaned, water is used in electricity generation. In the on-farm scenarios, water is used in the production of nitrogenous fertilisers (men's suit), while sheep in the hot and dry pastoral zones have a high intake of drinking water. The mill used to provide the overall data for the men's suit scenario was a relatively high user of water, largely because the multiple processes used to finish high-quality woven wool fabrics can be water-intensive.



3.4 Water usages through the wool garment life cycle.

3.6.6 Energy use and the carbon footprint

The current study did not perform fundamental and first-principle energy studies for other fibres; however in asserting that wool uses low energy over its life cycle but has high greenhouse gas emissions, it is important to consider the relationship between energy and carbon emissions. For textile processing, data on energy usage are relatively readily available. Greater complications occur in estimating the associated CO_2 emissions that arise in the production of the energy, whether from coal, electricity, natural gas, etc., in the different countries where processing is performed. In the current study, the SimaPro software was allowed to perform the calculations for CO_2 emissions based on the source of the energy using regional data where available. It is well known that the output of CO_2 depends heavily on the source of the energy. There are in-built inefficiencies associated with use of electricity compared with direct use of thermal energy. In addition, even with thermal energy, steam is a less efficient energy source than direct-fired gas heating in a mill. The source of electricity in a process will have a significant impact on the carbon footprint. Electricity generated from wind, solar or nuclear sources has low carbon emission factors, whereas brown coal, with its high moisture content, has a high emission factor. This means that a specific process will have different carbon emissions depending on where it is located.

Most of the textile reports that have provided information on total energy usage have not calculated CO_2 emissions, nor do they generally provide sufficient data on energy sources to calculate the associated carbon footprint. The energy required to produce 1 kg of polyester fibre has been variously estimated as 109 MJ/kg (Marks and Spencer Streamlined LCA study – Collins and Aumônier, 2002) and 112 MJ/kg (Franklin Associates, 1993) – made up of resin manufacture (97 MJ/kg) and from fibre production (15 MJ/kg). There are several other estimates but most are similar.

Few studies provide a sufficiently accurate breakdown of the fuel mix for textile production to generate accurate data on carbon emissions. The Franklin Associates study of a polyester blouse did provide an inventory of fuel types used, and, on the basis of the fuel mixture, the New Zealand Merino study (Barber and Pellow, 2006) calculated an emission of 6.9 kg CO_2/kg polyester fibre produced or 62 g CO_2/MJ of energy.

As a basis for comparison, a number of sources show that black coal generation of electricity produces 278 g CO_2/MJ of electricity (Anon., 2009). Quantities of ozone, sulphur dioxide, oxides of nitrogen and other gases as well as particulate matter are also produced.

Morris recently estimated an emission of 4.2 kg CO_2/kg polyester staple or about 40 g CO_2/MJ of energy (Morris, 2008). This probably reflects production in Europe where nuclear, gas and hydroelectric power are extensively used. Morris noted that France has the lowest CO_2 emissions because its electricity is mainly generated from hydro and nuclear resources. His report also observed that coal-based processing in China increased the carbon emissions per kilogramme of fibre, especially if transport energy was included.

Wiseman (1981) reported an energy for wool production figure of 38 MJ/kg while the New Zealand Merino study (Barber and Pellow, 2006) calculated an energy usage of 46 MJ/kg to produce wool top, half of which was on-farm. The New Zealand study calculated a CO_2 emission for production of wool staples of 2.2 kg CO_2/kg (corresponding to 50 g CO_2/MJ of energy). This value of 2.2 kg/kg wool appears to have been used by Morris in his comparison of fibres, but the New Zealand study ignored enteric methane and N_2O emissions.

The carbon footprint of commodities is the subject of a British Standard, PAS 2050, and this initiative is being supported by major retail chains. Many commodities are viewing this development very seriously and it is anticipated that carbon footprints of commodities will begin to have an impact on market access (Mello, 2007). Energy ecolabelling is also being proposed for textiles in Europe (Anon., 2008e). Many farmers in Australia are planting trees to offset their on-farm carbon emissions and The Merino Company in Australia has developed a scheme to source ZeroCO2 Wool™ for markets that are seeking a carbon-neutral product.

3.7 Outcomes

LCA studies are data intense and outcomes depend on the assumptions made, both in the foreground and in the background. At a practical level, the task of the LCA practitioner is to evaluate the importance of a particular assumption to the outcome. If the result is important to the outcome, the practitioner must spend time obtaining the best data. If the outcome has a minor effect, less time needs to be spent on improving data quality and accuracy. However, it is important that the assumptions are clear and transparent so that the user of the study can decide if the overall outcomes are appropriate.

Some of the commercial LCA programs have different strengths, e.g. GaBi has a very detailed textile finishing database, which would be very useful for benchmarking European processing sequences (GaBi, 2009). However, because of the variability of the environmental practices of different mills, there is little substitute, if detailed comparisons of specific products are to be performed, for studies to be conducted for all stages of manufacture at the mill level. Unfortunately there is a paucity of background LCA environmental data for Asian mills, where the bulk of textile processing is currently performed.

There are some overall conclusions from the current study of three wool production scenarios for the manufacture of typical Australian wool products.

- Biogenic methane is the major contributor to the carbon footprint, and the Australian industry is intensively developing technologies to reduce enteric emissions.
- Garment care during normal wear accounts for most water consumption, and much energy (heating water and electrical drying).
- More research is needed to address gaps in our background environmental knowledge, especially for electricity and energy production in Asia.
- The environmental performances of the different potential participants in any supply chain vary widely – there are opportunities to optimise the environmental performance for specific products by selecting the participants in the supply chain. Unfortunately the data to make such a selection are not generally available.

3.8 Sources of further information and advice

- Further information on the properties of wool and its applications in garments and in technical textiles can be obtained from the CSIRO website in a series of information sheets (CSIRO, 2009). Links to other wool information sites (Australian Wool Innovation, Australian Wool Testing Authority) are also available.
- The suppliers of the major LCA software packages provide a great deal of background information and even training packages on the use of their software.
- The Society of Environmental Toxicology and Chemistry (SETAC) has published several books on the theory and practice of LCA.
- The monthly trade magazine, *Ecotextile News*, is an important source of environmental information on trends, issues and news releases.
- The EU BREF document (EIPPCB, 2002) is a major resource that defines good environmental practices for textile processing. It was written using European data that were obtained between 1999 and 2001 and reflects that viewpoint; however it remains a valuable benchmarking document.
- The EU eco-label textile-specific website is found at http://ec.europa.eu/environment/ecolabel/product/pg_clothing_textiles_en.htm. The site links to many other useful articles, including to the current suppliers of ecolabel textiles. The background material describing the reasons for setting the specific criteria are valuable.

3.9 Acknowledgements

This study was supported by funding provided by the Australian Government to CSIRO and by Australian wool growers through funds administered by Australian Wool Innovation (AWI). Information provided by colleagues in CSIRO, especially as part of the Agricultural Sustainability Initiative, and from the AWI Project Advisory Team and the AWI Project Manager, Dr Paul Swan, is gratefully acknowledged.

3.10 References

ACCC (AUSTRALIAN COMPETITION and CONSUMER COMMISSION) (2008). 'Green marketing and the Trade Practices Act', http://www.accc.gov.au/content/index.phtml/tag/greenmarketing/, accessed 24 April 2008.

AKIHIRO O (2008), 'Tech-upgradation leads to mass scale textile recycling', http://www.fibre2fashion.com/news/association-news/jcfa/newsdetails.aspx?news_id=61061, accessed 11 February 2009.

ALFORD JM, LAURSEN SE, DERODRIGUEZ CM and BOCKEN NMP (2006), 'Well dressed, the present and future sustainability of clothing and textiles in the United Kingdom', http://www.ifm.eng.cam.ac.uk/sustainability/projects/mass/UK_textiles.pdf, accessed 10 February 2009.

ANON. (2008a), 'Wal-Mart's green new deal', *Ecotextile News*, **19**, November, 15.

ANON. (2008b), 'Textile waste plan', *Fashion Business International*, June–July, 4.

ANON. (2008c), 'US consumers still buying "green"', *Ecotextile News*, **15**, June, 7.

ANON. (2008d), 'EU eco-label tops sustainability study', *Ecotextile News*, **19**, November, 12.

ANON. (2008e), 'Energy eco-labelling', *Fashion Business International*, June–July, 4.

ANON. (2009), 'Environmental concerns with electricity generation', http://en.wikipedia.org/wiki/Environmental_concerns_with_electricity_generation, accessed 30 January 2009.

AUSTRALIAN WOOL TESTING AUTHORITY (2009), http://www.awta.com.au/en/Home/Education/Historical-Material/Brief-History-of-Wool-in-Autralia/, accessed 29 January 2009.

BARBER A and PELLOW G (2006), '*New Zealand Merino Industry: Merino Wool Total Energy Use and Carbon Dioxide Emissions*', The AgriBusiness Group, Pukekohe, Auckland, New Zealand.

BATEUP BO, CHRISTOE JR, JONES FW, POOLE AJ, SKOURTIS C and WESTMORELAND DJ (1996), 'Effluent management', in Proceedings of Top-Tech '96 Conference, CSIRO Division of Wool Technology, Geelong, Australia, 11–14 November, p. 388.

BIDE M (2008), http://www.colourclick.co.uk/colourclick/articleimages/China%20Conf%20Report_full.pdf, accessed 30 January 2009.

BRENT AC and 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.

BRITISH TEXTILE TECHNOLOGY GROUP (1999a), '*Report 5: Waste Minimisation and Best Practice*', http://www.e4s.org.uk/textilesonline/content/6library/fr_library.htm, accessed 11 February 2009.

BRITISH TEXTILE TECHNOLOGY GROUP (1999b), '*Report 4: Textile Mass Balance and Product Life Cycles*', http://www.e4s.org.uk/textilesonline/content/6library/fr_library.htm, accessed 11 February 2009.

COLLINS M and AUMÔNIER S (2002), *Streamlined Life Cycle Assessment of Two Marks & Spencer plc Apparel Products*, Environmental Resources Management, February, http://www.satradingco.org/Reports/LCA_Final.pdf, accessed 30 January 2009.

COOPER P (2007), 'Clearer communication', *Ecotextile News*, **4**, May, 30–33.

CSIRO (2009), http://www.csiro.au/science/Wool-Textiles/Publications.html, accessed 10 February 2009.

DEBOOS A (2008), 'Wool industry tweaks standards', *Ecotextile News*, **15**, June, 28.

DEFRA (2000), 'Consumer products: green claims code', http://www.defra.gov.uk/environment/consumerprod/gcc/index.htm, accessed 11 February 2009.

DEFRA (2008), 'M&S leads – legislation may follow', *Ecotextile News*, **14**, May, 29.

DRAPER S, MURRAY V and WEISSBROD I (2007), 'Fashioning sustainability', http://www.forumforthefuture.org/files/Fashionsustain.pdf, accessed 10 February 2009.

EIPPCB (EUROPEAN INTEGRATED POLLUTION PREVENTION and CONTROL BUREAU (2002), *Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques for the Textiles Industry*, VD/EIPPCB/TXT BREF FINAL, November.

EU (2007), 'A database of green suppliers', *The Flower News*, **2**, 4, http://ec.europa.eu/environment/ecolabel/pdf/flower_news/2007_oct/flower_0207_en.pdf, accessed 30 April 2008.

EU REGULATION (2006), *Registration, Evaluation and Authorisation of Chemicals*, Regulation No. 1907/2006, http://eur-lex.europa.eu/JOHtml.do?uri=OJ:L:2007:136:SOM:EN:HTML.

FERRATINI S (2008/2009), 'UN develops EU eco-label plan', *Ecotextile News*, **20**, December/January, 36.

FRANKLIN ASSOCIATES (1993), *Resource and Environmental Profile Analysis of a Manufactured Apparel Product – Life Cycle Analysis (LCA): Woman's Knit Polyester Blouse*, Franklin Associates, Kansas, USA.

GABI (2009), 'New database on fabrics and processes in the textile finishing industry available', http://www.gabi-software.com/fileadmin/user_upload/database_textile_finishing_01.pdf, accessed 29 January 2009.

GRAY D (2009), 'The free ride on the sheep's back is over', *The Age*, 31 January, Business Day, 1.

INTERNATIONAL WOOL TEXTILE ORGANISATION (2009), http://www.iwto.org/WhyWool/WoolHistory.htm, accessed 29 January 2009.

KALLIALA E and TALVENMAA P (2000), Environmental profile of textile wet processing in Finland, *Journal of Cleaner Production*, **8**, 143–154.

KANWAR P (2008), 'The EU sets the standard', *SGS Consumer Compact*, **III**(4), 2, http://newsletter.sgs.com/eNewsletterPro/uploadedimages/000006/ConsumerCompactNewsletterJanuary2008.Pdf, accessed 30 April 2008.

KARP E (2008), 'I can eat it, I clean with it – now do I have to wear it?', *Ecotextile News*, **18**, October, 39–41.

KELLY B (2008), 'Life cycle analysis the key to meeting eco demands', *Wool Record*, January, 28.

LAURSEN SE, HANSEN J, BAGH J, JENSEN OK and WERTHER I (1997), '*Environmental Assessment of Textiles*', Environmental Project No. 369, Ministry of Environment and Energy, Denmark.

LENZING GROUP (2008), http://www.lenzing.com/images/lenzing_kk/NH_Brosch_EN_2008_SCREEN.pdf, accessed 30 January 2008.

LI L and SUN G (2007), 'Policies and measures on energy efficiency improvement and renewable energy development', www.oecd.org/dataoecd/15/52/38332844.pdf, accessed 11 February 2009.

LYONS B (2008), 'Positioning Australian Merino as an environmental and ethical fibre of choice: the challenges of life cycle analysis for a natural fibre', In RITE Conference, London, 7 October 2008.

MELLO F (2007), 'Top labels spy a stylish edge in carbon labelling', *The Age*, 17 September, http://www.theage.com.au/news/business/top-labels-spy-stylish-edge-in-carbon-labelling/2007/09/16/1189881340189.html, accessed 30 April 2008.

MEYER WS (1997), 'Water for food – the continuing debate', http://www.clw.csiro.au/publications/water_for_food.pdf, accessed 11 February 2009.

MOHR T (2005), 'Reputation or reality? A discussion paper on greenwash & corporate sustainability', www.greencapital.org.au/index.php?option=com_docman&task=doc_download&gid=12, accessed 23 April 2008.

MORRIS D (2008), 'The carbon challenge for textile fibres', *Ecotextile News*, **16**, July, 30.

PAILLAT B (2008), 'Eco-levy on clothes to boost recycling', *Ecotextile News*, **17**, August, 36.

REUTERS (2008), 'Lake pollution could hit deliveries', *Ecotextile News*, **6**, July, 10.

TRIVEDI B (2008), 'Kangaroos to the rescue', *New Scientist*, 20/27 December, 48.

WASTE ONLINE (2004), http://www.wasteonline.org.uk/resources/InformationSheets/Textiles.pdf, accessed 10 February 2009.

WISEMAN LA (1981), 'Oil and the textile industry', *Textiles*, **10**, 24.

WOO PN (2008), 'RITE Conference energises industry', *Ecotextile News*, **19**, November, 20.