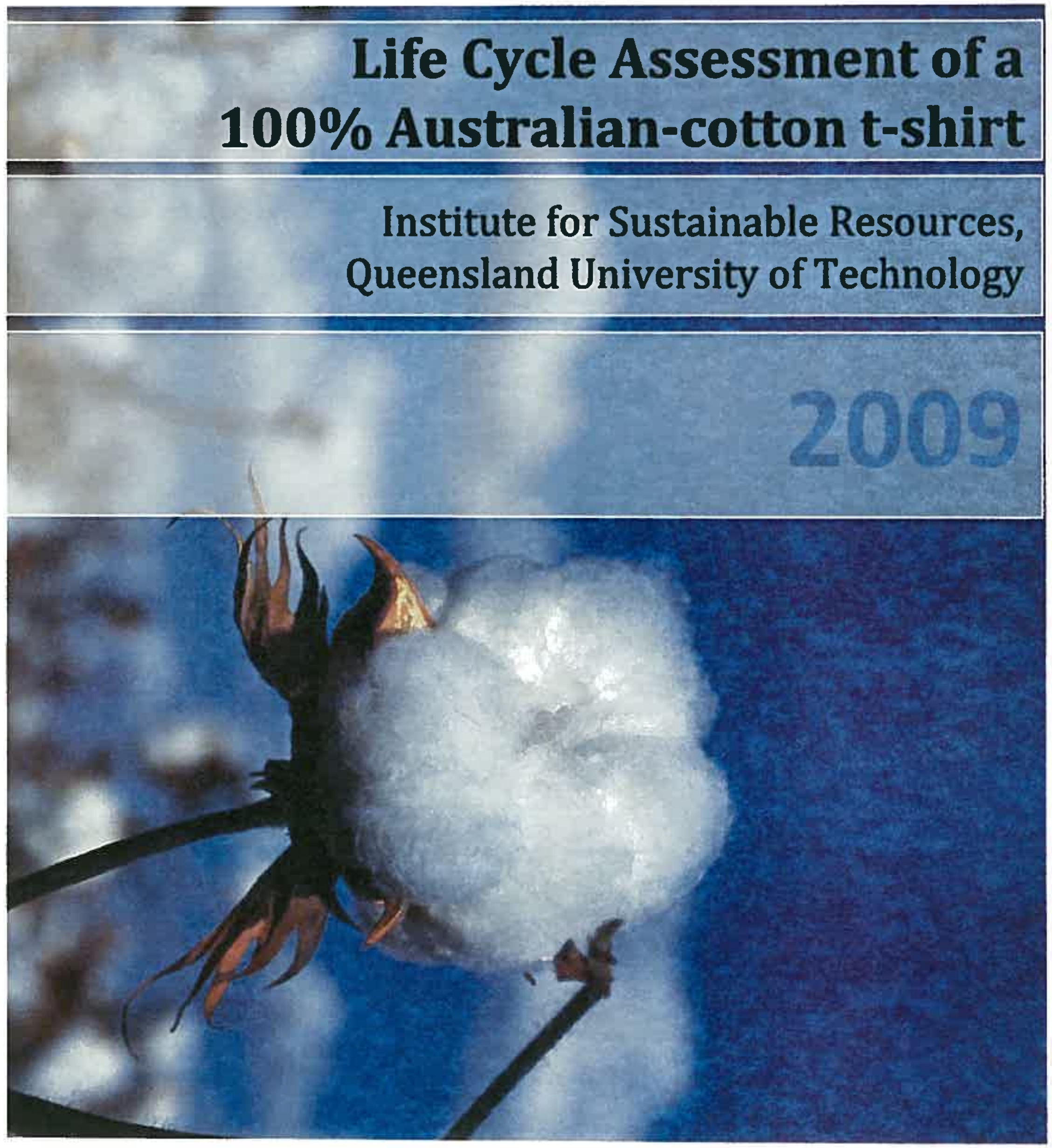
Life Cycle Assessment of a 100% Australian-cotton t-shirt

Institute for Sustainable Resources, Queensland University of Technology

2009



QUT2

Institute for Sustainable Resources
Level 3, D Block
Queensland University of Technology
Gardens Point Campus
GPO Box 2434
BRISBANE QLD 4001
Email: fi.navarro@qut.edu.au
Phone: (07) 3138 1904
Fax: (07) 3138 4438

Director: Professor Peter Grace

QUT isr Institute for Sustainable Resources

Life Cycle Assessment of a 100% Australian cotton T-shirt

Undertaken by the

Institute for Sustainable Resources

Queensland University of Technology

for

Cotton Research and Development Corporation

November 2009

QUT isr
Institute for Sustainable Resources

Acknowledgements

We would like to thank Stuart Gordon from CSIRO Materials Science and Engineering in Victoria for the essential data on cotton manufacturing and his advice. Many thanks to Greg Constable (CSIRO) and Mick Foster (Auscott) for their advice and to Craig Baillie and Guangnan Chen for their help and data on Australian farms greenhouse gas emissions. We are also very grateful to Jannick Højrup Schmidt and Frede Hvelplund (Aalborg University) and Kim Christiansen (LCA 2.0 Consultants) for their most valuable input and advice on this report.

Finally, very special thanks to Bruce Pyke and Helen Dugdale from the Cotton Research & Development Corporation for their funding and help throughout the project.

Table of contents

Figures and Tables

Part 1 - Introduction

Title: Life cycle assessment of a 100% Australian cotton T-Shirt

Prepared for:

The Cotton Research and Development Corporation
2 Lloyd Street (PO Box 282)
Narrabri NSW 2390

Purpose:

The Queensland University of Technology (QUT), through the Institute for Sustainable Resources (ISR), aims to identify the environmental footprint of a cotton t-shirt throughout its life cycle using a cradle-to-grave approach. Life Cycle Assessment methodology was chosen as it is a scientifically sound and quantitative analysis framework.

Institute for Sustainable Resources
Queensland University of Technology
2 George Street (GPO BOX 2434)
Brisbane QLD 4001

Key Research Team:

Professor Peter Grace – Research Director, ISR
Michelle Gane – Project Manager, ISR
Francisco Javier Navarro Garcia – Researcher, ISR

1.1 Cotton Research and Development Corporation

The Cotton Research and Development Corporation (CRDC) is a partnership between the Australian cotton industry and the Australian Government. The role of the CRDC is to invest in research and development specifically intended to achieve economic environmental benefits to the industry, regional communities and the nation, ensuring the Australian cotton industry is globally competitive and responsible.

1.2 Research scope

The purpose of this research report is to analyse and evaluate the greenhouse gas (GHG) emissions from the production, use and disposal of an Australia grown, 100% cotton t-shirt when compared against the production, use and disposal of a 100% polyester t-shirt using a Life Cycle Assessment (LCA).

Determining and understanding where these emissions occur will assist in reducing costs and environmental impacts. This report provides recommendations on the necessary reforms to achieve more efficient and sustainable production, use and disposal of a cotton t-shirt.

The product analysed is a short sleeve everyday t-shirt.

This report will address the following questions in particular:

- What are the environmental impacts in the production, use and disposal of 100% Australian cotton t-shirts sold in Australia?
- What opportunities exist to reduce environmental impacts during the production, use and disposal phases?
- What are the limitations in existing ready-made impact assessment methods? What future research would assist in developing assessment methods applicable to Australian environmental conditions.
- Which product is more greenhouse-friendly: A 100% Australian cotton t-shirt or a 100% polyester t-shirt?

1.3 Limitations

LCA offers a systematic way to analyse and communicate complex environmental information. The Society of Environmental Toxicology and Chemistry (SETAC) and the International Organisation for Standardisation (ISO) have made significant contributions in the creation of a uniform LCA methodology. That effort was fuelled by serious concerns in the early years of LCA about its inappropriate use in marketing.

LCA performed under a standard methodology (ISO 14040), should be sufficient to overcome scepticism about objectivity and outcomes. However, the lay reader can still become sceptical of the results unless informed about interpreting the information correctly. Baumann and Tillman (2004) explain that LCA results only make sense in the context set by the product or project goal and scope definition. LCAs typically start with a very broad question such as 'which product is better?'. But as the question becomes more specific, precise decisions need to be made about what actually will be assessed.

> *"There is no such thing as stand-alone LCA results, only LCA results in relation to a goal definition with a specific purpose. An LCA tries to answer certain questions, and methodology is chosen to answer the questions posed. Other choices of methodology lead to other numerical results and usually mean that answers are given to other questions." (Baumann & Tillman 2004)*

The critical choices of methodology, *definition of functional unit, system boundaries and allocation procedure, type of data used* and *impact assessment*, are presented in Part 5 of this report. They form the basis for correct interpretation of the results.

Part 2 - Introduction to LCA

The accountability and reduction of GHG emissions is fast becoming an essential business practice for all industries. Companies and industries are increasingly marketing (or wanting to) market their products or services as 'green', 'low emission' and 'carbon friendly'. To do so in a credible and reliable manner requires a complete understanding about the total impacts and costs of the product on the environment. From raw materials and manufacturing through to distribution, use and ultimately disposal. One internationally recognised approach to evaluate the potential environmental impacts of products and services is a Life Cycle Assessment (LCA).

LCA investigates each stage in the life cycle of a product or service and identifies where the highest environmental impacts may occur (Figure 1). By determining where these impacts occur, interventions can be formulated to reduce them and the associated costs. This can lead to more sustainable and efficient production that is less expensive, providing a marketing edge over competitors.

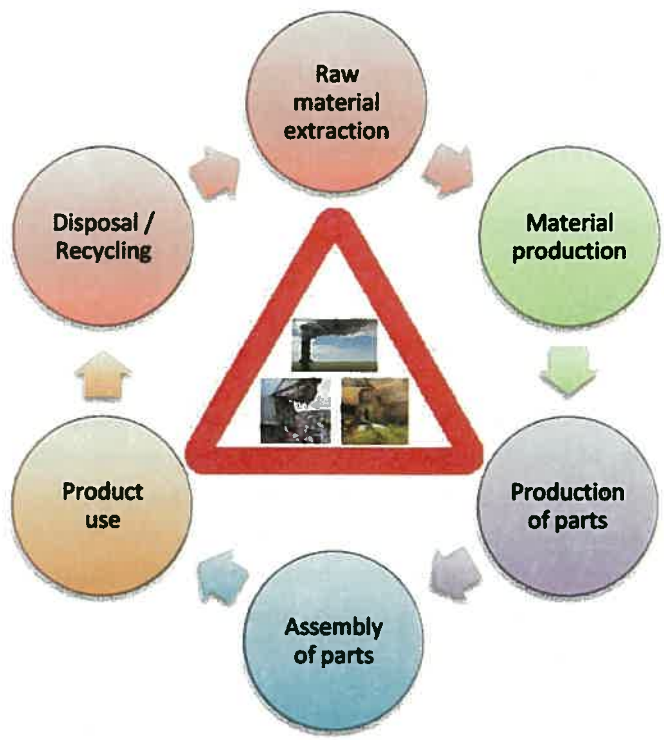


Figure 1. Life Cycle Assessment

LCA also enables the estimation of cumulative environmental impacts resulting from all stages in the product life cycle, sometimes referred to as a 'cradle-to-grave' approach. This allows for the inclusion of impacts that are not usually considered in more traditional analysis, such as resource extraction, material transportation and product disposal.

LCA can provide an estimate of a product's environmental impacts based on scientific, quantitative data. Using Life Cycle Impact Assessment (LCIA) methods, materials or energy flows from the environment to the product's life cycle or vice versa (elementary flows) are translated into potential impacts to the environment or human health.

A quantitative approach makes it possible to compare different impacts occurring throughout the product's life cycle, identify those with the greatest impact and how the impacts relate to the product or service. Similarly, LCA allows for product comparisons to be performed, which is why industries, governments and individuals are using it as the preferred method.

LCA uptake has grown rapidly and with this specialised software and databases have emerged.

The databases provide large amounts of reliable data on the elementary flow exchange associated with other industrial processes, including energy production and distribution, raw material extraction and processing, transport and the production and processing of other products. The availability of such data makes it possible for the practitioner to include impacts of background processes that are indirectly related to the analysed product, thus achieving a much more realistic base for the analysis.

The databases used in this study are:

- ECOINVENT v2.0
- Australian LCA Database (2007).

Ecoinvent is an internationally recognised LCA database that contains data on thousands of industrial activities. Although it does not provide any site-specific data, a limited amount of country-specific data can be accessed. The strength of this database is its reliability, the amount of information available and its usefulness. Country- specific (Australian) LCA databases are based on the Ecoinvent framework. The Australian LCA Database (2007)includes a limited amount of industrial processes but the fact that it provides Australian data is a major strength.

LCA has the potential to objectively evaluate the impact of products and services on Australia's environment. Provided that the LCA science keeps advancing at the rate that it has in the past, it will continue to be one of the preferred environmental assessment tools in the future.

2.1 Types of LCA

There are two types of LCA that can be used depending on the question being asked:

1. 'Attributional' LCA (or 'Accounting' LCA)
2. 'Consequential' LCA (or 'Change-oriented' LCA)

Attributional LCA answers questions of the 'What environmental impacts is this product responsible for?' type, by collecting ***retrospective*** average data on all the processes involved in the product's life cycle and adding up their outcomes.

Consequential LCA follows a different approach. It handles questions of the "If production increases or decreases, how would this affect the environment?" type, by using ***prospective*** market data and marginal data (data from the most competitive/flexible suppliers and technologies).

Example 1 – Cotton exports

Attributional LCA: Australia currently exports cotton to, among others, China, Indonesia, Thailand and Korea. Transport processes will be modelled by averaging the transport data to all importers (distance, means of transport etc.). Manufacturing data used will be the average for all importers.

Consequential LCA: An increase in Australian cotton production will not be met by a proportional increase in demand by all the importing countries. Only the country best positioned to increase its production will respond (Weidema 2003), that is, China. Therefore, transport processes will be modelled using transport data to China. Manufacturing data used will be data that resembles Chinese production.

Example 2 – Energy use

Attributional LCA: Australia obtains energy mainly from coal (44%), crude oil (34%), natural gas (17%), hydroelectric (1%) and biomass (5%). Energy production processes will be modelled on the above energy proportion.

Consequential LCA: Even though there are a variety of energy sources, the marginal source for Australia is coal. If Australian cotton production increases, so will energy consumption. In this case, the technology most capable of meeting this increase in demand is coal. Therefore, energy production processes will be modelled using data from coal energy.

Attributional LCA treats all suppliers and technologies as equally relevant; therefore they must all be included in the model. Consequential LCA, on the other hand, uses market data to determine which suppliers/technologies are more competitive (marginal) and thus readier to meet changes in demand. The kind of market data used in consequential LCA spans political issues, availability of raw materials, constraints to growth, and different production factors.

> *Throughout the life cycle, only the most competitive (marginal) suppliers/technologies will be affected by an increase/decrease of production of the analysed product. Therefore, only their environmental impact is relevant.*

Another way to classify LCAs is according to their level of detail:

1. Conceptual LCA
2. Screening LCA
3. Detailed LCA

A *conceptual* LCA is a relatively simple and fast assessment of environmental impacts on qualitative data. It is usually the first step when examining advantages, disadvantages and uncertainties for an existing or new product. It is not appropriate for public dissemination of results as no detailed information analysis has occurred (Thrane & Schmidt 2007).

Screening LCAs comprise mostly quantitative data and assess one or more environmental impacts without the need for consistency checks, uncertainty analysis or sensitivity analysis.

Data collection in *screening* LCAs can be limited to a few parameters, resulting in studies that can take a few weeks to several months, depending on the goal and scope. *Screening* provides a significant degree of freedom regarding the number of impacts analysed and the amount of detail and data to collect.

In contrast, a *detailed* LCA must include extensive and detailed information. Specific data quality requirements exist such as assessing a large number of impact categories, undertaking uncertainty and sensitivity analysis and to having the results peer reviewed (Thrane & Schmidt 2007).

Finally, LCAs can be standalone or comparative. When an LCA is used for a comparison between two products, the standard requirements are equivalent to undertaking a detailed LCA. ISO 14040 introduced this requirement in order to reduce scepticism surrounding LCA's objectiveness and outcomes, and thus protect its reputation.

2.2Phases of an LCA

The LCA framework consists of four phases:

1. Goal and scope definition:
   Where the study's intended application is declared and the methodological choices justified.
2. Life Cycle Inventory Analysis (LCI):
   The data of physical exchanges between the system analysed and the environment is gathered, processed and analysed. The result of this phase is a *very* long inventory of environmental loads (resource use and pollutant emissions) of the system.
3. Life Cycle Impact Assessment (LCIA):
   Where the extensive inventory data is aggregated to a number of impact categories such as climate change, resource depletion, land use, toxicity and eutrophication to ease interpretation. The aggregation is based on scientifically-proven physico-chemical mechanisms of how the different substances contribute to the different impact categories.
4. Interpretation:
   Results are explained in relation to the chosen goal and scope. In any LCA results are not absolute, they depend on the methodology chosen in the goal and scope phase. These choices must be justified.

2.3 LCA methodology used

This research report uses the Danish LCA methodology as described in Weidema (2003), which is based on the LCA standard (ISO 14040) (Figure 2). It is discussed in further detail in Part 6.

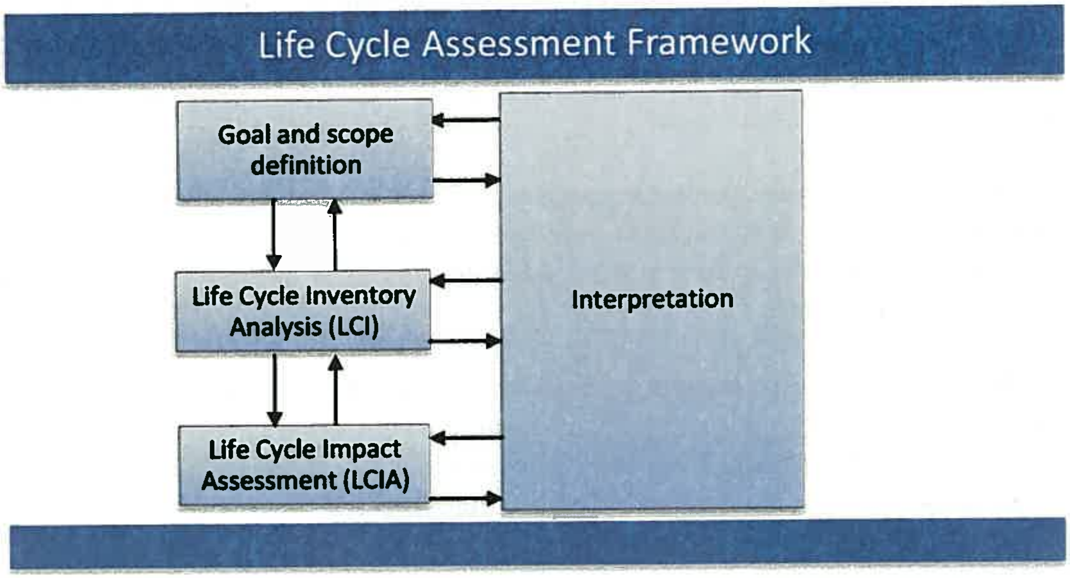


Figure 2. ISO 14041 LCA Standard

Part 3 - Summary of Australia's environmental challenges

The following section is a brief introduction to some of the environmental challenges that Australia is dealing with and will be facing in the coming decades. Ideally, all the main challenges should be addressed in a detailed LCA.

Despite its status as the second driest continent in the world (Antarctica is the driest), Australia is rich in natural resources. Since European settlement, Australia has been highly effective at exploiting its natural resources — the agriculture and mining sectors contribute over 50% to our nation's exports.

The public's concern with environmental issues is higher than ever and the community is demanding better environmental protection and management. Increasing pressure is being applied to governments and landholders to implement sustainable land management practices. The Australian Government Treasury recently considered natural resource degradation to be a serious economic issue.

It is widely accepted that the most important environmental challenges for Australia in the coming decades fall into the following categories (ACF 2008; DEWHA 2008):

- climate change
- water availability and water system health
- biodiversity preservation (including both animal species and remnant vegetation)
- land clearing and land use.

What makes these challenges important is that they are all inter-related (Figure 3).

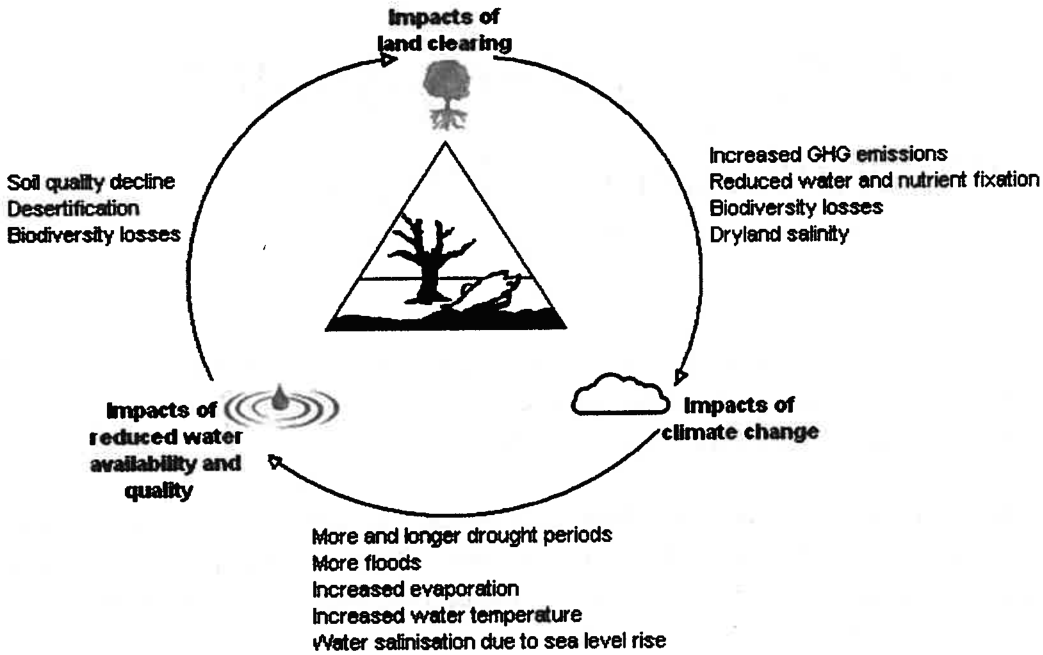


Figure 3. The inter-related environmental challenges that Australia faces

3.1 Climate change

Climate change has emerged as a new priority for Australian agriculture. Concentrations of GHG in the atmosphere are continuing to increase as a result of human activities on a global scale. As a result, the Australian climate will be warmer, mostly drier, and is likely to be subject to more extreme weather events. The occurrence and intensity of droughts will increase, decreasing the soil's water and nutrient absorption capacity. At the other end of the scale, heavy rainfall periods are expected to increase with associated flooding. Flood events will have a greater impact as drought events decrease soil water absorption. Increased nutrient runoff into adjoining water bodies, combined with warming temperatures will increase algae growth, reducing water oxygen levels and causing eutrophication.

Reducing the impacts of climate change depends on reducing emissions of GHGs —and agriculture can play an important role. Emissions from agriculture account for up to 30% of the national total (including land-use change and energy used in agricultural production). Importantly, GHG emissions also represent the loss of valuable resources from farming systems. Cost-effective actions to reduce agricultural emissions present opportunities for increasing productivity and financial gains, as well as delivering broad-based environmental benefits.

3.2 Water

Australia is the lowest, flattest and second-driest continent in the world, with (the lack of) water, being the single most important factor affecting land use and rural production. Changes in the physical environment (the abiotic component) can have a direct impact on the living environment (biotic component). The Australian landscape is particularly susceptible to changes in soils, air and water. Land deterioration from wind, water, gravity or temperature are characterised by changes in soil composition, structure and depth, and in watery quality. Accelerated forms of land degradation due to human activities manifest in wind and water erosion, dryland salinity, irrigation salinity and waterlogging, soil compaction, vegetation loss, mass movements of soil, chemical contamination of soil and water, and soil acidification. Water is a significant factor in Australian land degradation processes. However, it is also the most fundamental natural resource commodity in Australia.

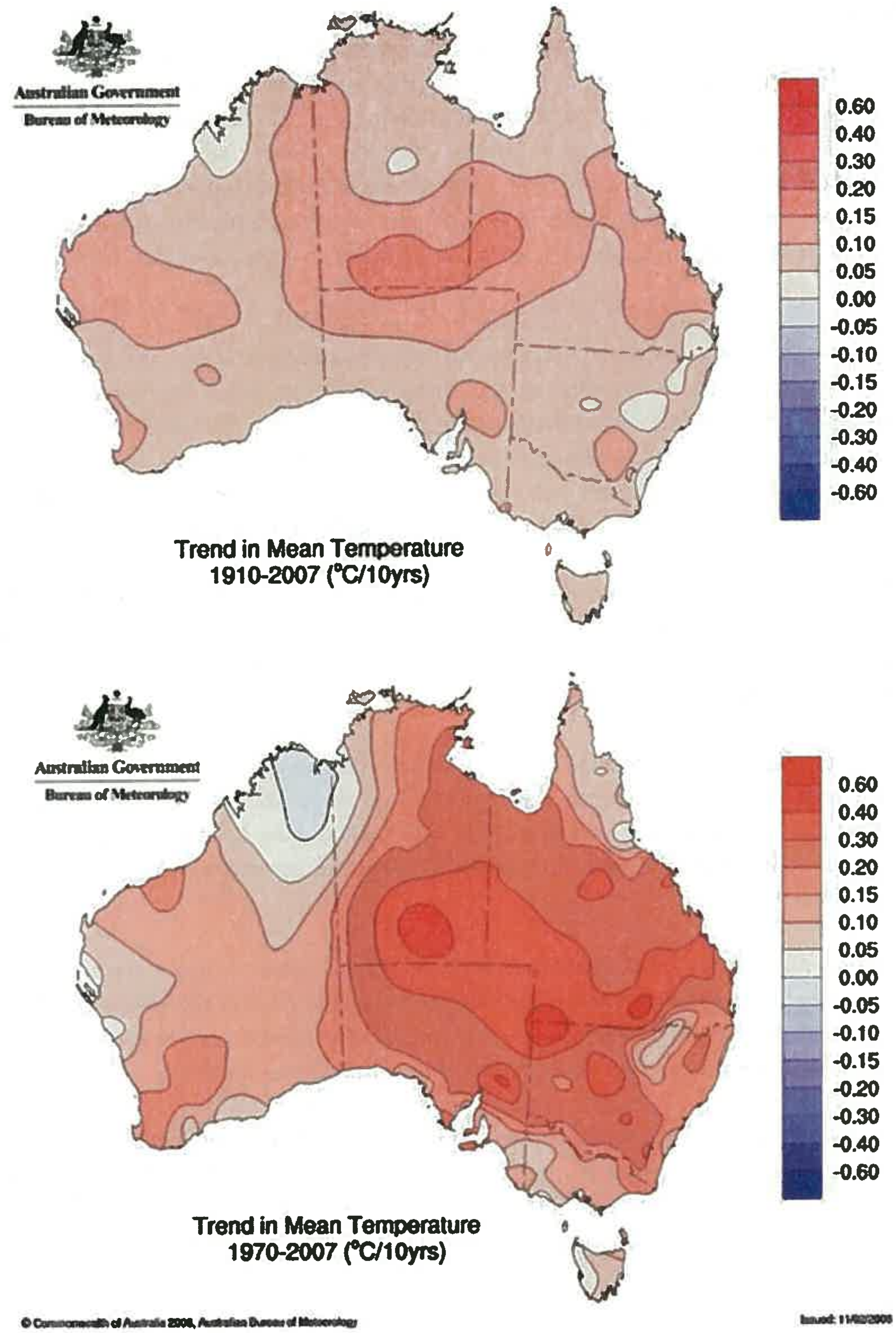
Environmental awareness in Australia has grown significantly since the most recent drought began in 2002. As Australia struggles through one of the worst recorded droughts in its history, major concerns about climate change have been raised. Australia has always had a variable climate and is particularly prone to drought (Quiggin 2007). The severity of droughts, incidence of heatwaves and a decline in the number of cold nights is foreseen to worsen in the following decades due to increases in global GHG emissions.

The trend in mean temperature and annual rainfall across Australia from 1910 to 2007 is outlined in Figure 4. The progress very clearly indicates a trend of increasing mean temperatures and decreased rainfall on the eastern coast, which is where all cotton production occurs.

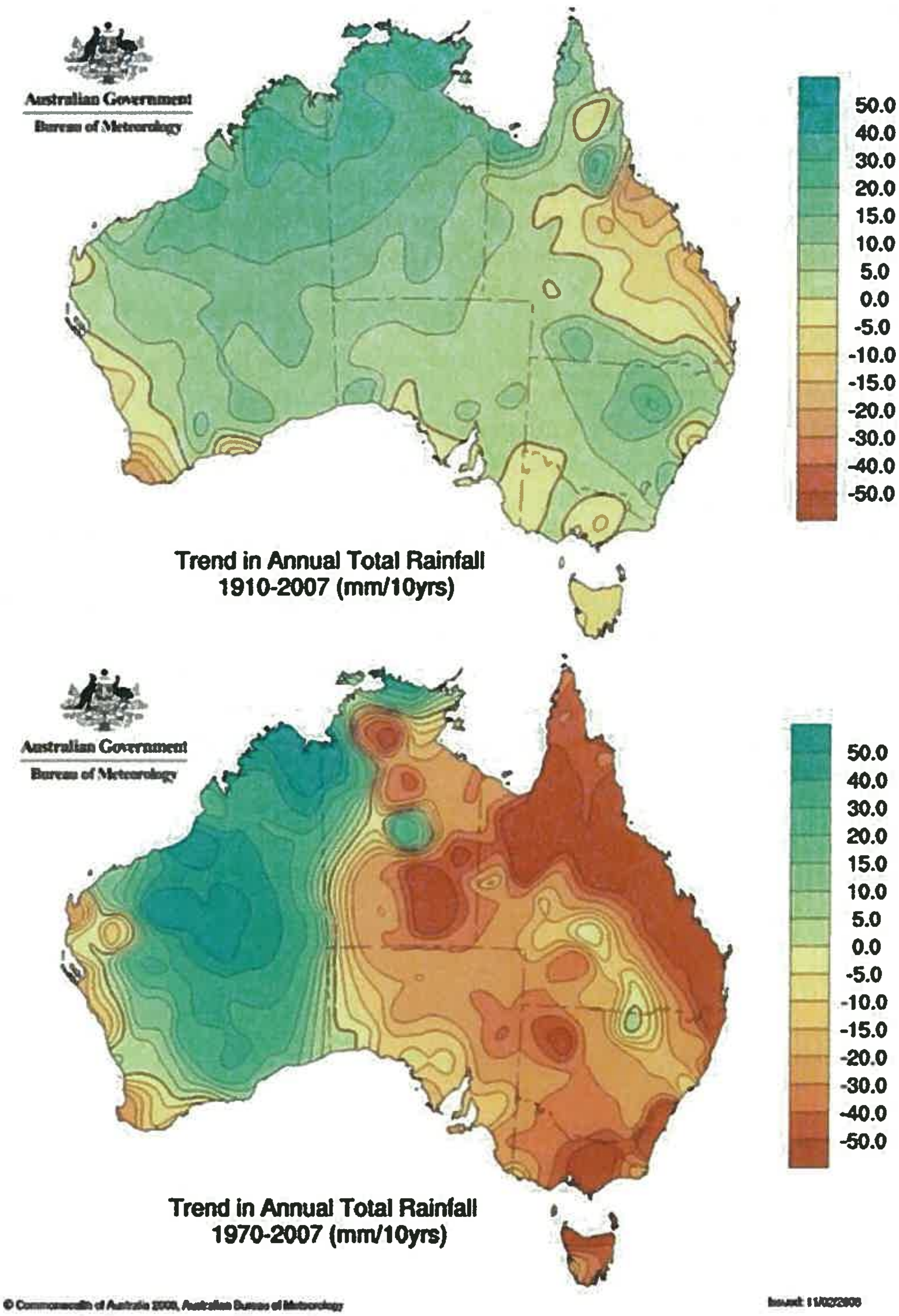
One of the Intergovernmental Panel for Climate Change (IPCC) forecasts is that high rainfall areas will experience even higher rainfall and dry areas will experience even less rainfall (ibid. 2007) (Figure 4). Quiggin (2007) also explains how climate change can affect agricultural production and push food prices upwards, further threatening the Australian public's quality of life.

Overall Australia is a small contributor to global GHG emissions; however, the agricultural sector is the second highest emitter of GHGs for developed countries (McRae el al. 2007). Climate change and the reduction of GHG presents a number of challenges for the agricultural sector, but is also presents a suite of opportunities for producers.

It will be evident in this report, in the case of cotton for textile production, that not all solutions to reduce GHG emissions rest on the production side. In fact, the most effective and efficient solutions rests on the consumer's side.


Australian Government
Bureau of Meteorology
0.60
0.40
0.30
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.30
-0.40
-0.60
Trend in Mean Temperature
1910-2007 (°C/10yrs)
Australian Government
Bureau of Meteorology
0.60
0.40
0.30
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.30
-0.40
-0.60
Trend in Mean Temperature
1970-2007 (°C/10yrs)

(a)



(b)

Figure 4. Trend in mean temperature (a) and annual total rainfall (b) from 1910 to 2007 (McRae et al. 2007)

3.3Land use, land clearing and biodiversity

Biodiversity is under threat from a variety of factors and habitat loss and fragmentation is considered by conservation biologists worldwide to be the primary cause of loss. Land-clearing in Australia is considered to be the single-most important cause of environmental degradation, with depletion of ecological communities and subsequent loss of species. Invasive species, pollution, climate change, population growth and over-exploitation of natural resources also contribute significantly to biodiversity loss (Industry Commission, 1998).

Past land management practices have been responsible for the many of the current environmental problems. Governments have inadvertently contributed to many of these adverse environmental problems, particularly relating to natural resources and agriculture. They have sponsored and encouraged the majority of land clearing in Australia (e.g. the Brigalow Belt Development Scheme —(Seabrook, McAlpine, & Fensham, 2006). Their reasoning was considered to be in the best interests at the second half of the 20th century.

Historically, conservation services in Australia have been provided by the public sector through regulations and the designation of national parks. With only 4% of Queensland registered as some form of protected area, the contribution of private landholders[1] to conservation and environmental management cannot be overlooked. Formal conservation reserves cannot protect the full range of Queensland's biodiversity and ecological systems (Stephens, 2001).

Most of the land clearing in Australia is for land-use transformation from native vegetation to agricultural land. Land clearing contributed to 13% of Australians GHG emissions in 1996.

[1] Land tenure and regulations relating to private land use can have some important impacts on private conservation initiatives because more than 60% land in Australia is privately owned or Crown leasehold land.

Part 4 – Production of polyester

Polyester is a synthetic fibre derived from coal, air, water and petroleum. It is not just a textile but also a plastic made from polyethylene terephthalate (PET), the same material used to make plastic drink bottles.

Polyester fibres are formed from a chemical reaction between acid and alcohol. In this reaction, two or more molecules combine to make a large molecule with a structure that repeats throughout its length. Polyester fibres can form very long molecules that are stable and strong. It is used in the manufacture of many products, including clothing, home furnishings, industrial fabrics, computer and recording tapes, and electrical insulation.

In 1926, the United States E.I. du Pont de Nemours Company began research into large molecules and synthetic fibres. This early research evolved into nylon, the first synthetic fibre. British research chemists also started working with synthetic polymers in 1939 (they later created Terylene). DuPont purchased the manufacturing rights for polyester in 1946 and in the 1950s the new textile became popular. Since then, the company has done extensive research and devised a number of uses beyond textiles. Polyester accounts for 30% of the US market, the single-most used fibre.

Currently there are two primary types of polyester, PET and PCDT (poly-1, 4-cyclohexylene-dimethylene terephthalate). PET, the more popular type, is applicable to a wider variety of uses. It is stronger than PCDT, though PCDT is more elastic and resilient. PCDT is suited to the heavier consumer uses, such as draperies and furniture coverings. PET can be used alone or blended with other fabrics to make clothing that is wrinkle and stain resistant and retains its shape

Polyester fabric is known for its resilient, quick drying (low water absorption) qualities, resistance to biological damage from agents such as mould and mildew, for being easy to wash and holding its shape well. It is also easily dyed and is often spun together with other fibres. Stained fabrics can be cleaned through pre-treatment with special stain-removing substances; however, if this is not done before laundering, there is a serious risk of the stain becoming permanent. Another weakness of polyester is that, if the garment is tumble dried to remove deep wrinkles but not removed from the tumble-dryer as soon as it stops, the fabric will develop extremely difficult to remove wrinkles.

Part of the success of polyester fabric is due to its easy maintenance and crease resistance, which makes tumble drying or ironing unnecessary in most cases (Joseph 1988). Another advantage of the fabric is its durability and abrasion resistance.

4.1 Composition

Although PET is the most typical compound used in the manufacture of polyester, various types of synthetic polyesters are available: polybutylene terephthalate (PBT), polymethylene terephthalate (PTT), polyethylene naphthalate (PEN), and from other fibre-forming polymers polycarbonate (PC), polylactide (PLA) and polyethylene oxalate (PEO). PET is composed of the following raw materials, among other reaction chemicals: purified terephthalic acid (PTA) (Figure 5) [and in about 10% of cases dimethyl terephthalate (DMT), but use of DMT will become insignificant in the next 10 years (Aizenshtein 2006)], and monoethylene glycol (MEG) (Figure 6). PTA's main uses are production of polyester and metal-organic frameworks, whereas MEG is mainly used as an automotive antifreeze liquid and is toxic if ingested.

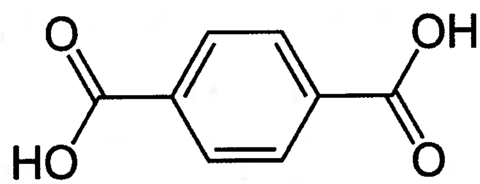


Figure 5. Terephthalic acid molecule

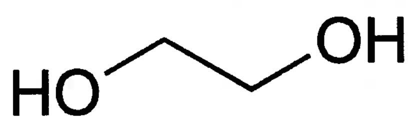


Figure 6. Monoethylene glycol molecule

As a synthetic plastic, polyester originates from refined petrol. In the case of PET, PTA is a petrochemical comprising, among other chemicals, xylene, and requires 0.8 kg of crude oil for each kilogram of xylene produced. The Ecoinvent LCA database indicates that approximately 0.9 kg of PTA and 0.3 kg MEG are required per kilogram of PET.

4.2 Polyester extrusion

Polyester is typically provided in granulate form and can be manufactured by one of several methods. The method used depends on the final form the polyester will take. The four basic forms are filament, staple, tow and fibrefill. In the filament form, each strand of polyester fibre is continuous in length, producing smooth-surfaced fabrics. In staple form, filaments are cut to short predetermined lengths. In this form, polyester is easier to blend with other fibres. Tow is a form in which continuous filaments are drawn loosely together. Fibrefill is the voluminous form used in the manufacture of quilts, pillows, and outerwear. The two forms used most frequently are filament and staple.

In order to obtain fibres, the polyester must be heated until it becomes a viscous liquid and extruded. Extrusion is a process by which a viscous substance is forced through a tiny hole — in this case a tube as fine as a thread — which is quickly cooled. The material retains its new shape. It is the same process by which plastic pipes are manufactured.

The extrusion process results in a long continuous thread (which is needed for certain applications). However, staples are needed for t-shirts and the polyester thread is cut, blended with other fibres if needed and spun into a yarn.

Part 5 – Production of cotton

Cotton is soft fibre that grows out of the seed of the cotton plant. Cotton originates from the tropical regions in Asia, Africa and South America, and it has been used as a textile for thousands of years.

5.1 Basic concepts

When ready to harvest, the cotton plant is comprises several by-products: lint (or fibre), seeds and plant material. Lint is used as fibre for the production of fabrics and textile products. Cotton seeds are most commonly used as animal fodder but also for production of cottonseed oil. The remaining plant material is either removed, or if left in the field to decompose, may need to be treated to avoid the spread of pathogens.

In Australia, lint picking is a mechanical process. It is obviously faster than hand picking; however, seeds and other parts of the cotton plant are also picked up. In order to separate the three products, the 'raw' cotton (the picked up lint + seeds + plant material) are packed and sent to a cotton gin. Ginning is the process of separating cotton lint from the seeds and other impurities. After ginning, the fibres are packed in bales (2.5 kg/bale) and sent to textile manufacturing mills to produce fabrics and textile products.

5.2 Cotton growth in Australia

Australia's main cotton growing regions are on the East coast: Emerald, Darling Downs, McIntyre Valley, Gwydir Valley, Namoi Valley, Macquarie Valley, Bourke, Theodore, Biloela, St. George, Dirranbandi, Menindee, Lachlan, and Murrumbidgee (ANRA 2000) (Figure 7). Investigations are underway to examine the possibility of growing cotton in north Queensland, in the Burdekin catchment area and in the Northern Territory (Roth 2004).

Cotton is normally exported from Brisbane to Shanghai by transoceanic freight (DFAT 2008). The average distance from a cotton farm to Brisbane is 476 km by road.

Figure 7. Australian cotton growing regions

The cotton production model used in this LCA uses site-specific data to reflect the characteristics of an Australian cotton farm. For example, fuel and electricity use data has been obtained from Guangnang Chen and Craig Baillie (2007) from the National Centre for Engineering in Agriculture (NCEA) at University of Southern Queensland (Table 1). Chen and Baillie (2007) analysed 13 Australian cotton producing farms. Note that the average yield in Australia is currently 1800 kg textile per hectare (Roth 2004) or 4,734kg cotton per hectare (because 2.65 kg cotton equates to 1 kg of textile). Also note that the value used for diesel density is 0.85 kg/litre (this is useful because the fuel use in the LCA software is expressed in kg/ha) (Table 1).

Table 1. Fuel use from on-farm operations (Chen & Baillie 2007)

Operation	Fuel use (L/ha)	Fuel use (kg/ha)
Subsoiling + ploughing	25	21.25
Harrowing	8	6.8
Conventional drilling	5	4.25
Fertilising by broadcaster	3	2.55
Boom (tractor) spraying	2.5	2.1
Aerial spraying	0.035	0.03
Picking + stripping	56	47.6
Slashing + pulling	15	12.75

In addition to cotton their data comprises other crops such as sorghum, corn, wheat and chickpea that are used in farm crop rotation schemes. Since cotton-growing farms also plant other crops, a dilemma arises: Are cotton products accountable for the impact caused by other crops in the farm? Cotton is the primary production, but the other rotational crops contribute to maintaining soil quality and provide extra income. Since all the crops are physically and economically related, this LCA has allocated all the impacts to cotton. When it is possible to accurately quantify how much cotton benefits from crop rotation, a different allocation will be justifiable.

The other main source of GHG emissions on a cotton farm is the release of carbon dioxide (CO_2) from soil (normally as a result from tilling). Nitrous oxide (N_2O) is also released from the application of nitrogen-based fertilisers. The average amount of nitrogen applied is 200 kg/ha. The amount of CO_2 released is dependent on the location as different soils contain different amounts of carbon.

The Institute for Sustainable Resources (ISR) has developed a Cotton Greenhouse Gas Calculator[2] that is consistent with the Department of Climate Change guidelines for calculating emissions. The calculator is available on the ISR website and can be used to determine total GHG (including N_2O) (Figure 8).

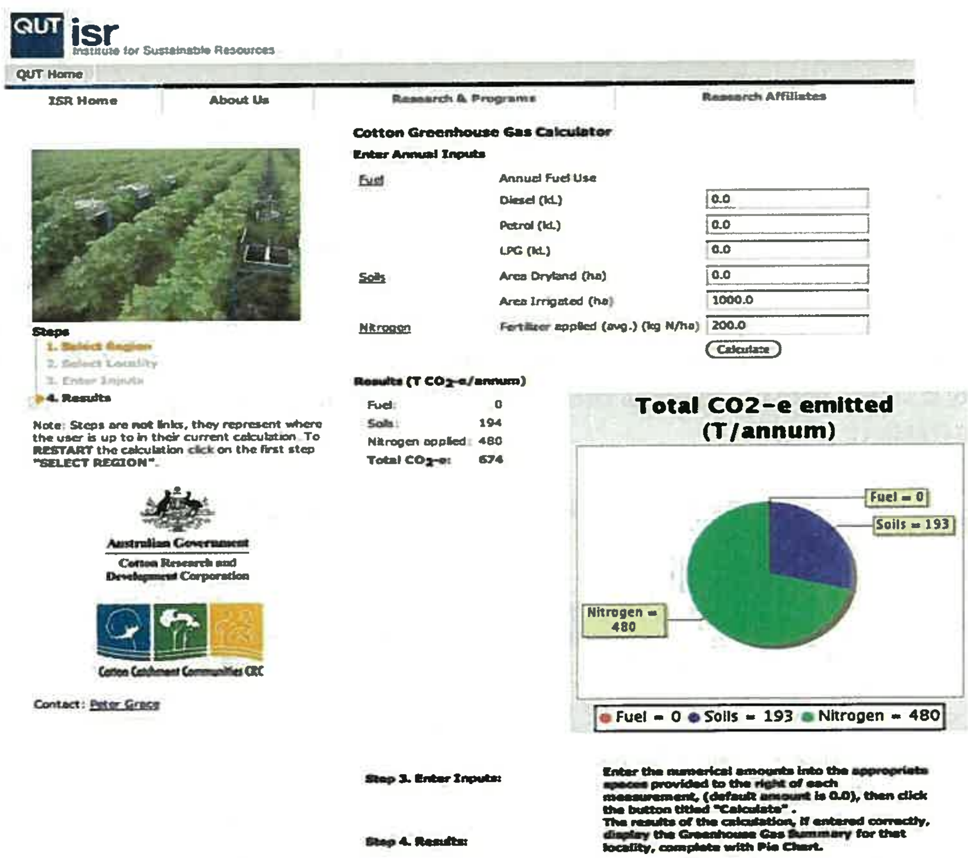


Figure 8. Cotton Greenhouse Gas Calculator

---

2 www.isr.qut.edu.au/tools/index.jsp

Using the calculator, soil carbon emissions from six cotton growing areas (Emerald, Dalby, Goondiwindi, Bourke, Narrabri and Warren) were determined. With a standard application of 200 kg of nitrogen (active ingredient) per hectare, soil emissions equate to 0.376 tonnes CO_2e per hectare or 0.21 kg CO_2e per kg textile.

CottonInc (2007) states that for each kilogram of textile produced, 1.49 kg CO_2e is sequestered and 1.07 kg of oxygen emitted.

5.3 Cotton ginning

As outlined in section 5.1, ginning is the process of separating cotton lint from the seeds and other impurities. After ginning, the fibres are packed in *bales* (2.5 kg/bale) and sent to textile manufacturing mills to produce fabrics and textile products.

Experts agree the output of the ginning process is typically:

- 38% lint
- 50% seed
- 5% moisture
- 7% gin trash (plant material and impurities).

Energy consumption during the ginning process is 0.33 kWh/kg textile. This data has been obtained from CSIRO and includes the transportation from field to gin.

Part 6 - LCA methodology used in this study

LCAs are used for a variety of purposes: decision making at a corporate or national level, marketing, product development and purchasing, identification of improvement possibilities etc. (Baumann & Tillman 2004). Even though the LCA standard (ISO 14040) provides a common methodology, the requirements on it change with the intended application.

Table 2 provides examples of requirements on methodology set by different applications:

Table 2 Requirements on LCA methodology based on intended application

Application	Requirement on methodology
Decision making, choice between alternative actions	Needs to analyse the environmental consequences of different choices (e.g. organic vs. conventional farming).
Market communication e.g. Environmental Product Declaration	Methodology needs to be fair (not deliberately place one of the products in disadvantage). Report needs to be peer-reviewed to ensure credibility. Methodology needs to be highly transparent and report needs thorough documentation.
Product development and purchasing (little time and competence of user of results)	Results don't need high disaggregation.
Decisions on national level	Data used must represent national average
Identification of improvement possibilities, own product	Data must be site-specific

Source: Baumann & Tillman (2004)

Part 6 provides a clear and specific definition of the study's intended application and justification of methodological choices, covering the topics:

- intended application
- choice of functional unit
- choice of impact categories and method of impact assessment
- choice between attributional or consequential LCA
- choice of system boundaries:
  - boundaries with natural systems
  - geographical boundaries
  - time horizon.

6.1 Intended application

This LCA has two main applications (see Table 2, p. 30):

- market communication — to communicate the environmental properties of cotton and in some cases compare them to those of polyester
- identifying possible improvements to cotton production.

Site-specific inventory data has been gathered for identifying possible improvements to cotton production. Only life-cycle impact assessment categories that can be assessed reliably for the Australian environment will be used. The product assessed is a t-shirt made of 100% Australian cotton and sold in Australia.

Since the LCA will also be used for market communication, the functional unit has to enable cotton and polyester to be compared in under the same conditions. For example, cotton's textile quality (in g/m^2) needs to be high so that both products have a similar durability. Similarly, the report needs high transparency and thorough documentation.

The intended audience is primarily the Australian cotton industry and Australian t-shirt consumers. Other important stakeholders are the federal and state governments. The actions that each of these stakeholders could take to reduce cotton's footprint are considered.

6.2 LCA methodology

The level of detail of the assessment can be classified as a screening LCA. This research report uses the Danish LCA methodology as described in Weidema's (2003) report 'Market information in life cycle assessment'. The Danish LCA methodology is consistent with the LCA standard (ISO 14040) and it represents what is generally accepted as best practice in LCA in Denmark, one of the leading countries in the field.

6.3 Functional unit

The functional unit is the purpose of the product under analysis. It determines the basis over which two products are compared or what alternatives to the analysed product are sought (Thrane & Schmidt 2007). The cotton and polyester t-shirts to be compared fulfil a range of functions, including:

- basic clothing
- fashion
- comfort
- freshness
- protection from abrasion
- warmth
- UV protection.

An LCA will only include some of these and the functional unit determines which ones.

The Danish LCA methodology (Weidema 2003) recommends a 5-step systematic definition of the functional unit. A systematic definition is preferred as it enhances the assessment's transparency and analytical soundness. This reduces the amount of subjectiveness and creates more reliable results. Weidema's procedure (2003) uses market information to delimit the functional unit:

1. Describe the product by its properties.
2. Determine the relevant market segment.
3. Determine the relevant product alternatives.
4. Define and quantify the functional unit, in terms of the obligatory product properties required by the relevant market segment.
5. Determine the reference flow for each of the product systems.

6.3.1 Description of product properties and determination of market segments

The product analysed is a short-sleeve everyday t-shirt, defined as one that the user would wear to social events. A t-shirt that is only worn when the image is unimportant (e.g. at home or playing sports), is not included in this definition. The product is defined by its mandatory properties which are that it:

- provides clothing
- provides warmth on torso and shoulders
- has good visual properties, by the consumers' standards
- has high durability.

Durability is defined by the quality of the textile and by the requirement for the product to have good visual properties. If these were not a requirement, then the product would be useful until it literally tore apart. But fashion and social standards determine that a t-shirt is acceptable as long as it looks reasonably new. Laursen et al. (1997) stated that a high quality cotton t-shirt (about 250 g/m^2) can maintain its visual properties for approximately 75 washing/drying cycles. After that, the textile deteriorates and becomes more likely to not be used as an everyday t-shirt.

Mandatory properties define what a t-shirt is. Market positioning properties are the basis to compare the different technologies to create the same product (e.g. cotton and polyester).

It is assumed that the average consumer has sufficient garments, so a single t-shirt is used only once per week. Therefore, a t-shirt would last on average 1.5 years. Even if its physical durability was greater than this, it is argued the user would substitute the t-shirt for newer versions due to the influence of fashion and consumerism.

Market positioning properties are the basis of comparison between different technologies (in this case cotton or polyester). The positioning properties considered here are comfort, freshness and environmental friendliness.

The environmental market is divided into several segments (Weidema 2003). Each segment determines a certain willingness to trade off functionality for reductions in environmental footprint. Weidema (2003) defined three segments: environmentally concerned customers (environmentalist niche), environmentally conscious customers (normal) and environmentally neutral customers (no trade-off). Environmentally concerned customers are willing to have fewer functional products but require them to be more environmentally friendly. Environmentally neutral customers demand increasing functionality regardless of the effect on the environment. Environmentally conscious customers demand reductions in environmental footprints and don't demand an increase in the product's functionality (Figure 9).

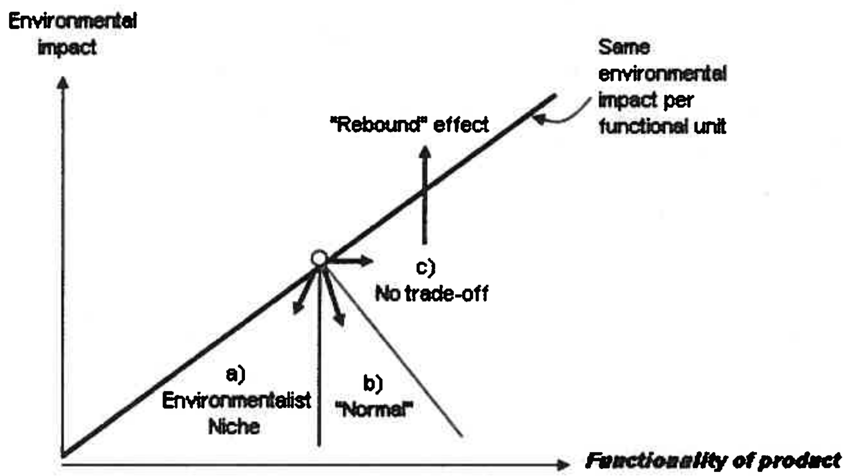


Figure 9. Strategies to gain market share in environment niches (Weidema 2003)

It is assumed that the typical Australian consumers are environmentally conscious customers. This implies that:

- A reduction in a t-shirt's functionality is not a valid way to reduce its footprint.
- Environmental information can make consumers willing to pay more for a product with better environmental properties.

6.3.2 Product alternatives

Any product that complies with the mandatory properties could be compared in this LCA. However, since Australian consumers are environmentally conscious customers, only products that can be perceived as having environmental advantages fall within the scope of product alternatives. Moreover, due to this report's requirements, the scope of comparison is reduced to products with a high market share. Cotton and polyester are the only alternatives that comply with all the requirements. They both occupy a large market share and are direct competitors.

Polyester production is generally perceived to use less water and land area, and is considered more durable than cotton. However, the fact that polyester is a crude-oil-based product is its major weakness. Although cotton production uses larger amounts of water and contributes to land and water quality deterioration due to the use of pesticides, herbicides and fertilisers, it is valued as a natural fibre and seen as a potential GHG sink and source of biomass.

6.3.3 Quantification of the functional unit

The functional unit is defined as:

75 wears of an everyday t-shirt, once a week, for 1.5years.

For polyester and cotton technologies to be comparable, the cotton t-shirt must be of high quality: 250 g/m^2 (Laursen et al. 1997). The quantification of the functional unit is done on the basis of the defined mandatory properties; therefore comfort and freshness are beyond the scope. The basis for the quantification of the functional unit can be found in section 6.3.1.

6.3.4 Reference flows

The reference flow is the amount of product needed to deliver the performance described in the functional unit (Weidema 2003). The functional unit is based on the performance of one 100% cotton or one 100% polyester t-shirt. Even though a 100% polyester t-shirt can last longer due to the fabric's durability, it is likely that after 1.5 years of weekly use, the t-shirt would no longer be considered an everyday garment for other reasons (e.g. fashion consciousness or boredom with product). Therefore, for most of the analysis, a cotton and a polyester t-shirt deliver the same performance

However, part of the analysis will examine the possibility of washing clothes less frequently, at lower temperatures, using environmentally friendly detergents, hang drying them and avoiding ironing when possible (Allwood et al. 2006). Washing clothes less frequently is not equally viable using both technologies (cotton and polyester) as discussed in the following paragraphs. Therefore more polyester t-shirts will be needed to equal the functionality of one cotton t-shirt. Until recently, Research and published literature has paid very little attention to odour intensity of worn garments, the mechanisms involved in its creation and the differences between fibres. However, McQueen et al. (2007a; 2007b; 2008) have published several detailed articles on odour retention and intensity in apparel fabrics. They compared odour intensity for a variety of fibre types and fabric structures to find out which fibre/fabric properties control odour release.

Their research is important because the current tendency is for producers to control the creation of axillary odour (relating to the armpit) on garments through anti-bacterial treatments applied during textile manufacturing. Such treatments alter the users' natural micro-flora and pose a public health risk because they are linked to the emergence of antibiotic-resistant bacterial strains. It is imperative to find natural ways to control odour intensity.

McQueen et al. (2008) found that odour release is mostly related to the chemical structure and physical morphology of the fibre. High intensity odour is related to polyester fabrics, whereas odour in cotton or wool fabrics is much less intense (McQueen et al. 2008). Polyester is highly hydrophobic-oleophilic, so the fabric attracts grime or stains without adsorbing them (that is, the stain sits on the surface of the fabric). Odour is a by-product of bacteria. Bacteria are too large to penetrate into fibres, but their 'food' (the grime or stain) is sitting on the surface and available to be metabolised into odorous compounds (McQueen et al. 2008). Cotton avoids this problem by absorbing the moisture and grime *into* the fibre, where bacteria cannot reach (McQueen et al. 2008).

Based on the characteristics outlined above, cotton garments could have a higher re-use rate than polyester garments. This report analyses the potential impact of Australian consumers reducing their washing frequency. Several re-use rates have been considered: low (5%), medium (10%) and high (20%) re-use rates. Cotton t-shirts being re-used means more polyester t-shirts are needed to provide the same functionality as cotton t-shirts.

6.4 Impact categories and method of impact assessment (LCIA)

Current LCIA methods assess a wide variety of impact categories, enough to cover all the relevant environmental challenges that Australia will face during the 21st century. As explained in Part 2, LCIA methods relate pollutant emissions and resource consumption to environmental impacts through scientifically-proven, physico-chemical mechanisms. An example of a physico-chemical mechanism is the absorption of infrared light (heat) by different gases present in the atmosphere, which is the basis of the greenhouse effect.

Some environmental impacts are global. This means that differences in the characteristics of local environments do not change how ecosystems or human health are affected. Climate change, ozone layer depletion, the depletion of mineral resources and the depletion of fossil fuels are all global environmental impacts and can be assessed without specific information on local environmental conditions.

Other environmental impacts are site specific. This means that some local environments will be more sensitive to those impacts than others. Therefore, the effect of site-specific impacts is difficult to assess without data on the characteristics of the local environment. Eutrophication, soil and water acidification, photochemical smog, ecosystem toxicity, human toxicity, water balance, soil salination, biodiversity and soil life support functions are all site-specific impacts.

LCIA methods are designed to consider the effects of pollutants in a certain geographical area. This means LCIA methods are useful in that or very similar geographical areas, but not when the site assessed is very different. It would be too costly to create an LCIA method for every possible region in the world. Most existing LCIA methods have been designed for use in Europe. Therefore, existing LCIA methods are useful to assess global environmental impacts in Australia, but not for assessing site-specific impacts (Goedkoop 2005).

An alternative to site-specific assessment would be to disregard the environmental differences due to geography and just assume that in Australia the effect of pollutants is not diminished due to local factors (for example in Australia the health effects of airborne pollution are lessened by a lower population density). Some LCIA methods are global (not site specific), as they assess *potential* impacts rather than actual impacts. The current tendency in LCIA research is; however, to develop site-specific methods in order to assess actual impacts. This will increase LCA's accuracy and reliability.

Site-specific methods for Australia are lacking and there is a tendency to not assess site-specific impacts with global LCIA methods. Therefore, this LCA will only consider the following global impacts until better LCIA methods become available:

- climate change
- ozone layer depletion
- mineral resources depletion
- fossil fuels depletion.

6.4.1 LCIA method used in the analysis

The LCIA model that is used in the analysis is the ReCiPe 2008 model created by Pre consultants in partnership with the CML University of Leiden, the Radboud University of Nijmegen and RIVM in Bilthoven, Netherlands. It is adequate to assess the actual impacts on climate change, ozone depletion and resource depletion for the Australian context.

6.5 Attributional or consequential LCA?

One approach to classifying LCA is as 'attributional' or 'consequential'. Consequential LCA is considered a better approach because it models the production chain in a far more realistic way than attributional LCA. Part 2 explains the differences between both approaches.

The use of consequential methodology has affected the definition of the functional unit (section 6.3) and the following definition of system boundaries.

6.6 System boundaries

System boundaries set the limit between the product's production/consumption chain and the environment. All the processes in the chain can be part of the system, but consequential LCA shows that not all the processes are necessarily relevant because some might not be affected by changes in demand for cotton t-shirts.

Weidema (2003) outlines a procedure to set the system boundaries and to identify which processes are actually affected by changes in demand for the product:

1. Identify the scale and time horizon of the studied change.
2. Delimit the market geographically.
3. Identify the market trend.
4. Identify production constraints.
5. Identify the suppliers/technologies most sensitive to change.

6.6.1 Scale of change and time horizon

The production of cotton t-shirts is a relatively efficient and cost-effective process. It is on that basis that a radical change in technology is not likely to occur in the short term. It is also assumed that any change in the use of cotton t-shirts will be on a small scale and over a long time period. The methodology recommends that, when there is no information to justify the contrary, the default assumption is to consider small changes over long time periods.

6.6.2 Market geographic delimitation, market trend, production constraints and supplier sensitivity to change

Market geographic delimitation

Both cotton and polyester are produced and manufactured in many different countries. An LCA dealing with the general cotton industry would need to distinguish between the different suppliers and identify which of them should be studied; however, this report is only focusing on Australian-grown cotton.

Australian cotton is in high demand as the industry has an international reputation for producing the highest quality cotton (DFAT 2008). Furthermore, the industry is continually working at ensuring Australian cotton is not only of the highest quality, but environmentally friendly, through better land management and reduction of pesticides and herbicides.

1998 statistics show that Australia exported 79% of its cotton production to more than 12 countries. Recent data indicates that 90% of all Australian cotton production is exported, with 38% of export going to China (DFAT 2008)[3] (Figure 10).

---

[3] In 1998, Indonesia was the largest importer of Australia cotton (30%), followed by Japan (20%) and Thailand (10%), together with China in the 6th position (6% of exports). However, in 2006 China has taken the lead as the major importer of Australian cotton (38%), followed by Indonesia (21%), Thailand (15%), Korea (12%), and Japan in 5th position (6%) (DFAT 2008).

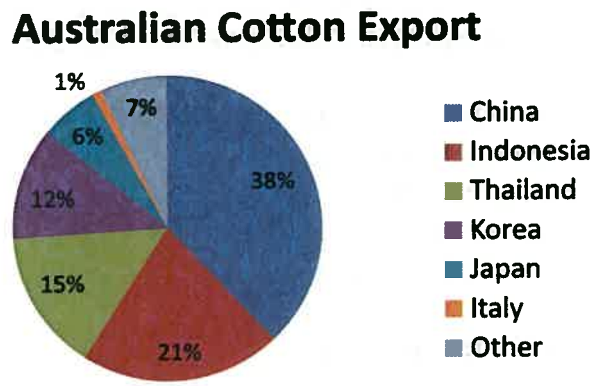


Figure 10. Cotton export by country (DFAT 2008)

Market trend

Australian cotton production in 1998 was 731,000 tonnes of cotton, approximately 7 bales (225 kg) per hectare. 2005 saw the yield grow to 8 bales per hectare, making Australia one of the most efficient cotton producers in the world (Pfeffer 2008).

Throughout the 20th century, Australian cotton has experienced strong market growth and further long-term growth is expected (Figure 11). Particularly given the industry's pro-active implementation of best-practice environmental management as a result of the recent drought.

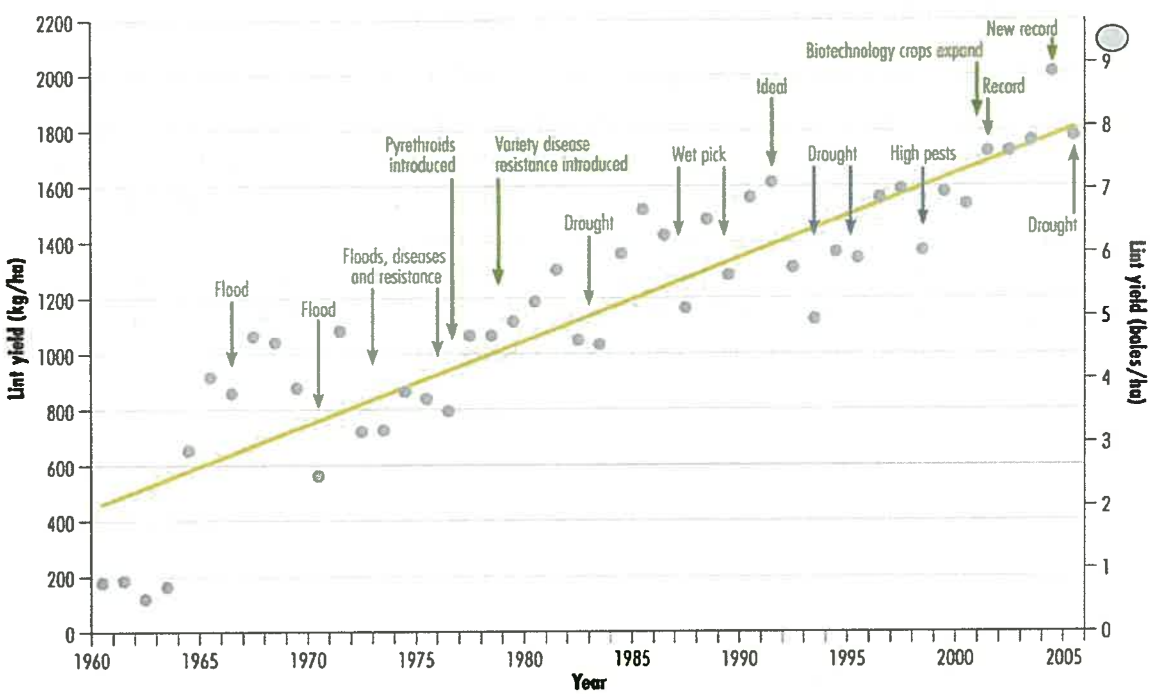


Figure 11. Cotton's market trend (Roth 2004)

Production constraints

There are no production constraints on the Australian cotton industry. If demand increases, cotton producers can increase the area dedicated to cotton farms.

Supplier sensitivity to change

In April 2005, Australia and China commenced negotiating the Free Trade Agreement[4] which will aid in increasing exports to China. Industry experts believe the recent export trend to China will remain, at least for the mid-term. Australian cotton is highly valued in the Chinese market as it is contaminant free, high quality fibre, shipped on time and within a short time frame (18 days) and is produced in accordance with international standards of best practice (DFAT 2008). China's strong demand for importing cotton for manufacture provides a secure, long-term international market for Australian cotton (more so than the domestic market) (Figure 12). China is not only the world's biggest producer of cotton garments, but also the biggest importer of Australian cotton.

The Australian cotton industry chose to focus on only its own footprint for this LCA under the is it chose this scenario that Australian cotton is shipped to China, manufactured into a t-shirt and shipped back to Australia where it is used and disposed of. In reality, Australian cotton fibres are mixed with other fibres of similar quality in the Chinese textile mills. Australian consumers cannot actually obtain a 100%-Australian cotton t-shirt.

Polyester t-shirts sold in Australia also come from China, which produces and manufactures 63% of the world's polyester (Aizenshtein 2006).

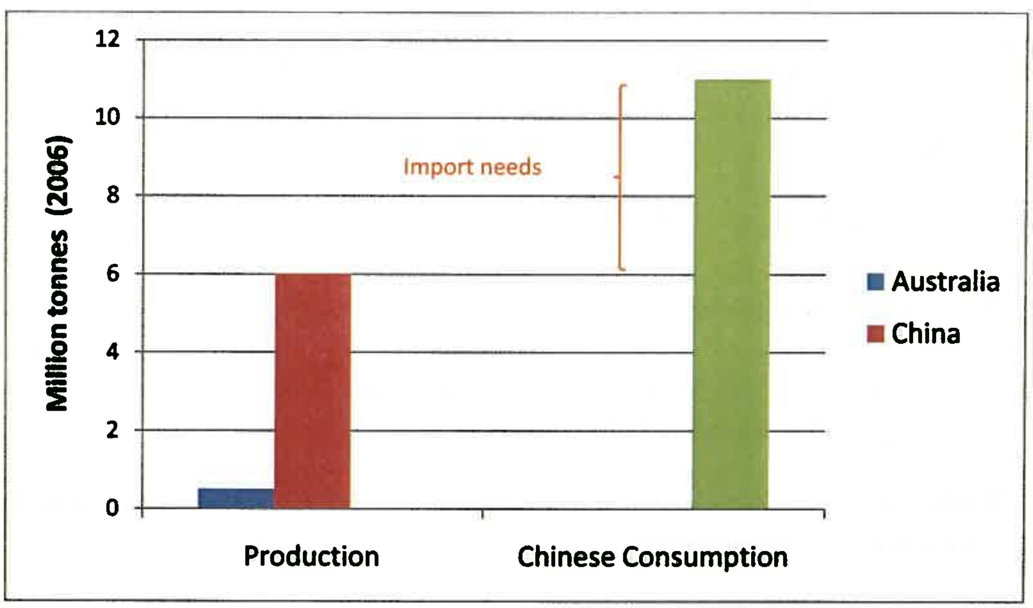


Figure 12. Chinese cotton import needs vs. Australian production (DFAT 2008)

[4] At the time this report was published, they were up to the 13th round of negotiations.

Using the above market data and applying the decision tree found in Schmidt (2008b), this report concludes that:

1. All the processes involved in cotton production are relevant.
2. Cotton growth in Australia would be affected if there was an increase in demand for cotton t-shirts.

6.7 Co-product allocation

Co-product allocation in a multi-output process is the allocation of responsibility for the total environmental burden among the different outputs. ISO 14040 states that allocation should be avoided whenever possible, and when that is not possible, system expansion is the preferred alternative. System expansion is also the mandatory method to deal with co-product allocation in *consequential* LCA and is adopted in this report.

Examples of system expansion can be found in several processes throughout a cotton and polyester life cycle:

- cotton growth: provides a mixture of cotton lint and seed and the plant and roots are a co-product that could be used as biomass
- cotton ginning: separates cotton lint from cotton seeds and removes impurities that become cotton gin trash[5]. Cotton gin trash and cotton seeds could also be used as biomass; however, gin trash is mainly used as animal fodder.
- recycling of cotton plant, cotton seeds, cotton gin trash and disposed t-shirts.

The avoidance of allocation through system expansion is focused on fossil fuel substitution because the main impact categories of the analysis are climate change and resource depletion, including fossil fuel depletion. Product substitution in this analysis is directed towards those applications that can bring the most credit in the relevant impact categories.

6.8 Further LCA work

There are several other very relevant indicators for agricultural LCA that have not yet been integrated or adapted for use in data collection or software packages. Relevant indicators include land use, salination, erosion, water use, biodiversity, human toxicity, eutrophication and soil life-support functions.

A future area for LCA research in the agricultural industry would be to incorporate the categories above into a case study.

---

[5] In Australia cotton is picked with machines. The picking process collects more than just lint, it also collects seeds stuck to the lint and plant material. All the material is packed in bales and sent to the gin, where the lint is separated from the seeds and the unwanted plant material. Any material coming out of the gin that is not lint or cotton seeds is consider gin trash.

Part 7 – Textile manufacturing process and t-shirt use

The t-shirt production scenario used is Australian cotton is shipped to China for manufacturing, processing, and returned to Australia for consumption (refer Part 6). Part 7 explains the textile manufacturing process in detail, including:

- the import of relevant raw materials and energy to China
- the different stages of textile manufacturing.

7.1 Chinese supply of energy, polyester production sites and textile manufacturing sites

In 2004, China was affected by a series of blackouts as the electricity supply failed to meet the demand; there was not enough coal to produce electricity required (BBC 2004). Since then, China has been importing multiple forms of energy from numerous countries; Russia for oil supply, Australia for liquefied natural gas (Foreign Affairs 2005, NY Times 2002). Importing energy impacts climate change due to the emissions caused by raw material transport and the construction of distribution networks.

As mentioned previously, polyester is manufactured from crude oil. China imports oil from Russia through a new pipeline from the Siberian Oil extraction fields to Daqing in north-east China (ChinaOrbit 2008). The approximate distance for the pipeline is 3,872 km (Figure 13). It is assumed that the relevant petrochemicals are manufactured in refineries located in Daqing.

Figure 13. Oil transport from Russia to China

The majority of polyester manufacturing industries are located in JiangSu, south of Daqing, China. Assuming the relevant petrochemicals are transported by rail, the distance is approximately 1,979 km (Figure 14).

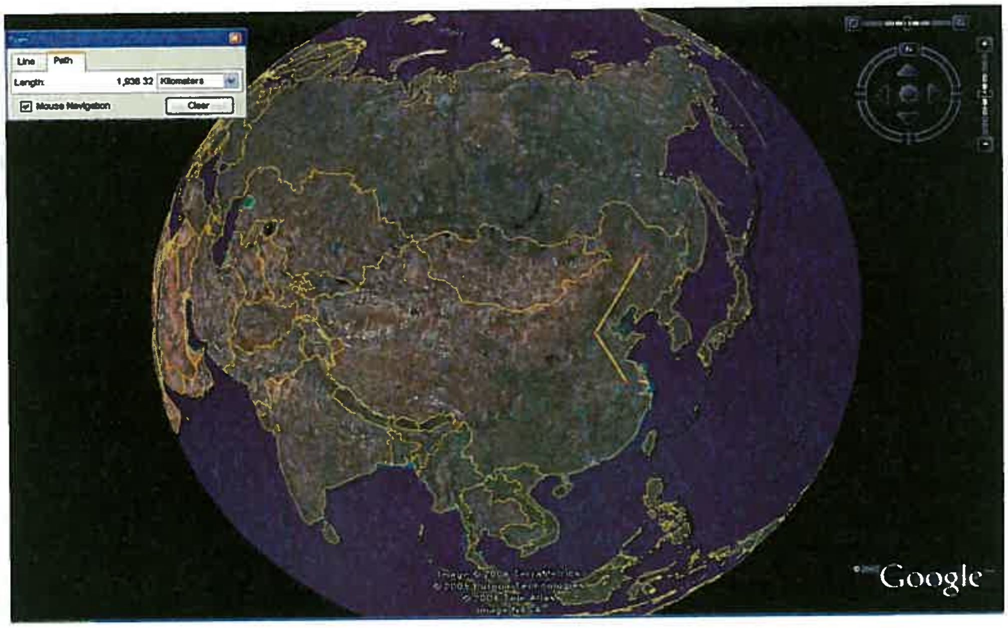


Figure 14. Petrochemical transport from Daqing to Jingsu

From Jiangsu, polyester fibres are transported to the textile manufacturing mills. Polyester and cotton garments are manufactured in the same mills. Australian cotton bales arriving at Shanghai will travel to the same factories (Figure 15).

Figure 15. Location of textile manufacturing companies

The textile manufacturing companies are roughly grouped together. The average distance travelled from Jiangsu or Shanghai to a manufacturing mill is approximately 471 km.

7.2 The t-shirt manufacturing process

The following section provides concise information about the different stages involved in the polyester t-shirt manufacturing chain. The mechanical actions performed and the chemical reactions involved in t-shirt manufacturing, as well as in cotton growth or polyester production, are very complicated and involves more detailed information than is required for this LCA. This section aims to provide the reader with sufficient insight into the steps involved in manufacturing a t-shirt from raw textile material.

The t-shirt manufacturing process consists basically of the yarn formation processes, fabric formation processes, wet processing of the fabric to provide it with colour and/or other properties, and finally t-shirt fabrication processes (Figure 16).

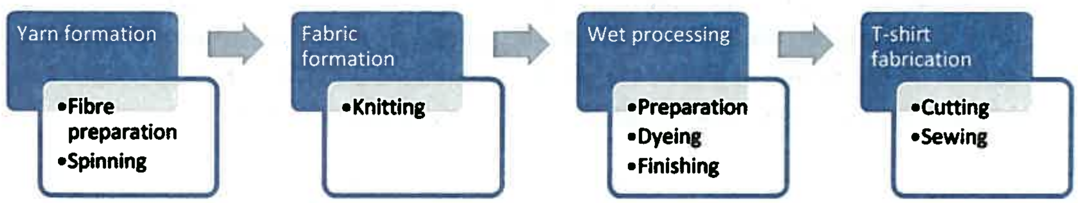


Figure 16. The textile manufacturing process (both for cotton and polyester)

7.2.3 Yarn formation

This section covers the processes of fibre preparation and manufacturing into a single thread that can be later used to create fabrics. The operations involved in this category are: bale opening and optional blending, carding, drawing, roving and spinning (Figure 17).

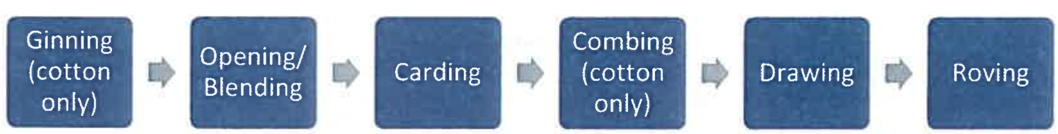


Figure 17. Yarn formation processes

Textile fibres are converted into yarn by grouping and twisting operations used to bind them together. Although most textile fibres are processed using spinning operations, the processes leading to spinning vary depending on whether the fibres are natural or synthetic.

Natural fibres, known as staple when harvested, include animal and plant fibres, such as cotton and wool. These fibres must go through a series of preparation steps before they can be spun into yarn, including opening, blending, carding, combing and drafting. Synthetic fibres may be processed into filament yarn or staple-length fibres (similar in length to natural fibres) so that they can be spun. Filament yarn may be used directly or following further shaping and texturising.

Threads of different fibres can be blended after opening the bales. Carding is the process by which fibres are disentangled, cleaned and arranged in a continuous rope-like thread, commonly known as sliver. In a later process known as drawing, the slivers are stretched and their thickness reduced. This process is sometimes taken further in the roving stage, which produces even thinner slivers with some twist. Finally, the spinning stage takes individual fibres and twists them into a yarn (Laursen et al. 1997).

CSIRO advised that both cotton and polyester are typically manufactured in the same textile mills. Therefore it has been assumed that the energy consumption of the yarn formation processes is the same in both cases: 2.8 kWh/kg.

7.2.4 Fabric formation

There are two main methods for transforming yarn into fabric, weaving (Figure 18) and knitting (Figure 19). Weaving creates tough fabrics that are very resistant but do not feel as soft as knitted fabrics. A good example of woven fabric is denim, whereas t-shirts, blouses, jumpers and other kind of soft clothes are made out of knitted fabric.

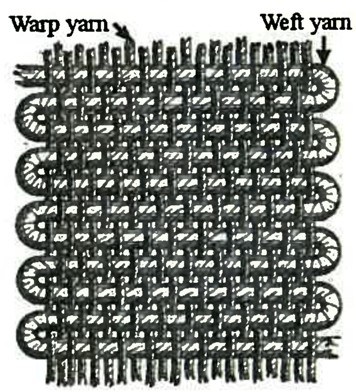


Figure 18. Woven fabric

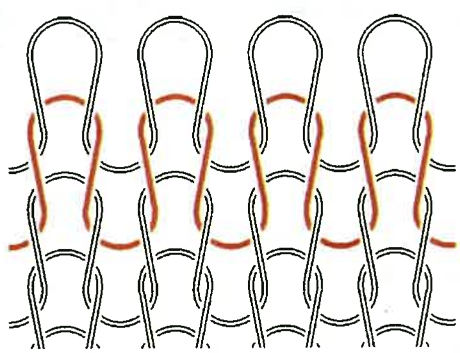


Figure 19. Structure of knitted fabric

Weaving uses a loom to arrange sets of yarn perpendicular to each other. Firstly, one of the yarns is arranged side to side, becoming the warp. The second yarn is passed under and over the different segments of the warp, becoming the filling. The weaving process interlaces warp and filling creating a strong fabric used in products such as cloths, bags and clothing (Laursen et al. 1997).

Knitting is the process when a single yarn is arranged in loops (stitches), which are intertwined with loops that are placed below and above them in parallel courses. Knitting provides a fabric that is much more elastic than woven fabric and is softer, making it ideal for socks, t-shirts, underwear etc.

7.2.5 Wet processing

Wet processing includes all the chemical and mechanical actions performed on the fabric to provide it with even colour absorption capacity, UV protection, softness, anti-odour capacity etc. (EC 2003). Wet processing is a complex process used to finish the fabric and it involves a number of steps (Figure 20).

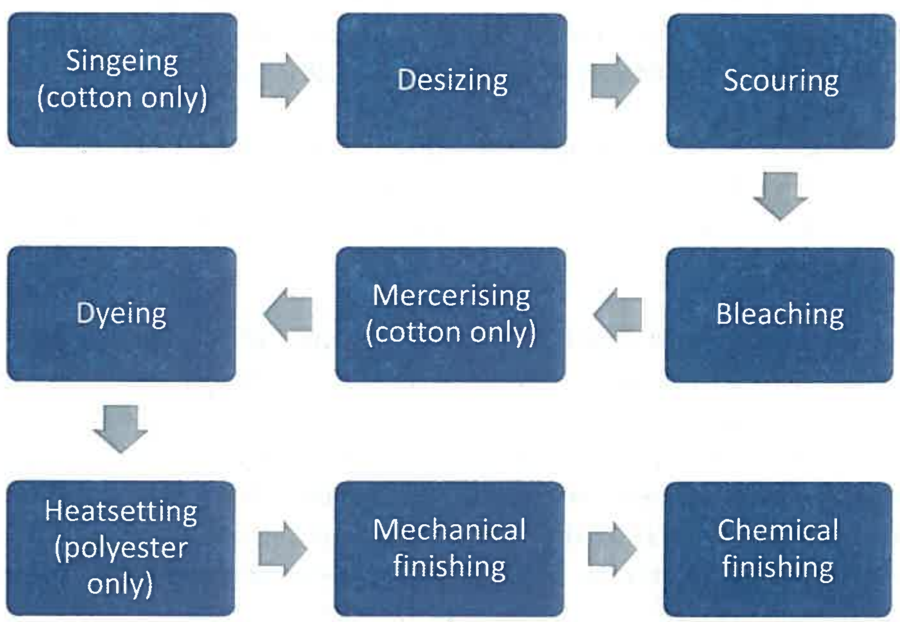


Figure 20. Wet processing steps

Singeing smooths the fabric's surface by removing extra fibres that stick out; it usually involves passing the fabric over a row of gas flames and rapid cooling. Desizing removes the chemicals used in previous stages and that have built up in the fabric. Desizing is achieved by soaking the fabric in one or several solutions, depending on the nature of the chemicals to be removed. Scouring is a similar process that can be performed together with desizing. The fabric is boiled to remove impurities such as fat, waxes, proteins, phosphates, oxides, and remaining chemicals. Bleaching is performed to remove stains prior to dyeing and to improve the fabric's luminosity. Mercerising (in cotton manufacturing only) is meant to improve tensile strength and dimensional stability of the fabric, which also improves the fabric's dyeing efficiency (EC 2003). Heat setting involves heating up the fabric to provide it with further dimensional stability, higher volume, and wrinkle and temperature resistance (Laursen et al. 1997). Finally, chemical and mechanical finishing are used to make the fabric less prone to wrinkling and developing odours, more resistant to flames, softer etc. (EC 2003).

7.2.6 T-shirt fabrication

T-shirts are made from processed fabrics. This is a purely mechanical process in which the fabric is cut into the desired shape and sewn together. No chemicals are involved apart from those used in machine maintenance. The main environmental impact of fabrication is the use of energy and generation of textile waste (Laursen et al. 1997).

7.3 T-shirt usage in Australia

Products are used differently in different countries due to the influence of weather, consumer demands, fashion, culture, price etc. For example, Australians typically do not tumble dry their clothes because of favourable climatic conditions and household size is convenient for frequent hang drying (ABS 2005). However, in locations with more humid climates or smaller household size, tumble dryer use would increase.

Previous research on textiles has noted that the 'use' stage (which consists of the processes of wearing, washing, drying and ironing the t-shirt) has the highest energy consumption due to the intensive energy processes of washing, tumble drying and ironing (Laursen et al. 1997).

Some years have passed since those results were published and greater awareness has generated a significant change in consumption and use patterns. Australians have become more environmentally conscious than ever before. The increasing awareness of climate change has sparked campaigns encouraging more efficient energy use and residential rebate programs for energy efficient whitegoods. The humble laundry has not escaped this attention as water and energy consumption in the average Australian laundry has decreased. Current and site-specific data has been gathered to determine whether Australians have significantly reduced the actual energy consumption of the 'use' stage.

A 'typical Australian household laundry' model has been built around informed assumptions and statistics regarding: typical characteristics of washing machines and tumble dryers (maximum load, energy efficiency), percentage of households that possess a tumble dryer, typical use of washing machine and tumble dryer (frequency of use, load related to maximum load, water temperature) and chemical composition of typical detergent.

7.3.1 The average Australian washing machine

The Minimum Energy Performance Scheme (MEPS) is an eco-labelling scheme for household appliances introduced in 1999 (DEWHA 2008; AG 2008). The energy requirements for a significant variety of household appliances only started to be issued in 2003. The first energy efficiency rebates for three-star equipment only started recently. Currently in Queensland, rebates are only offered for equipment that has a four-star or higher efficiency rating (AG 2008).

The average life expectancy for washing machines is 10 years. The effect of the different awareness campaigns and rebates still has not produced a widespread effect on the energy performance of the average Australian household laundry. Therefore, out of a maximum of five stars, this LCA study considers the average Australian washing machine's energy and water efficiency is two stars.

The most common washing machine capacity for a small family (two adults and two children) is 6 kg (Shopwiki Inc. 2006). The first annual world environment review poll showed that 80% of Australians wash their clothes with cold water (ABS, 2005). Washing machines use very little energy during cold wash, resulting in an average of 0.15 kWh per wash.

To determine how much energy a washing machine uses *per t-shirt,* the energy used *per cycle* is needed. ABS data states that 26% of Australian households only use the washing machine for a full load. Using 250-g t-shirts, a full washing machine load for a 6-kg machine equates to 20 –24 t-shirts (both cotton and polyester).

The model determines accountability using three scenarios:

1. **Washing machine operated with *full load***

   According to ABS, 26% of Australians only use the washing machine when it is full (ABS 2005). If the washing machine is completely full, each t-shirt accounts for 4% ($\frac{1}{24}$) of the washing's energy use; meaning that washing uses 0.0016 kWh per t-shirt.

2. **Washing machine loaded with *more than a quarter of its capacity***

   Assuming that most Australians are willing to wash their clothes as efficiently as possible, it seems reasonable to deduce that most Australians (about 70%) would not load their washing machine with less than one-quarter of its capacity. If the washing machine is at one-quarter capacity, each t-shirt accounts for 25% of the washing's energy use; meaning that washing uses 0.026 kWh per t-shirt.

3. **Washing machine operated with *minimum load* (maximum waste of energy)**

   This scenario considers those users who wash regardless of the quantity of clothing to be washed. It is assumed that the load here is so small that the whole energy use is dedicated to a single t-shirt; meaning that washing uses 0.15 kWh per t-shirt. Very few people are expected to wash this way because of nation-wide water shortages and the rising cost of electricity.

The following calculation provides an estimation of t-shirt energy accountability in Australia:

(0.15 kWh × 4% impact × 26% population) +

(0.15 kWh × 25% impact × 70% population) +

(0.15 kWh × 100% impact × 4% population) = 0.033 kWh per t-shirt

Note: These calculations are based only on informed assumptions. Although published data or statistics would be preferable to reduce uncertainty in the figures, such information is not yet available.

7.3.2 The average washing detergent

Omo washing detergent has the largest share of the Australian market (Nielsen 2009). The owners of the *Omo* brand (*Lever Rexona*) dominate 33% of the washing detergent market. It is reasonable to assume that the typical detergent used in Australian laundries is from this company. Sainio (1996) determined the composition of *Omo Micro* (concentrated detergent from the Omo brand) to consist of the following:

- 13.8% silicate
- 5.8% anionic tensides
- 3.1% non-ionic tensides
- 1.9% boron
- 6% aluminium
- 50% zeolites
- 20% unknown.

7.3.3 The average tumble dryer

According to ABS data, 55% of Australian households had a tumble dryer in 2005, with an insignificant increase in ownership of 3% since 1992.

40% of the tumble dryers purchased had a high energy rating (meaning they are energy inefficient), making them a larger energy consumer than washing machines. However, 72% of the households stated they only use tumble dryers seasonally, rarely or even never. Assuming tumble dryers have a longer life expectancy due to the lower usage, energy rebates and campaigns will have a limited effect on the typical tumble dryer.

The energy rating of the average tumble dryer is two stars, with a load capacity of 6 kg (Shopwiki Inc. 2006) which consumes 4.76 kWh per drying cycle (DEWHA 2008).

Out of all the households have own a tumble dryers, 39% of households indicate they rarely use it in summer and 16% use them frequently (which means the remaining 46% use it moderately) (ABS 2005). In winter, 23% of households that own a tumble dryer use it very rarely while 32% use it frequently (ABS 2005).

Earlier assumptions indicated that a 250 g cotton or polyester t-shirt lifetime is 75 laundry cycles (washing, tumble drying and ironing). This translates into a total of 18.75 kg of textile (cotton or polyester) to be dried. Realistically only 10.3 kg are tumble dried because only 55% of households have a tumble dryer (18.75 x 0.55 = 10.3). According to the above statistics, only a portion of that 10.3 kg is tumble dried, reducing the typical Australian household laundry's energy use.

Assuming that 'tumble drying rarely' means only using it for 20% of the laundry and that 'tumble drying frequently' means tumble drying 80% of the laundry, the following formulas calculate the amount of textile material that the average Australian household tumble dryers:

$$[(10.3 \times 23\%) \times 20\%] + [(10.3 \times 32\%) \times 80\%] = 3.11 \text{ kg during winters}$$

$$[(10.3 \times 39\%) \times 20\%] + [(10.3 \times 16\%) \times 80\%] = 2.12 \text{ kg during summers}$$

$$\frac{3.11 + 2.12}{2} = 2.62 \text{ kg textile tumble dried per t-shirt}$$

Therefore, this model of an average Australian laundry considers that, throughout the lifetime of a t-shirt, instead of using energy for 75 tumble dry cycles, Australian households are only using energy for 10.5 tumble dry cycles. This model lacks any base data on tumble dryer usage patterns; therefore it has been assumed that each t-shirt accounts for the whole impact of each cycle.

7.3.4 T-shirt ironing

Laursen et al. (1997) states an average household iron consumes about 0.022 kWh/minute at a temperature suitable to iron cotton. It also takes approximately 3 minutes to iron a t-shirt, making the total energy consumption for ironing a cotton t-shirt 0.066 kWh/t-shirt. The energy required to iron a polyester t-shirt is 0.033 kWh/t-shirt as they can be ironed at a much lower temperature than cotton (plus they rarely require ironing).

It was impossible to determine how much Australian families iron their clothes as there is no published data in this area. Based on the fact that some people iron t-shirts, it has been assumed that cotton t-shirts get ironed 10% of the time and polyester t-shirts get ironed 5% of the time.

7.4 T-shirt disposal (re-use and recycle)

Miranda et al. (2007) states the net calorific value of cotton fibre is 17.1 MJ/kg. The heating value of PET is approximately 22.5 MJ/kg (Pohorely et al. 2006). Both studies claim that pyrolysis can produce close to 100% combustible material (Miranda et al. 2007; Pohorely et al. 2006). 80% of Australians re-used and recycled textile material in 2005 (ABS 2005).

No data could be found on what actually happens to the textile when it is recycled. This LCA used two assumptions: i) none of the textile waste is pyrolysed and secondly ii) that all of it is pyrolysed. Assuming a 45% energy conversion efficiency (as justified in section 6.4.1) a 250-g polyester t-shirt can provide 1.56 kWh and a cotton t-shirt can provide 1.19 kWh.

The report 'Well Dressed?' (Allwood et al. 2006) deals with the same sort of problems as this report and recommends that given the high impact of user laundry habits, users should extend the life of their garments as long as possible and that they should try to re-use (re-wear) their garments several times between washes. This research also considered whether a similar recommendation was feasible for cotton and polyester t-shirts.

What would the 'ideal' consumer do?

- Buy second-hand clothing and textiles where possible.
- Buy fewer but longer lasting garments and textile products.
- When buying new products, choose those made with least energy and least toxic emissions.
- Only buy products made by workers paid a credible living wage with reasonable employment rights and conditions.
- Lease clothes that would otherwise not be worn to the end of their natural life.
- Wash clothes less often, at lower temperatures and using eco-detergents, hang-dry them and avoid ironing where possible.
- Extend the life of clothing and textile products through repair.
- Dispose of used clothing and textiles through recycling businesses who would return them for second-hand sale wherever possible, but otherwise extract and recycle the yarn or fibres.

(Allwood et al. 2006)

A realistic approach for t-shirt re-use, is for those that have been worn for short amounts of time and under non-intense conditions to be re-worn. Re-wearing just 1 out of every 20 t-shirts reduces energy consumption significantly.

As outlined in section 6.2.4, McQueen et al. (2008) found that odour release is mostly related to the chemical structure and physical characteristics of the fibre. High intensity odour is related to polyester fabrics, whereas odour in cotton or wool fabrics is much less intense (McQueen et al. 2008). Based on these results, it is argued that cotton garments have a higher re-use rate than polyester garments. If Australian consumers were willing to reduce their washing frequency by 5% to 20%, 5% to 20% more polyester t-shirts would be needed to provide the same functionality as cotton t-shirts.

The analysis will look at a cotton t-shirt's environmental performance when its re-use rate is somewhere between 5% and 20% higher than polyester's.

7.5 Opportunities to reduce, re-use, and recycle during production

This last section deals with the possibility of recycling cotton or polyester t-shirts to obtain energy. However, in the case of cotton, the recycling options do not end there, as there are a number of possibilities to recycle cotton lint co-products and plant waste. It is not this report's goal to determine which option is the best in each case, but to briefly summarise the alternatives found and analyse the potential to reduce the total life cycle impact on climate change.

Pyrolysis and gasification are two processes which involve heating material under controlled conditions for temperature, pressure, humidity, oxygen availability etc. (Juniper 2008). In a sense these two processes are similar to incineration; however, they aim to obtain valuable intermediate products that can be further processed for recycling of materials or energy recovery, while avoiding the ash produced during incineration.

Pyrolysis is achieved by thermally degrading material in the absence of air, and producing bio-oil, synthesis gas (syngas) and biochar (Juniper 2008). Gasification involves the breakdown of hydrocarbons in the presence of a controlled amount of oxygen to obtain syngas (Juniper 2008). It can be argued that as an energy-optimising process, gasification is less efficient than pyrolysis, the latter providing a variety of outputs with different applications.

Zheng et al. (2007) believe an energy efficiency of 45% is achievable through pyrolysis of agricultural by-products. This is the efficiency level adopted for this analysis. However, the efficiency considered for pyrolysis of textile material is 100% (Miranda et al. 2007; Pohorely et al. 2006).

7.5.1 Cotton seed

The Minnesota Valley Testing Laboratories determined that the calorific value for cottonseed is 21.6 MJ/kg to 6 kWh/kg (CottonInc 2007). If cotton seeds were fed into a pyrolysis conversion system, a maximum energy value of 2.7 kWh/kg could be achieved. This could recuperate 59% of the energy used to grow cotton.

Cotton seed is rarely converted to energy as dairy farmers are willing to pay high sums for cotton seed as meal. Cotton seed has a high fat content (16% to 18%), making it a preferred food source for producing high dairy yields (Delta Farm Press 2008). Additionally, the high fibre and protein content of cotton seed contributes to the stock's health (Delta Farm Press 2008).

7.5.2 Cotton plant stalk

Zheng et al. (2007) studied the production of bio-oil from pyrolysis of cotton stalks between 480 °C and 530 °C, which resulted in a product that can directly substitute fuel oil for use in boilers or furnaces. Alternatively, it can be refined to be used in vehicles. Their results show that for each kilogram of cotton stalk, 2.72 kWh of energy is produced as bio-oil. The DEC's National Greenhouse Accounts Factors Workbook states that the energy content of automotive diesel is 38.6 MJ/kg, or 10.72 kWh/kg, meaning 3.94 kg of bio-oil are needed to substitute 1 kg of diesel. However, energy is also obtained in the form of gas (0.46 kWh/kg stalk) and charcoal (1.33 kWh/kg stalk), and energy is needed for the pyrolysis process (2.1 kWh/kg stalk), which means that the net production of energy is 2.41 kWh/kg stalk. The energy efficiency of the process is 42% if only the bio-oil production is considered, and 69% if gas and charcoal production are added (Zheng et al. 2007).

Chen and Baillie (2007) found that an Australian farm consumes on average 0.62 kWh electricity/kg textile and 3.95 kWh diesel/kg textile. Industry experts state that approximately 1.1 kg of plant mass (stem and roots) are produced per kg of raw cotton, which means that pyrolysis produces 2.65 kWh/kg textile. As much as 58% of the direct energy consumption on the farm can be recuperated by this process.

7.5.3 Production of biochar

Research is currently underway on the properties of biochar and its potential to increase soil health and production, and its ability to sequester carbon dioxide. Gaunt and Lehmann (2008) note that past research shows that nitrous oxide (N_2O) and methane (CH_4) emissions from soil, fertiliser and nutrient leaching can be significantly reduced by application of biochar. Char is an output from the pyrolysis process. Biochar (also known as agrichar) is the combination of char and syngas or bio-oil.

Gaunt and Lehmann (2008) studied the energy balance and CO_2 emissions associated with energy and biochar production through pyrolysis. They found that for wheat straw[6] a pyrolysis process optimised to obtain biochar can produce an energy yield of 6.9 MJ/MJ energy consumed in field, transportation and pyrolysis, and a biochar yield of $534 \frac{kg}{ha\ x\ year}$ (Gaunt and Lehmann 2008). Extracting from their data, a system designed to deliver not only bioenergy but also biochar from wheat straw for land application can avoid about 400% to 500% more CO_2e emissions than a system optimised for energy production (Gaunt and Lehmann 2008).

7.5.4 Production of biopolymers

Aizenshtein (2006) studied world production and consumption of polyester fibres. In his report, he mentions that the future of PET containers is limited as regulations all over the

[6] Zabaniotou et al. (2000) state wheat straw is fairly similar to cotton straw.

world will soon ban their use. PET for packaging will be substituted by biopolymers (a grain product base material) such as polylactide (PLA) (Aizenshtein 2006).

PLA packaging can decompose in approximately 80 days and is produced from renewable sources, making it environmentally friendly. In addition to cotton forming biopolymers, its fibres can also be blended with PLA to produce molded bottles. PLA bottles produced with a turmeric-based compound provide an extra 45% UV protection compared to PET (Aizenshtein 2006).

7.5.5 Cotton gin waste

Zabaniotou et al. (2000) studied the pyrolysis of cotton gin waste and the conditions under which the maximum yield is produced. This is a potential source for recycling as 7% of the picked cotton becomes cotton gin waste. The energy potential from cotton gin waste to be used as biomass is 14.65 MJ/kg which has an energy conversion efficiency of 45% (or 6.6 MJ/kg cotton gin waste) (Koroneos et al. 2008). Industry experts state that cotton gin waste is currently left to decompose and is ploughed back into the field to help maintain soil health and productivity. Of interest would be to compare the benefits of producing energy and applying biochar on field, to the benefits of applying decomposed gin waste on the field. Zabaniotou et al. (2000) show how at about 500 ºC the production of synthesis gas (a substitute for natural gas) and biochar is maximised.

Part 8 - LCA results

Part 8 examines the impact of different processes on the environmental life cycle of a cotton t-shirt with respect to climate change, ozone depletion and resource depletion. In order to do this, results are organised into stages (Figure 21):

- cradle-to-grave analysis
- cradle-to-gate analysis
- comparison between cotton and polyester
- energy recycling in the production and disposal phases
- energy saving in the use phase
- uncertainty analysis.

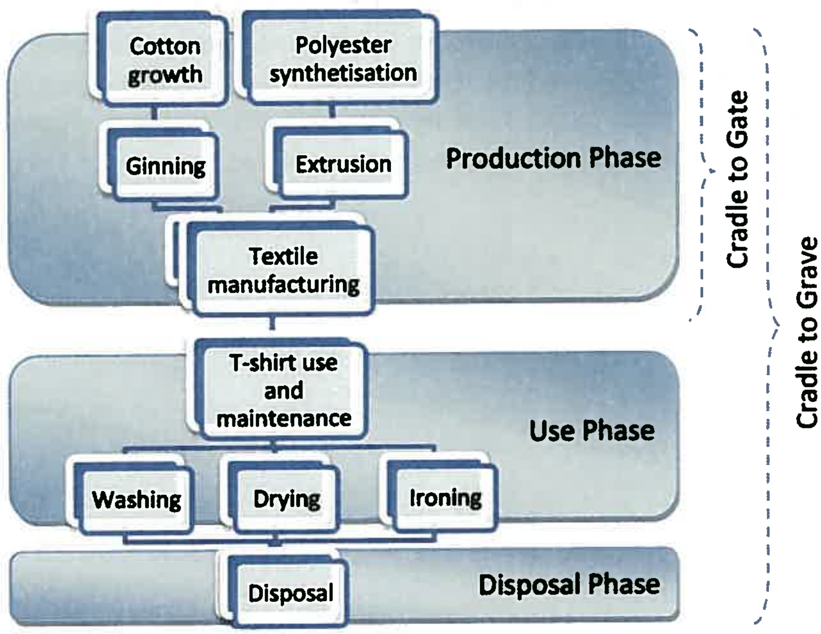


Figure 21. Phases of the cotton and polyester life cycles

The following is a quick guide to interpreting the graphics featured in Part 8.

8.1 How to interpret LCA graphs

The horizontal axis contains all the processes that have been analysed. The vertical axis represents the impact measured in Eco-Indicator points (or Eco-Points – Pt)[7]. Eco-Points are dimensionless units that represent average European citizens. 1000 Eco-Points represent the yearly environmental burden of an average European citizen (Pré 2000). Some graphs will

[7] due to the fact that the chosen LCIA method is ReCiPe

use milli-Eco-Points (mPt) as units; 1 mPt is one thousandth of an Eco-Point (Pt). However, the absolute value of a process or cycle in Eco-Points can be regarded as irrelevant because their purpose is to provide a basis for comparison of products, components or processes (Pré 2000).

The total clothes washing footprint is 41% lower than the tumble drying footprint (Figure 22). Yarn production is the most burdensome part of the cotton production process and its footprint is 96% lower than tumble drying's footprint. The graph also indicates a cotton t-shirt has a very small impact on ozone depletion.

8.2 Cradle-to-grave analysis

Consistent with previous research, the environmental impacts during the production phase are fairly insignificant compared to the impacts during the use phase (Figure 22). Production is only accountable for about 5% of the total life-cycle impact (0.12 Pt out of 2.24). Tumble drying potentially causes the largest environmental impact, responsible for about 63% of the total (1.4 Pt). Clothes washing causes the second highest environmental impact totalling 32% (0.82 Pt).

The highest proportion of impact in laundry processes is due to the depletion of fossil fuel resources (Figure 22). Tumble drying is the most energy intensive process in the life cycle as it is repeated up to 75 times. Why clothes washing is second highest is not straightforward, as the majority of Australians wash their clothes in cold water, which requires very little energy consumption.

This analysis has used site-specific data to describe t-shirt usage and maintenance patterns among Australians. The use of site-specific data is critical for the LCA's accuracy due to the high influence of the use phase in the total footprint. For example, a simple usage model could assume every household has a tumble dryer. However, statistics show that 80% of Australian households do not possess a tumble dryer. There is a great difference between general and site-specific data in this case.

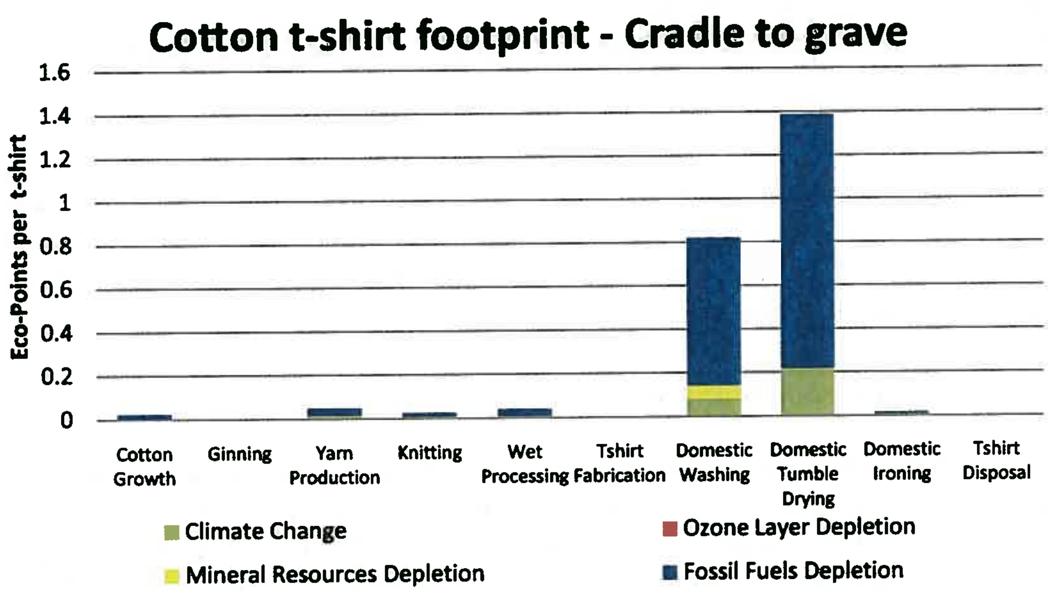


Figure 22. Characterisation of cotton impacts from cradle to grave (i.e. the whole life cycle)

The household washing footprint is detailed in Figure 23. The *electricity-low voltage* process shows among the smaller impacts, which is consistent with the fact that washing in cold water uses very little energy. The processes causing the highest impacts are the production of *fluorescent whitening agents* (40–45%), *zeolites* (12–17%) and *aluminium* (10–12%). Aluminium and zeolites are responsible for about 92% of the mineral resources depletion that could be observed in Figure 22.

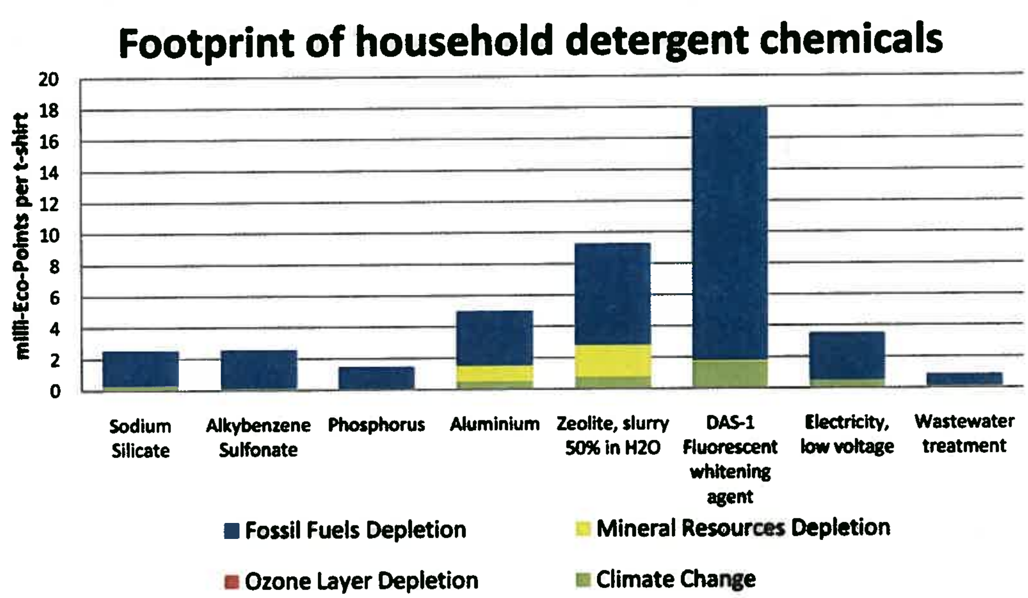


Figure 23. Characterisation of the impact of household detergent chemicals

8.3 Cradle-to-gate analysis

Another way to look at the cotton t-shirt's footprint is by analysing what happens during the initial processing stages, terminating the analysis at the factory gate (hence 'cradle to gate').

Cotton growth and ginning are the smallest contributors to climate change (contributing 10% in total) (Figure 24), due to their lower energy consumption when compared to other manufacturing processes. Cotton growth, however, uses considerable amounts of diesel for on-farm operations which makes it the third largest contributor to fossil fuel depletion (20%).

The analysis shows that textile manufacturing (yarn production, knitting, wet processing and t-shirt fabrication) produces nine times more GHG emissions than cotton production and uses four times more fossil fuels to operate. The total environmental impact of cotton growth and ginning is estimated at 27 mPt, whereas the total impact of the whole manufacturing process is estimated at 109 mPt. This means in total, cotton growth is accountable for 20% of the total environmental impact, mostly due to fossil fuel depletion. The two high impact processes are yarn production and textile refinement/wet processing. The contribution to ozone layer depletion is again insignificant.

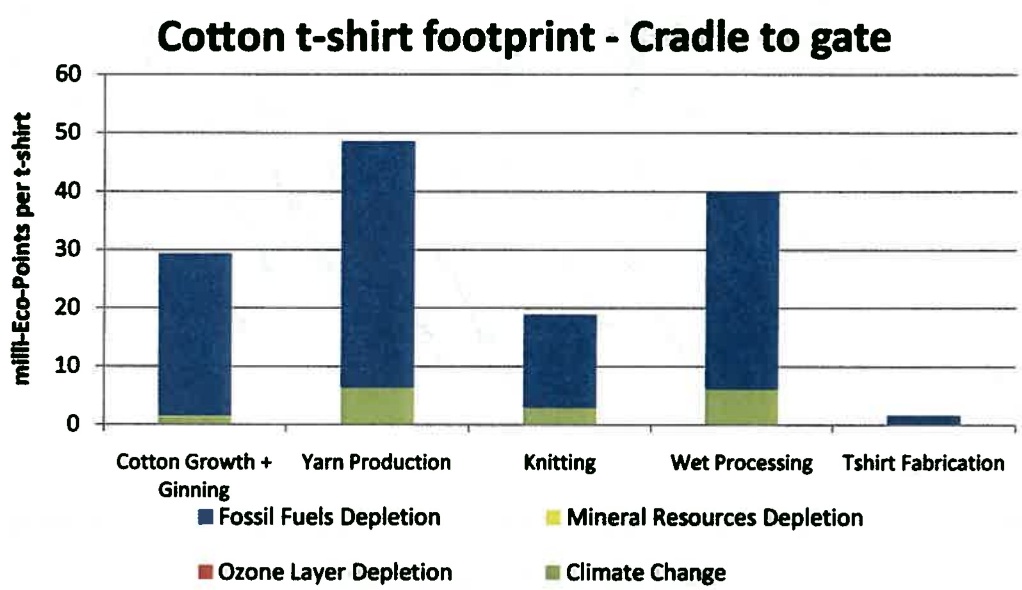


Figure 24. Characterisation of cotton impacts without the use phase (and no recycling)

8.3.1 How can cotton farms reduce their carbon footprint?

Some cotton farm activities generate GHG emissions. The two most important are N_2O emissions as a result of soil management and fertiliser application and CO_2 emissions from diesel use for contract work. However, most of the GHG emissions cotton farms are accountable for do not occur on site; they occur at the factories that create the raw materials they use, such as fertilisers and electricity.

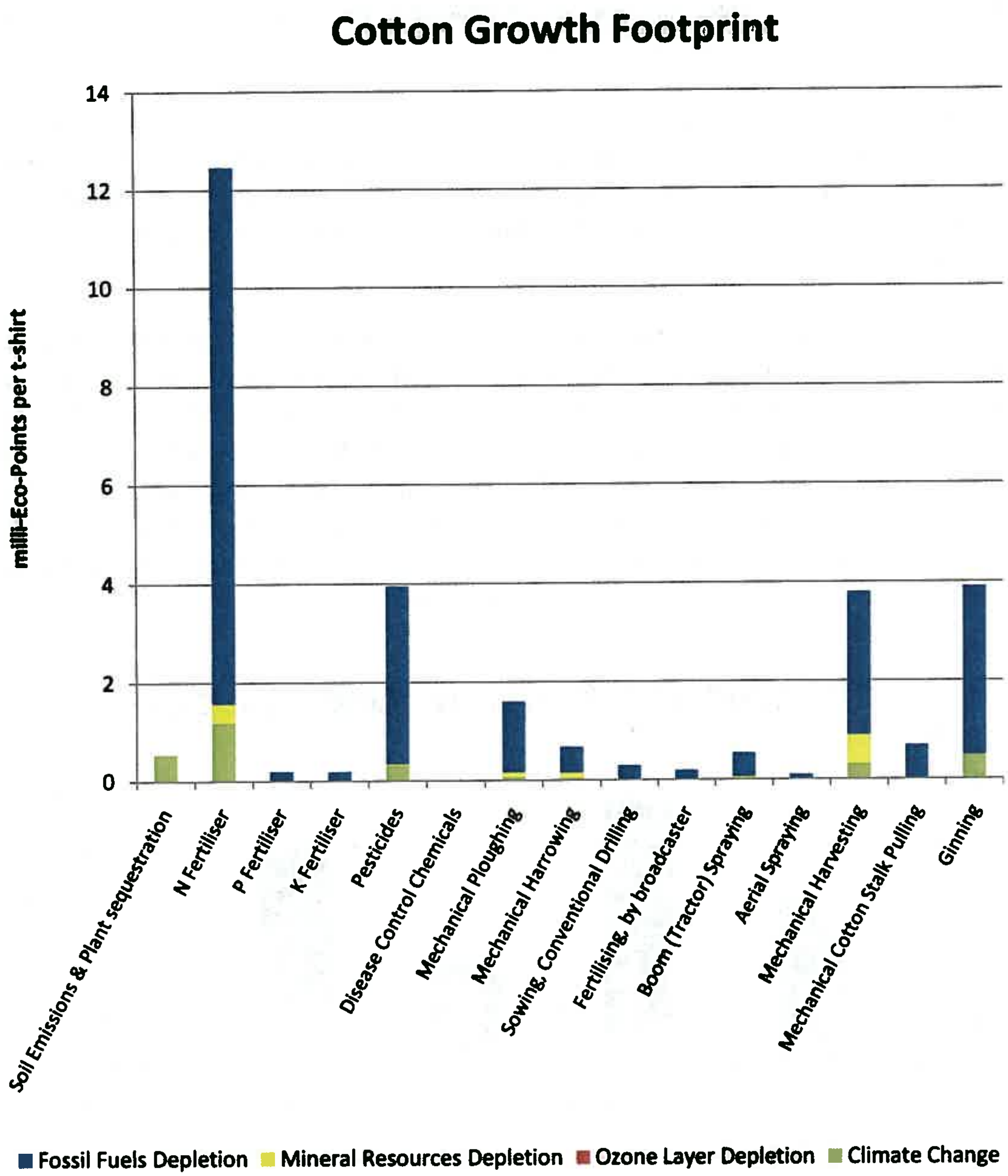


Figure 25. Footprint of cotton growth

The most effective measures to reduce the carbon footprint in a cotton farm are (Figure 25):

1. Use fertilisers that use less fossil fuel during their production or use natural fertilisers such as manure. The advantage of natural fertilisers is that they do not lead to an increase in the total carbon pool, whereas the use of fossil fuels does increase that pool.

2. Use more fuel-efficient machinery or promote the use of alternative fuels when possible.

Section 8.5 investigates how the cotton industry can lower its carbon footprint through alternative use of agricultural by-products.

8.4 Comparison between cotton and polyester

Cotton and polyester have been compared in four ways:

- from cradle to gate (comparing production phases)
- from cradle to gate including energy recovery through pyrolysis of textile and agricultural by-products
- from cradle to grave (comparing production, use and disposal phases)
- from cradle to grave including cotton t-shirt re-use

The results of all comparisons is summarised in Table 3.

Table 3. Summary of cotton and polyester comparison

Comparison	Cotton	Polyester
Cradle to gate	✓	✗
Cradle to gate + pyrolysis	✓✓	✗
Cradle to grave	=[8]	=
Cradle to grave + re-use	✓✓	✗

Note: ✓ means cotton performs better
✓✓ means cotton performs much better
✗ means polyester performs worse
= means cotton and polyester's performance is similar

Figure 26 compares the footprints of a cotton and a polyester t-shirt. This comparison takes into account all the processes from cradle to grave. In every category, assessed cotton has a lower footprint than polyester. The difference between both is very small, 1 to 2%. Is cotton's footprint *significantly* lower though?

[8] Cotton performs better than polyester from a cradle-to-grave perspective, but only slightly. Table 3 treats them as equal to highlight that the advantage is stronger in other comparisons.

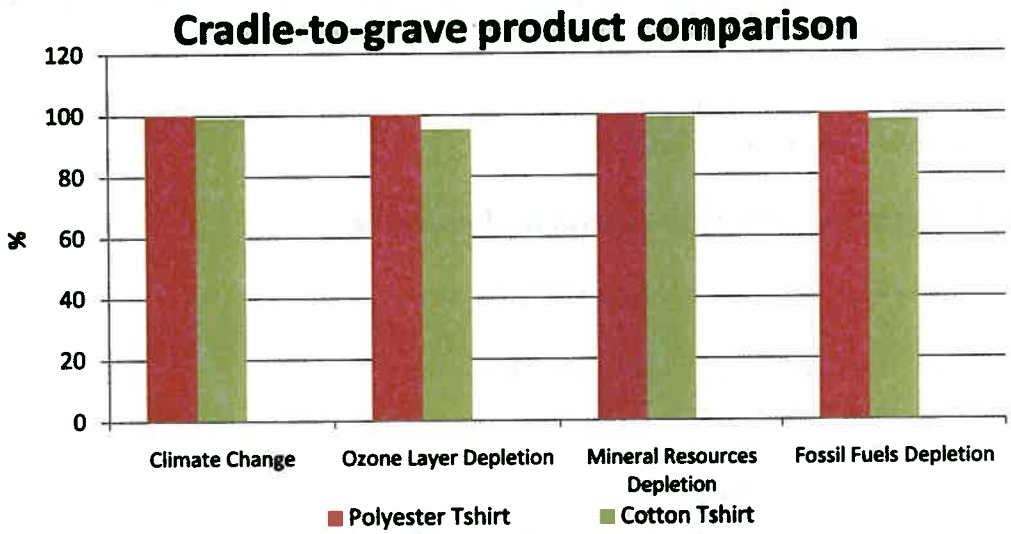


Figure 26. Cradle-to-grave comparison

Figure 27 shows the same product comparison, but only taking into account the processes between the cradle and the gate. The production of cotton has a significantly lower footprint in every impact category assessed. More specifically, cotton fibre production causes 23% less climate change than polyester fibre production, 31% less mineral resources depletion, 49% less ozone layer depletion, and 21% less fossil fuel depletion.

In cradle-to-grave analysis the domestic washing and tumble drying processes dominate because their impact is almost 25 times higher than the total impact of the remaining processes, causing the product difference to be insignificant in Figure 26 and very significant in Figure 27. Cotton t-shirt production has a significantly lower footprint than polyester t-shirt production, but the total footprint really depends on consumer behaviour.

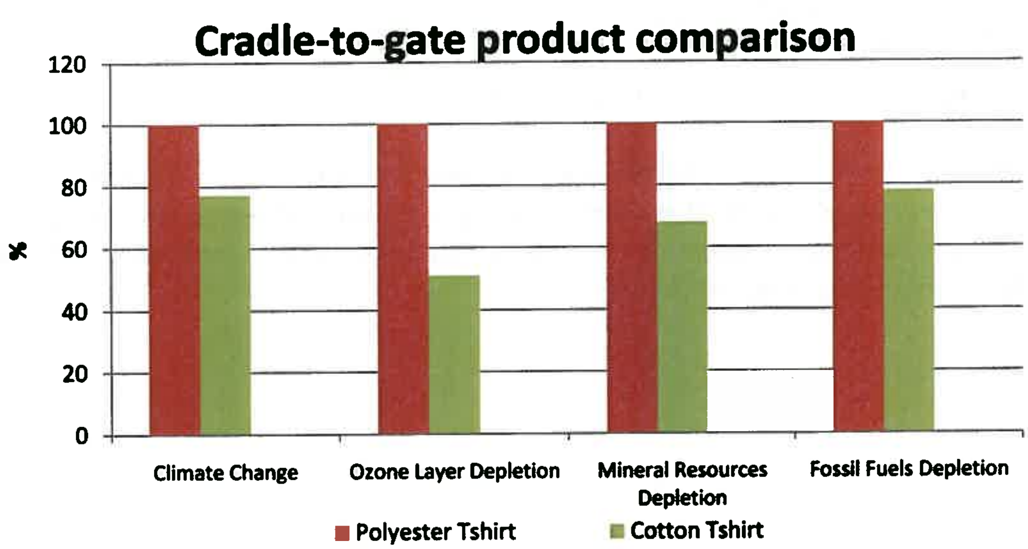


Figure 27. Cradle-to-gate comparison

Polyester synthesis and its extrusion into a fibre has greater impacts than those that occur at each stage of textile manufacture (Figure 28). By comparison, cotton growth and ginning have much lower impacts than the textile manufacturing processes (Figure 24). This highlights the difference between the two processes from cradle-to-gate.

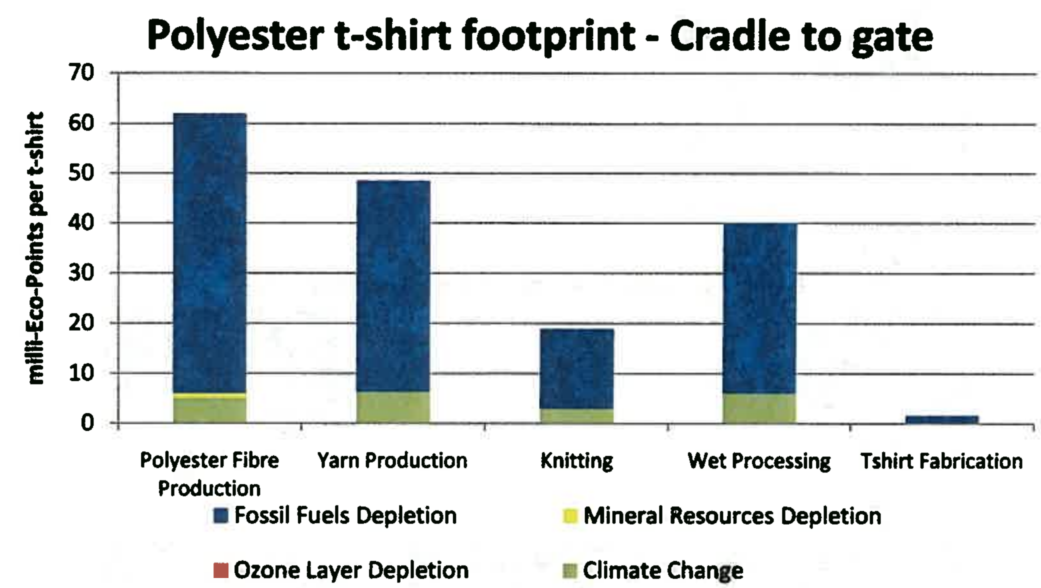


Figure 28. Characterisation of polyester impacts without the use phase (and no recycling)

Polyester production is a high energy demanding process. The high impact is due to the use of xylene as a raw material for purified terephthalatic acid (PTA), which produces PET. Xylene is a petrochemical (obtained directly from crude oil) with a footprint containing the impacts of crude oil extraction and transport. This is its main disadvantage as the extraction and transport of crude oil are processes that consume very high amounts of energy, and they also contribute very significantly to the depletion of the world's mineral and fossil fuel resources and the depletion of the ozone layer. The dependence of polyester production on the use of crude oil as a raw material is the single highest contributor to its environmental footprint.

The flow of environmental impacts through the PET production chain is shown in Figure 29. The thicker the arrows, the greater the impact passed on, and in this case the highest impacts can be traced back to crude oil and ethylene production. Consumption of electricity plays a minor role in PET production's footprint.

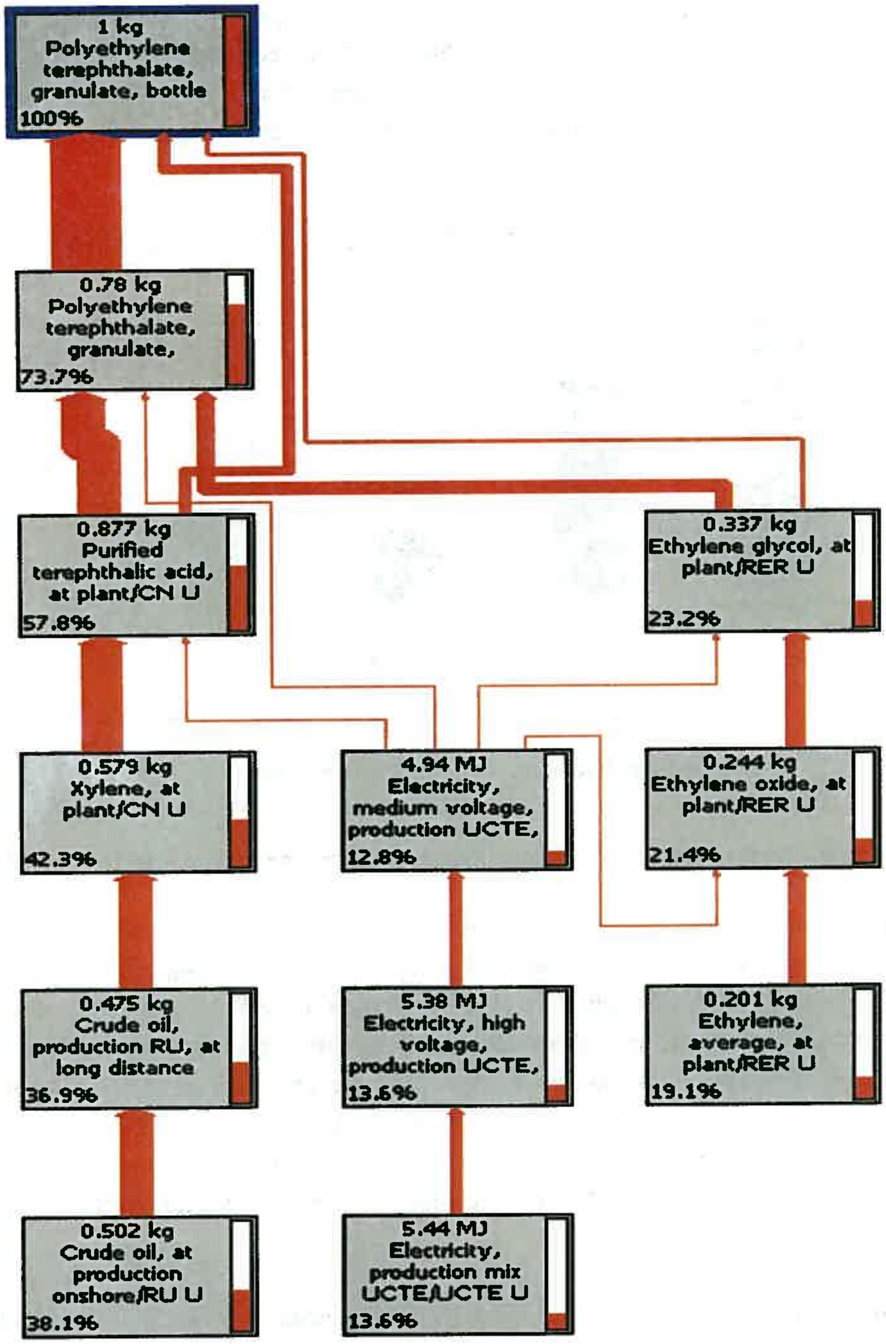


Figure 29. Network PET

8.5 Energy recycling in the production and disposal phases

This section focuses on analysing the potential of a number of energy or fossil fuel saving options to improve cotton's life cycle performance.

The options considered are the use of different cotton lint by-products and wastes as a source of biomass to obtain energy through pyrolysis. Pyrolysis is a process of controlled burning of material that aims at maximising the production of useful bio-oil, synthesis gas and char while minimising the production of useless ash (unlike incineration). The by-products considered for energy recycling are: Cotton plant stalks, cotton gin waste, cottonseeds and used t-shirts.

Textile waste pyrolysis could reduce fossil fuel depletion by about 64%. Second best option is cottonseed pyrolysis, cotton stalk third and gin waste fourth (Figure 30).

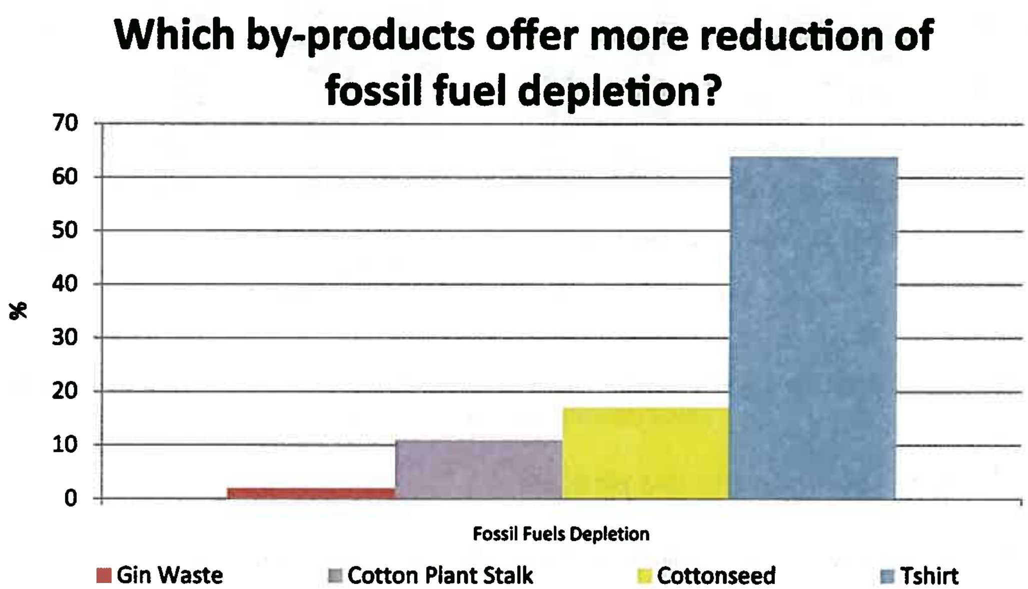


Figure 30. Comparison of the potential effect of different pyrolysis options, not considering use phase

However, these are estimations of the potential energy recovery options. No in-depth analysis of cotton by-product pyrolysis has been undertaken. The objective is to suggest future research areas using reliable data obtained from literature. Limitations of this analysis are:

- Data on emissions during the pyrolysis process has not been gathered
- Default 42% energy conversion efficiency has been assumed for all processes based on Zheng et al. (2008).
- The baseline case (no pyrolysis) does not consider disposing of textile waste in landfill. This does not affect the current study because land use impacts are not assessed, but in the future some of the avoided landfill impacts could be included in the results as positive footprints.

The potential benefits of energy saving through pyrolysis appear clearer in figure 31. Together, cottonseed, cotton gin waste and t-shirt pyrolysis could reduce the level of fossil fuel depletion by about 90%. This would reduce cotton's total carbon footprint dramatically.

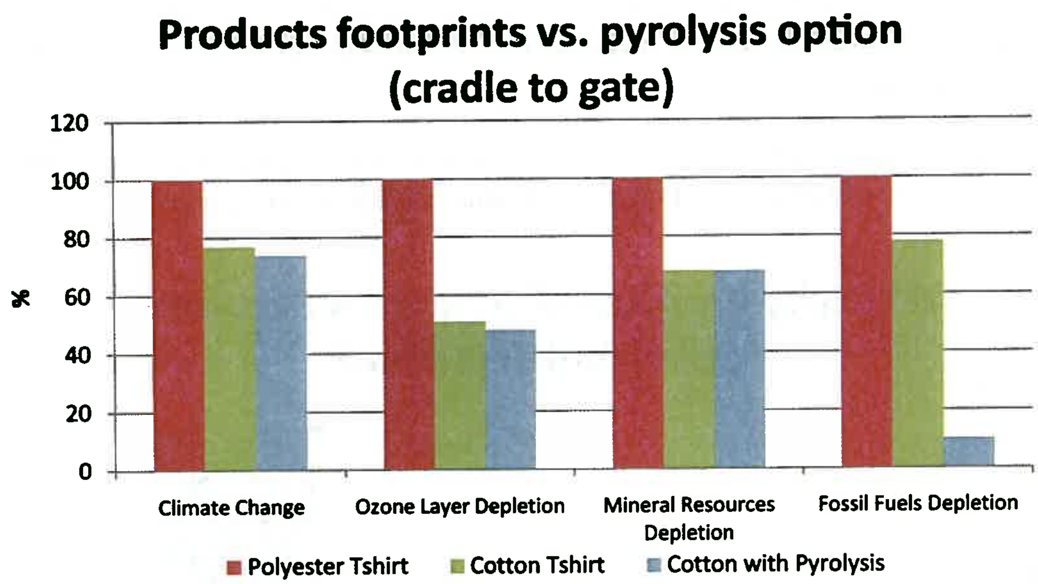


Figure 31. Characterisation of life-cycle impacts of cotton vs. polyester t-shirts not including use phase (recycling included, no re-use)

8.6 Energy saving in the use phase

Energy-saving options in the use phase have been investigated to determine:

1. Can Australian consumers significantly reduce their contribution to a cotton t-shirt's footprint?
2. Would the footprints of cotton and polyester t-shirts decrease equally?
3. Are the options available to consumers more effective than the options available to the cotton industry?
4. Which options are most cost effective to consumers?

8.6.1 Reducing washing frequency

In their report 'Well Dressed?', Allwood et al. (2006) argue that the 'ideal' consumer would, among other things, wash clothes less often, hang-dry them and avoid ironing whenever possible. However, he acknowledges several barriers to this kind of behaviour, such as: consumers not recognising a connection between their use of clothing and their environmental consequences; consumers washing clothes in order to 'freshen' them (even if they are not stained) due to the lack of an intermediate 'freshening' process.

The results show that re-using one t-shirt per month is equivalent to implementing all the energy recycling options during the production and disposal phases. The potential reduction is very high for no cost (Figure 32).

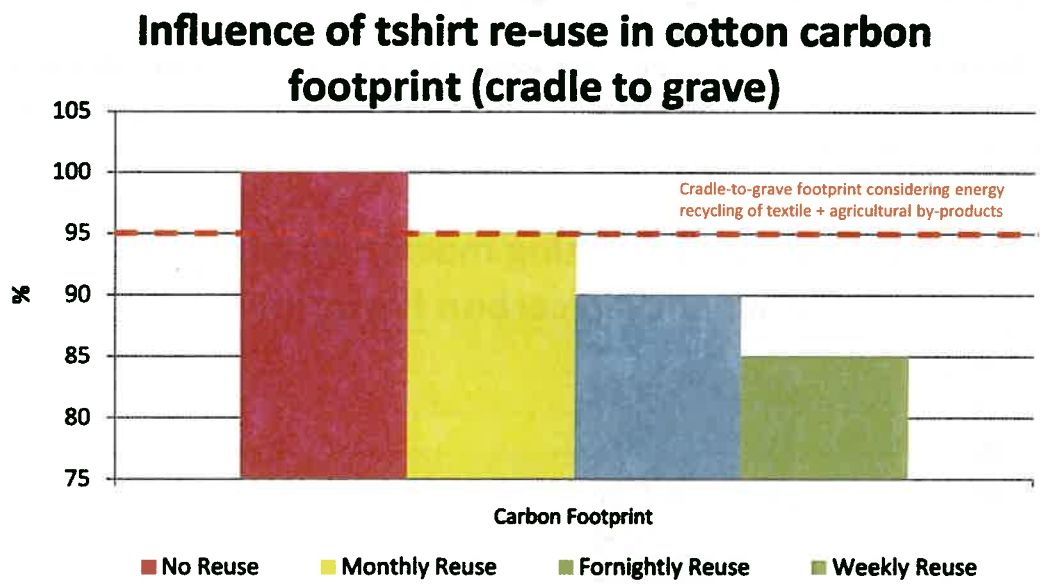


Figure 32. Reduction of cotton carbon footprint through t-shirt re-use

Section 6.2.4 argues that 'freshening' is more difficult in polyester than in cotton t-shirts, meaning it is unlikely that polyester garments would be re-used as much as cotton ones. A cotton t-shirt would be between 5% and 20% more environmentally friendly than a polyester t-shirt (Figure 33).

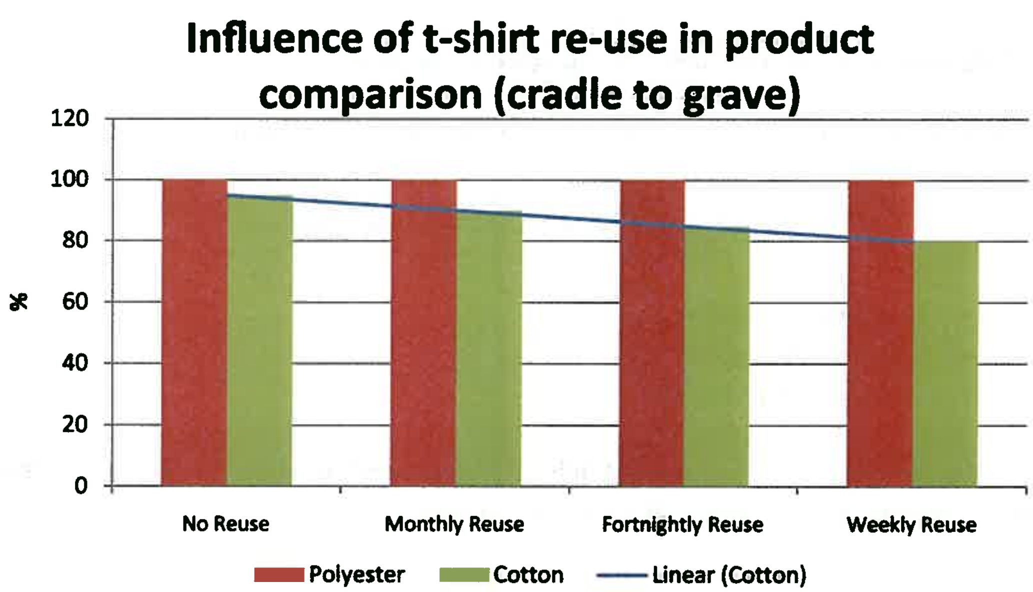


Figure 33. Influence of t-shirt re-use in product comparison (cradle to grave)

8.6.2 Appraisal of 4-star energy efficient washing machines

The change from 2-star energy-efficient washing machine to a 4-star one provides a significant but minor (1–2%) decrease in carbon footprint (Figure 34). Re-using one t-shirt per month is more effective.

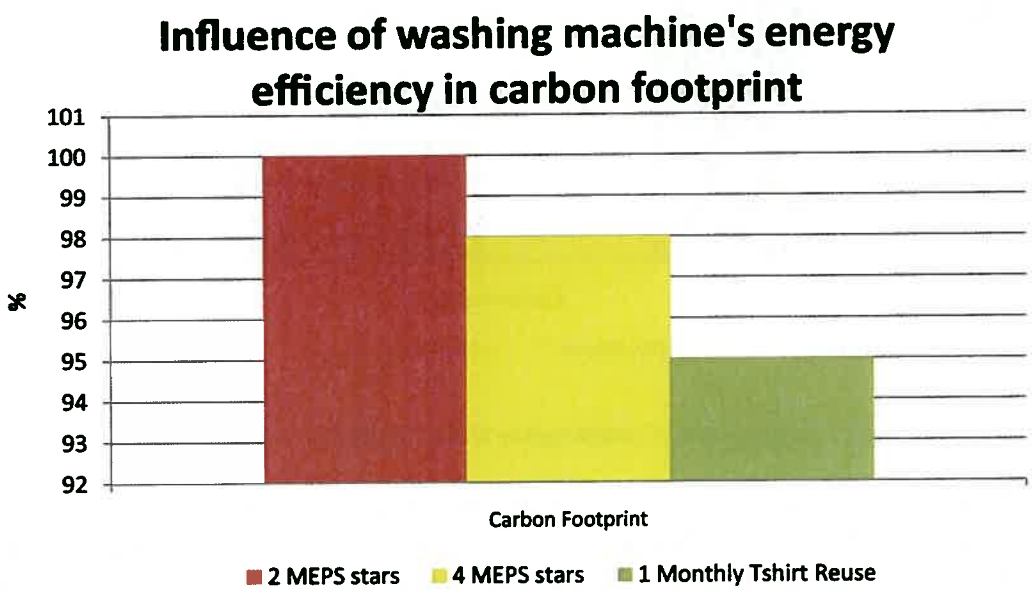


Figure 34. Characterisation of cotton impacts, improving washing machine energy efficiency from 2 stars to 4 stars

8.6.3 Appraisal of a 4-star energy efficiency tumble dryer

The energy consumption of tumble dryers is provided in DEWHA (2008):

$$\text{Consumption} = \frac{291.5\ \text{kWh/year} \times 0.85^{\text{stars}-1}}{52}$$

- 2 stars = 4.76 kWh/cycle
- 3 stars = 4 kWh/cycle
- 4 stars = 3.44 kWh/cycle

Every star gained reduces the depletion of fossil fuel resources by about 5% (Figure 35). This is as effective as t-shirt re-use but at a much higher cost.

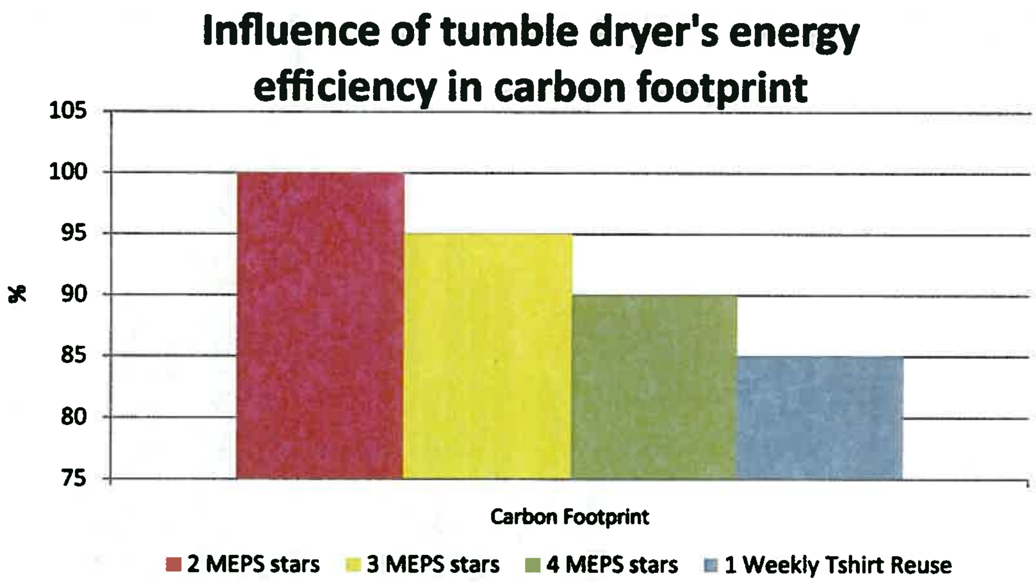


Figure 35. Difference in cotton impact characterisation when using a 2-star (a), 3-star (b), and 4-star (c) energy-efficient tumble dryer

8.7 Uncertainty analysis with Monte-Carlo Simulation

Uncertainty analysis is a method for determining whether the uncertainty in the data used can significantly vary the outcome of the assessment.

In order to enable SimaPro to conduct such analysis, all the data introduced has to be analysed using a pedigree matrix that helps evaluate the uncertainty of the data. SimaPro gets the user-introduced data and varies it within the limits set by the uncertainty values. In this analysis 1000 different cases have been tested and the difference between cases mapped in a probability distribution graph. Most of the data used in this assessment comes either from research reports, statistics or publicly available market information. Therefore, the number of assumptions made has been greatly reduced, lowering the overall uncertainty.

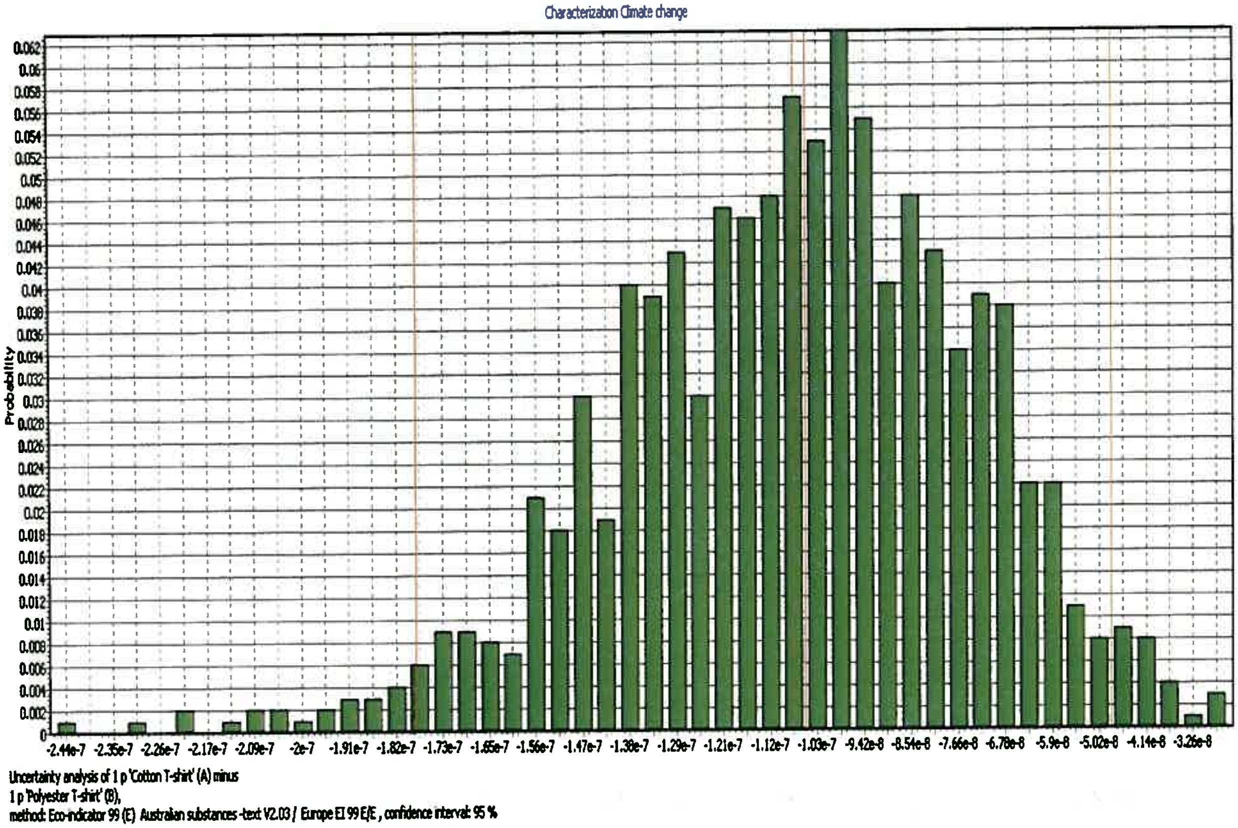


Figure 36. Uncertainty analysis distribution — climate change

Figures 36 to 39 show the distribution of uncertainty for the baseline case, which considers no recycling or re-using. The majority of the bars are green indicating that even considering data uncertainty, a cotton t-shirt's footprint is lower than a polyester t-shirt's footprint in 99% of the 1000 simulations. Following is a more detailed explanation.

In this uncertainty analysis, green bars being the majority indicates that cotton displayed a lower footprint in most of the 1000 cases analysed. The LCA results are therefore very robust.

The distribution shows the subtraction of the impacts of a polyester t-shirt (B) from those of a cotton t-shirt (A). Green bars mean negative values, that is polyester's impact is higher than cotton's; and red bars mean the opposite. 95% of the tested cases figure cotton impacting much less on climate change and fossil fuel depletion than polyester (Figures 36 and 37). This is the case as well in the uncertainty of mineral resources depletion (Figure 38) and ozone layer depletion (Figure 39). However, the mean value of the distribution in these two cases is closer to 0 (no difference) than in the first two cases. Overall, statistics show that only 1.1% of the tested cases show polyester having a lower footprint than cotton; however, those cases are out of the interval of confidence (defined as 95%) and the advantage is virtually negligible. The uncertainty analysis therefore shows the results of the assessment to be very robust.

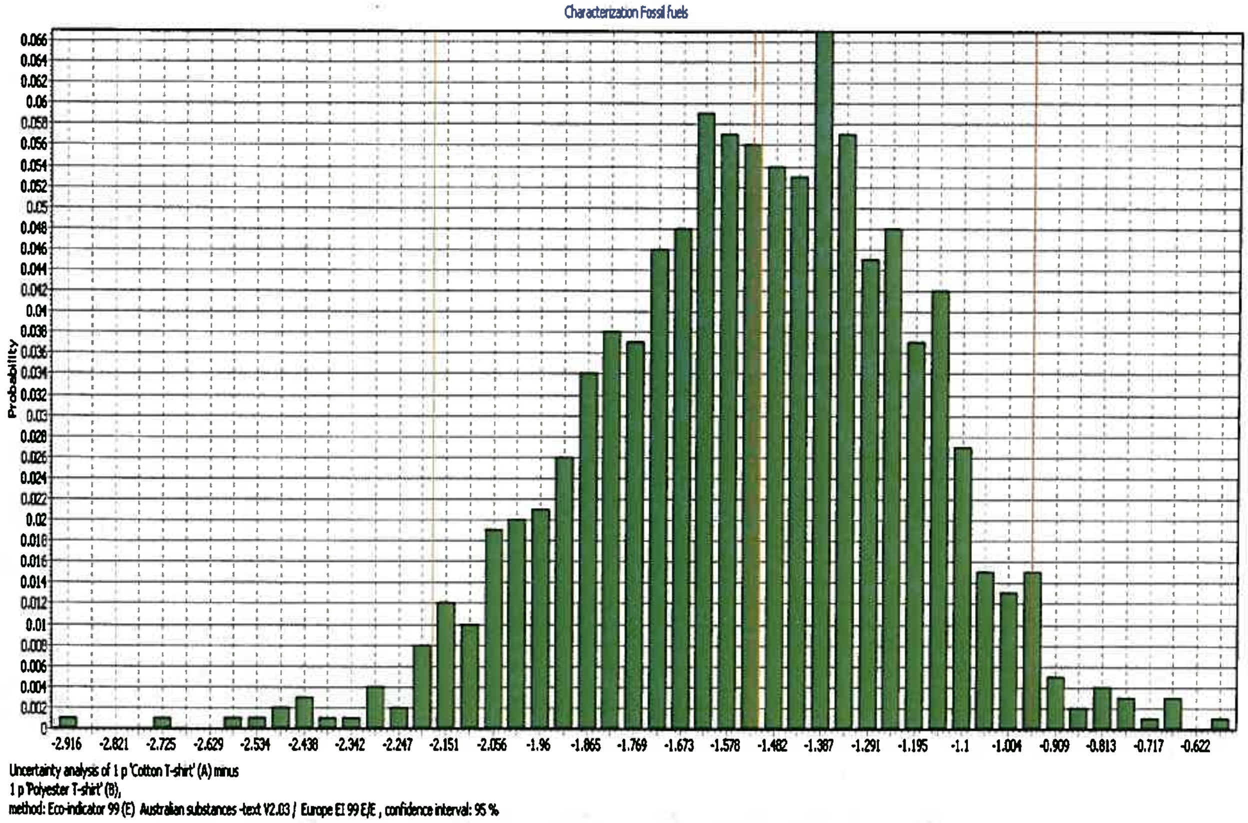


Figure 37. Uncertainty analysis distribution — fossil fuel resources depletion

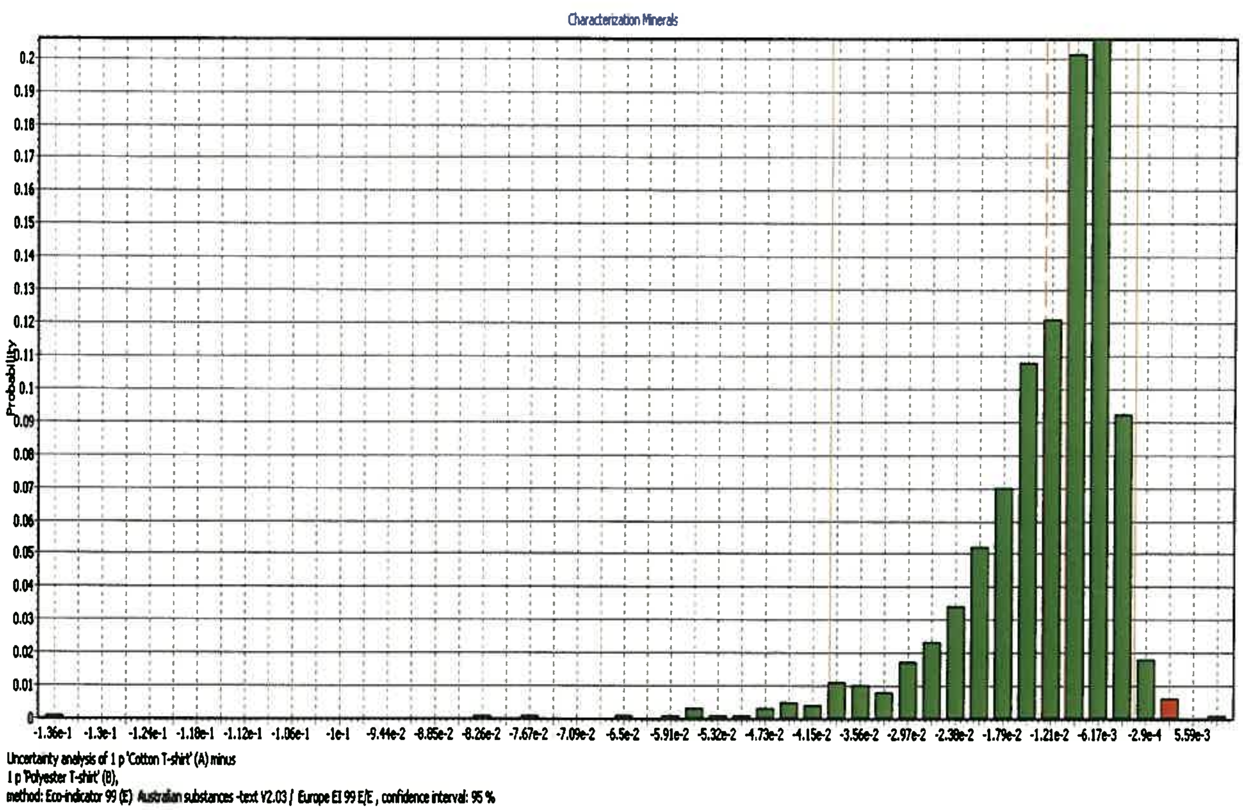
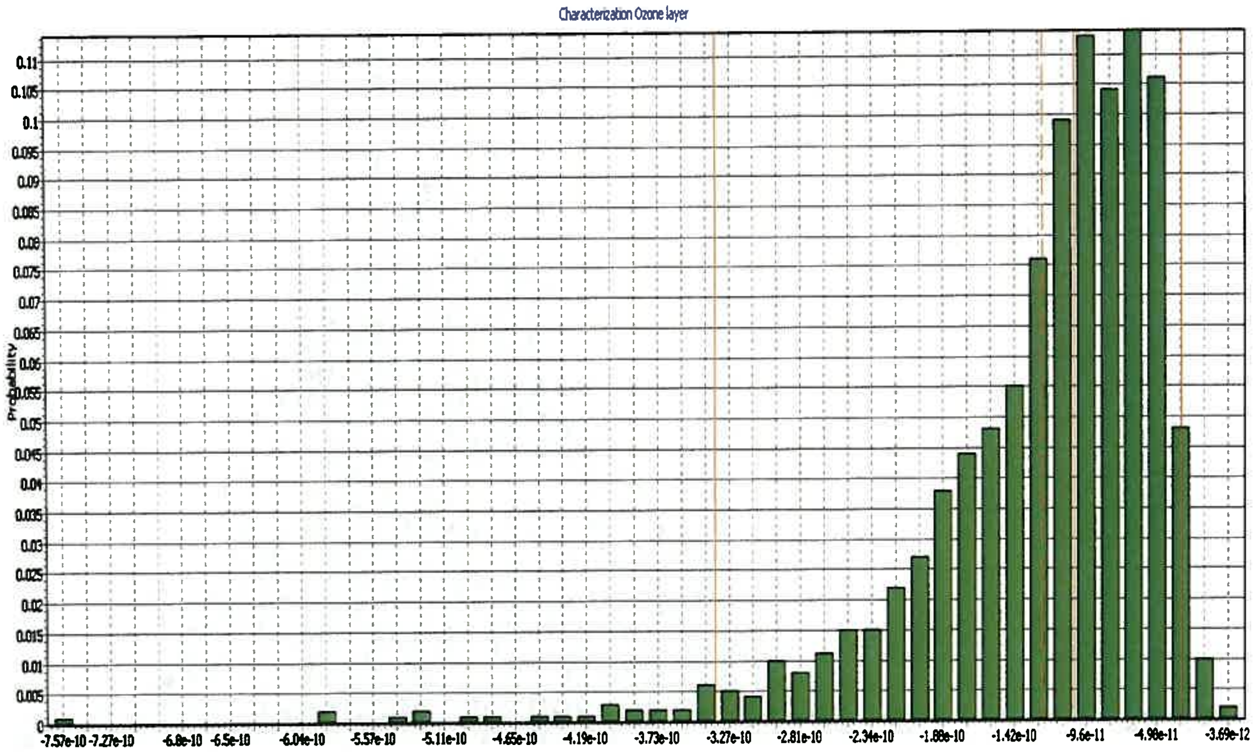


Figure 38. Uncertainty analysis distribution — mineral resources depletion



Uncertainty analysis of 1 p 'Cotton T-shirt' (A) minus
1 p 'Polyester T-shirt' (B),
method: Eco-indicator 99 (E) Australian substances -text V2.03 / Europe EI 99 E/E , confidence interval: 95 %

Figure 39. Uncertainty analysis distribution — ozone layer depletion