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Comparative Life Cycle Assessment of hemp and cotton fibres used in Chinese textile manufacturing

Vergelijkende Life Cycle Assessment van hennep- en katoenvezels gebruikt in de Chinese textielindustrie

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ABSTRACT

This study aims at assessing the environmental impacts of the production of hemp textiles compared to those of cotton textiles. The idea originated from popular literature and hemp textile marketing, where the fibre is presented as the miraculously sustainable alternative to cotton fibre, which is generally considered as a crop with major environmental impact. Because all hemp textiles are currently produced in China, the scope of this study is limited to comparing hemp from the Heilongjiang province to Chinese cotton from the Yellow River Region. The focus of this study is to uncover the intrinsic differences of hemp and cotton fibres and their processing technologies and the influence this has on the total environmental impact of textile manufacturing. Using the life cycle assessment methodology an objective and parallel comparison is made of both hemp and cotton textiles. The crop cultivation stage is assessed in detail per kg fibre. Two scenarios per crop are used: one for the common agricultural practices and one for recommended practices. Additionally, the textile manufacturing process is assessed up to 1 kg greige fabric, ready for further dyeing (cradle-to-gate). Here a reference scenario of cotton is constructed with data from scientific literature and three hemp scenarios are constructed based on data from an anonymous Chinese textile mill.

The cultivation of hemp has significantly less environmental impact compared to cotton. Regarding climate change, acidification, eutrophication and several toxicity categories the impact of hemp is far lower than that of cotton. Hemp also uses only half of the land. This only applies to fibres used in technical applications like biocomposites. The hemp textiles used in textiles are further processed, called degumming. Adding this process to the cultivation scenario makes that degummed fibre have a higher impact in every relevant impact category except for marine eutrophication and terrestrial ecotoxicity. Much of the impact is related to the energy use in the degumming process. This is therefore the absolute environmental hotspot for hemp fibres. Comparing the fabric scenarios shows that there is no considerable technical difference when adding hemp to cotton fabrics except for the degumming process. Again marine eutrophication is the only impact category with a higher impact for cotton fabrics. This is partly because the contribution of fibre production to the total impact is fairly limited.

NEDERLANDSTALIGE SAMENVATTING

Het doel van deze studie is om de milieu impact van henneptextielproductie te vergelijken met de impact van katoentextiel. Het idee is afgeleid uit de populaire literatuur en de huidige marketing rond hennep. Hierin wordt hennep omschreven als hét duurzame alternatief voor katoenvezel. Katoen wordt namelijk algemeen beschouwd als een gewas met grote gevolgen voor het milieu. Deze studie wordt beperkt tot een vergelijking van henneptextiel uit de Heilongjiang provincie, China, met katoen uit de Gele Rivier-vallei omdat alle productie van henneptextiel momenteel plaatsvindt in China. Het ultieme doel hierbij is om de intrinsieke verschillen tussen hennep- en katoenvezel en de nodige bewerkingsstappen bloot te leggen en de gevolgen hiervan aangaande de milieu impact te kwantificeren. Hiervoor zal de life cycle assessment, of LCA, methodologie gebruikt worden. Het stadium van de vezelproductie wordt vergeleken op basis van 1 kg vezel. Hiervoor zijn twee verschillende scenario's opgesteld per vezel: één voor de huidige landbouwpraktijken en één voor de aangeraden praktijken. Verder wordt het hele productieproces vergeleken op basis van 1 kg geweven stof, klaar om te verven. Een referentiescenario van katoen en drie verschillende hennepproductiescenario's worden hierbij gebruikt. Deze laatste zijn gebaseerd op data van een anonieme, Chinese textielproducent.

De productie van hennepvezel heeft een beduidend lagere milieu impact dan die van katoen en dit zowel voor klimaatsverandering, verzuring, eutrofiëring en verschillende toxiciteitscategorieën. Ook gebruikt hennepproductie slechts de helft van het land vergeleken met katoenvezels. Deze vergelijking past echter enkel voor technische vezelapplicaties zoals bio-composietmaterialen. Hennepvezels in textiel worden verder verwerkt met een 'degummingproces'. Wanneer de impact van dit proces wordt toegevoegd aan het vezelproductiescenario, is de impact van verwerkte hennepvezels hoger dan die van katoen voor alle impactcategorieën behalve mariene eutrofiëring en bodemtoxiciteit. Het merendeel van de impact is gerelateerd aan energieverbruik binnen het degummingproces. Dit is dan ook de absolute hot spot voor in de milieu impact van hennepvezels. Uit het vergelijken van de stofscenario's blijkt dat er geen belangrijke verschillen zijn tussen hennep- en katoentextielproductie op het degummingproces na. Ook in dit totaal is mariene eutrofiëring de enige relevante impact categorie waarvoor katoen een hogere impact heeft. Dit is deels het gevolg van het relatief kleine aandeel van vezelproductie in de totale milieu impact.

GLOSSARY

ALO	Agricultural land occupation
C2Ga	Cradle-to-gate
C2Gr	Cradle-to-grave
CC	Climate change
CED	Cumulative energy demand
COD	Chemical oxygen demand
CP	Common practices
ET	Evapotranspiration
EU	Energy use
FD	Fossil resource depletion
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
Ga2Ga	Gate-to-gate
GAP	Good agricultural practices
GHG	Greenhouse gas
GOT	Ginning outturn
GWP	Global warming potential
HT	Human toxicity
IR	Ionizing radiation
ME	Marine eutrophication
MET	Marine ecotoxicity
MRD	Mineral resource depletion
NLT	Natural land transformation
Nm	Metric count number
OD	Ozone depletion
PMF	Particulate matter formation
POF	Photochemical oxidant formation
TA	Terrestrial acidification
TET	Terrestrial ecotoxicity
THC	Delta-9-tetrahydrocannabidiol
ULO	Urban land occupation
USDA	United States Department of Agriculture
WD	Water depletion
YRR	Yellow River Region

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1 INTRODUCTION

1.1 A history of hemp

Evidence for the use of hemp in paper and ropes dating back to 6000 BC has been found in China. References on medicinal use, hemp textiles and eating hemp seeds later on are abundant in Chinese archaeological sites. Over time, the use of the crop spread from the Far East towards India, the Middle East and arriving in Europe by 2000 BC (Allegret 2013). Ever since, the uses of hemp multiplied to ultimately become one of the most important resources for paper, textiles, ropes and canvas throughout the entire European continent. Hemp was of major strategic importance to the European powers of that time, as it was a key component of sailing ships that dominated naval exploration from the 15th to the 19th century (the word 'canvas' is derived form the old French 'chanevaz' literally 'made from hemp'). The slow demise of hemp sets in with the first steam ships in 1830, the rise of wood-based paper in 1850 and ultimately the breakthrough and competition of cotton for textiles throughout the 1800s, all fuelled by the rise of cheap fossil energy (Allegret 2013). At beginning of the 20th century, the United States experienced a sudden rise of the drug marihuana, derived from the same species of plants. This ultimately led to the Marihuana Tax Act labelling hemp as a narcotic drug in 1937 (Johnson 2013). This effectively banned hemp cultivation from the United States and destroyed the domestic hemp industry (Smith-Heisters 2008). After World War II the US imposed their view on hemp and marihuana in the UN, prohibiting the cultivation and possession of cannabis (Johnson 2013).

1.2 The rise of cotton and man-made fibres

From the beginning of the 19th century, when the mechanical cotton thresher was invented, cotton became real competition for hemp fibres (Allegret 2013). Cotton was naturally softer than the strong, raw hemp-linen fabrics and was considered a more luxurious fibre. As cotton production became cheaper because of labour-saving technologies, it almost completely replaced hemp in textile application by the 1920s (Johnson 2013). With the arrival of the petroleum era and the development of the first cheap, man-made fibres, like viscose and especially nylon in 1937, hemp was effectively banished from use in textiles. By now cotton comprises 39% of the entire

European textile market, while all man-made fibres combined comprise around 54% of the market (Beton et al. 2012).

1.3 The question of sustainability

During the past three decades, however, cotton started to draw serious attention from the environmentalist corner. A growing mass of literature is being devoted to understanding and quantifying potential environmentally and socially hazardous effects of cotton production (Muthu 2014b). Especially the consequences of intensive irrigation practices, excessive mineral fertilizer and harmful pesticide use are the main concerns (Bärlocher et al. 1999; Kooistra & Termorshuizen 2006; Selman et al. 2008). Other relevant aspects in every industry these days are the impact on global warming and fossil fuel consumption. Intensive agriculture, and therefore also conventional cotton production, contributes significantly to the former (Nemecek & Kägi 2007) Overall, it is assumed that cotton is not a sustainable crop at all.

1.4 A new dawn for hemp

It is in the light of this environmental awareness that hemp recently regained interest. Until the 1980's hemp was a forgotten crop. Limited production continued in the Soviet Union, China and Eastern Europe and also France continued breeding research (Van der Werf et al. 1996). Real renewed interest in hemp only arose somewhere in the 1990's when the first projects researched the viability of hemp as an alternative sustainable fibre source. Hemp is believed to have very beneficial agronomical characteristics such as high yield potential and limited fertilizer or pesticide requirements (Piotrowski & Carus 2011).

Hemp today is still mostly known for the iconic palmate leaf with 5 to 9 leaflets, often associated with the drug, marihuana. The confusion between industrial fibre hemp and marihuana is justified, as both are varieties belonging to the same species. Marihuana is a name for the flowers of female cannabis plant coming from varieties high in THC-content. THC, or delta-9-tetrahydrocannabidiol, is the main psychoactive compound in cannabis and is present in industrial hemp only in minor concentrations: Canadian and EU legislation require THC content of industrial hemp cultivars to be below 0.2 wt-% (Johnson 2013). Although many countries legalized the cultivation of hemp throughout the 1990's, like Canada in 1998, it is still prohibited in countries like the US and India (Bouloc et al. 2013). The US Farm Bill signed early 2014 does include an amendment that allows the growing of hemp for scientific reasons at universities (Stansbury & Steenstra 2014). Steenstra believes this to be the first step towards US hemp production and manufacturing opportunities as pro-hemp legislation is being passed in many states already.

Anno 2015, the interest in hemp is threefold: fibres, seeds and pharmaceuticals. Hemp fibres are derived from the stems and have many applications. The inner core is used in animal bedding or construction material while the outer bast fibres are applicable for use in high quality papers, insulation material, biocomposites, ropes and textiles depending on the quality and processing (Piotrowski & Carus 2010). The majority of the seeds is used in food or feed as whole seeds or pressed into oil or in cosmetics (Carus et al. 2013). The most recent surge in hemp popularity is devoted to the pharmaceutical potential of non-THC-cannabinoid compounds found in the leaves and flowers. Extracting these compounds is a new opportunity for hemp as a high value cash crop.

1.5 Hemp as a textile fibre

The focus of this research thesis is on hemp in the textile industry. Several European projects were set up over the past 15 years to develop a European hemp industry: the HEMP-SYS project (5^{th} framework programme) back in 2002 with the goal develop new techniques for hemp textiles in Europe, the Multihemp project (7^{th} framework programme) focussing on biomaterials in 2012 and also the Fibra project (7^{th} framework programme) in cooperation with Chinese partners again including textiles in the picture (Horizon 2020 2015; Multihemp 2015; Fibra 2015). At the moment, however, China is the only country of significance regarding hemp textiles. All hemp textiles currently on the market are produced there (Personal communication Robert Hertel, December 29^{th} 2014). These textile products are marketed and described in popular literature as the sustainable alternative to cotton because of the lower water and input requirements and higher fibre output. These statements form the basis for the research hypothesis in this thesis. The methodology of life cycle assessment (LCA) will be used to assess and compare the environmental impact of hemp textiles to those of cotton.

1.6 Life cycle assessment

Life cycle assessment or LCA is an ISO-standardized environmental assessment methodology defined as "*the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*" (International Standards Organization 2006). The ISO standards ISO 14040/44 provide a framework for the LCA methodology that is based on four phases. The first phase determines scale and scope of the analysis and is based on a well-defined functional unit (FU). This is followed by the inventory analysis that quantifies all inputs and outputs throughout the FU life cycle. An environmental impact is then assigned to all inventory elements and results are carefully interpreted. The method originates from the 1960s as an energy-focused assessment and evolved together with environmental awareness into a holistic environmental impact assessment (Muthu 2014a). Corporations use LCA to an increasing extent for identifying and remediating environmental hotspots throughout their production processes, product development and as a form of brand enhancement as consumers demand more sustainable products (GreenResearch 2011). LCAs currently also shape environmental policy in both developed regions like the EU and USA and emerging economies like India and China (Guinée et al. 2011).

1.7 Research objectives and thesis outline

The following study provides an in-depth analysis of hemp and cotton textiles as currently produced in China. The tree main research objectives to which this thesis is devoted are:

- Are hemp textiles or hemp/cotton blends that are currently produced in China more environmentally sustainable than comparable cotton textiles?
- Can the environmental performance of the textile industry potentially be improved with the use of hemp fibres as an alternative to cotton?
- What are the main differences between hemp fibres and cotton fibres in textile manufacturing both from technical and environmental point of view?

The structure of the thesis is as follows: firstly the state of the art literature on hemp fibre (section 2.1), cotton fibre (section 2.2) and natural fibre processing (section 2.3) is reviewed to get a complete understanding of the textile processing chain. Additionally all contemporary literature on previous sustainability assessments of hemp and cotton is discussed in section 2.4. The actual life cycle assessment consists of a more extensive introduction to the methodology (section 3.1), the definition of goal and scope (section 3.2) and the construction of the life cycle inventory (section 3.3). The results are then presented in the life cycle impact analysis (section 4.1) followed by the interpretation and discussion (section 4.2). A final conclusion with the most important insights is provided at the end (chapter 5).

2 STATE OF THE ART

2.1 Hemp

2.1.1 Botanical description

Hemp, or *Cannabis sativa*, is an annual, herbaceous plant from the Cannabaceae family, including among others the genus of hops (Species2000 2014). The centre of origin of hemp is located in Eastern and South-central Asia (Hancock 2012). The genus *Cannabis* includes three species: *C. sativa*, *C. indica* and *C. ruderalis.* The first is the industrial hemp species used for fibre and seed production. Both *C. sativa* and *C. indica* have marihuana varieties and *C. ruderalis* is the wild form. Hemp is a typical short day plant. It will only make the transition to the generative stage when the hours of daylight are below a critical photoperiod of 14 hours. This means vegetative growth takes place in spring and early summer until the reproduction starts in early autumn (Hall et al. 2012). These photoperiodic requirements imply that hemp is grown in temperate to subtropical regions, like flax, making it a suitable industrial fibre crop for production in China, Europe, Russia and the US. The northern limit of hemp production is 65° N (Hall et al. 2012). The southern limit is highly cultivar-dependent.

Hemp breeding has focused on several points. Firstly, the photoperiodism is important for industrial production because after flowering the efficiency of biomass accumulation drastically decreases (Struik et al. 2000). Genotypes selected for a longer vegetative period can therefore significantly increase fibre yields (Amaducci & Gusovius 2010). Also, hemp occurs naturally as a dioecious plant. In the selection of modern cultivars, however, monoecious varieties are preferred (Amaducci et al. 2014). Because staminate plants flower earlier, a monoecious hemp cultivar results in a more homogenous crop and fibre quality at the time of harvest. The effects on fibre content are unclear, as different studies bare contrasting results (Amaducci & Gusovius 2010).

In European conditions, hemp is sown from the end of March until half of May after which it will take around 100 growing degree days (GDD) to emerge (Struik et al. 2000; Desalnis et al. 2013). Emergence is followed by a 25- to 35-day basic vegetative phase in which growth is dependent on thermal conditions (Amaducci et al.

2008). After this period, vegetative growth becomes photoperiod-dependent and is thus determined by sowing time, latitude and cultivar. This period can take up to 70 days before the reproductive stage is induced and another 7 days before flowering actually starts (Amaducci et al. 2008).

Hemp fibres are plant fibres categorized as bast fibres. They are derived from the stem of the plant. This stem consists of two fibre types: xylary or wood fibres and extraxylary or bast fibres (Amaducci & Gusovius 2010). The xylary fibres comprise the xylem and form the inner woody core. Separated from the bast, these are called hurds or shivs (Sponner et al. 2005). The bast fibres consist of two distinct types as well. The primary bast fibres are formed directly by the apical meristem. Individual fibres stretch during plant growth to an average length and diameter of 20-28 mm and 10-50 μm respectively (Franck 2005a; Amaducci & Gusovius 2010). Aggregates of primary fibres form fibre bundles with dimensions up to 2500 mm (Ellison et al. 2000). Subsequent to longitudinal growth, the cambium forms secondary bast fibres. They have a typical length of around 2 mm and are much alike the xylary fibres. These secondary, extraxylary fibres are not favourable for textile uses (Amaducci & Gusovius 2010). The timing of harvest is crucial in obtaining a maximum yield of primary bast fibres. When lignification starts after flowering the relative primary fibre content and fibre quality decreases (Bócsa & Karus 1998; Westerhuis et al. 2009). Westerhuis et al. (2009) also report the fibre-to-wood ratio before this point to be constant. This implies that the maximum fibre yield can be obtained at flowering.

The main chemical compounds of plant fibres are cellulose and hemicelluloses. Other important constituents are pectins and lignin (Franck 2005a). The exact chemical composition differs between natural fibres and together with physical dimensions it is a base for the variability in fibre characteristics. Cotton fibres consist of cellulose for more than 90% (Chaudhry 2010). Hemp fibre bundles on the other hand have relatively high concentrations of pectins (18%) and lignin, found in the matrix that encloses individual fibres (Vignon et al. 1996). This matrix of thermally instable compounds is undesired in thermal processes like composite moulding (Ouajai & Shanks 2005). It also causes the typical rigidity and wrinkles, or linen look, of untreated hemp textiles.

Tensile strength of hemp fibre varies with reported values between 580-1110 MPa, on average higher than cotton (Bledzki & Gassan 1999; Batra 2006). For comparison, however, specific strength, or tenacity, is a more appropriate measure, as tensile strength is highly dependent on fibre dimensions. Hemp has a reported tenacity of 25-62 cN tex^{-1} (Franck 2005a). It is not mentioned whether this applies to raw or treated hemp fibre. With the right treatment, degummed or bleached fibres are up to 70% stronger because inter-fibrillar substances are removed enabling greater interactions between cellulose fibrils (Kostic et al. 2008).

2.1.2 Cultivation

Site requirements

Hemp is a crop that can be cultivated in a wide range of climatic conditions. It can thrive in Northern European and Mediterranean as well as subtropical conditions (Amaducci et al. 2014). In China, for example, hemp is produced between 25°-50° N. The zero vegetation point lies around 1-2° C and optimal growth between 19-25° C (Desalnis et al. 2013). Soil conditions are important for optimal root development and nutrient uptake. Medium soils like sandy loam or clay loam are well suited because of their favourable structure, water holding capacity and nutrient content (Amaducci et al. 2014). For the same reasons sandy soils are less favoured. The crop is sensitive to lower soil pH than the optimum of pH 6-8 and to drought in early crop stages (Desalnis et al. 2013). Water requirements, however, are fairly limited: in Mediterranean conditions with high evapotranspiration (ET) demands, water requirements are between 250-500 mm (Amaducci et al. 2014).

Production practices

Hemp production systems vary with environmental conditions and did not change much until the end of the 1990s (Clarke 2010). Only then the renewed interests in hemp triggered research to modernize and mechanize hemp production practices (Amaducci & Gusovius 2010). Today hemp is often cultivated on a small scale and organically with practices depending on the end use of the fibres. Planting density for example has a significant impact on fibre quality and quantity. Higher densities stimulate elongation through competition for light. This results in longer internodes and thus longer and thinner fibre (Amaducci et al. 2014). Another feature of high densities is the increased ratio of cortical surface to plant mass and therefore increased primary fibre yield. Typical densities for textile applications are reported between 150-200 plants m^{-2} and even up to 500 plants m^{-2} (Amaducci & Gusovius 2010; Amaducci et al. 2014). Fibres for technical applications have lower densities, typically for example 90 plants m^{-2} for paper pulp production (Amaducci & Gusovius 2010). Mechanization is widespread in European and northern Chinese production as scale increases. While in the mountainous south of China, many field operations are still performed by hand. But whatever the degree of mechanizations, hemp production remains labour intensive and this is considered a major obstacle for its competitiveness (Amaducci et al. 2014).

A relevant agronomic aspect is the limited nutrient requirements of hemp compared to traditional European crops. Common practice for mineral fertilizer in European industrial hemp production for nitrogen (N), phosphate (P_2O_5) and potassium (K_2O) are 80-100 kg ha^{-1}, 30-100 kg ha^{-1} and 100-150 kg ha^{-1} (Turunen & van der Werf 2006; González-García et al. 2010; Piotrowski & Carus 2011). Sponner et al. (2005) confirm these ranges and explicitly state that the limitation of nitrogen fertilization to a maximum of 110 kg ha^{-1} is very important for high fibre quality. Similar to lower numbers have also been suggested for hemp production in China (Amaducci et al. 2014). Finnan & Burke (2013) contradict the need for potassium fertilization in rich soils because hemp will have luxury consumption without growth response. It seems, however, that actual nitrogen fertilizer use in China is more than double of the recommended amounts (Liu 2013).

Little information is available on irrigation in hemp production. Both in China and in Western European conditions, hemp is grown under rainfed conditions (Amaducci et al. 2014). Canadian growers state that irrigated hemp production makes the crop economically unfeasible (Danckaert et al. 2006). The only studies on hemp irrigation have been carried out in Southern Europe, where hemp is actually grown under irrigated circumstances. These studies report water amounts for irrigation between 250 and 450 mm ha^{-1} (Di Bari et al. 2004; Cosentino et al. 2013).

Hemp is relatively insensitive to pest or diseases and most sources agree that hemp can easily be grown without any application of pesticides (Van Der Werf et al. 1996; Fortenbery & Bennett 2004; Amaducci et al. 2014). Piotrowski & Carus (2011), however, state that in France it is common practice to spray against hemp flea beetle once every eight years. Often herbicides are used to clear the field before sowing

(González-García et al. 2010; Barth & Carus 2015). Especially in fields with hemp broomrape or *Orobanche ramose,* chemical treatment might be needed. However, hemp grows vigorously and as early growth is directed to the leaves, the canopy cover rapidly closes (Amaducci et al. 2014). In this period, photosynthetically active radiation is high and capturing a high proportion of this incident radiation further stimulates rapid biomass accumulation. A consequence of early canopy closure is that hemp can outgrow most other weeds and thus functions as natural weed control (Piotrowski & Carus 2011). Also, most herbicides are phytotoxic to hemp, which excludes post-emergence treatment with herbicide (Legros et al. 2013). It also leaves the ground weed-free after harvest. Probably the low disease stress can partly be attributed to the small scale of current hemp production. It is observed, however, that in crop rotations hemp can alleviate stress from both nematodes and difficult weeds and enhance soil micro fauna (Desalnis et al. 2013).

Harvest and retting

In most producing countries harvest is performed mechanically with specially adapted harvesters that cut the stems and leave them on the field in parallel bundles. In southern China, however, harvest is still done by hand (Amaducci et al. 2014). For optimal fibre quality, harvest takes place at flowering (Bócsa & Karus 1998; Desalnis et al. 2013). This implies that with textile-grade hemp fibres, hemp growers cannot benefit from extra revenues of hempseed.

In a next step, the bast fibre bundles have to be separated from the woody core. To facilitate this, the stems go through a process called retting. During the retting process, which can take different forms, pectinases partially degrade the matrix and set free fibre bundles (Desalnis et al. 2013). The fibre can then be easily separated from the woody core with a mechanical breaking or scutching process. Retting increases the relative amount of cellulose in hemp fibres and results in better fibre quality. Pectin content in individual hemp fibres is as low as 1% (Akin 2010). The most common practices for retting are dew retting and water retting. In the latter, the hemp stalks are placed in big water reservoirs heated up to around 30° C and stay there for 5-6 days (Sponner et al. 2005; Turunen & van der Werf 2006). Natural bacteria cause an aerobic and subsequent anaerobic digestion that degrades the fibre matrix. 10% of the stem mass is lost to microbial mass and air and water emissions (Turunen & van der Werf 2006). The former also uses natural bacteria to break down the pectin matrix. It does so in the field during several weeks using rainfall and dew as source for sufficient humidity. This means fibre quality is highly dependent on environmental conditions and thus on harvest time and chance (Amaducci et al. 2014). Alternatives have been researched to ensure constant fibre quality. In practice, additional degumming and bleaching is performed or the green stems are scutched and then chemically or enzymatically degummed to remove pectin and lignin (Riddlestone et al. 2006; Turunen & van der Werf 2006). Riddlestone et al. (2006) reported from their trials some important technical and economical flaws that remained. These methods are further discussed in section 2.3.1 below.

Water retting was still used in Eastern Europe and China, but has now almost completely disappeared due to labour intensity and heating requirements (Turunen & van der Werf 2006; Personal communication Robert Hertel, December 29th 2014). For European industrial fibre, dew retting is used. In China both dew retting with scutching or hand-peeling and green scutching are common practice (Personal communication Robert Hertel, December 29th 2014).

Yield

Hemp has a high yield potential. Amaducci & Gusovius (2010) report yields of up to 20 tonnes of dry mass per ha. According to Struik et al. (2000) total dry mass yields may even be 25 t ha^{-1} of which 20 t ha^{-1} stem matter. These yields, however, can only be established after a complete cropping cycle. Real biomass yield with current agronomic techniques and harvest at flowering amounts to around 8 t ha^{-1} of dry matter in Europe and between 9.9 and 16.7 t ha^{-1} in Kunming, China, depending on soil conditions and harvesting time (Danckaert et al. 2006; Amaducci et al. 2014). The EU (2012) only indicated an average yield of around 7 t ha^{-1} in a statistical overview of European agriculture. Amaducci & Gusovius (2010) and Jankauskienė & Gruzdevienė (2013) report the fibre content of dry hemp stems to be between 20-30%. This is confirmed by Turunen & van der Werf (2006) who describe a fibre yield of just over 25% in Hungarian processing operations. For every tonne of fibre, between 1.25-2 t of shivs are produced (Turunen & van der Werf 2006; Carus et al. 2013; Barth & Carus 2015).

Economics of hemp production

The current European annual average production area for hemp is between 10,000-15,000 ha (Carus et al. 2013). Canadian hemp production in 2011 was covering more than 15,000 ha (Bouloc 2013a). These numbers include production of both fibre and seeds. Data on hemp outside Western producer areas like Europe and Canada are often unreliable because the crop is not or insufficiently covered in official studies and statistics (Graupner & Mussig 2010). Contributing to the uncertainty is the fact that more than 60 names exist for bast fibres containing the word hemp that have nothing to do with *C. sativa* (Schnegelsberg 1996). Kenaf for example is also called ambary hemp. European fibre production in 2010 was 25,589 t on an area of 10,480 ha. This same area also produced more than 43,000 t of shivs which are mostly used as high-end animal bedding (Carus et al. 2013). Carus (2014) estimates the global hemp fibre production at around 80,000 t.

Information on the costs of hemp production is scarce. Bouloc (2013b) calculated average production costs over the period 2000-2004 of EUR 0.10-0.15 kg^{-1} of hemp straw. On the other hand, a comparable number of EUR 0.15 kg^{-1} of scutched fibre has been reported by Riddlestone et al. (2006). Degumming and refining the fibre to textile quality, however, increased the cost to EUR 4.88 kg^{-1}.

2.2 Cotton

2.2.1 Botanical description

Cotton is the name for a collection of perennial plant species from the *Gossypium* genus. It is a plant native to and mostly grown in tropical to subtropical regions. The northern and southern borders of cotton cultivation are located between 30° and 45° N or S (Lord 2003f; Tobler-rohr 2011c). Four species are currently cultivated worldwide (Table 1). The most important is *Gossypium hirsutum* with more than 87% of global production. *Gossypium barbadense* is the second most important cotton species with around 8% of global production (Chaudhry 2010; Tobler-rohr 2011c). This species is commonly known as Egyptian cotton, Pima cotton or extra long staple cotton because of the significantly longer fibre lengths it produces. It is considered a superior quality because of the good spinnability for very fine yarns. A premium is therefore paid for such long fibres (Zhang 2011).

Table 1: Overview of economically important cotton species.

Name[1]	Common name[1]	Centre of origin[2]	Global cultivation %[1,3]
Gossypium hirsutum	American cotton	Latin America	87-96
Gossypium barbadense	Egyptian cotton	Latin America	3-8
Gossypium herbaceum	Levant cotton	Sub-Sahara Africa	marginal
Gossypium arboreum	Tree cotton	India/Pakistan	marginal

[1] Tobler-rohr 2011c
[2] NGRP 2014
[3] Chaudhry 2010

Cotton germinates from a minimum of 15°C with an optimum between 18-30°C and early vegetative growth happens preferably above 20°C (Kooistra & Termorshuizen 2006; Chaudhry 2010). The plant forms palmate leafs with varying depth of cuts between the lobs. Flowering starts 60 to 70 days after establishment. The plant has yellow to white, complete flowers that should be cross-pollinated. In practice, however, cotton is mostly self-pollinating (Munro 1987). Pollinated flowers will wither and form cotton bolls. During the next 40 to 60 days cotton bolls mature and ultimately open (Kooistra & Termorshuizen 2006; Chaudhry 2010). Open bolls contain the fluffy, pale fibres attached to the black cottonseeds. Cotton fibres have dimensions of 12 to 50 mm and a typical aspect ratio in the order of 10^3 (Lord 2003f). The aspect ratio is the ratio of fibre length to fibre diameter. Silva et al. (2011) report an aspect ratio of 3,012 for cotton fibres. With reported values between 287-600 MPa, tensile strength of cotton fibres is slightly lower than that of hemp fibres (Bledzki & Gassan 1999; Batra 2006). Tenacity of cotton fibre varies between 15-55 cN tex^{-1} (Franck 2005a). The fibres consist of around 91-92% cellulose microfibrils (Moriana et al. 2014). These are covered with a protective wax layer embedded in a pectine and hemicellusose matrix (Akin 2010). In contrast to hemp and other bast fibres, cotton does not contain lignin. All of this makes an important difference in processing, as hemp requires additional steps to result in a fine, single cellulose fibre.

2.2.2 Cultivation

Site requirements

Cotton is by origin a perennial tree but in modern agricultural systems it is cultivated in an annual production cycle. As mentioned in section 2.2.1, cotton is a tropical crop. It is highly sensitive to low temperatures but can tolerate extremes up to 40°C (Kooistra & Termorshuizen 2006). It has an extensive root system for the uptake of water and nutrients that allows it to survive periods of serious drought. It is therefore considered as a dryland crop (Chaudhry 2010). For optimal yield, however, water requirements, calculated from potential ET, are between 600-2500 mm depending on environmental conditions (Wang et al. 2013; Perry et al. 2012). Cotton grows on a wide range of soils but medium to heavy soils with good water retention are preferred (Kooistra & Termorshuizen 2006). Too heavy soils prevent proper root formation. Optimal soil pH is between pH 6-7 (Oldham & Dodds 2014). Lower pH can be tolerated but will ultimately result in underdevelopment of roots and decreased yield.

Production practices and critical issues

There are two main production systems for the majority of global cotton production: the large-scale, highly mechanized method used in the United States, Israel and Australia; and labour intensive production by smallholders in most parts of Asia and Africa (Dai & Dong 2014). Highly mechanized production is mainly aimed at the most cost-efficient way of production on large areas. Like with other crops, this system mainly developed in regions with abundant land but expensive manual labour. Intensive smallholder production on the other hand is aimed at optimizing yields on a small area with large amounts of inputs and labour. Natural fibre production policy in China for example has been and still is focused on increasing output and quality without increasing acreage as fertile land for food production is scarce (Zhang 2011). Therefore, improved seeds for increasing quality, mineral fertilizer and pest management are all being financially supported. Smallholder mechanization also increases as this Chinese production model is under pressure. The cost of labour rapidly increases as millions of farmers migrate to the city every year (Dai & Dong 2014). For many smallholders in developing countries cotton is an important cash crop that is worth sacrificing part of their food production for (Bärlocher et al. 1999). One final aspect that separates production systems with high and low mechanization is the use of intercropping systems. To increase total land productivity smallholders often intercrop wheat and cotton (Zhang 2007).

Apart from mechanization, cotton production in countries with leading productivity is input intensive. According to Kooistra & Termorshuizen (2006) nutrient requirements are not very high with N/P/K requirements of 100-180/30-60/50-80 kg ha^{-1}. They also report actual application rates in China to be the double. Oldham & Dodds (2014) and also Lemon et al. (2009) suggest an application of 50 lbs. of nitrogen in any form per bale $acre^{-1}$ of lint yield or ca. 56 kg for every 247 kg ha^{-1} yield. Extrapolated to the global average yield of 770 kg ha^{-1} this suggests 175 kg N ha^{-1}, thereby confirming the suggestion by Kooistra & Termorshuizen. Potassium is crucial in cotton cultivation as it interacts with the fibre strength and length (Oldham & Dodds 2014). In personal communication, cotton expert Tian Changyan (November 24^{th}, 2014) reports common fertilizer ranges in China of 280-325/40-80/50-150 kg N/P/K ha^{-1}. For cotton production on sandy soils or on soils low in soil organic matter, sulphur and boron should be added as well.

Although cotton is considered a dryland crop, fibre yields are sensitive to drought. This is mainly because flowering and boll setting depend on sufficient water (Dai & Dong 2014). As potential ET can be as high as 2600 mm (above), rainfall often does not cover the water requirements and cotton is intensively irrigated. 53% of the global cotton acreage is irrigated producing 73% of the global cotton production (Kooistra & Termorshuizen 2006). The percentage of irrigated US cotton acreage is 40-46% depending on different sources (Janet et al. 2009; Barnes et al. 2012). In China, however, this percentage is estimated around 69% (Barnes et al. 2012). Irrigation techniques differ widely but are mostly very inefficient. Bärlocher et al. (1999) estimated the efficiency of global irrigation at 40%, while Bevilacqua et al. (2014) state that the efficiency of only flood-and-furrow irrigation is around 40%. It is generally accepted that using drip irrigation could save more than 50% of water due to increased water use efficiency (Muhammad et al. 2010; Barnes et al. 2012). Common practice in the Chinese province of Xinjiang is the combination of drip irrigation with plastic mulching to further reduce ET. In a region where potential ET can reach 2500 mm and yearly precipitation is below 200 mm this results in common irrigation practices of only 375-675 mm (Zhou et al. 2012; Personal communication Tian Changyian, November 24^{Th} 2014).

Finally, cotton is prone to many pest and diseases, but mainly insects. Some of the most important pests on cotton are the cotton bollworm, *Helicoverpa armigera*, pink bollworm, *Pectinophora gossypiella*, Egyptian bollworm, *Earias insulana*, several spider mites, thrips and white fly, *Bemisia gossypiella.* Yield loss by these pests can amount up to 10-15% (Wu & Guo 2005; Kooistra & Termorshuizen 2006). It is estimated that 11% of global pesticide production is used on cotton production while cotton only accounts for 2.4% of the global area of arable land (FAOSTAT 2014). For insecticides this was even estimated at 25% of the global production (Bärlocher et al.

1999). This is one explanation for the attractiveness of Bt-cotton production. Globally in 2011, 70-80% of the cotton area planted was genetically modified (GM) cotton. In China alone, GM cotton accounted for 71.5% of the total area (Clive 2011). Since the introduction of Bt cotton late 1990s, yield losses to insect pests and annual number of pesticide applications in China were reduced by 50% and 40% respectively (Wu & Guo 2005).

Harvest, ginning and yield

Cotton is harvested after a production cycle of 140-180 days, either mechanically or handpicked. Of the major cotton producers, China, India, Pakistan and Turkey pick the majority by hand (Chaudhry 2000). Greece, Uzbekistan and Brazil use both methods and Australia and the US have 100% machine-picked cotton (Chaudhry 2000). The harvested material is the seed boll of the plant and is called seed cotton.

The final agricultural practice of cotton production is considered to be ginning. In order to have a marketable agricultural commodity, cotton lint or cottonseed, both first have to be separated from each other (Wakelyn et al. 2005). Different sources report cottonseed production to be between 1.5-1.7 kg per kg of cotton lint (Adanacioglu & Olgun 2011; Bevilacqua et al. 2014). A separate industry has developed around these seeds based on the extracted cotton oil. The seedcake, left after oil extraction, is used as protein source in animal feed, energy source or organic fertilizer (Turunen & van der Werf 2006).

In the gin, seed cotton is first blown through drying towers that reach temperatures of up to 200°C. Then it is cleaned from sticks and shells and transported into the gin stand where saws pluck the lint from the seeds (Lord 2003a). Reported ginning efficiencies vary greatly (Table 2). Adanacioglu & Olgun (2011) mention a ginning outturn (GOT) of 38.31% and 3.75% thrash in Turkish gins. This means 38.31% of the weight in seed cotton was recovered as lint output from the gin. Tobler-rohr (2011b) on the other hand reports a far lower GOT of 20.7% with 30.7% thrash for Chinese gins.

Table 2: Ginning outturn (GOT) from gins in different countries and sources.

Country	Lint (%)	Thrash (%)	Seed (%)
Turkey[1]	38.31	3.75	57.94
China[2]	39.40	/	/
China[3]	20.70	30.70	48.60
USA[2]	25.10	33.10	41.80

[1] Adanacioglu & Olgun 2011
[2] Zhang 2007
[3] Tobler-rohr 2011b

Cotton lint yields vary greatly across the world. Global average production is estimated at 760-790 kg ha^{-1} (Johnson et al. 2014; USDA 2015b). Country averages range from more than 1800 kg ha^{-1} in Israel or Australia to less than 200 kg ha^{-1} in countries like Zambia and Zimbabwe (USDA 2015b). The upper ranges of yield are very input intensive, while farmers in countries in the lower ranges often cannot afford artificial fertilizer, pesticides or irrigation. Chinese farmers cultivate cotton on more than 5 million hectares with an average yield of 1438 kg ha^{-1} in 2012 and estimated to be between 1380-1490 kg ha^{-1} in 2014 (Dai & Dong 2014; Johnson et al. 2014; USDA 2015b). Such yields are high compared to the other top-producing nations ranging from 194% and 45% more compared to India and the US and 87% more compared to the global average. One explanation might be the heavy subsidizing of agricultural inputs by the Chinese government.

Economics of cotton production

Both Johnson et al. (2014) from the USDA and FAOSTAT (2014) report a global cotton production in 2014 of just under 26 million tonnes on 33 million hectares. The five major cotton producers are China, India, United States, Pakistan and Brazil amounting to 27.4%, 24.9%, 11.3%, 8.1% and 6.3% of the world production respectively (Johnson et al. 2014). As seen in Figure 1, China has been the world's top producer for the past 25 years. But Chinese production has recently dropped and is predicted to stagnate the coming years (Johnson et al. 2014). If India continues its steady increase in production it might soon become the largest cotton producer in the world. The cultivation latitudes imply that production possibilities in Europe are limited to the southernmost regions. Greece and Turkey produce more than 93% of the European cotton (USDA 2015b).

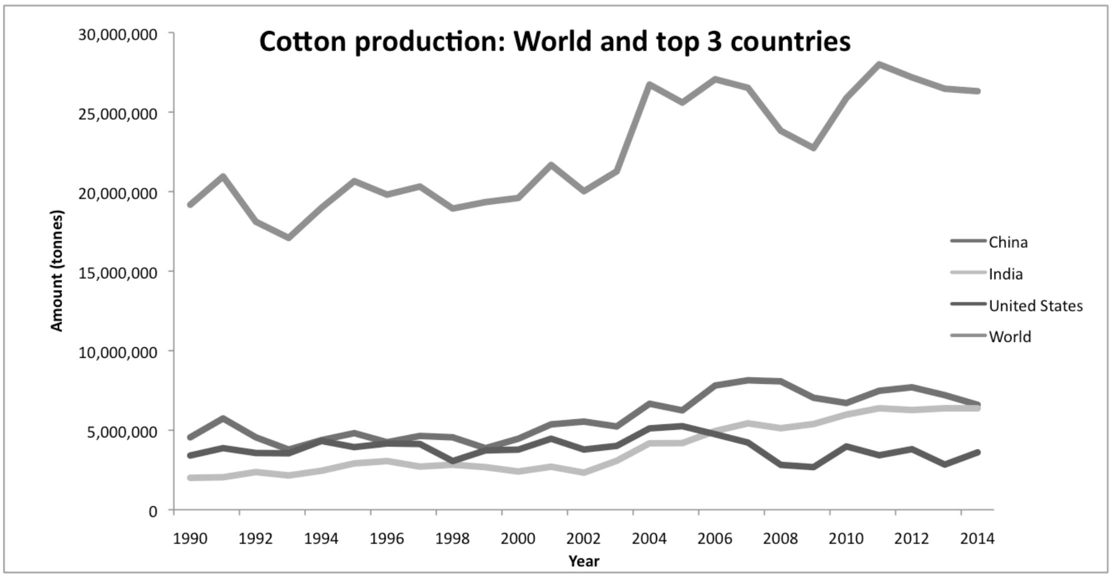

Figure 1: Cotton production: World and top three countries.
This graph represents the global cotton production and the top three producing countries from 1990 to 2014. Data from USDA (2014).

In 2007, the global average cost for producing 1 kg cotton lint was USD 1.04 (Chaudhry 2008). Big differences can occur between countries. Turkey (USD 1.63 kg^{-1}), China (USD 1.52 kg^{-1}) and the US (USD 1.42 kg^{-1}) were in the top range whereas Pakistan (USD 0.63 kg^{-1}) and India (USD 0.50 kg^{-1}) had significantly lower costs. Central Asian countries like Uzbekistan and Kazakhstan closed the ranks (Chaudhry 2008). Expensive labour and labour-intensive practices mostly explain the high costs of Turkish cotton (Chaudhry 2008). Chinese cotton production is expensive due to excessive costs on mineral fertilizer and rising labour costs. While Indian cotton farmers on average use far less fertilizer and use minerals more efficient as cotton follows wheat in rotation (Chaudhry 2008). Major components in the global cost structure are fertilizers (14%), ginning (11%), harvesting (9%) and insecticides (9%) (Chaudhry 2008). These costs all include labour. It can be assumed that these costs significantly increased since 2007, especially for labour- and input-intensive systems like in China. Firstly, handpicking cotton already was more expensive and thus rising labour prices and relatively low energy prices will only have increased the discrepancy. Also, fertilizer prices in 2014 have increased significantly since 2007: 60% for urea and more than 100% for triple superphosphate (World Bank 2014). The world price of cotton is currently at a five-year low on the other hand. With USD 1.52 kg^{-1} it is even equal to the average production cost of cotton in China in 2007 and thus below the current estimated production cost (USDA 2015b).

2.3 Natural fibres

2.3.1 Processing of hemp and cotton

Ginned cotton or scutched hemp fibre can be processed into yarn. A high aspect ratio is necessary for use in spinning technology and thus for textile purposes. Fibres with higher aspect ratios result in stronger yarns for the same yarn count compared to lower aspect ratios (Lawrence 2010). They have more inter-fibre contact between individual fibres. This implies that finer yarn with equal strength can be spun from cotton or hemp compared to fibres with lower aspect ratios like sisal or jute (Akin 2010). Cotton fibre is a short staple fibre (STF) and is thus processed with STF spinning technologies. Hemp is both considered long-staple fibre (LSF) when fibre bundles are used or STF after cottonization (Figure 2). LSF are spun like flax or wool, the latter has typical lengths of 70-450 mm (Lord 2003b).

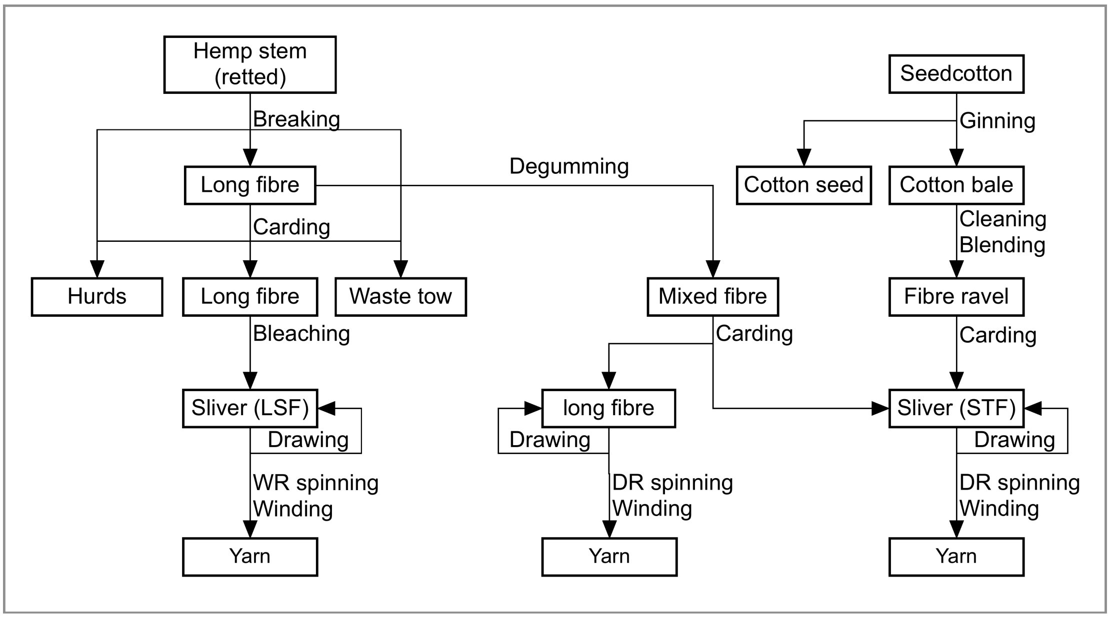

Figure 2: Flow chart of hemp and cotton fibre processing into sliver and ultimately yarn. This flow chart represents the fibre flow in both cotton and hemp processing from raw fibre into sliver. WR spinning is wet ring spinning and DR spinning is dry ring spinning. Figure is adapted from Lord (2003d); Sponner et al. (2005); Kostic et al. (2008); Amaducci & Gusovius (2010).

Cotton and hemp fibre preparation

The first process in a cotton mill is the opening of the bales. Bales are placed next to each other and a bale plucker takes the top layer from each bale as it passes by (Estur & Knappe 2007). This operation blends fibres from different bales, which might have slightly different qualities, so that the resulting yarn is highly homogenous. A consequent cleaning step removes foreign material, like stones, sand, seed coat and neps from the desired fibres. Neps are immature cotton fibres that collapse during drying and ginning. They form small balls of fibre and are a nuisance in processing as they form serious inconsistencies in the yarn (Lord 2003f). The following carding process disentangles the ravel of fibres and arranges them in a parallel orientation. Dirt particles that were retained after cleaning will be removed as well. The resulting bundle of loosely, aggregated fibres is called sliver. Drawing then combines four to eight slivers to form one new mixed sliver. Stretching and combining different slivers reorganises the inter-fibre entanglement and enhances the intimate parallel aggregation (Lord 2003e).

As seen in Figure 2, the processing methods of hemp are more variable, depending on region and end use of the fibre: two main process routes are used. In both processes, the retted stems first go through a breaking or scutching process that parts most of the shivs from the fibre (Amaducci & Gusovius 2010). In scutching, the shivs are whipped of the fibres by rotary blades (Sponner et al. 2005). In the traditional method, fibre bundles are then cleaned and parallelized in the hackling, or carding, process into a sliver. The sliver is then chemically bleached to partly remove pectins and lignin (Turunen & van der Werf 2006; Personal communication Robert Hertel, December 29th 2014). Previous processes produce tow (STF) as by-product. This is a ravel of shorter, weaker bundles and individual hemp fibres that separated from the long bundles. Tow can be pre-carded and carded for use in coarse yarns or industrial applications (Sponner et al. 2005; Kozłowski et al. 2013; Robert Hertel Personal Communication, December 29th 2014). To result in cotton-like fibres, the fibre bundles are cottonized right after breaking or scutching (Personal communication Robert Hertel, December 29 2014). This cottonization process is also referred to as degumming and happens in practice by boiling the fibres in an alkaline solution after which all lignin and pectins are washed off. This latter step is the main difference with bleaching, where the mixture of lignin and pectins is used to glue the fibres together during spinning. The degummed fibres are carded to separate the longest fibres from the sliver. The shortest fibres are used in blends with other fibres (mainly cotton) while the longest, finest fibres can be dry spun into pure hemp yarn (Personal communication Robert Hertel, December 29th 2014). Experiments show that enzymatic cottonization is possible as well (Riddlestone et al. 2006; Kozłowski et al. 2013). The main hurdle according to small-scale tests by Riddlestone et al. (2006) was finding an economic degumming method. Also in India research is performed to find a truly economic and ecological method (Personal communication Bijay Ghosh, October 8th 2014).

Spinning technologies

The two main STF-spinning methods are ring and rotor spinning. It is estimated that 80% of the total global cotton yarn production is ring spun whereas only 20% is rotor spun. For China these estimated percentages are 83% and 17% (Plastina 2009). Ring spinning requires a roving step. This process reduces the linear density of the sliver and introduces a first twist before placing it onto a bobbin (Lord 2003d). The roving is then spun using a rotating spindle. The twists introduced in spinning are necessary to improve the yarn strength and fibre integrity (Estur & Knappe 2007). This spinning process uses small bobbins around which the spindle twists the yarn. Because of their limited size, these bobbins are afterwards rewound onto bigger cones in order to reduce yarn-handling costs in further processing. Open end or rotor spinning directly uses the sliver to feed fibre into the spinning process. A rotor spinning at speeds up to 120,000 rotations per minute twists it into yarn (Lord 2003d). As the twisting and winding processes are separated, the winder is capable of producing larger cones and therefore no rewinding is necessary. Very fine blended yarns of up to 200 Nm have been spun with a 50/50 hemp/cotton ratio with OE spinning (Kozłowski et al. 2013). Hemp fibres in this case were enzymatically cottonized.

LSF hemp used to be only wet spun. In this process the rove is fed through a 60° C water bath and the yarn afterwards had to be dried. This makes it uneconomical and energy-intensive (Salmon-Minotte & Franck 2005). Dry spinning LSF techniques are worsted, semi-worsted or woollen spinning and are adapted to longer fibre lengths like wool or ramie fibres (Lord 2003b). The future potential for hemp fibres, however, is believed to be STF-spinning (Personal communication Robert Hertel, December 29th 2014).

Weaving and knitting

From one to three dimensions, there are two main techniques for manufacturing yarn into fabric: knitting and weaving. In the former, loops of yarn are interlinked with each other by up to 100 needles in order to get a 3-dimensional structure (Tobler-rohr 2011b). Knitting produces a light, flexible fabric like the fabric used in t-shirts. Typical yarns for a single Jersey t-shirt knit have counts of around 50 Nm and result in fabric of 110-160 g $(m^2)^{-1}$. Interlacing cross-oriented weft yarns with length-oriented warp yarns produces fabric of the latter kind. A bobbin of yarn is needed for every yarn in the warp (Tobler-rohr 2011b). This warp is first processed with a textile-sizing agent. These water-soluble polymers like starch, polyvinyl alcohol or carboxymethyl cellulose protect the warp against abrasive forces during interlacing (Brodmann et al. 1985).

2.3.2 Current use

The uses of natural fibres and hemp fibres in particular are abundant (Figure 3). They can be used as a raw fibre or refined fibre. Applications of hemp as raw fibre are fluid seals, rough insulation material or source of cellulose for paper pulp. Fibres can also be processed into non-wovens like advanced insulation or for agricultural applications, or into yarn for textile purposes. In many different forms the fibres can be added to composite materials for the production of biocomposites (Graupner & Mussig 2010). In 2008, 26 million t of natural fibres were used for industrial purposes. The majority of this is cotton (86%). Jute, kenaf, hemp and flax form only a minority (Raschka & Carus 2012). These fibres are interchangeable in composite materials and are often used in blends (Bouloc et al. 2013). This is mostly out of necessity because of price and supply considerations.

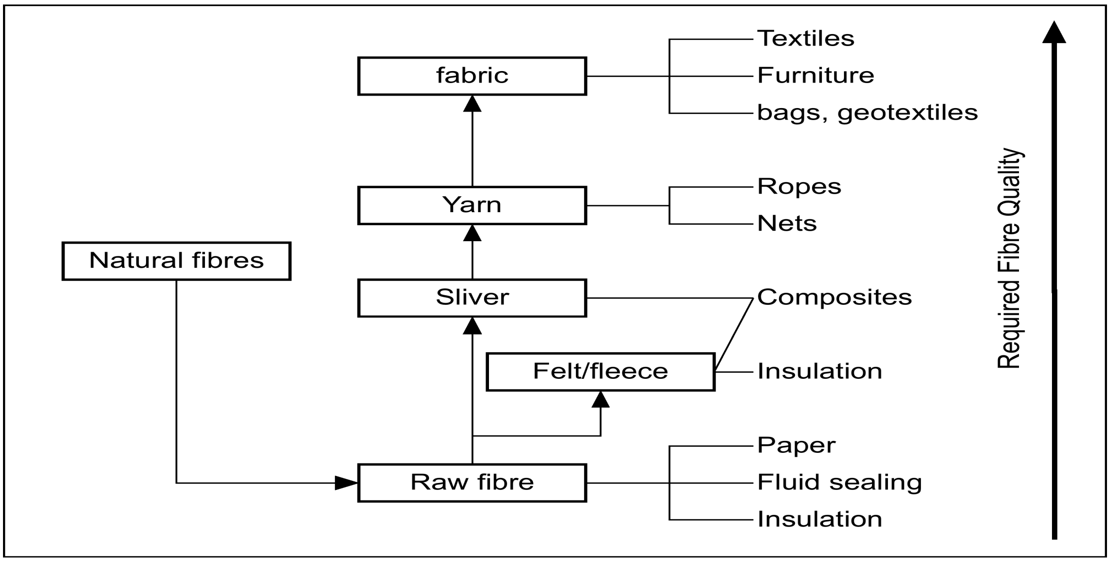

Figure 3: Natural fibre processing qualities and related end-uses.
A flow chart of the different steps in natural fibre processing and the end-uses related to this processing step. Different end-uses are ranked by the required fibre quality. Adapted from Graupner & Mussig (2010).

Textile-grade hemp fibre is mainly produced in China. More than 600 t hemp yarn with a value of USD 12 million was exported there in 2013 (Wang 2014). The majority of hemp textiles, however, is produced within China and thus exported as apparel. The annual US market for hemp clothing is estimated at around USD 100 million (Johnson 2013). This is of course utterly low compared to estimated annual revenues of USD 320 billion in the Chinese cotton yarn and fabric industry (IBIS World 2014).

The most important use of hemp fibres in Europe is the production pulp and paper, followed by insulation material and biocomposite materials (Carus et al. 2013). Hemp fibres for paper production can be of lowest purity, still containing the largest percentage of shivs. It is used in specialty papers, like cigarette paper, or as a reinforcement of recycled paper (Snauwaert & Ghekiere 2011). Especially with shortages and sustainability issues of forest resources, non-wood pulp sources may gain importance in the future (González-García et al. 2010). Hemp would have a serious growth potential in insulation materials as a sustainable alternative to mineral and glass wool if production costs could be reduced (Carus et al. 2013). In composite materials, hemp fibre can replace glass fibres to reinforce plastics. These so-called biocomposites are lighter but as strong as traditional composites used in the automotive industry. Again the problem is stable supply: the German automotive industry still uses more than 45,000 t of cotton in biocomposites (Piotrowski & Carus 2010). As long as European policy is biased towards energy crops because of biofuel goals, but not biobased materials, hemp fibre will never live up to its potential (Carus et al. 2013). Growing hemp is just not as profitable.

Cotton is mostly known as a textile fibre. With 43% of the textile mass, cotton is the most important fibre in the European apparel market (Beton et al. 2012). Other, but minor applications include the reinforcement of composite materials and cordage (Chaudhry 2010). The remaining fibres on the seed after ginning are called linters and are a source of cellulose used for example in the production of USD bank notes.

2.4 Sustainability evaluation of hemp and cotton

2.4.1 Type of sustainability assessments

Numerous methodologies have been developed to perform sustainability assessments in an industrial context. Literature on the sustainability of textiles in particular pointed out three types of assessments most commonly used. The first and most extensive assessment is a complete LCA. Depending on the methodology used, this assessment gives a holistic overview of environmental impacts of a products life cycle and the related inputs (Guinée 2002). Both midpoint and endpoint methodologies exist. Midpoint or problem-oriented methods focus on primary impact of the product, e.g. rise in greenhouse gas (GHG) emissions. Endpoint methodologies, however, will relate these primary impacts to ultimate damages to the environment, e.g. the loss in biodiversity (Menoufi 2011). A second type is a Cumulative Energy Demand (CED) assessment. This life cycle based analysis is used to calculate all direct and indirect energy necessary to produce a product. Direct energy includes all energy sources needed in production while indirect energy comprises energy carriers, like production inputs, that have been extracted and produced using direct energy inputs (Goedkoop et al. 2008). The second and often parallel-performed analysis is the carbon footprint analysis in which the global warming potential (GWP) is assessed. This is in fact an LCA that focuses solely on GHG emissions, although very often only emissions from (in)direct energy production are included (UNEP/SETAC 2011). The results of all previous methods are highly dependent on the assumptions made and the system boundaries that have been taken into account. Assessments can be performed on a cradle-to-grave (C2Gr) basis, i.e. the entire life cycle, or on a cradle-to-gate (C2Ga) and gate-to-gate (Ga2Ga) basis, i.e. including only parts of the life cycle (Guinée 2002). Furthermore, factors for assigning weight to different components may differ from source to source. All of this has to be taken into account when comparing different assessments.

Table 25 (Appendix 1) offers an overview of all sustainability assessments found on both hemp and cotton. This table includes for every source the type of assessments and other aspect that have to be taken in account for comparison. A subdivision is made to indicate groups of assessments that can be compared together.

2.4.2 Cradle-to-gate: Crop cultivation

CED and GWP

A first and important group of assessments are those that include separate results on crop cultivation. Figure 4 represents all found CED and GWP values for both hemp and cotton production per kg of fibre. All three hemp assessments only cover European data. Turunen & van der Werf (2006) and González-García et al. (2010) have a per weight functional unit (FU). The former does not include any details on system boundaries, as it is not the actual analysis performed in the report. It was used to compare with results on cotton so it can be assumed that both systems were similar

(Turunen & van der Werf 2006). The latter was an analysis on fibres entering a paper mill. No details are provided on yield or proportions of allocation, except that economic allocation was used. When comparing paper fibres to textiles fibres, the mass proportion of fibres used would have been far lower as quality requirements increase and the price would be higher. Therefore we expect more impact to be allocated per kg fibre in case of textiles. Van der Werf (2004) used an area-based FU and thus assumptions on economic allocation and fibre yield were made to calculate values kg^{-1}. Calculations based on estimates and mass allocations from van der Werf & Turunen (2008) result in 2,400 kg CO_2 ha^{-1} and 11,845 MJ ha^{-1} compared to 2,330 kg CO_2 ha^{-1} and 11,400 MJ ha^{-1} in van der Werf & Turunen (2008). Therefore the exact fibre content and EA of the former were used. It has to be noted that González-García et al. (2010) takes fibre separation into account, while van der Werf (2004) does not. Van der Werf & Turunen (2008) calculated a contribution of fibre separation to GWP of around 25% of total fibre production stage (cultivation and separation). This gives an indication of the effect that the inclusion of separation in the assessment of van der Werf (2004) might have.

The assessments for cotton show larger discrepancies in CED and GWP outcomes. An important difference in system boundaries is again whether or not ginning is included in the assessment. Yilmaz et al. (2005) and Matlock et al. (2008) are the only assessments excluding ginning. From surveys carried out by Khabbaz (2010) with Australian cotton farmers it appears, however, that ginning and transport to the harbour only account for 2-16% of total CED. Differences potentially explained by ginning are thus not of the magnitude of differences witnessed in Figure 4. Yilmaz et al. (2005) also used an area-based FU but this can be converted with the specified yield of 3112 kg seed cotton ha^{-1} and a seed-to-fibre-ratio of 1.5/1 (Table 2). The outcome of Van Der Velden et al. (2014) is based on Chinese production data available in Ecoinvent v2.2. Barnes et al. (2012) only include direct energy use from electricity and fuel. All other CED assessments include all direct and indirect energy. Another factor is the geography of the assessed cotton production. Barnes et al. (2012) and Matlock et al. (2008) estimated global weighted averages using data from US, China and India and US, Asia and Australia respectively. These are significantly lower compared to average outcomes in the Turkey, US, Australia and China reported by Yilmaz et al. (2005), Reed & Barnes (2009), Khabbaz (2010) and Van Der Velden et al. (2014) respectively.

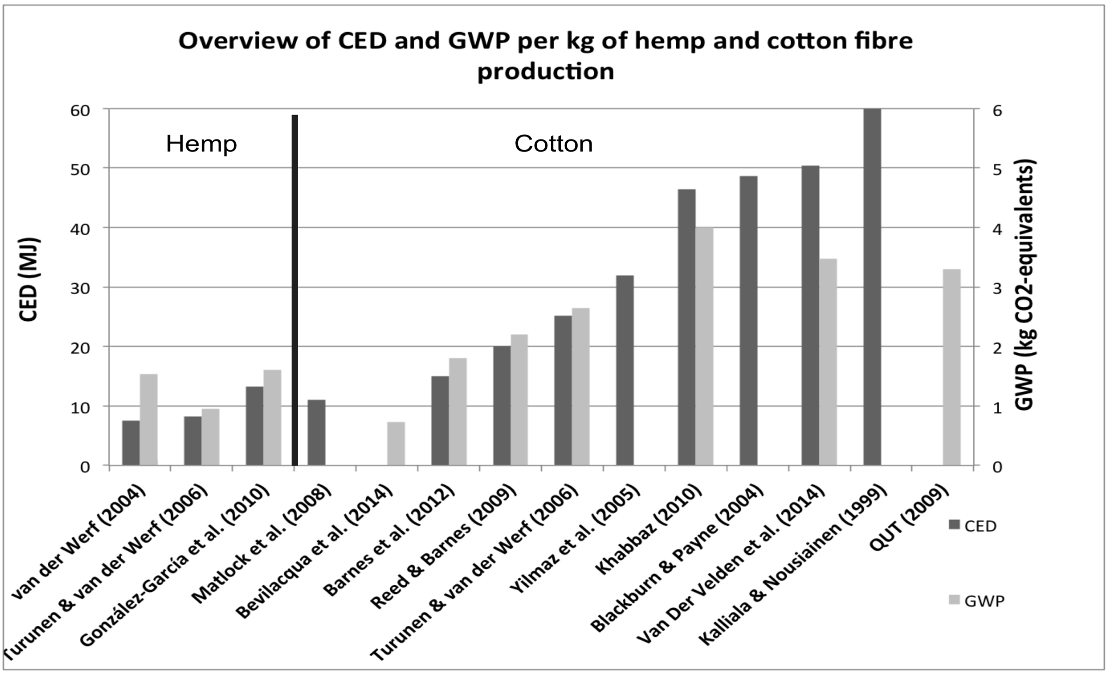

Figure 4: Summary of cumulative energy demand and global warming potential per kg fibre. This graph represents the values as calculated in the different cumulative energy demand (CED) and (global warming potential) GWP assessments. Interpretation of these values is highly dependent on the assumptions made in the assessment. The first three comprise studies on hemp. The latter 11 are values for cotton.

Table 3 compares some striking differences between two assessments. Firstly, the yield of Turkish handpicked cotton is, as expected, higher compared to machine-picked US cotton. With a CED kg^{-1} of the former up to 50% higher, this means that the total energy consumption in MJ ha^{-1} is way higher. Reasons for this are among others a difference in fertilizer use and energy used for field operations with a respective factor of 2 and 5.5. Especially the latter is remarkable because Yilmaz et al. (2005) report the cotton to be handpicked, while Reed & Barnes (2009) report 40% of the 2,761 MJ are attributed to harvesting. Additionally, Yilmaz et al. (2005) include the indirect energy of the agricultural machinery, whereas Reed & Barnes (2009) does not. A final peculiarity is the Energy use efficiency (Table 3). Yilmaz et al. (2005) in effect state that the total energy output from cotton production is only 74% of the total energy input, while Reed & Barnes (2009) report that to be 159%. One of the reasons for this discrepancy, apart from the large difference in input energy, is the factor used for the energy contained in the seed. This again shows how difficult such assessments can be compared and how dependent results are on factors, assumptions and system boundaries. Matlock et al. (2008) also stress the uncertainty due to lack of publicly available data when analysing countries like China and India.

Table 3: Comparison between two cotton CED assessments indicating major differences.

Source	Yield ($kg\ ha^{-1}$)	EUE[1]	E_{seed}[2] ($MJ\ kg^{-1}$)	Fertilizer ($kg\ ha^{-1}$)	Operations ($MJ\ ha^{-1}$)	Machinery ($MJ\ ha^{-1}$)
Yilmaz et al. (2005)	1,244	0.74	11.8	340	15,468	13,210
Reed & Barnes (2009)	933	1.59	32.4	170	2,761	/

[1] EUE = Energy Use Efficiency: Ratio of energy output to energy input.
[2] E_{seed} = Factor for energy contained in a kg cottonseed.

Although averaging the results from Figure 4 is not entirely correct because of the large intrinsic differences of the studies, it does give an indication of the magnitudes of both CED and GWP related to cotton and hemp production. Mean CED of hemp and cotton fibre is calculated at 9.6 ± 3.1 MJ kg^{-1} and 34.3 ± 17.6 MJ kg^{-1} respectively. The two are significantly different at a 0.05 significance level (p-value = 0.0012). The same is true for the mean GWP of respectively 1.4 ± 0.4 kg CO_2-eq kg^{-1} and 2.6 ± 1.1 kg CO_2-eq kg^{-1} (p-value = 0.01).

LCA midpoint results

Some studies are complete LCAs in which more impact categories are included, other than GWP. The eutrophication potential (EP) per kg hemp fibre seems to be a lot higher compared to that of a kg cotton fibre (Figure 5). As there is only one result for cotton, no real conclusion can be drawn on this matter. The large difference is notable, however, because 80-90% of EP is determined by fertilizer use (González-García et al. 2010; Barnes et al. 2012). This is therefore the main place to look for discrepancies between the assessments. The emission and characterization factors of both van der Werf (2004) and González-García et al. (2010) are feasible (De Klein et al. 2006). Fertilizer applied is low to normal for the former and normal to rather high for the latter. The only factors able to further influence the EP are yield and allocation method. González-García et al. (2010) mention low yields, but don not give figures, and yields for van der Werf (2004) are considered equal to the yield reported by Turunen & van der Werf (2006). Barnes et al. (2012) on the other hand have a more complex nutrient model and do not mention any emission factors. Rough estimations from other studies, however, also indicate EP of 6-9 g PO_4-eq kg^{-1} cotton fibre compared to 3.8 g PO_4-eq kg^{-1} (Steinberger et al. 2009; Levi Strauss & Co 2008). Concerning AP, Figure 5 shows a trend similar to Figure 4. AP is greatly affected by both NH_3 and N_2O and SO_2, of which important sources are fertilizer emissions and energy production respectively. These results are, however, somewhat contradictory: Barnes et al. (2012) report over 60% of the AP to be attributed to field emissions and “strongly affected by ammonia”. NH_3 has indeed a stronger acidification potential than SO_2 (Huijbregts 1999). AP in Barnes et al. (2012) is over a factor 2 larger compared to the hemp studies. For EP on the other hand, NH_3 also has the largest potential of all nitrogen emissions (Huijbregts 1999). Nitrate leaching, however, contributes most to EP because of its quantity (Barnes et al. 2012). This would imply that far less nitrate leaches in cotton production compared to hemp production, which seems unlikely looking at the respective fertilizer regimes used.

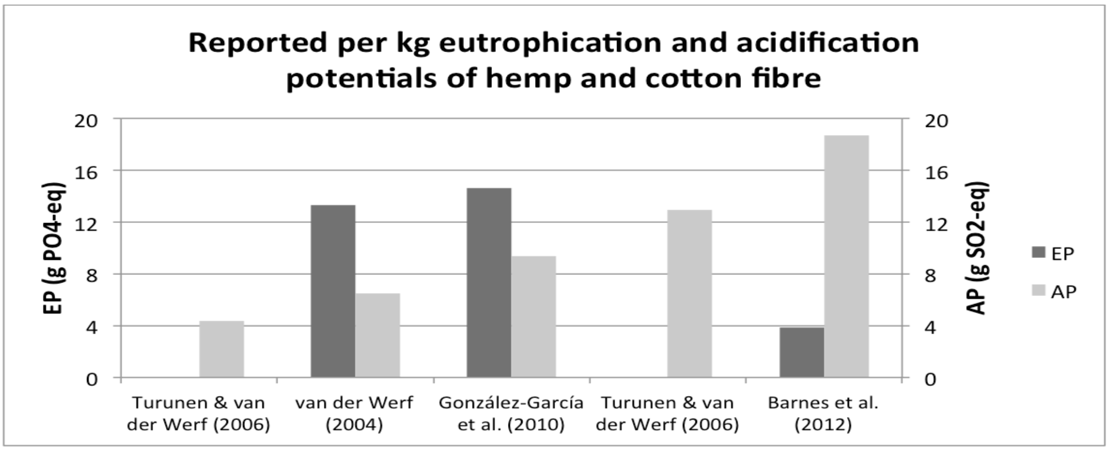

Figure 5: Summary of eutrophication and acidification potential per kg of hemp and cotton fibre. This graph represents the eutrophication potential (EP) and acidification potential (AP) as calculated in five LCAs on fibre production. The first three comprise studies on hemp, the latter two studies on cotton.

Impact distribution in cultivation

Table 4 summarises the major contributions to the four previously discussed impact categories. Some differences appear but in terms of CED fertilizer production, fuel use and irrigation are the most important contributors. Especially N-fertilizer production has a very high impact on energy use (Bevilacqua et al. 2014). A point of attention is the rather large discrepancy in CED for ginning (Barnes et al. 2012; Khabbaz 2010). Whether or not irrigation is used, is a major factor for variation CED (Matlock et al. 2008). Differences in yield, however, always have to be taken into account. Fertilizer production, fuel use, irrigation and field emissions coming from fertilizer use are the most important sources of GWP and AP. Lastly EP is predominantly determined by field emissions. All of the above stresses the major impact of mineral fertilizer use in crop cultivation and thus proper field management and fertilizer efficiency is of great importance in reducing environmental impacts of fibre production (Cherret et al. 2005; González-García et al. 2010; Barnes et al. 2012).

Table 4: Summary of the major contributions to CED, GWP, EP and AP in fibre production.

	Source	CED	GWP	EP	AP
Hemp	González-García et al. (2010)	47% fuel 39% fertilizer	35% fertilizer 35% field em.[1] 20% fuel	80% field em.[1] 10% fertilizer	33% fuel 30% fertilizer 27% field em.[1]
Cotton	Barnes et al. (2012)	37% fertilizer 27% ginning 21% irrigation	30% fertilizer 20% field em.[1] 10% irrigation	>70% field em.[1]	>60% field em.[1] 10% irrigation 10% fuel
	Yilmaz et al. (2005)	31% fuel 29% fertilizer 27% machinery			
	Reed & Barnes (2009)	32% fertilizer 27% irrigation	31% irrigation 21% field em. 16% fertilizer		
	Khabbaz (2010)	2-16% ginning and transport			
	QUT (2009)		66% fertilizer prod. + em. 21% fuel		
	Cherret et al. (2005)	40-59% fertilizer prod. and appl.			

[1] field em. = field emissions

Non-life-cycle-based sustainability assessments

Some widely cited numbers originate from a sustainability report on water resources in cotton production by Bärlocher et al. (1999). They stress the impact of conventional cotton production on freshwater resources stating water consumption for cotton production of 7,000-29,000 l kg^{-1}. These calculations, however, are based on very out-dated yield and irrigation numbers so they are not applicable anymore anno 2015 (Personal communication Tian Changyan, November 24th 2014). The severity of environmental impact of cotton production due to soil salinity, eutrophication and water use and pollution should not be underestimated though. All of these impacts are present in medium to severe extent in the major cotton producing river valleys like that of the Indus (Pakistan), Yangtze River (China), Yellow River (China) and Amu-Dar (Uzbekistan) (Bärlocher et al. 1999; Kooistra & Termorshuizen 2006; Selman et al. 2008). Cotton farmers do use more irrigation water to rinse salt sediments from the soil as salinity increases (Dong et al. 2008). Over the past 30 years, marine eutrophication has been an important issue in the estuaries of the Yellow River, Yangtze River and the Mississippi among others (Selman et al. 2008). All three rivers are found in the most important cotton-producing regions in the world (Barnes et al. 2012).

Plastic mulch is used to reduce ET, and therefore the need for irrigation water in arid cotton-producing regions. This is an increasingly problematic measure in China (Dai & Dong 2014). Dai & Dong (2014) estimate that 20-25% of all non-biodegradable plastic mulch remains in the soil after harvest. This increasing amount of plastic can have a severe effect on soil capillary, microbial activity, root development, etc. They also stress the importance of correct pesticide application because 99% of sprayed pesticides end up in non-target soil and water bodies (Dai & Dong 2014). Wu & Guo (2005) report a reduction in use of pesticides in China since the introduction of Bt-cotton in the 1994-2001 period. But damage by secondary pests like mired bugs has been increasing ever since (Dai & Dong 2014).

2.4.3 Cradle-to-gate: Yarn and fabric manufacturing

LCAs including yarn and fabric manufacturing

Figure 6 graphically represents the results of eight C2Ga CED and GWP assessments on hemp and cotton. Because studies on fabric also include spinning into the results, both yarn and fabric are represented in the same figure. The term spinning in this case refers to the actual spinning and all preparation steps preceding this process. Weaving refers to the actual weaving, pre-treatments and in some cases dyeing. This is out of necessity as not all results are separately available.

The spinning technique used for all three assessments on hemp is wet ring spinning. The difference between the traditional hemp method (1) and green decorticated hemp (2) spinning is mainly found in the heating of water for the degumming liquor used in the latter (Cherret et al. 2005). Figure 6 shows a major discrepancy, however, in CED and GWP of wet ring spinning as reported by Cherret et al. (2005) and Turunen & van der Werf (2006). The CED and GWP range between 13.5-242.2 MJ kg^{-1} and 2.2-10.9 kg CO_2-eq kg^{-1} respectively. It gets even more contradictory when looking at both allocation procedures: Turunen & van der Werf (2006) use EA and allocate 67.4% of the impact of spinning to the yarn while Cherret et al. (2005) use a mass multiplier in order to allocate all impacts to the final yarn. This implies that the actual impact of the former is even larger. Turunen & van der Werf (2006) takes all direct and indirect energy carriers into account. This is unclear in the report of Cherret et al. (2005) as this is mainly focussed on results rather than on the methodology used.

Comparing the CED values as reported for hemp spinning to the five assessments on cotton we would expect them to be higher on average (see 2.3.1). Within the same report of Cherret et al. (2005) this expectation holds, but these values are in general exceptionally low, whereas GWP values are acceptable. Kalliala & Nousiainen (1999) also report a rather low CED value including weaving, spinning and all treatments. No information is available on the distribution of GWP.

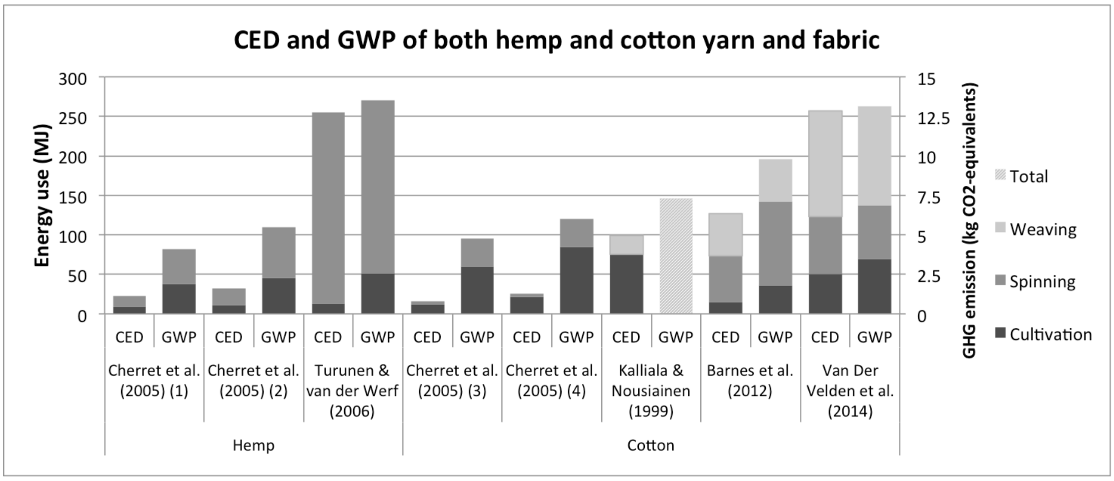

Figure 6: Cumulative Energy Demand and Global Warming Potential for yarn and fabric.
This graph summarises all reported values on CED and GWP for both yarn and fabric production. Estimations adapted from Cherret et al. (2005) include traditional hemp methods (1), green decorticated hemp (2), energy-extensive cotton production in India (3) and energy-intensive cotton production in USA (4).

Turunen & van der Werf (2006) report CED values for spinning three times higher than the most energy-intensive assessment by Van Der Velden et al. (2014). The inventory of the latter, consisting of industry data, indicates that only direct energy use is included in the assessment. The same is true for the assessment of Barnes et al. (2012). Calculating direct energy use as found in the life cycle inventory of Turunen & van der Werf (2006), without taking material losses into account, results in an estimated CED of 67 MJ kg^{-1} yarn. This is comparable to the 58.2 and 72.9 MJ kg^{-1} in aforementioned cotton assessments and thus not higher as would be expected. It is unclear, however, whether all additional CED just results from indirect energy carriers. It should also be noted that for the hemp assessments fibre separation is included in the preparation process while for cotton ginning is not. Furthermore it is proven that the energy requirements for the actual spinning are inversely related to the yarn count in measured dtex (Van Der Velden et al. 2014). Turunen & van der Werf (2006) use a coarse 385 dtex yarn while the values in Van Der Velden et al. (2014) correspond to a finer 150 dtex yarn. For comparable yarn counts the CED of the former should thus relatively increase compared to the latter. This inverse relation makes that no actual conclusion about spinning can be drawn from Barnes et al. (2012) as no yarn count is specified.

While values for cotton spinning are rather similar, the two most reliable sources report very different results for both CED and GWP of the weaving process. Barnes et al. (2012) report a CED and GWP of 53.8 MJ and 2.7 kg CO_2-eq kg^{-1}. This includes pre-treatment and continuous pad dyeing. Van Der Velden et al. (2014) on the other hand report 134 MJ and 6.2 kg CO_2-eq kg^{-1}. These latter values only comprise semi-finished fabric and thus include pre-treatments but no dyeing. Solely the weaving processes take CED-values of 21.3 MJ and 35.5 MJ kg^{-1} (17.8-118.4 MJ kg^{-1} dependent on yarn count) respectively. Again, energy use for the actual weaving process is inversely related to yarn count in dtex (Van Der Velden et al. 2014). Most literature, however, does not mention yarn counts. Excluding dyeing from the analysis makes sense as many different techniques and practices are available on which energy and resource efficiency are highly dependent (Yuan et al. 2013; Van Der Velden et al. 2014). Yuan et al. (2013) assessed pre-treatment and pad-dyeing technology for cotton fabrics and conclude that scouring, bleaching, dyeing and wastewater treatment have the largest normalized impact. In the finishing stage, stentering and setting are other major contributors as well.

A final interesting fact is the difference between woven and knit fabric. Knit fabric has a significantly lower CED and GWP compared to woven fabrics as CED for weaving can be as much as 20 times higher (Steinberger et al. 2009; Barnes et al. 2012; Van Der Velden et al. 2014). A difference in impact, although much smaller, is also confirmed by Tobler-rohr (2011a): an LCA using the Ecoindicator 99 impact assessment gave a knitted t-shirt and a woven t-shirt a respective micro point score of 387 and 1,100, clearly indicating the larger impact of weaving.

Impact distribution of cultivation, spinning and weaving

Figure 7 shows the average distributions of GWP and CED of the earlier discussed assessments. This indicates that in these particular assessments spinning and weaving are relatively more important than cotton cultivation regarding GWP and CED. This is contradicted, however, by other assessments (Figure 6). The ReCiPe points are applicable to woven cotton fabric made with yarn of 150 dtex (Van Der Velden et al. 2014). This shows an increase in the impact of cultivation and a decrease of spinning. ReCiPe points include toxicity categories that are highly dependent on chemical inputs used as agricultural inputs and treatment products. The spinning process barely uses additional inputs and thus the relative contribution is expected to drop compared to CED and GWP. This particular assessment includes yarn counts from 300 dtex to 70 dtex. The proportions of impact that can be attributed to cotton cultivation strongly decreases for finer yarns than 150 dtex. For 300-dtex yarns, however, more than half of the ReCiPe score is due to cotton cultivation. This stresses the importance of correct and detailed descriptions of boundary conditions and assumptions in LCA.

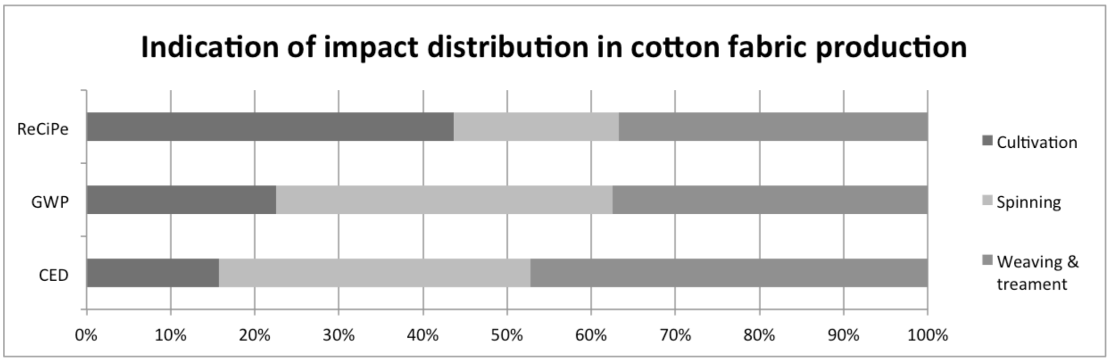

Figure 7: Distribution of CED, GWP and ReCiPe impact in cotton fabric production.
This graph represents the distribution of of CED, GWP and ReCiPe impact along the cotton fabric production chain. This is merely an indication because averaged numbers were not entirely comparable. Values were adapted from Barnes et al. (2012) and Van Der Velden et al. (2014).

2.4.4 Cradle-to-gate and cradle-to-grave: Product LCA

The FU in a product LCA is mostly one unit of production as made by a certain company. This makes product LCAs rather difficult to compare. They are mostly used to identify environmental or energetic hotspots within a production process. Typical FUs for textiles are one t-shirt or one pair of jeans. For these FUs we can look at the stages up until a finished product (C2Ga) and including use and disposal (C2Gr).

Table 5: Cradle-to-gate product LCAs of cotton products.

FU	Source	CED (MJ)	GWP (kg CO_2-eq)	EP (g PO_4-eq)
T-shirt	QUT (2009)		4	
	Lehmann-Pollheimer (2006)		5.2	
	Steinberger et al. (2009)	43.9	2.9	
Jeans	Levi Strauss & Co (2008)	179.7	14.2	3.5
Towel	Blackburn & Payne (2004)	194.6		

The GWP of all T-shirt assessments are comparable. However, Lehmann-Pollheimer (2006) has a very minimal estimate, excluding the production of all inputs. QUT (2009) and Steinberger et al. (2009) on the other hand do include all most important direct and indirect sources of GHG into the assessment. Taking this into account these values are less comparable. Furthermore, Lehmann-Pollheimer (2006) report 48.1% of GWP to come from water heating in the dyeing process. While for QUT (2009) cultivation, spinning, knitting and processing respectively contribute 23%, 33%, 14% and 30%. Steinberger et al. (2009) report 63% and 64% of GWP and CED respectively to come from cultivation, concluding that cotton production in India is very energy-intensive. A pair of jeans and a towel have comparable weights (ca. 600 g) and comparable yarn counts (Blackburn & Payne 2004; Levi Strauss & Co 2008). Therefore the order of magnitudes can be roughly compared and the CED values are both feasible.

What we can compare is the relative distribution of impact over the entire life cycle. Figure 8 clearly shows that all five studies attribute the majority of CED and GWP to the use and disposal phase: Values range between 58-78% and 59-96% for CED and GWP. The impact on AP is more evenly distributed (Steinberger et al. 2009).

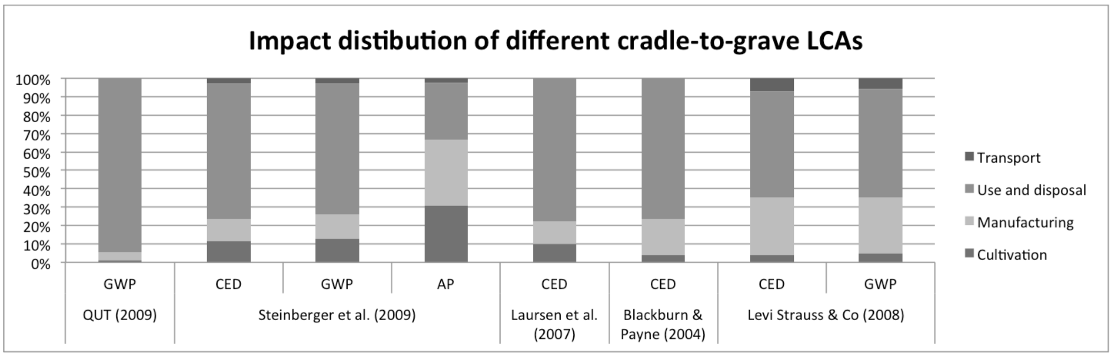

Figure 8: Impact distribution of different cradle-to-grave Life Cycle Assessments of cotton. This figure represents the relative distribution in CED, GWP and AP impact of different stages in the life cycle of cotton products. The products considered are respectively three T-shirts, a towel and a pair of jeans.

Van Der Velden et al. (2014) reject such conclusions of most other LCAs based on the European energy consumption labelling scheme: to wash at 40°C with A-rated appliances and machine dry 1 kg of cotton fabric 50 times they report 67 MJ and 3.1 kg CO_2-equivalent. Scenarios of 50 washes calculated by Steinberger et al. (2009), however, varied from 60°C, C-rated appliances, to 40°C, A-rated appliances, with a respective GHG emission of 10 and 7 kg CO_2-equivalent per T-shirt, which is assumed to weigh 250 g. Barnes et al. (2012) confirm that the impact of the use phase is very sensitive to its assumptions. But this does not explain a tenfold difference.

2.4.5 State-of-the-art conclusion

All of the above shows how hard it is to make inter- and intra-fibre comparisons based on current LCA literature. To obtain an objective comparison of the sustainability of textiles made of hemp and cotton fibres both LCAs have to be constructed in perfect parallel. The following important conclusions from current LCA literature should hereby be taken into account:

- There is strong need for local and publicly available data as priority should be given to local industry, LCA or scientific data instead of adapting process data to regional infrastructure. This is especially important in developing countries as several pollutants like NO_x and SO_2 follow an environmental Kuznets curve (Matlock et al. 2008; Steinberger et al. 2009).
- It is highly important to clearly explain assumptions, system boundaries and emission or impact factors, as all of these can be a major source of variation between assessments (van der Werf & Turunen 2008; Yilmaz et al. 2005; Reed & Barnes 2009).
- More generic assessments tend to result in lower impacts, potentially because more assumptions have to be made (Figure 4).

And more specifically:

- On cultivation: Major impacts come from (nitrogen-)fertilizer-related emissions, fuel use and irrigation and are highly dependent on yields (Table 4). The quality of hemp fibres should be taken into account for obtaining correct results.
- On processing: It is highly important to take into account the inverse relationship of yarn counts (linear weight) and energy use and impact (Van Der Velden et al. 2014). Improvements of spinning technology are a major hotspot for the impact of hemp processing (van der Werf & Turunen 2008).
- On cradle-to-grave: The impact proportion of the use phase is highly sensitive to assumptions and is often overestimated and thus reducing the relative impact of cotton cultivation and processing (Barnes et al. 2012; Van Der Velden et al. 2014)

3 MATERIALS AND METHODS

3.1 Introduction to the methodological aspects of LCA

3.1.1 Four phases of LCA

LCA starts with the definition of goal and scope of the analysis (Figure 9). The goal can be among others to compare different products or to identify environmental hotspots in a product life cycle. Depending on this goal (I) the functional unit, (II) temporal, geographical and technological system boundaries, (III) allocation procedures and (IV) impact categories are chosen (Guinée 2002; Achten 2010).

Life cycle inventory (LCI) analysis consists of the collection and calculation of inputs and outputs of all unit processes throughout the life cycle. Among the elements quantified are energy use, resource consumption, waste and air, soil and water emissions (Muthu 2014a). The latter are often quantified using specific emission factors.

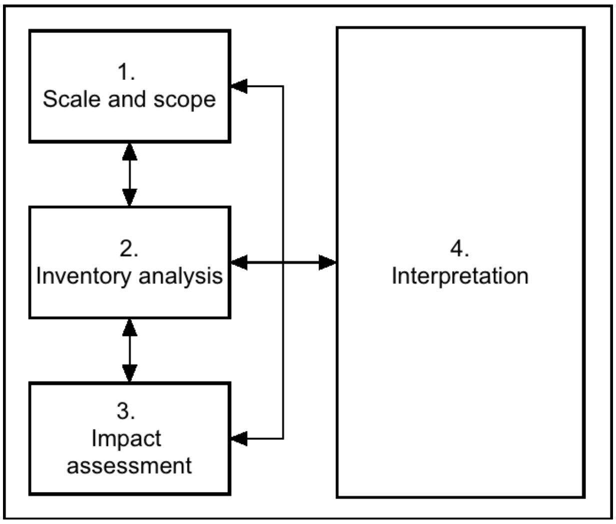

Figure 9: The four phases in LCA methodology.
The four phases are defined as *Scale and scope, Inventory analysis, Impact assessment* and *Interpretation*. Adapted from International Standards Organization (2006).

Life cycle impact assessment (LCIA) consists of (I) classification of the LCI results to certain impact categories, (II) characterization or the actual modeling of impacts and (III) facultative normalization, grouping and weighting of the modeled results. Specific LCA software and impact models often perform this particular stage (Guinée 2002).

All three stages interact with each other and are interpreted by the LCA practitioner. In this phase it is important to (I) evaluate on consistency, completeness and limitations, (II) interpret final results and (III) draw conclusions and recommendations for further research (Guinée 2002; Muthu 2014a).

3.1.2 Allocation methods

An important decision of the LCA practitioner is the allocation method that is used. The researched systems can result in multiple products and by-products from one process. Allocation methods determine how the impacts of this and preceding processes are divided among the products. Preferably, allocation should be avoided by using single-function processes that have already been allocated or by expanding the system boundaries (Guinée 2002). In case allocation is needed, however, the ISO standards allow for three main allocation methods based on economic value, mass or energy content (International Standards Organization 2006). Economic allocation is the most used and preferred method (Guinée 2002). Impacts are then distributed according to the proportional value of the products. This proportional value is computed from both product amounts and market price or price statistics and is a percentage of the total value of the process output (Turunen & van der Werf 2006). This represents the incentive for production and should therefore also represent allocation of environmental impact. The practitioner should clearly describe and justify the chosen allocation methods to ensure proper interpretation of the LCA results.

3.2 Goal and scope

3.2.1 Goal and system boundaries

The purpose of this LCA is to compare the environmental performance of hemp and cotton in textile applications. The focus lies on the intrinsic differences between both fibre sources to research if hemp fibre is a more sustainable alternative to cotton. But on the impact of the currently used production methods, to assess whether the current marketing of hemp is accurate. The different scenarios thus have to be entirely comparable. Differences result from agronomical properties, different processing steps and the level of processing technologies. Therefore, the scope is limited to a field-to-fabric (C2Ga) assessment instead of the full textile life cycle (Figure 10). By not including use and disposal phase we assume that there is no significant difference in durability between hemp and cotton products. Van Der Velden et al. (2014) also report that the impact of the use phase is totally dependent on consumer behaviour instead of textile types or properties. Geographical boundaries are limited to China, as this is the only relevant area concerning hemp textiles. The processes included into scope are field operations and crop production inputs, harvesting, post-harvest fibre separation, fibre preparation, yarn spinning, sizing treatment and weaving. The system boundaries contain direct and indirect energy use, production of inputs and emissions to air, water and soil (Figure 11). They do not include buildings, machinery production and maintenance used in hemp or cotton production and manufacturing. Also transport is omitted from the analysis because this is clearly no intrinsic property of the fibre. The sequestration of carbon dioxide by the hemp and cotton plants is omitted as well. Including this without a proper end-of-life scenario would skew the results and might lead to false conclusions. Also no information is available on what happens to other plant residues after harvest. This should also be included as they too contain biogenic carbon. Section 4.2.1 below will provide further details on this.

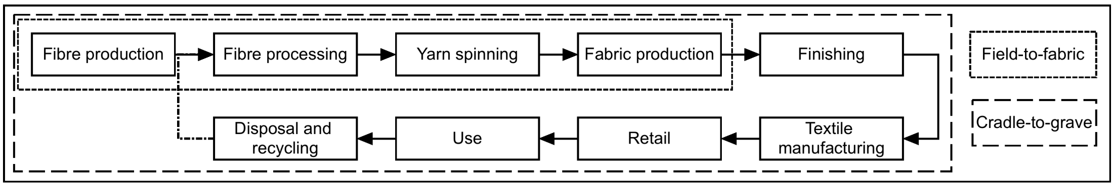

Figure 10: Graphic representation of the LCA scope in the textile value chain.
This figure represents the two most common system boundaries in textile LCAs: Field-to-fabric in small dashed lines and Cradle-to-grave in large dashed lines. Adapted from Steinberger et al. (2009)

3.2.2 Functional unit and LCA scenarios

The functional unit is 1 kg greige woven fabric produced in China and ready for dyeing (Figure 11). The yarn count of the yarn in this fabric is 36 Nm and fabric weight is around 120 g m^{-2}. Greige fabric is textile jargon for unfinished fabric that comes from the weaving loom and has not been treated except for the sizing of warp yarn (Van Der Velden et al. 2014). Further fabric treatments like bleaching, scouring and dyeing are omitted from the analysis because they are highly dependent on the choice of processing method and are not intrinsically different between two similar cellulose fibres (Personal communication Robert Hertel, December 29th 2014).

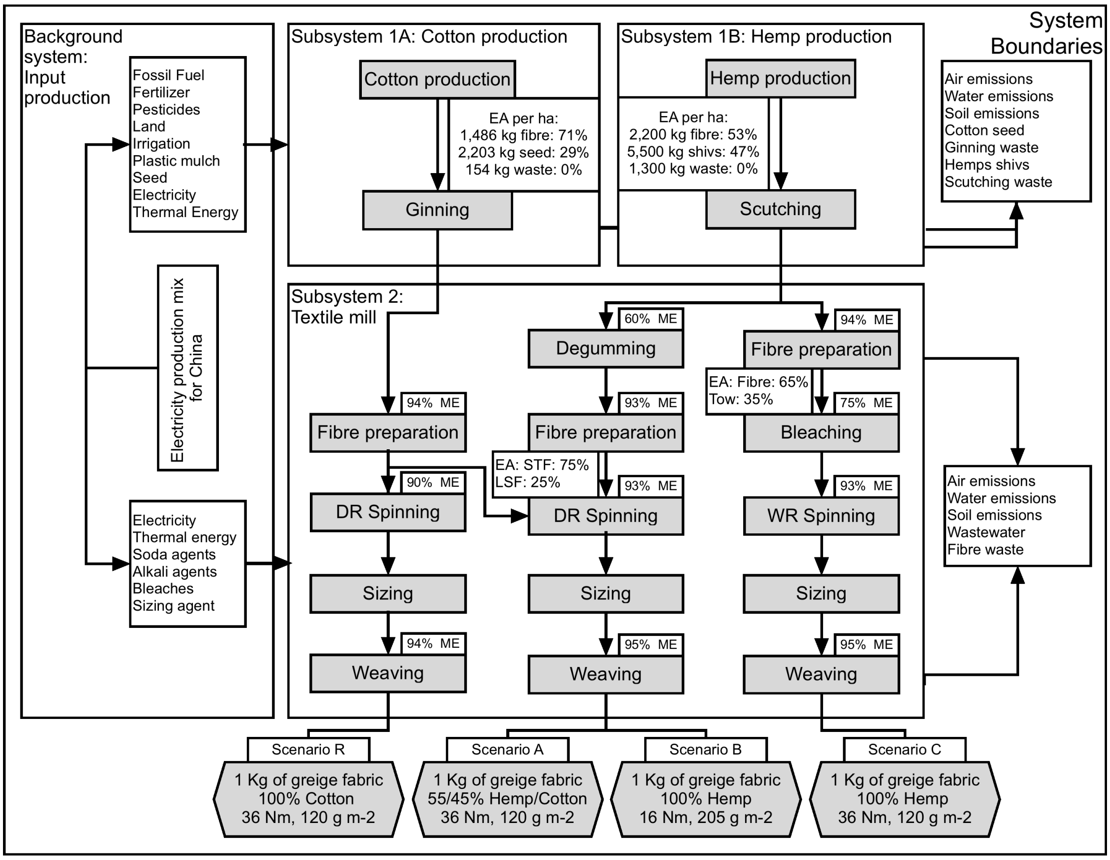

Figure 11: System boundaries of the comparative lifecycle assessment.
The system boundaries of the LCA comprise three subsystems: Subsystem 1 includes fibre production and separation (1A for cotton and 1B for hemp), subsystem 2 includes all operations in the textile mill and subsystem 3 consists of all background systems of input production. The different spinning methods are wet ring (WR) and dry ring (DR) spinning. Economic allocation (EA) and material efficiencies (ME) are specified as well.

Cotton is used as reference scenario in this LCA (Scenario R). This allows for the benchmarking of the environmental performance of the three different hemp scenarios with the cotton reference system (Figure 11). Figure 11 also shows the different processes and material flows in the hemp scenarios. Scenario A involves dry ring spun 36 Nm 55/45% hemp/cotton yarn and is the most important for accurate comparison. This allows for assessing the real impact of partly replacing cotton with hemp in a totally comparable system. Scenario C contains wet ring spun 36 Nm 100% hemp yarn. Due to current technological limitations, the functional unit of scenario B is slightly different. This scenario involves dry ring spun 16 Nm 100% hemp yarn and is expected to have a lower impact for spinning and weaving (Conform section 2.4.5).

Subsystem 1A and 1B will be assessed as well to review the impact of hemp and cotton cultivation in detail. The literature review also indicates a large discrepancy between actual nutrient needs and current fertilization practices (See 2.1.2 and 2.2.2). In order to better understand the intrinsic fibre differences additional scenarios have to be added to the fibre production phase: a good agricultural practice (GAP) and common practice (CP) scenario for each crop. These scenarios will be considered separately as well with the functional unit of 1 kg of separated fibre.

3.2.3 Data collection and quality

The LCI contains both primary and secondary data (Table 74 and Table 75). The focus in data collection has been on local industry and local scientific data (Conform section 2.4.5). This was not possible for every aspect of the LCI, so assumptions and generalizations where made where necessary (See section 3.3 for details). Data on cotton cultivation are limited to China and more specific, the Yellow River Region (YRR). The Chinese government effectively wants to reduce the share of cotton production in favour of food crops in this region (Zhang 2008).

Hemp cultivation data focus on the Northern region near Heilongjiang province, as this is the most concentrated area of hemp fibre production (Heping 2013). In personal communication Martha Barth of Nova-Institute, Köln (April 13th 2015) assessed the feasibility of the hemp production inputs while Professor Tian Changyan (November 24th 2014), cotton expert at the Xinjiang Institute of Ecology and Geography, did the same for cotton. Reliable industry data on the two subsequent stages in cotton textile production are scarce. Therefore the reference scenario is based on a benchmarking study for Europa, taking into account differences in energy-efficiencies afterwards (See section 3.3.2 for details). For hemp on the other hand, the LCI includes mainly primary data from a Chinese textile mill, which prefers to remain anonymous. The quality of the data is ranked with low, medium and high uncertainty (Table 74, Appendix 6.1 and Table 75, Appendix 6.2). This ranking will be linked with the uncertainty analysis (section 4.1.3) to assess the quality of the LCA. The Monte Carlo sensitivity analysis, which is often used for LCA, cannot b applied in this case (Andrianandraina et al. 2015). This analysis requires probability density functions for the values of the input data that are not available. The analysis will simply check the robustness by assessing how the results react to certain changes in the input parameters (Guinée 2002).

3.2.4 Applied methodology

The methodology used for life cycle impact assessment (LCIA) in this LCA is the World ReCiPe Hierarchist method and will be performed in Simapro LCA software

(Goedkoop et al. 2008; Goedkoop et al. 2013). This method is the successor of both the Eco-Indicator 99 and the CML 2002 methods (Van Der Velden et al. 2014). Where the former is an endpoint method and the latter a midpoint method, ReCiPe combines both midpoint and endpoint assessment into a single method (Menoufi 2011). It is currently the most recent and most used LCIA method available (Muthu 2014a).

Traditionally there have been large and confusing differences between midpoint and endpoint LCIA models. ReCiPe harmonizes the two by modelling the LCI results through the most important environmental mechanisms associated with characterization factors into a problem-oriented midpoint impact in one of the 18 categories. Through the same environmental mechanism this midpoint impact is then modelled into an ultimate endpoint damage to the environment (Goedkoop et al. 2013). Normalization factors initially focussed on Europe but were expanded afterwards to the world as well.

The focus will be on midpoint assessment as the goal is to compare if and in what way hemp could be more sustainable than cotton. Normalization of the midpoint impact categories will determine which are relevant to discuss in detail. Climate change, acidification, eutrophication and toxicity categories are expected to be relevant. Furthermore the Hierarchist method is used because this is most used and generally accepted as best (Goedkoop et al. 2013). This method is a compromise between the Egalitarian and Individualist method: the former considers long timescale effects and models following the precautionary principle while the latter assumes most damages can be avoided by technological development and hence considers a very short timescale (Muthu 2014a). Appendix 2 shows the 18 midpoint impact categories, or environmental issues, as well as the three endpoint categories. The indicators are the actual physical or chemical phenomena that are being modelled. This is done through a set of characterization factors assigned to each midpoint category (Appendix 2).

3.3 Life cycle inventory

The following section contains the reasoning behind and the results of the LCI analysis. Both fibre production scenarios are discussed in parallel (section 3.3.1). The reference scenario of cotton processing is then discussed separately (section 3.3.2) from the three hemp-processing scenarios (section 3.3.3). Inputs are discussed on a process level, while Table 72 and Table 73 (Appendix 5) present the actual input into Simapro.

3.3.1 Subsystem 1A and 1B: Cotton and hemp fibre production

Product output: Yield and allocation

Scenario R assesses cotton production in China with a focus on the YRR. We assume an average yield of 1,486 kg cotton lint ha^{-1} after ginning (USDA 2015b). This is the 2013/14 USDA estimate for the average yield of Chinese cotton production. YRR-specific yield averages are comparable with a range of 1,430-1,652 kg ha^{-1} (Barnes et al. 2012; Dai & Dong 2014). Furthermore, the agricultural policy goal for average lint yield in YRR is 1,500 kg ha^{-1}, proving that this is a solid assumption (Zhang 2011). Next to lint, the ginning process produces cottonseed and waste. The average percentage of lint recovered from seed cotton is calculated at 38.7% from values reported by Adanacioglu & Olgun (2011) and Zhang (2011) (Table 27, Appendix 3.1). Because Adanacioglu & Olgun (2011) state that 4% is waste, this results in a seed yield of 2,203 kg ha^{-1} and 154 kg ha^{-1} of waste (Table 28, Appendix 3.1). Ginning is the only process for cotton that applies economic allocation (Table 29, Appendix 3.1). The allocation to fibre and seed of 71.2% and 28.8% respectively is rather remarkably low, as the cotton fibre price is currently at a five-year low. Because no average price data are available for cottonseed March 2015 data were used for both cottonseed and fibre (USDA 2015a; USDA 2015b). It should be noted that cotton is also grown in intercropping systems with wheat. Due to lack of information this is not taken into account for the LCA.

An assumption of 10 t dry stems ha^{-1} was made taking into account several sources on hemp yields (Table 52, Appendix 4.1). Averaged data on hemp yields are more uncertain as no reliable statistics exist for China. Zheng et al. (2013), however, reports a recoverable fibre content of 22.3%, significantly lower than European averages, and shivs content was assumed the same comparable to Europe (Barth & Carus 2015). This results in a yield of 2,200 kg scutched hemp fibre ha^{-1} and 5,500 kg shivs ha^{-1}. Before scutching, a certain amount of biomass is lost in the retting process. Turunen & van der Werf (2006) state this to be around 10% (Table 53, Appendix 4.1). All of this only applies to machine-scutched, mediocre quality hemp lines, like the main Chinese supply source of hemp over the past two years (Personal communication

Robert Hertel, December 29th 2014). Economic allocation is based on European price insights provided by Martha Barth of Nova-Institute (Personal communication, March 27th 2015). This results in a 52.8% and 47.2% allocation to fibre and shivs respectively (Table 54, Appendix 4.1).

Pesticides

The pesticide use in cotton production is calculated as the average from both a Chinese best-practices farm in the Xinjiang area as reported by Bevilacqua et al. (2014) and the average US application amounts as reported by the USDA (2006) (Appendix 3.2). Bevilacqua et al. (2014) use three insecticides and three herbicides in their LCA with a total amount of pesticides per ha per year of 4.1 kg active ingredients. These values correspond to the best farm in their survey. For a more realistic number on average pesticide use, this is averaged with the application rates for the three most common insecticides and herbicides used in US cotton production (Table 30, Appendix 3.2). This results in a yearly application of 6.9 kg active ingredients ha^{-1}. This value is still rather low compared to the 5.6-8 kg ha^{-1} range as reported by Peshin & Dhawan (2009) for the Punjab area in India; cotton cultivation in this region is very input-extensive. Production impact of these pesticides is included in the LCA from the Ecoinvent v3.1 (2015) database. Products that are not in the database individually are included as their product class.

Hemp in Northern China is grown with the use of pre-emergence herbicide application (Liu 2013). Table 55 (Appendix 4.2) shows the calculations: 3 l of 65% metolachlor emulsion is used in this LCA (Amaducci et al. 2014). This is confirmed by a list presented by Legros et al. (2013) about several herbicides tested in hemp cultivation that contains the very similar compound acetochlor. Furthermore, Guokun (2002) reports a similar application rate metolachlor in Chinese flax production.

Fertilizer

As fertilizer input we assume mineral fertilizer instead of organic forms. This has an impact on fertilizer emissions (Barth & Carus 2015). No mentions were found for organic fertilizer in conventional Chinese cotton practices so also for hemp only mineral fertilizer was assumed. Values for total fertilizer use in Chinese cotton production vary from 300-550 kg ha^{-1} (Barnes et al. 2012; Dai & Dong 2014; Personal communication Tian Changyan, November 24th 2014). Dai et al. (2014) performed their experiment according to local best practices in the YRR. Their reported numbers are thus the best option to use for the cotton GAP scenario. After adjusting the values proportional to the assumed yield, this makes a feasible total of 346 kg ha^{-1} (Table 31, Appendix 3.3). Lemon et al. (2009), Bevilacqua et al. (2014), Dai & Dong (2014) and Changyan (Personal communication, November 24^{th} 2014) all state actual fertilizer rates, and especially nitrogen fertilizer, to be much higher. The cotton CP scenario therefore includes a higher amount of N-fertilizer.

The same method is applied to hemp fertilizer rates. Here, an evenly large discrepancy exists between recommended and actual rates for cultivation in Northern China (Table 56, Appendix 4.3). Only half of the nitrogen and potassium is applied in the hemp GAP scenario compared to the hemp CP scenario, resulting in 270 kg and 425 kg mineral fertilizer ha^{-1} respectively (Liu 2013; Amaducci et al. 2014).

Irrigation

Irrigation in China is a process defined in the Ecoinvent v3.1 (2015) database and is included in the LCI as such. Only the amount of irrigation water has to be calculated. As no data are available, an estimation is made based on the following principle: for optimal growth the amount of irrigation water should equal the difference between ET and rainfall. The average climate of the YRR is very similar to the humid cultivation areas in the US (Table 32, Appendix 3.4). It was thus assumed that ET values should be similar as well. An average of 637 mm ha^{-1} is reported for this region and this would result in an average irrigation need of 144 mm ha^{-1} (Suleiman et al. 2007; Perry et al. 2012). After correction for efficiency of flood-and-furrow irrigation and the percentage of cotton irrigated in YRR this makes a total of 151.2 mm or 1,512 m^3 ha^{-1} (Table 33, Appendix 3.4). Hemp is grown under rain-fed conditions in China (Amaducci et al. 2014).

Seeds

Cotton is sown at high densities with varying reported amounts of seed ha^{-1}. The value used in this LCA is 35.8 kg ha^{-1}, the average of the values found for YRR practices (Table 34, Appendix 3.5). The impact of cottonseed is taken from the Ecoinvent v3.1 (2015) database.

No impact is available in Ecoinvent v3.1 (2015) for the production of hempseeds. The impact was therefore calculated from the average sowing rate, seed yield and impact of hemp cultivation per hectare (Table 57, Appendix 4.4). Here we assume that the seeds have been produced with the same production inputs as hemp fibre. The average seed rate is 80 kg ha^{-1} (Liu 2013).

Plastic mulch

The amount of mulching plastic is calculated using the estimated mulched area, the percentage of field covered, the average thickness and the density of low-density polyethylene film (LDPE film) that is used (Table 35, Appendix 3.6). This totals to 41.3 kg LDPE film ha^{-1}. This is included into the LCA as the production of LDPE from Ecoinvent v3.1 (2015). No end-of-life scenario was taken into account for the plastic mulch. Hemp cultivation on the other hand does not require plastic mulching.

On-farm fuel use

Only 48% of cotton farming practices in China is currently mechanized (Dai & Dong 2014). In YRR this amounts to 69% of all (inter)tillage, sowing, fertilization and mulching (Table 36, Appendix 3.7). Most of this mechanization comes from small or even hand tractors. For the LCA this needs to be generalized to one type of tractor. First, a comparison on weight, power and fuel use h^{-1} proves that all these characteristics differ approximately proportionally to each other. They differ with an average ratio of around 1 to 10 for a hand tractor to a normal tractor (Table 37, Appendix 3.7). It can thus be assumed that all field operations are done with a hand tractor; a small tractor will have higher hourly fuel use but also has more power enabling wider tillage area or higher speeds. Ultimately this would result in approximately the same fuel use. Fuel use ha^{-1} is calculated with the number of handlings, average speed and estimated treatment width (Table 38, Appendix 3.7). This value is multiplied with the 69% correction factor, resulting in 93.3 l diesel ha^{-1}. This does not include harvesting and pesticide applications as this is performed entirely by hand (Dai & Dong 2014). Fuel use is incorporated in the LCA as the production of diesel from Ecoinvent v3.1 (2015).

Agriculture in Northern China, and Heilongjiang province in particular, is highly mechanized compared to the rest of the country (Huanwen 2008). Field operations in hemp cultivation specifically are mainly performed with machinery. The calculation follows the exact same principles and applies an 85% mechanization rate: mechanized tillage, sowing, fertilization, pesticide application and harvesting results in 69.4 l diesel ha^{-1} (Table 58, Appendix 4.5). Due to a total lack of data, the operations of turning and picking up the retted straw were omitted from the analysis. It is unclear whether this is still done partly by hand or entirely by machine. In the LCA of Turunen & van der Werf (2006) these operations contribute an insignificant amount to the total energy use anyway.

Ginning and scutching

Energy is the only input considered in the cotton ginning process. Both for electricity and heating the calculations are based on literature averages (Table 39 and Table 40, Appendix 3.8). This results in 2,095 MJ ha^{-1} of electricity and 681 MJ ha^{-1} of heating from natural gas. The former is included in Simapro from the background system 'Electricity production mix for China'. The impact of the latter comes from Ecoinvent v3.1 (2015).

Separation of the hemp bast from the stems happens in different ways. Most common practices in China are hand-peeling, green scutching and normal scutching (Clarke 1995; Amaducci et al. 2014). In the highly mechanized Heilongjiang province hemp stems are mostly separated mechanically. Therefore dew retting and normal scutching is assumed. As normal scutching technology did not evolve much over the past decennia and data are scarce, electricity consumption averages from Europe were used resulting in 3,146 MJ ha^{-1} (Table 59, Appendix 4.6).

Output: fertilizer emission

Different environmental emissions related to nitrogen and phosphorus fertilizer use have been calculated for both GAP and CP scenarios. These calculations are based on emission factors from several sources (See Appendix 3.9 and Appendix 4.7). The recommendations of Nemecek (2013) on the calculations of fertilizer emissions for LCA were followed whenever possible. The generic nature of LCAs often implies that no site-specific data are available and thus tier 1 models have to be used (Table 6). Non-methane volatile organic compounds (NMVOC) are calculated with a tier 1 model from Hutchings et al. (2013) (Table 6). Ammonia emissions are calculated with the tier 2 model as advised by Nemecek (2013) (Table 42, Appendix 3.9 and Table 61, Appendix 4.7). From this model the pH-dependent factors where removed (Hutchings et al. 2013). Ammonia emissions from urea are pH-independent and as it is unknown which compound source is additionally used in cotton fertilization, the most conservative emission values were assumed. Nitric oxides are calculated with the tier 1 model because the tier 2 model requires to much detailed soil data (Table 43, Appendix 3.9 and Table 62, Appendix 4.7)

Table 6: Main emissions and emission factors coming directly from fertilizer use.

Compound	Emission factor	Emission: (kg ha-1) Cotton CP	GAP	Hemp CP	GAP	Model type
NMVOC[1]	0.86 kg ha^{-1}	0.86	0.86	0.86	0.86	Tier 1
NH_3[1]	0.037 kg kg^{-1} NH_4-N 0.243 kg kg^{-1} Urea-N	45.3	28.5	48.1	21.7	Tier 2
NO_x[1]	0.026 kg kg^{-1} fertilizer-N	16.7	10.5	11.0	5.0	Tier 1
N_2O (D)[2]	0.01 kg N_2O-N kg^{-1} N-fertilizer	4.8	3.0	3.1	1.4	Tier 1
N_2O (ID)[2]	0.01 kg N_2O-N kg^{-1} NOx/NH3-N 0.0075 kg N_2O-N kg^{-1} NO_3-N	1.7	1.1	1.4	0.6	Tier 1
NO_3[2]	0.3 kg NO_3-N kg^{-1} fertilizer-N	398.2	250.8	263.7	118.7	Tier 1
CO_2[2]	1.57 kg kg^{-1} Urea-N	264.9	165.8	315.3	141.9	Tier 1
PO_4[3]	See Appendix 3.9	0.9	0.9	0.9	0.9	SALCA

[1] Hutchings et al. (2013)
[2] De Klein et al. (2006)
[3] Nemecek (2013)

Nitrous oxide emission are calculated with the advised tier 1 model (Nemecek 2013). Direct (D) N_2O emissions from the soil are proportional to the soil nitrogen level and emissions are thus estimated as proportional to the total human-induced N additions (Table 6). Indirect (ID) N_2O emissions come from volatilized NH_3 and NO_x and from leached NO_3 (De Klein et al. 2006). Emissions of the latter three are then corrected for the conversion to N_2O (Table 45, Appendix 3.9 and Table 63 Appendix 4.7). A final nitrogen emission is the leaching of nitrate. The nitrate leaching factor is based on the leaching fraction as proposed by Mosier et al. (1998) for developing the De Klein et al. (2006) emission guidelines (Table 44, Appendix 3.9 and Table 64, Appendix 4.7). This is a slight overestimation using for the GAP scenarios while for the CP scenarios it is a feasible estimation (Silgram et al. 2001). The SQCB model, as proposed by Nemecek (2013), includes to much detailed and site-specific data.

Next to nitrate, phosphate is the most important aquatic emission. Nemecek (2013) recommends using the SALCA model (Table 46, Appendix 3.9 and Table 65, Appendix 4.7). Only run-off and leaching phosphates have been taken into account. Erosion is left out due to insufficient data. Finally, CO_2 is released in the process of breaking down urea (Table 47, Appendix 3.9 and Table 66, Appendix 4.7). The tier 1 model is simply based on the stoichiometric equation that one molecule of CO_2 is released per urea molecule (De Klein et al. 2006).

The final fertilizer-related emissions are those of heavy metals contained in the mineral fertilizer. Computing the average heavy metal input with the average bio assimilation by cottonseed and fibre or hemp stems and bast results in the estimation for the addition of heavy metals to the soil (Table 48, Appendix 3.9 and Table 67, Appendix 4.7). In case of hemp this could also be a net uptake of heavy metals as the plant is know for its bioremediation potential.

Output: pesticide emissions

Because site-specific data are unavailable the modelling of pesticides is strongly simplified. Three environmental fates are assumed for the applied pesticides: volatilization to the air, leaching or run-off to ground water and immobility in the soil. The fraction of volatilization depends on the vapour pressure as proposed by Webb et al. (2013). The remaining fraction is divided among soil and water bodies, taking into account soil mobility and adsorption data from literature (Table 49, Appendix 3.10 and Table 68, Appendix 4.8). These environmental fates are used for including pesticides in the LCI to account for toxicity. They do not take persistence data into account (Table 50, Appendix 3.10 and Table 69, Appendix 4.8).

Output: On-farm fuel use emissions

Emissions from on-farm fuel use are simply calculated with emission factors for diesel fuel in agricultural machinery as found in literature (Nemecek & Kägi 2007; Winther et al. 2013). Emission factors in the range below mg kg^{-1} fuel were omitted from the calculations for being insignificant (Table 51, Appendix 3.11 and Table 70, Appendix 4.9).

Output: retting emissions

Environmental emissions from dew retting are a considerable uncertainty in hemp LCAs (Barth & Carus 2015). Some experiments have been performed on methane and volatile organic emissions from jute and flax water retting (Banik et al. 1993; Mudge & Adger 1994; Islam & Ahmed 2012). But while water retting is considered mostly an anaerobic process, hemp dew retting happens spread out on the field and can therefore be assumed as a rather aerobic process. Stefano Amaducci (Personal communication, March 27th 2015) reports that specific experiments are scheduled for autumn 2015 in the Multihemp project. But for now only assumptions can be made.

Aerobic microbial degradation of pectin and lignin mainly results in metabolic oxidation to CO_2 and assimilation into microbial biomass (Personal communication Chris Michiels, March 26th 2015). Because initial assimilation of CO_2 into the hemp plant is not counted as a negative emission, this release of CO_2 does not have to be taken into account either. Nitrogen emissions, however, are considered in the LCI. They are estimated with the most conservative emission factors available because no relevant data are available on this topic (Table 71, Appendix 4.10). The lost biomass in retting is simply assumed as decomposed plant residues and thus the nitrogen contained in this mass returns to the soil. Emissions of nitrous oxide, ammonia and nitric oxide are included.

3.3.2 Subsystem 2: Textile mill cotton scenario R

All electricity use data of scenario R are based on the textile LCA benchmarking study performed by Van Der Velden et al. (2014). As mentioned above, it is important to use yarn-count-specific energy data (section 2.4.5). This benchmarking study summarizes most literature that does include yarn counts and used this in combination with self-gathered industry data to construct two linear regression models for total electricity consumption in both cotton spinning and weaving in function of yarn count. These models, however, apply to European, modern (energy-efficient) textile manufacturing. Therefore the energy-intensity of both the European (Germany, 2005) and Chinese textile industry (2014) were compared (Table 7). Hasanbeigi et al. (2012) computed energy-intensity as energy use per production unit. Due to data availability, it was assumed that the ratio of total energy use in the textile industry over the total industry revenue could serve as an equal energy-intensity indicator. This implies that the Chinese textile industry uses 1.83 times more energy per EUR of revenue. This factor will correct the European values as reported by Van Der Velden et al. (2014). The German values date from 2005 and energy use is still decreasing globally, so we can assume that this factor is definitely not an overestimation of the difference (Pardo Martínez 2010).

Table 7: Comparison of the energy-intensity of the European and Chinese textile industry

Country	Year	Total industry EU (TJ)	Total industry revenue (EUR)	Ratio (MJ/EUR)	Source
Germany	2005	35,570	22 billion	1.62	Pardo Martínez (2010)
China	2014	2,060,000	693 billion*	2.97	National Bureau of Statistics of China (2014)

* 5,544 Billion yuan at the average 2014 exchange rate of RMB 8 / EUR.

All the following processes have a specific material efficiency and inputs are calculated per kg process output. For the LCI in Simapro, however, these material efficiencies are taken into account in multiplying inputs/outputs to 1 kg of fabric. The material efficiency is the mass of useful process output produced as a percentage of the input fibre mass.

Fibre preparation and spinning

The electricity data for 'spinning' as reported by Van Der Velden et al. (2014) include all processes between bale opening and winding of yarn (Figure 2). The electricity consumption amounts to 24 MJ kg^{-1} yarn (Table 76, Appendix 7.1). Fibre input for this process is based on a cumulative material efficiency of 84.6% as reported by Blackburn & Payne (2004) (Table 77, Appendix 7.1). The lost material is waste and for reasons of simplification it is not subdivided in dust and sellable lint. Nor price data, nor mass percentages for economic allocation are readily available to do so.

Table 8: LCI of the fibre preparation and spinning process of scenario R.

Type	Category	Compound	Quantity*	Unit	Impact
Ouptut	Product	Spun 36 Nm 100% cotton yarn	1	kg	
Output	Waste	Fibre waste	0.182	kg	Waste
Input	Material	Ginned cotton lint	1.182	kg	
Input	Energy	Electricity consumption	24	MJ	

* No economic allocation is used for the impacts.

Warp sizing

Part of the yarn, the warp, is sized before weaving it into fabric (section 2.3.1). The applied sizing agent is plain starch. The same amount of 90 g starch kg^{-1} warp was used as for the sizing of 36 Nm hemp yarn (see Table 18). Normally rice starch is used in China (Personal communication Robert Hertel, December 29th 2014). This input, however, is not available in the Ecoinvent v3.1 (2015) database and was therefore replaced by potato starch. Electricity consumption is included in the total for 'weaving' as reported by Van Der Velden et al. (2014). Heating energy in the form of steam is not included in this total and is taken from the LCI of Barnes et al. (2012) (Table 9). This value of 2.21 MJ kg^{-1} warp is consistent with values reported for hemp sizing.

The main emission of sizing is wastewater, containing chemical oxygen demand (COD) from starch. Because water use varies greatly, COD is expressed as a total amount instead of the usual concentration (Table 9). Yuan et al. (2013) report 92% efficiency in removing COD from Chinese textile wastewater. This results in 83 g COD treated and 7 g of COD environmental emission kg^{-1} yarn (Table 78, Appendix

7.2). Treated COD is incorporated in the LCA as an energy-requiring process from Ecoinvent v3.1 (2015).

Table 9: LCI of the sizing and weaving process of scenario R.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	100% cotton fabric	1	kg	
Output	Waste	Fibre waste	0.07	kg	Waste
Input	Material	Spun 36 Nm 100% cotton yarn	1.07	kg	
Input	Sizing	Potato starch	51.3	g	
Input	Energy	Heat in the form of steam	1.26	MJ	
Input	Energy	Electricity consumption	35	MJ	
Output	Sizing	COD environmental emission	4.1	g	Water
Output	Sizing	COD removed in wastewater treatment	47.2	g	

* No economic allocation is used for the impacts.

Weaving

Electricity consumption throughout sizing and weaving is calculated exactly like before and again the waste has no economic value (Table 79, Appendix 7.3). The weaving process uses 0.57 kg warp kg^{-1} fabric in accordance with hemp weaving value (Table 19).

3.3.3 Subsystem 2: Textile mill hemp scenario A, B and C

Scenario A, B and C are discussed simultaneously in the following section. Processes are discussed in chronological order according to Figure 11. Each subtitle indicates to which scenarios the process applies. Material efficiencies for these processes are calculated from data provided by the Chinese textile mill. The efficiencies for bleaching and degumming are 75% and 60% respectively and also spinning efficiency of ca. 93% is provided. Calculations in Appendix 8.1 result in proportions of 70/23/7% for short fibre/long fibre/waste in scenario A and B and 50/44/6% for sliver/tow/waste in scenario C. And for cotton carding in scenario A the efficiency is 91%. No value is attributed to waste streams, conform scenario R (section 3.3.2). Unless stated otherwise, all data come from the Chinese textile mill. One important remark is that the provided electricity consumption data might be inaccurate.

Scenario A, B: degumming

The chemical degumming process in scenario A and B uses scutched hemp fibres as input. The textile mill provided unclear energy data for heating the degumming liquor. It was therefore assumed that all degumming and washing steps require a total of 50 l of water at 90°C (Turunen & van der Werf 2006; Kostic et al. 2008). The heating energy is estimated as the energy from burning coal needed to heat the water from

15°C to 90°C with a 10% energy loss (Table 85, Appendix 8.2). The textile mill did provide an electricity use of 5.76 MJ kg^{-1} degummed fibre. Furthermore, a total 327 g caustic soda, peroxide, soda ash and penetrant is used (Table 10). Other liquor compositions exist as well, but all require substantial amounts of chemicals and water at very high temperatures (Yu 2013). The final factor taken into account in the LCI is a total material efficiency for the degumming process of 60% (Table 86, Appendix 8.2).

The degumming liquor is treated with a 92% efficiency for COD removal as well (Yuan et al. 2013). We assume all material loss from pectin and lignin degradation to be dissolved organic material in the liquor, resulting in an emission of 53.4 g COD to the environment (Table 87, Appendix 8.2). Sodium hydroxide is emitted as sodium ions and both soda ash and polyoxyethylene ether penetrant are emitted to water as well (Table 10).

Table 10: LCI of the degumming process in scenario A and B.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	Degummed hemp fibre	1	kg	
Input	Material	Scutched hemp fibre	1.67	kg	
Input	Energy	Heat in the form of steam	17.3	MJ	
Input	Energy	Electricity consumption	5.76	MJ	
Input	Degum	Deionized water	50	kg	
Input	Degum	Caustic soda	187	g	
Input	Degum	Hydrogen peroxide	80	g	
Input	Degum	Soda ash	55	g	
Input	Degum	Penetrant: polyoxyethylene ether	5	g	
Output	Degum	Sodium ions	107.5	g	Water
Output	Degum	Soda ash	55	g	Water
Output	Degum	Polyoxyethylene ether	5	g	Water
Output	Degum	COD environmental emission	53.4	g	Water
Output	Degum	COD removed in wastewater treatment	614.6	g	

* Table contains LCI before economic allocation form further stages.

Scenario A, B, C: carding

The carding process takes place at different moments resulting in different kinds of fibres: for both scenario A and B carding comes right after degumming while for scenario C it already takes place in between scutching and bleaching (Figure 2). The Chinese textile mill provided electricity and material data for this mechanical process, which differ between the scenarios (Table 11 to Table 13). In scenario A and B the input of the carding process is degummed fibre and it results in long fibres (used in scenario B), short fibres (used for blending in scenario A) and waste. Because no value can be assigned to either of these fibre outputs, equal values are assumed and economic allocation thus becomes mass-based allocation (Table 88, Appendix 8.3).

The waste fraction is not included in allocation resulting in a 25% and 75% allocation to long and short fibres respectively.

Carding in scenario C, however, produces hemp sliver, tow fibre and waste. This tow fibre can be sold for use in coarse twines and ropes and therefore has a significant value. Economic allocation is used based on European price data provided by Martha Barth (Personal Communication on March 27th 2015) as no reliable Chinese data are available (Table 88, Appendix 8.3). 65.2% and 34.8% of the impact is allocated to sliver and tow respectively. This allocation of course applies to all inputs and therefore also to the foregoing production of hemp fibre.

As scenario A exists of a hemp/cotton blend, cotton carding is also taken into account. No separate data for carding are used in section 3.3.1, so it was assumed that energy consumption of cotton carding in this particular mill is equal to that of carding degummed hemp (Table 12).

Table 11: LCI of the carding process in scenario A and B.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	Carded degummed short fibre	1	kg	
Output	Product	Carded degummed long fibre	0.33	kg	
Output	Waste	Fibre waste	0.1	kg	
Input	Material	Degummed hemp fibre	1.43	kg	
Input	Energy	Electricity consumption	3.6	MJ	

* Table contains LCI before economic allocation to short and long fibres.

Table 12: LCI of the cotton carding process in scenario A.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	Carded cotton fibre	1	kg	
Output	Waste	Fibre waste	0.095	kg	
Input	Material	Ginned cotton fibre	1.095	kg	
Input	Energy	Electricity consumption	3.6	MJ	

* No economic allocation is used for the impacts.

Table 13: LCI of the carding process in scenario C.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	Carded hemp sliver	1	kg	
Output	Product	Carded tow fibre	1.146	kg	
Output	Waste	Fibre waste	0.146	kg	
Input	Material	Scutched hemp fibre	2.292	kg	
Input	Energy	Electricity consumption	4.5	MJ	

* Table contains LCI before economic allocation to sliver and tow fibres.

Scenario C: bleaching

Carded hemp sliver is bleached before further processing in a wet spinning line (Figure 2). Again, water and heat data are unclear and thus a similar assumption is made compared to degumming (Table 85, Appendix 8.2). Bleaching, however, does not require additional washing and therefore not 50 l but 30 l of water at 90°C is assumed (Blackburn 2009). 8.3 MJ electricity and 10.4 MJ from burned coal is used

kg^{-1} of bleached sliver (Table 14). Additionally, 137 g of caustic soda, peroxide, hypochlorite and penetrant is added to the liquor (Table 14). Bleaching results in a material efficiency of 75%. The same principles as for degumming are used regarding wastewater (Table 87, Appendix 8.4). The only difference is that not soda ash but hypochlorite is used, which is released into the environment after the bleaching reaction as sodium and chlorine ions.

Table 14: LCI of the bleaching process in scenario C.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	Bleached hemp sliver	1	kg	
Input	Material	Carded hemp sliver	1.33	kg	
Input	Energy	Heat in the form of steam	10.4	MJ	
Input	Energy	Electricity consumption	8.3	MJ	
Input	Degum	Deionized water	30	kg	
Input	Degum	Caustic soda	90	g	
Input	Degum	Hydrogen peroxide	30	g	
Input	Degum	Hypochlorite	12	g	
Input	Degum	Penetrant: polyoxyethylene ether	5	g	
Output	Degum	Sodium ions	61.2	g	Water
Output	Degum	Chlorine ions	9.4	g	Water
Output	Degum	Polyoxyethylene ether	5	g	Water
Output	Degum	COD environmental emission	26.6	g	Water
Output	Degum	COD removed in wastewater treatment	305.9	g	

* No economic allocation is used for the impacts.

Scenario A, B, C: drawing

The Chinese mill only provides energy data and no material data on the drawing process (Table 15). It was therefore assumed that this was incorporated into the overall input and output data from which material efficiencies were computed. Electricity consumption was 3.6 MJ and 2.2 MJ kg^{-1} roving for scenario A, B and scenario C respectively. Scenario A is a 55/45% hemp/cotton blend so the input material was assumed to be 55% hemp sliver and 45% cotton sliver.

Table 15: LCI of the drawing process in scenario A, B and C.

Type	Category	Compound Quantity*:	Scenario A	Scenario B	Scenario C	Unit
Output	Product	Roving	1	1	1	kg
Input	Material	Carded degummed short fibre	0.55			kg
Input	Material	Carded degummed long fibre		1		kg
Input	Material	Bleached hemp sliver			1	kg
Input	Material	Cotton sliver	0.45			kg
Input	Energy	Electricity consumption	3.6	3.6	2.16	MJ

* No economic allocation is used for the input impacts.

Scenario A, B: dry ring spinning and winding

Dry ring spinning only requires electricity and fibre roving as input. Electricity consumption of spinning and winding for both scenario A and B is reported to be 14.4 MJ kg^{-1} yarn and the material efficiency for both is 93% (Table 16).

Table 16: LCI of the dry ring spinning process in scenario A and B.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	Dry spun yarn	1	kg	
Output	Waste	Fibre waste	0.08	kg	
Input	Material	Roving	1.08	kg	
Input	Energy	Electricity consumption	14.4	MJ	

* No economic allocation is used for the impacts.

Scenario C: wet ring spinning and winding

Wet ring spinning requires additional thermal energy and water next to electricity (Table 17). The Chinese mill reports an electricity consumption of 18 MJ kg^{-1} yarn and 3.1 kg steam consumption with a material efficiency of 93%.

Table 17: LCI of the wet ring spinning process in scenario C.

Type	Category	Compound	Quantity*	Unit	Impact
Output	Product	Wet spun yarn	1	kg	
Output	Waste	Fibre waste	0.08	kg	
Input	Material	Roving	1.08	kg	
Input	Energy	Steam	3.1	kg	
Input	Energy	Electricity consumption	14.4	MJ	

* No economic allocation is used for the impacts.

Scenario A, B, C: warp sizing

The energy data for sizing as provided by the Chinese mill vary across the three scenarios without real explanation. They are nonetheless included in the LCI as such, as the differences are relatively small (Table 18). Starch is used as sizing agent in the amounts of 90 g kg^{-1} warp in scenario A and C and 80 g kg^{-1} warp in scenario B. Wastewater is treated exactly the same as in sizing cotton yarn (See section 3.3.2) and therefore only the values for scenario B differ (Table 89, Appendix 8.4).

Table 18: LCI of the sizing process in scenario A, B and C.

Type	Category	Compound	Quantity*: A	B	C	Unit	Impact
Output	Product	Sized warp yarn	1	1	1	kg	
Input	Material	Yarn	1	1	1	kg	
Input	Sizing	Potato starch	90	80	90	g	
Input	Energy	Steam	6	8	7.8	kg	
Input	Energy	Electricity consumption	2.52	3.6	3.6	MJ	
Output	Sizing	COD environmental emission	7.2	6.4	7.2	g	Water
Output	Sizing	COD removed in treatment	82.8	73.6	82.8	g	Water

* No economic allocation is used for the input impacts.

Scenario A, B, C: weaving

The Chinese textile mill reports electricity consumption per m of fabric. Totals per kg fabric are computed from these values, fabric width and weight (Table 90, Appendix 8.5). Electricity values differ considerably due to differences in yarn quality and fabric weight (Table 19). The very high consumption in scenario C is because this fabric is woven on old, slow looms. The mill also provided data on material efficiency and amount of warp used in the fabric.

Table 19: LCI of the weaving process in scenario A, B and C.

Type	Category	Compound	Quantity*:	Scenario A	Scenario B	Scenario C	Unit
Output	Product	Fabric		1	1	1	kg
Output	Waste	Fibre waste		0.04	0.05	0.05	kg
Input	Material	Sized warp yarn		0.59	0.57	0.57	kg
Input	Material	Yarn		0.45	0.48	0.48	kg
Input	Energy	Electricity consumption		31.3	17.6	50.0	MJ

* No economic allocation is used for the impacts.

3.3.4 Background system: Input production

The background system that is included in the system boundaries contains all production impacts of the used inputs modelled in the Ecoinvent v3.1 (2015) database, as referred to in the foregoing sections. One special input considered in this LCA is electricity. Steinberger et al. (2009) stresses the importance of accurately modelling local electricity production for it has a serious influence on environmental emissions. The electricity production mix for China used in this LCA is modelled from 2012 International Energy Agency statistics (Table 20). Input production for each type of electricity generation is then taken from Ecoinvent v3.1 (2015) to model the impact.

Table 20: Chinese energy production mix.

Generation source	Production (%)
Coal	75.79
Hydro, reservoir	13.10
Hydro, run-off	4.37
Nuclear	1.95
Wind	1.92
Gas	1.72
Biofuel	0.67
Waste	0.22
Oil	0.14
Solar	0.13

Source: International Energy Agency (2012)

4 RESULTS AND DISCUSSION

4.1 Life cycle impact analysis

The results of the impact analysis will be presented and discussed in the following section. A first major part will include results on fibre production. The first section includes a comparison of hemp and cotton fibre production in the CP scenario (section 4.1.1). Subsequently the CP and GAP scenarios will be compared. The final part regarding fibre production is the comparison of degummed fibre and ginned cotton fibre. The second part of the LCIA contains the results on four fabric scenarios (section 4.1.2).

4.1.1 Hemp and cotton fibre production

Normalization of hemp and cotton CP scenario

The normalized comparison of 1 kg scutched hemp fibre and cotton fibre in the CP scenario is presented in Figure 12. The results indicate that 1 kg of ginned cotton fibre has a significantly bigger impact than 1 kg of scutched hemp fibre.

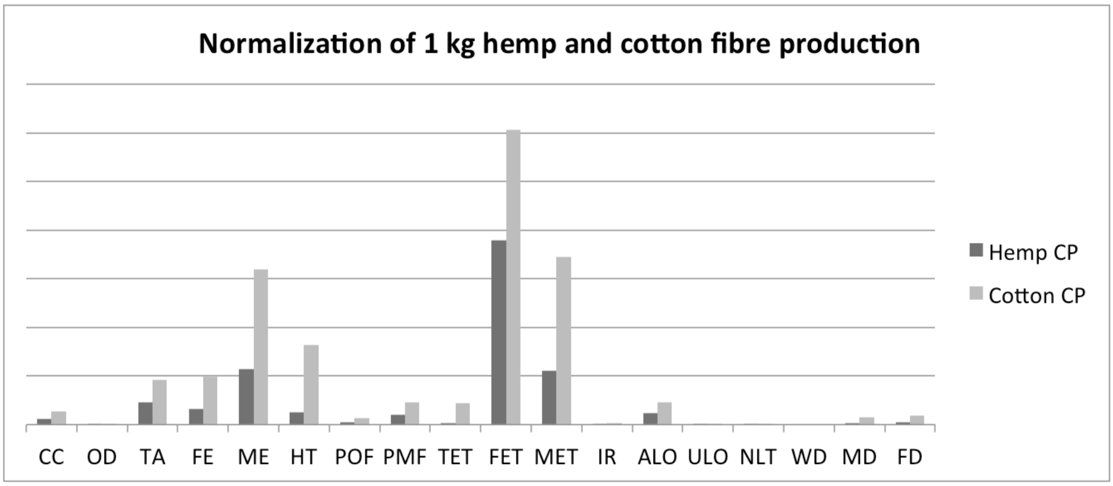

Figure 12: Normalization of 1 kg hemp and cotton fibre produced in China.
A graphical representation of the normalization results comparing the impact of production of 1 kg hemp and cotton fibre. The analysis used the common practices scenario for both crops.

The normalization process is used to identify the most relevant impact categories. The resulting categories are climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET) and agricultural land occupation (ALO). Five of these categories (CC, TA, FE, ME and PMF) were frequently assessed in previous LCA

(Table 26, Appendix 1). The others refer to toxic effects and land occupation. They are relevant for assessing the impact of chemicals in agriculture and textile manufacturing. All the relevant impact categories will be discussed in the following section.

Characterization of hemp and cotton CP scenario

Figure 13 contains the characterization of the most relevant impact categories in hemp and cotton production. This figure is based on the characterization data presented in Table 91 and Table 92 (Appendix 9.1). The results show that for every impact category the impact of hemp is significantly lower compared to cotton production. Less inputs, higher yield and the economic allocation method (more impact allocated to by-products for hemp) are responsible for this difference. The nature of the functional units, however, is not entirely comparable (see section 2 above) but insight is necessary for further interpretation.

CC is expressed in GWP and includes all IPCC defined GHG in the characterization. Hemp and cotton have a respective GWP of 0.97 kg CO_2-eq and 3.15 kg CO_2-eq kg^{-1} fibre. Respectively 64% and 71% of this GWP directly relates to fertilizer use; fertilizer production contributes respectively 22% and 38%, for which the main impact comes from CO_2 emissions in N-fertilizer production. Nitrous oxide, on the other hand, is the main contributor to the GWP of fertilizer emissions, contributeing respectively 42% and 33% of total GWP for hemp and cotton. Energy consumption in irrigation (11% of GWP_{cotton}), ginning (10% of GWP_{cotton}) and scutching (23% of GWP_{hemp}) are other significant contributing factors. Finally, fuel use by agricultural equipment only contributes 5% and 4% to GWP_{hemp} and GWP_{cotton}.

The most important contributors to the TA category are the field emissions of ammonia and nitric oxides from mineral nitrogen fertilizer. Respectively 83% and 82% of the total terrestrial acidification potential (TAP) (which is 36.02 g SO_2-eq for hemp fibre and 70.62 g SO_2-eq kg^{-1} for and cotton fibre) stems from fertilizer emissions. Other important contributors are sulphur dioxide and ammonia emissions emitted through energy and fuel use.

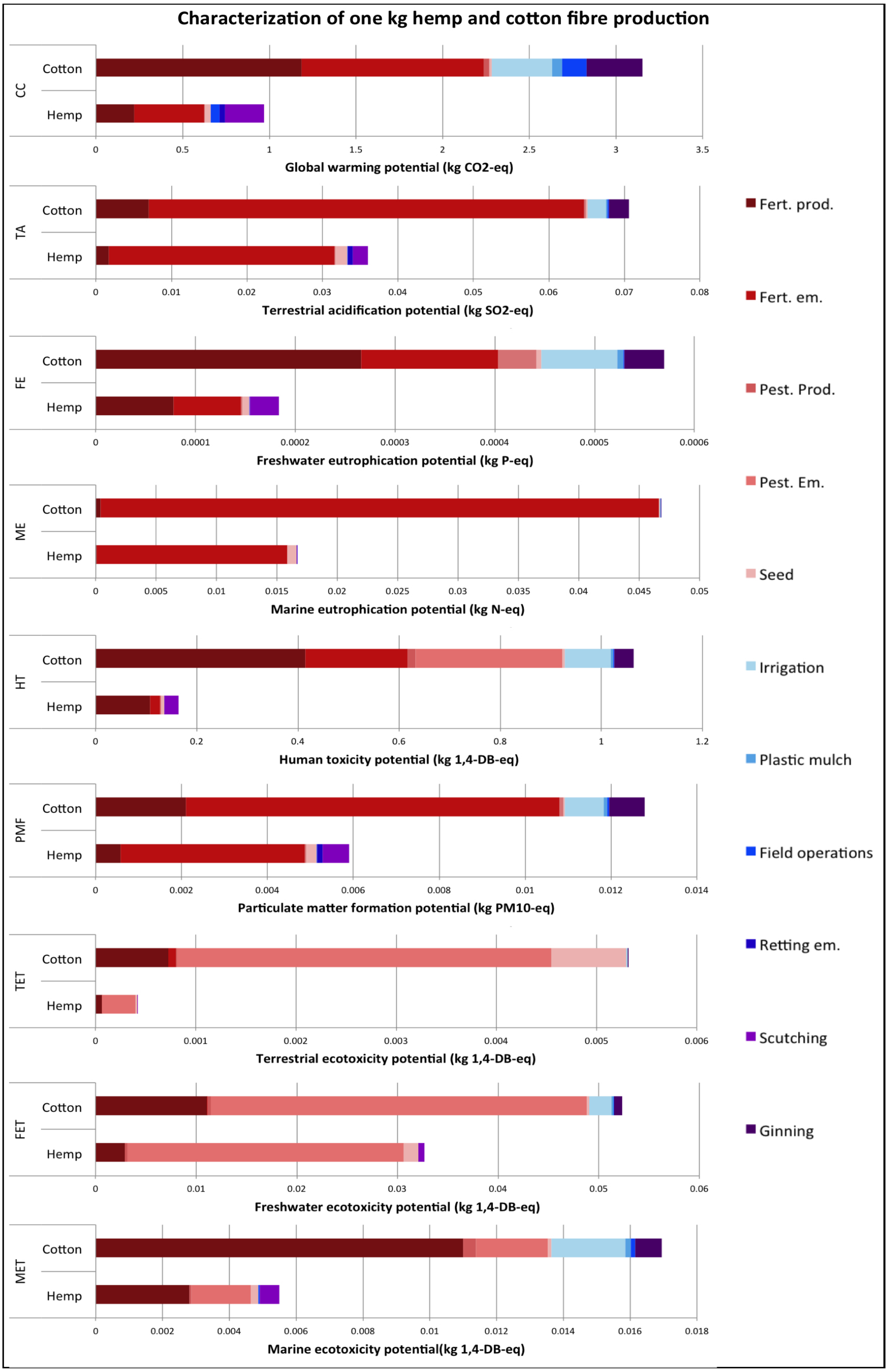

Figure 13: Characterization of the impact categories in hemp and cotton production.

This is a graphical representation of the characterization output from Simapro regarding the most important impact categories in hemp and cotton fibre production. Impacts are split according to the impact of input and output processes. The figure is based on data from Table 91 and Table 92 in Appendix 9.1.

Hemp and cotton have a respective freshwater eutrophication potential (FEP) of 0.18 g P-eq and 0.57 g P-eq kg^{-1}. It is remarkable that only 37% of FEP_{hemp} and 24% of FEP_{cotton} is caused by mineral fertilizer phosphate emissions. The majority of the FEP is indirect pollution from energy production caused by coal mining. Marine eutrophication potential (MEP), however, is caused for 95% for cotton and 99% for hemp by nitrogen emissions from mineral N-fertilizer. The total MEP_{hemp} and MEP_{cotton} amount to 16.70 g N-eq and 46.80 g N-eq kg^{-1} fibre.

Sulphur dioxide, ammonia and nitric oxides are next to actual particulates the most important contributors to PMF. The particulate matter formation potential (PMFP) of hemp and cotton is 5.90 g PM_{10}-eq and 12.79 g PM_{10}-eq kg^{-1} fibre. Fertilizer emissions contribute for 73% and 68% respectively to that total.

Lastly, there are four toxicity indicators. All these toxicity indicators are expressed in the reference unit of kg 1,4-dichlorobenzene-equivalent (1,4-DB-eq). The first, human toxicity potential (HTP), differs significantly for hemp and cotton. HTP_{hemp} and HTP_{cotton} are 0.16 kg 1,4-DB-eq and 1.06 kg 1,4-DB-eq kg^{-1} fibre. Major contributors to HTP_{cotton} are fertilizer production (39%), pesticide emissions (27%) and fertilizer emissions (19%). The impact of fertilizer production and emissions comes mainly from heavy metals, while acephate and aldicarb contribute the most to the HTP pesticide emissions. For hemp, however, only fertilizer production (66%) is the main contributor. This is because of the bio-remediating potential of hemp removing heavy metals from fertilizer emissions and because metolachlor has a rather low HTP.

Furthermore also terrestrial ecotoxicity potentials (TETP) show a large discrepancy between hemp and cotton with respective values of 0.39 g 1,4-DB-eq and 5.32 g 1,4-DB-eq. TET impact predominantly originates from pesticide emission with 85% and 70% respectively. Interesting is also the 7% reduction of $TETP_{hemp}$ because of the heavy metal accumulation in hemp. The relatively high impact of cottonseed (14%) is also due to pesticides used in seed production.

Freshwater ecotoxicity potentials (FETP) of hemp and cotton are more similar because of the high impact of metolachlor. Total values are 32.65 g 1,4-DB-eq and 52.30 g 1,4-DB-eq respectively. Again 84% and 71% of the impact is caused by pesticide emissions. The final toxicity category on the other hand is principally determined by heavy metal emissions. 51% and 65% of the marine ecotoxicity potential of hemp and cotton of 5.48 g 1,4-DB-eq and 16.95 g 1,4-DB-eq come from fertilizer production. Pesticide emissions are the second most important (33% and 13%) and also irrigation contributes significantly (13%).

The difference in ALO is not included in Figure 13 because it has no use to allocate the LCIA outcome to different processes. ALO_{hemp} and ALO_{cotton} are 2.54 m^2yr and 4.92 $m^2yr\ kg^{-1}$ fibre (Appendix 9.1). This discrepancy is totally dependent on fibre yield and allocation procedure. This does indicate that hemp fibre is more land-efficient.

Comparison of CP and GAP scenarios

Because of the large contributions of fertilizer-related emissions to the total impact of both hemp and cotton fibre production, it is interesting to analyse the difference between both the CP and GAP scenarios. Figure 14 presents the results of this analysis. This clearly shows that for cotton the fertilizer-dependent impact categories, like CC, TA, ME and PMF, can improve drastically if farmers would use more efficient fertilization practices. Categories of which the impact is not dependent on fertilization as much, obviously improve less in the GAP scenario. In any case the current impact of hemp (CP) remains below that of cotton. Also for hemp significant improvements could be made with better practices.

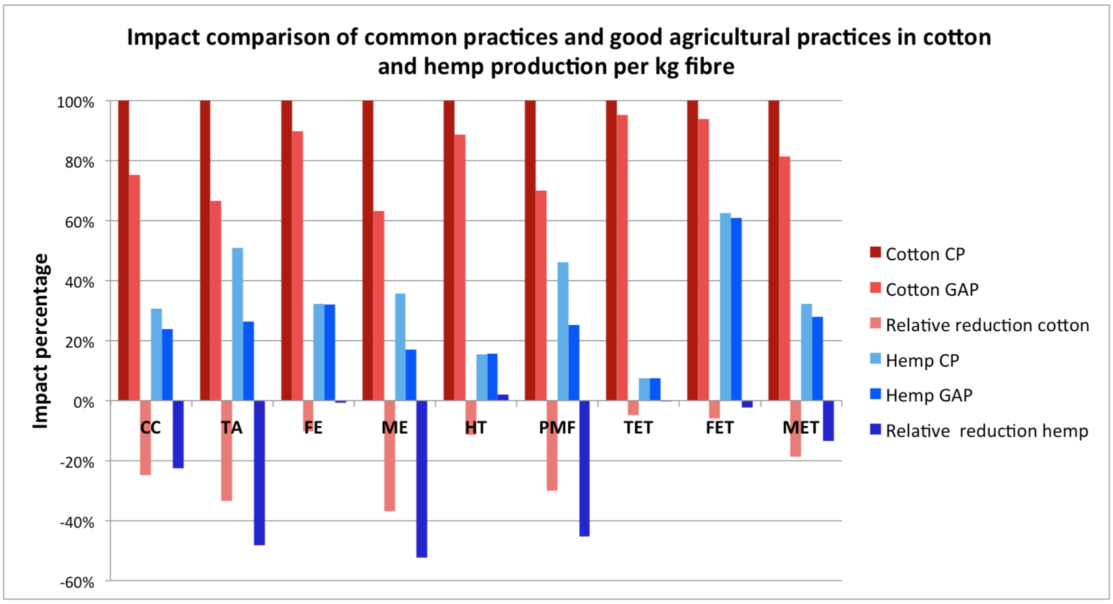

Figure 14: Impact comparison GAP and CP scenarios in hemp and cotton production.
This graph represents the impact of the common practices (CP) and good agricultural practices (GAP) scenarios as a percentage of the cotton CP scenario. The only difference between CP and GAP is the fertilization scheme. Additionally the reduction of impact is presented of the GAP scenario compared to the respective CP scenario.

The potential reduction of the impact of CC, TA, ME and PMF in cotton production ranges from 25% for CC to 37% for ME. Although the reduction for the different hemp scenarios is smaller in absolute terms, the relative impact reduction of GAP to CP is often even greater than that of cotton. For CC it is slightly smaller (23%) while for TA, ME and PMF it is significantly bigger with 48%, 52% and 45% reduction respectively.

Comparison of degummed hemp and cotton fibre

The abovementioned comparisons deal with scutched hemp and ginned cotton. These types of fibre should only be considered regarding technical fibre applications like biocomposites. In order to compare hemp and cotton as two very similar cellulose fibre types used in textiles the process of degumming should be included in the analysis as well. Figure 15 shows this comparison per relevant impact category and provides a valuable first insight in the current environmental performance of hemp fibre in textiles. This figure is based on data in Table 93 while the individual data of the degumming process are found in Table 94 (Appendix 9.1). This analysis contains the CP cultivation scenarios as it should reflect the real impact of hemp and cotton in today's textile industry

For most impact categories the potential impact of 1 kg degummed hemp fibre is significantly higher than of 1 kg ginned cotton. This is partly because the relative impact of hemp fibre production increased as more than 1 kg scutched hemp is used to produce 1 kg of degummed fibre (see section 3.3.3). But the main reason behind this turnaround is the high environmental impact of the degumming process.

GWP_{hemp} increased to 6.79 kg CO_2-eq kg^{-1} compared to 3.15 kg CO_2-eq kg^{-1} for cotton fibre. 37% of this GWP comes from direct heat input from coal, while the rest of the increase can be attributed to emission from electricity production (25%), wastewater treatment (7%) and the production of chemicals (7%). Hemp cultivation only amounts to 24%. Also the TAP_{hemp} of 90.03 g SO_2-eq and FEP_{hemp} of 1.50 g P-eq increased to above the levels of cotton. For TAP and FEP the increase is due to the impact of heating (13% and 51%), electricity production from coal (16% and 15%) and production of chemicals (3% and 10%).

Cotton does still have the highest MEP and TETP. MEP results almost entirely from N-fertilizer emissions. Less than 3% of the total MEP_{hemp} of 28.68 g N-eq comes from electricity production, coal mining and soda ash production combined. $TETP_{hemp}$ on the other hand is mainly influenced by pesticide emissions. However, degumming chemicals, and especially the polyoxyethylene ether production, contribute a significant 17%. Heating and electricity production accumulate to another 10%.

Then again, PMFP and all other toxicity categories have higher potential impact for degummed hemp. 42% of the 18.99 g PM_{10}-eq $PMFP_{hemp}$ comes from direct energy inputs in the degumming process while 52% comes from fibre production. HTP is also greatly increased by heavy metal emissions in electricity production from coal (16%), chemicals production (19%) and heating with coal (45%). And the same is true for FETP and METP: electricity production, chemicals production and coal heating contribute 6%, 10% and 15% respectively to FETP and 13%, 22% and 37% to METP.

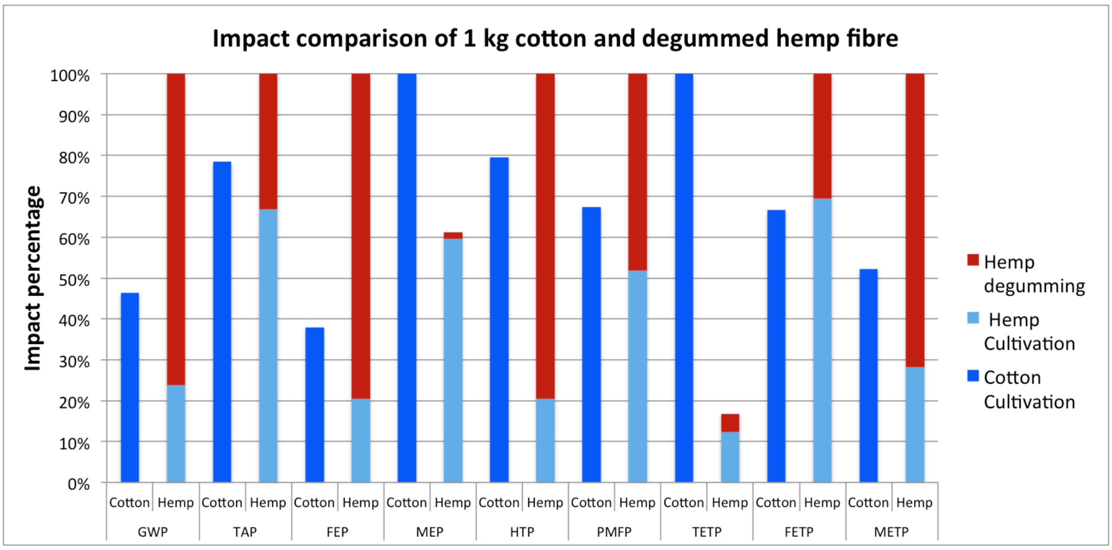

Figure 15: The impact comparison per kg of cotton and degummed hemp fibre.
This figure represents the impact of 1 kg ginned cotton fibre compared to 1 kg degummed hemp fibre. This degumming process requires 1.67 kg of scutched hemp fibre input. This figure is based on data from Table 93 in Appendix 9.1.

4.1.2 Scenario R, A, B and C

Normalization of scenario R, A, B and C

The normalization of the four fabric scenarios is presented in Figure 16. This normalization again determines which impact categories are relevant to discuss. CC, TA, FE, ME, HT, PMF, FET, MET and FD are the impact categories that are taken into account for analysing scenario R, A, B and C. Also ALO will be discussed shortly and compared to the previous section. Furthermore this figure gives a first impression that scenario C has a significantly higher impact. Scenario A and B also have a higher impact for some categories, while for other they are below scenario R.

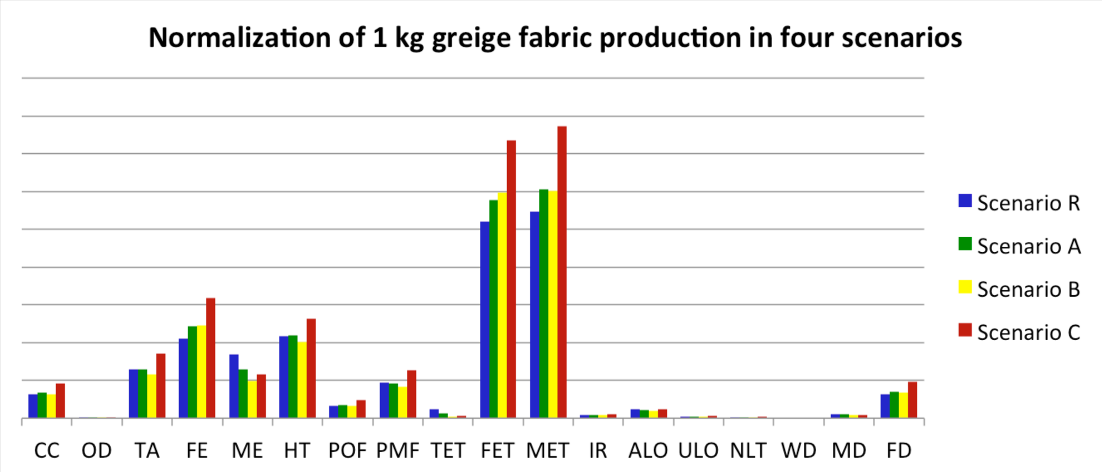

Figure 16: Normalization of 1 kg fabric production in four scenarios.
A graphical representation of the normalization results comparing the impact of four different greige fabric scenarios. R is the reference cotton scenario while A, B and C are three different hemp scenarios.

Characterization of scenario R, A, B and C

Figure 17 shows the important impact categories that will be discussed in the following section. This figure is based on data from Table 95 for scenario R, Table 96 for scenario A, Table 97 for scenario B and Table 98 for scenario C (Appendix 9.2). For simplification the sub-process of 'fibre preparation and spinning' will just be called 'spinning' and also 'sizing and weaving' will be shortened to 'weaving'.

Climate change

Firstly, scenario C has a significantly higher impact in the CC impact category than the other three: 31.83 kg CO_2-eq kg^{-1} fabric compared to 22.16 kg CO_2-eq, 23.48 kg CO_2-eq and 21.77 kg CO_2-eq kg^{-1} fabric for GWP_R, GWP_A and GWP_B respectively. Comparing GWP_R and GWP_A shows that for those two the absolute impact from spinning and weaving is very similar: respectively 7.59 kg CO_2-eq (34%) and 10.61 kg CO_2-eq (48%) for scenario R and 6.74 kg CO_2-eq (29%) and 10.66 kg CO_2-eq (45%) is emitted for spinning and weaving in scenario A. The total impact of scenario R is smaller, however, because of the 3.30 kg CO_2-eq from the degumming process. That results in 6.08 kg CO_2-eq (26%) allocated to the degummed fibre compared to 3.97 kg CO_2-eq (18%) for pure cotton. The same trend is visible in scenario B, where the impact of fibre production in only half of that of 100% cotton fabric. But the degumming process nullifies this entirely, ultimately resulting in the double amount of GWP. The reason for the lower impact of scenario B is the lower energy use in weaving and therefore lower contribution to the GWP. Scenario C requires more fibre but has less impact from bleaching. Spinning and weaving on the other hand require more energy and have a higher impact.

Overall, 48-58% of the GWP in all scenarios comes from direct emissions during electricity production from coal specifically. Another 19-22% is related to coal mining activities and for scenarios A-C 5-12% of emission come directly from water heating. Only 3-6% of the total GWP comes from fertilizer emissions.

Terrestrial acidification

Also in the category of TA, it is clear that scenario C has the highest impact: TAP_C is 324.30 g SO_2-eq while TAP_R, TAP_A, and TAP_B are 247.95 g SO_2-eq, 245.12 g SO_2-eq and 220.66 g SO_2-eq. Also TAP of spinning and weaving in scenario R and A are similar, although slightly lower for A: 66.77 g SO_2-eq (27%) and 92.37 g SO_2-eq (37%) for R and 58.93 g SO_2-eq (24%) and 89.64 g SO_2-eq (36%) for A. The production of fibre and the degumming in scenario A (96.55 g SO_2-eq or 39% of total) on the other hand has a bigger impact than cotton production (88.80 g SO_2-eq (36%)). Also in scenario B and C this is true, with 105.19 g SO_2-eq (48%) and 113.87 g SO_2-eq (35%). Again for scenario B the TAP of weaving is significantly lower (56.16 g SO_2-eq (25%)) while higher for scenario C (138.05 g SO_2-eq (43%)).

Electricity production from coal is responsible for 50-59% of the TAP. Fertilizer emissions from fibre production are the second most important source of TAP as 22-29% of the impact is attributed to this. Coal mining also contributes 7-8% next to some other small contributors like fertilizer production (2%).

Freshwater eutrophication

FE shows three clear levels of impact in between scenarios: Scenario R has the lowest FEP of 3.06 g P-eq, scenario A and B have very similar FEP values of 3.53 g P-eq and 3.57 g P-eq respectively, while FEP_C is 4.61 g P-eq. The difference between FEP_R and FEP_A results from the relatively high impact of degumming (0.76 g P-eq (22%)) that brings the total of production and degumming to 1.27 g P-eq (36%) compared to 0.72 g P-eq (23%) for cotton production in scenario R. FEP for spinning and weaving in both scenarios are similar: 0.98 g P-eq (32%) and 1.37 g P-eq (45%) for scenario R and 0.88 g P-eq (25%) and 1.37 g P-eq (39%) for scenario A. In scenario B, the lower impact of weaving (0.90 g P-eq (25%)) is nullified by the very high impact of degumming (1.40 g P-eq (39%)). The high impact of scenario C is mainly due to the higher FEP of weaving (2.08 g P-eq (46%)).

The main source of phosphor emissions is pollution from mining activities of coal for energy production and heating. This amounts to 90-95% of the total FEP. Only 3-5% of the total FEP is attributed to phosphate emissions from mineral P-fertilizer use and 1-2% to the production of it.

Marine eutrophication

Scenario R has the highest MEP, followed by scenario A, C and lastly B. The respective values are 62.13 g N-eq, 47.38 g N-eq, 42.52 g N-eq and 35.99 g N-eq. It is clear that this impact is mainly determined by fibre production: 89-95% of the MEP for the four scenarios (R: 95%; A: 92%; B: 90%; C: 89%).

Fertilizer emissions mainly explain the major contribution of fibre production to MEP. 88-93% of the total MEP is attributed to fertilizer emissions. Additionally, 3-7% comes from electricity production from coal and another 1-2% from coal mining activities. The impact of cotton production is also significantly higher that than of hemp production, agreeing with the analysis in Figure 15.

Human toxicity

HTP of scenario R and A are quite similar (3.54 kg 1,4-DB-eq and 3.57 kg 1,4-DB-eq) while that of scenario B is lower (3.28 kg 1,4-DB-eq) and of scenario C is higher (4.29 kg 1,4-DB-eq). The same trend applies to HT as with CC, TA and FE regarding spinning and weaving: it is similar for scenario R and A (0.92 kg 1,4-DB-eq (26%) and 1.28 kg 1,4-DB-eq (36%) for R and 0.83 kg 1,4-DB-eq (23%) and 1.30 kg 1,4-DB-eq (36%) for A), scenario B has a lower impact of weaving (0.86 kg 1,4-DB-eq (26%)) and scenario C has higher impact in both spinning and weaving (1.11 kg 1,4-DB-eq (26%) and 1.97 kg 1,4-DB-eq (46%)). Furthermore there is a large contribution of degumming or bleaching (A: 19%; B: 38%; C: 20%) and also of cotton production in scenario R and A (38% and 17% respectively). Once again the degumming process in A and B more than nullifies the entire benefit of hemp over cotton production.

The most important source of HTP is coal mining. 55-69% of all HTP come from pollution in these mining activities. Direct emissions from electricity production used along all processes amount to 15-20% of the HTP. Scenarios that include cotton have an additional contribution of 5-10% of pesticide emissions, while for hemp this is negligible. Fertilizer emissions also contribute 1-7% of total HTP.

Particulate matter formation

Also PMFP of scenario R and A are very similar (65.54 g PMF_{10}-eq and 65.31 g PMF_{10}-eq). The $PMFP_B$ is lower (58.01 g PMF_{10}-eq) while $PMFP_C$ is significantly higher (88.68 g PMF_{10}-eq). The abovementioned trend for weaving and spinning also applies to PMF: Similar values for spinning (R: 20.77 g PMF_{10}-eq (32%); A: 18.33 g PMF_{10}-eq (28%); B: 18.44 g PMF_{10}-eq (32%); C: 22.50 g PMF_{10}-eq (25%)) whereas weaving values are similar for scenario R and A (28.70 g PMF_{10}-eq (44%) and 27.79 g PMF_{10}-eq (43%)) lower for scenario B (17.37 g PMF_{10}-eq (30%)) and a much higher 42.85 g PMF_{10}-eq (48%) for scenario C. Scenario A-C have a lower PMFP than the cotton reference for fibre production only, but the sum of fibre production and degumming is higher again. This is mainly because there is no big difference between the total PMFP of hemp and cotton production (Figure 15).

The major part of PMFP is caused by direct emissions from electricity production with coal (55-63%). Other important contributions come from N-fertilizer emissions (11-17%) and pollution impact of coal mining (15-17%).

Freshwater ecotoxicity

Scenario R has the lowest FETP with a significant contribution of fibre production: of the 112.09 g 1,4-DB-eq 59% or 65.77 g 1,4-DB-eq are attributed to cotton production. Only 19.35 g 1,4-DB-eq (17%) and 26.97 g 1,4-DB-eq (24%) come from spinning and weaving respectively. All of this is comparable with scenario A, where 63.76 g 1,4-DB-eq (51%) comes from fibre production, 17.49 g 1,4-DB-eq (14%) from spinning and 28.01 g 1,4-DB-eq (23%) from weaving, if it weren't for the additional 15.22 g 1,4-DB-eq (12%) from degumming. Scenario B and C have an even higher FETP (128.66 g 1,4-DB-eq and 158.48 g 1,4-DB-eq) mainly because of higher impact of degumming (B) and fibre production and weaving (C).

The high impact of fibre production is mainly due to pesticide emissions, in total contributing between 41-44%. The rest of the impact comes from several polluting processes involved in coal mining.

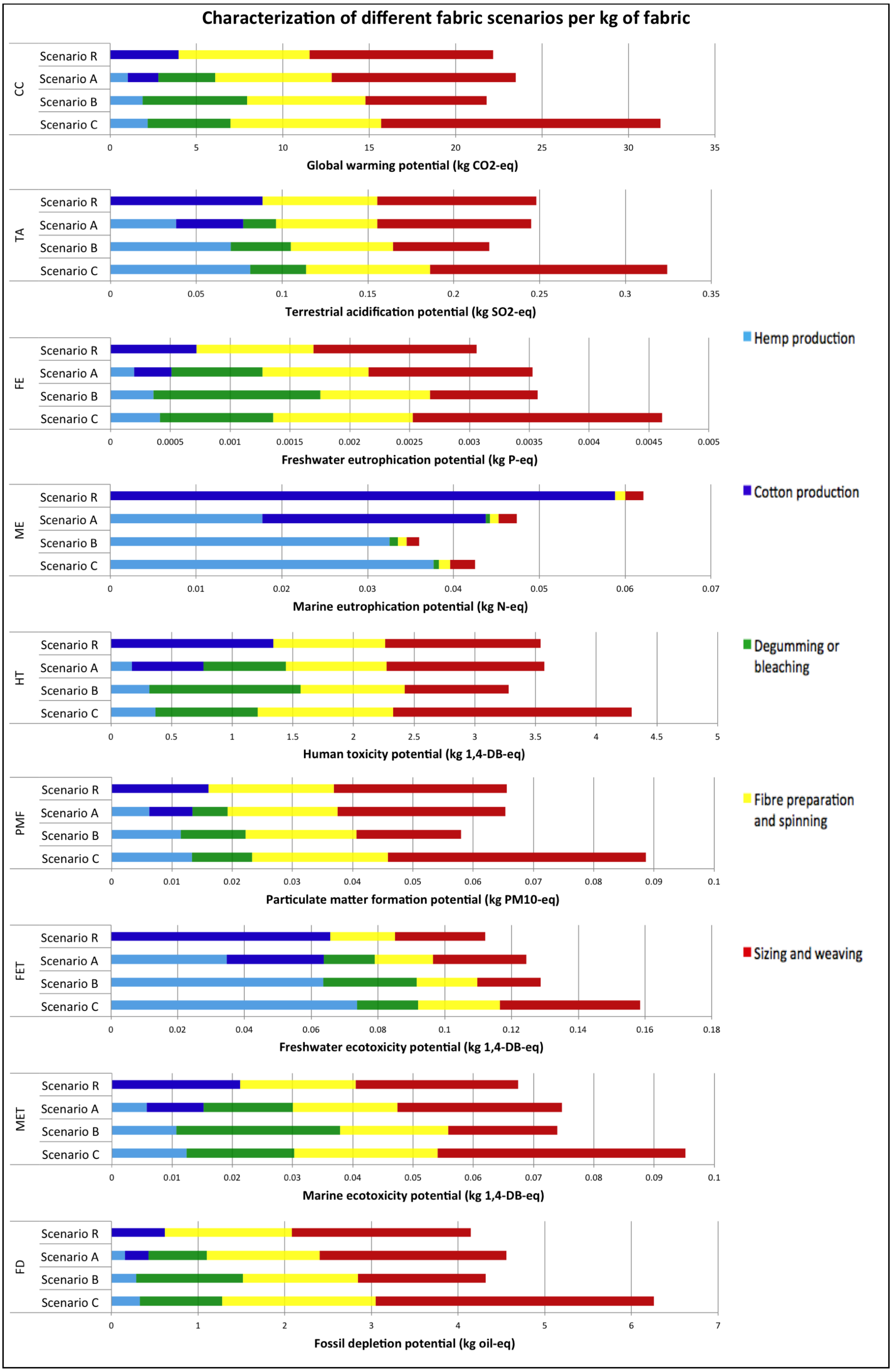

Figure 17: Characterization of fabric scenarios R, A, B and C.

This is a graphical representation of the characterization output regarding the most important impact categories in the four fabric scenarios. Impacts are split according to the impact of sub-processes. This figure is based on the data from Table 95, Table 96, Table 97 and Table 98 in Appendix 9.2.

Marine ecotoxicity

METP of scenario C is the highest (95.18 g 1,4-DB-eq) followed by scenario A and B (74.66 g 1,4-DB-eq and 73.95 g 1,4-DB-eq) and scenario R is lowest (67.38 g 1,4-DB-eq). $METP_R$ and $METP_A$ for spinning and weaving again are very similar. Also the impact of fibre production is lower compared to cotton. The total impact of scenario R is smaller, however, because of the impact from the degumming process (14.82 g 1,4-DB-eq). That results in 30.06 g 1,4-DB-eq (40%) allocated to the hemp fibre compared to 21.31 g 1,4-DB-eq (32%) for pure cotton. The same trend is visible in scenario B, where the impact of fibre production is only half of that of 100% cotton fabric (10.70 g 1,4-DB-eq (14%)). And again the degumming process more than nullifies this.

Most of the METP is energy-related with a large proportion attributed to coal mining pollution (75-76%). Minor impact comes from pesticide emissions (4-5%) and electricity production (3-4%).

Fossil depletion

FDP again has a very similar pattern: FDP_R is lowest with 4.15 kg oil-eq, then FDP_B and FDP_A with 4.32 kg oil-eq and 4.56 kg oil-eq and FDP_C is significantly higher with 6.26 kg oil-eq. Spinning contributes comparable amount in scenario R, A and B, but higher amounts in scenario C while for weaving the same is true except that here scenario B has a lower impact (R: 1.47 kg oil-eq (35%) and 2.06 kg oil-eq (50%); A: 1.30 kg oil-eq (29%) and 2.15 kg oil-eq (47%); B: 1.33 kg oil-eq (31%) and 1.47 kg oil-eq (34%); C: 1.77 kg oil-eq (28%) and 3.21 kg oil-eq (51%)). The contribution of fibre production is rather limited and higher for cotton than for hemp (5-15%). But again there is a high impact of degumming and bleaching on the results that cause the total impact of scenario A and B to be higher than the reference scenario.

Of course all the FDP comes from fossil resource extraction used for heat or electricity production. It is therefore a measure for the direct and indirect energy used in fabric production.

Agricultural land occupation

Figure 21 (Appendix 9.2) represents the ALO of the four fabric scenarios. The only land use incorporated in this category comes from agriculture. The cotton reference scenario R occupies the highest amount of 6.44 $m^2yr\ kg^{-1}$ fabric. Scenario B has the lowest impact (5.25 $m^2yr\ kg^{-1}$) and scenario A is right in between (5.75 $m^2yr\ kg^{-1}$ fabric). This is obvious, as scenario A is a mix in fibre composition between scenario R and B. Hemp scenario C, however, uses 6.16 $m^2yr\ kg^{-1}$ fabric because of the higher amount of hemp fibre needed. Because of the material efficiencies of hemp degumming and bleaching, the discrepancies between the fabric scenarios are much smaller than between hemp and cotton fibre in Figure 20.

4.1.3 Sensitivity analysis

The sensitivity analysis is performed on four different scenarios: Both on the cotton and hemp CP scenario to assess the sensitivity of parameters in the cultivation step (Table 22 and Table 21) and on scenario R and A to assess the sensitivity of parameters in the total LCA (Table 23 and Table 24). The parameters with the biggest impact in the characterization of both CP scenarios were included in the analysis. To perform the analysis, each parameter was increased by 10% while all others remain equal. The tables show the total change of the results per impact category. It should be stated that for economic allocation the allocation towards the fibre was increased by 10%. This means, however, that also the allocation to the by-products decreased by 10% as well. The analysis also tested what the results would be if another of the ReCiPe methods is used. As explained in section 3.2.4 above this is the Individualist and the Egalitarian method.

In both the cotton and hemp CP scenario the yield is an important parameter. A 10% increase results in an overall impact reduction of 9%. As expected from the characterization (Figure 13) the results of HT, TET and FET are very sensitive to changes in pesticide emissions. The other most important parameters are fertilizer use (increasing impact of fertilizer production and emissions) and fertilizer emission factors (increasing solely fertilizer emissions). The results are very sensitive to the allocation method as well. Irrigation, ginning electricity consumption and fuel use are insensitive parameters. The Hierarchist method lies in between the short-term Individualist and long-term Egalitarian method as predicted (Goedkoop et al. 2013). The Egalitarian method applies the precautionary principle and that is highly visible in the HT and MET category. Impact are included if only the slightest indication exists that the actually contribute.

Table 21: Sensitivity analysis of cotton CP scenario increasing eight parameters by 10% and using different LCA methodologies.

Factor	CC	TA	FE	ME	HT	PMF	TET	FET	MET
Total Yield	-9%	-9%	-9%	-9%	-9%	-9%	-9%	-9%	-9%
Irrigation	1%	0%	1%	0%	1%	1%	0%	0%	1%
Ginning energy	1%	0%	1%	0%	0%	1%	0%	0%	0%
Pesticides	0%	0%	1%	0%	3%	0%	7%	7%	1%
Fuel use	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fertilizer use	7%	9%	7%	10%	6%	8%	2%	2%	6%
Fertilizer emissions	3%	8%	2%	10%	0%	7%	0%	0%	0%
Economic allocation	14%	14%	14%	14%	14%	14%	14%	14%	14%
Individualist	10%	-16%	0%	0%	-67%	0%	0%	0%	-34%
Egalitarian	-25%	17%	0%	0%	2033%	0%	32%	1%	91728%

Table 22: Sensitivity analysis of hemp CP scenario increasing eight parameters by 10% and using different LCA methodologies.

Factor	CC	TA	FE	ME	HT	PMF	TET	FET	MET
Total yield	-9%	-9%	-9%	-9%	-9%	-9%	-9%	-9%	-9%
Scutching electricity	2%	1%	2%	0%	2%	1%	0%	0%	1%
Retting emissions	0%	0%	0%	0%	0%	0%	0%	0%	0%
Pesticide emissions	0%	0%	0%	0%	0%	0%	8%	8%	3%
Fuel use	1%	0%	0%	0%	0%	0%	0%	0%	0%
Fertilizer use	6%	9%	8%	9%	8%	8%	1%	1%	5%
Fertilizer emissions	4%	8%	4%	9%	0%	7%	0%	0%	0%
Economic allocation	19%	19%	19%	19%	19%	19%	19%	19%	19%
Individualist method	9%	-17%	0%	0%	-89%	0%	0%	-1%	-25%
Egalitarian method	-23%	17%	0%	0%	3427%	0%	63%	0%	71704%

The material efficiency parameter is calculated by increasing the fibre material input needed for producing 1 kg fabric by 10% in every process. Both in scenario R and A every impact category is sensitive to such changes. In the calculations of energy use in scenario R the energy-intensity multiplier was used to modify the European benchmarking values for a Chinese reality. This factor is increased by 10% in the sensitivity analysis. All impact categories with a high impact of energy use are naturally sensitive to this parameter (Figure 13). Both the amount of heat needed and the electricity use for hemp processing are assessed for sensitivity and are sensitive parameters. The sensitivity of degumming efficiency is calculated by increasing the efficiency from 60% to 70%. This naturally results in a significant reduction of the impact. The amounts of chemicals used in degumming practices is an insensitive parameter except for a small change in MET.

Table 23: Sensitivity analysis of scenario R increasing two parameters by 10% and using different LCA methodologies.

Factor	CC	TA	FE	ME	HT	PMF	FET	MET	ALO	FD
Material efficiency	5%	6%	6%	10%	6%	6%	8%	6%	10%	5%
Energy use	8%	6%	7%	0%	6%	7%	4%	7%	0%	8%
Individualist	24%	-7%	0%	0%	-75%	0%	0%	-29%	0%	0%
Egalitarian	-13%	10%	0%	0%	2824%	0%	1%	120545%	0%	0%

Table 24: Sensitivity analysis of scenario A increasing five parameters by 10% and using different LCA methodologies.

Factor	CC	TA	FE	ME	HT	PMF	FET	MET	ALO	FD
Material efficiency	5%	6%	6%	10%	6%	6%	8%	6%	10%	5%
Heat use	1%	0%	2%	0%	1%	0%	1%	1%	0%	1%
Electricity use	7%	6%	6%	1%	6%	7%	4%	6%	0%	7%
Degumming efficiency	-1%	-2%	-1%	-5%	-1%	-1%	-4%	-1%	-7%	0%
Chemical use	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%
Individualist	24%	-7%	0%	0%	-79%	0%	0%	-28%	0%	0%
Egalitarian	-11%	9%	0%	0%	3180%	0%	1%	123573%	0%	0%

4.2 Interpretation

4.2.1 Hemp and cotton fibre production

Scutched hemp fibre and ginned cotton

As mentioned before, the comparison of these two fibre types mainly applies to hemp and cotton as a resource for technical fibre applications, like biocomposites. For such applications the impact of hemp is considerably lower than that of cotton production. For fibre production in the CP scenarios the important impact of mineral fertilizer use, and especially N-fertilizer, is very clear (Figure 13). GWP, TAP, MEP and PMFP are all highly dependent on the impact of fertilizer production or field emissions. Hemp scores significantly better than cotton in these impact categories (70%, 49%, 64% and 54% less impact respectively). Hemp fibre cultivation also uses significantly less land compared to cotton. All of this is mainly because of the higher raw fibre yield compared to the used amounts of mineral fertilizer. Also, the higher economic allocation away from hemp fibre and to the shivs enlarges this difference. This results in even less fertilizer use, emissions and land use per kg fibre for hemp than for cotton and therefore a lower impact. One important remark is that cotton is sometimes intercropped with wheat in different systems. This might increase the nutrient-efficiency and land use of cotton even though total yields decrease (Zhang 2007). For hemp it is unknown whether such practices exist.

A remarkable impact is that of indirect pollution from electricity production due to coal mining on FEP. Where usually freshwater eutrophication problems are linked to agriculture, in this case only a relatively small percentage of the total FEP actually comes from agricultural operations.

Regarding human and ecotoxicity it is also clear that hemp scores better than cotton. The most important contributors are pesticide emissions (HTP, TETP, FETP) and heavy metals (HTP, METP). The better performance of hemp in HTP is partly a consequence of the bio-remediation potential of the plant. However, many different types and greater amounts of pesticides are used in cotton production and this obviously results in higher potential toxicity levels. There is no guarantee that this would still be the case if hemp were grown in large-scale monocultures, as this might increase disease stress. But at least it is more promising. Hereby it should be noted that an extremely simplified model was used to calculate the environmental fates of pesticides. In case primary data from agricultural practices can be gathered, more complicated and accurate models should be used to quantify the risks of pesticides. The lower toxicity impact might be part of the explanation why hemp is beneficial in crop rotation systems (section 2.1.2). Experiments should be performed for what hemp production scenarios this still holds; hemp is often grown without pesticides and with organic fertilizer.

Definite environmental hotspots for both fibres are fertilizer production and emissions, pesticide emissions and for cotton energy use in irrigation. As the end-of-life of the plastic mulch was not included, doing so would probably also have impact on the ecotoxicity categories. Figure 14 shows that efforts towards more efficient use of mineral fertilizer would really have major reducing effect on the total environmental impact of hemp and especially cotton production. Even in a more efficient scenario cotton will not have an impact below that of hemp. Next to environmental benefits, this would also be an important economical improvement: as assumed in section 2.2.2, the average Chinese cotton farmer is currently producing at costs above the global market price. Chaudhry (2008) also reported that a major part of this high production cost is because of the excessive use of fertilizer. Reducing this would automatically improve the competitiveness of Chinese cotton. A detailed analysis of the production costs of hemp in China is needed before any statements can be made on the impact of reducing mineral fertilizer use. In any case, following the same rationale, we can assume that this would increase the competitiveness of hemp as well. Some literature exists on the fertilizer-efficiency of hemp and the relation to fibre quality, but further research is needed, also differentiating between end use of the fibre. Of course the actual dissemination of information to the farmer is of key importance as well.

In total, this analysis provides an insight in the environmental performance of hemp and cotton in technical fibre applications. It indicates that for such applications hemp is inherently more environmentally sustainable than cotton fibre. Also in Europe, where better fertilization practices are used in hemp production, this would be true. Alternatives like kenaf, jute and flax exist, but a recent study shows that the difference in carbon footprint between those four fibres is not very significant (Barth & Carus 2015). Anyhow, the GWP impact of all four is significantly lower than the results for cotton. As stated in section 2.3.2, cotton is still used in composites for the German automobile sector. Developing a European policy to support a stable supply of alternative natural fibres would be an important step towards entirely replacing cotton. This, however, requires further economic analysis as well.

A final recommendation on further research regarding technical applications is to compare a hypothetical hemp fibre production scenario with cotton or other fibre production practices in the USA, both economically and ecologically. Recent developments in the US indicate that commercial hemp production will be allowed in the near future (Stansbury & Steenstra 2014). Industrial hemp might be a viable resource in the development of a truly sustainable bio-based industry, starting with biocomposites among others. Smith-Heisters (2008) suggest, while acknowledging that popular literature often exaggerates, that industrial hemp would be far more land-efficient, producing up to three times the amount of fibre, compared to US cotton production.

Parameter sensitivity and data quality

Table 21-22 and Table 74-80 assess the sensitivity and uncertainty respectively of important paramaters in the LCA. Parameters that are both sensitive and highly uncertain are detrimental for the LCA reliability. Pesticide emissions are such a parameter in the both the hemp and cotton CP scenario. As mentioned above, the modelling of pesticide emissions is highly simplified, which makes them rather uncertain. This indicates that future LCAs should focus on reducing uncertainty for this parameter. Fertilizer emissions are worth mentioning as well. They have a medium uncertainty but are highly influential on the results. The emissions are modelled through widely accepted emission factors (Table 6). These empirical models are a huge simplification of real field situations. This indicates the need for using more advanced, mechanistic emission models relying on site-specific data in agricultural LCAs to reduce the uncertainty. Yield and economic allocation are rather certain for cotton but a bit uncertain for hemp. This is important, as the results are very sensitive to changes in either of them. Because of the niche position of hemp there are no reliable price and yield statistics for hemp in China. This has to change if LCAs on hemp are to be used for determining policy measures.

Degummed hemp fibre and ginned cotton

Figure 15 quantifies for the first time the environmental impact of contemporary degumming techniques in Chinese hemp textile manufacturing. Except for MEP and TETP, 1 kg of degummed hemp has a higher environmental impact than 1 kg of cotton fibre. This has two main reasons: firstly the degumming process is rather inefficient in hemp fibre use and secondly energy-intensive processes seem to have a very high overall impact. Due to the inefficiency of the degumming process it requires 1.67 kg of scutched fibre per kg of degummed fibre. Improving this efficiency would directly affect the impact of degummed fibre and this especially for TAP, PMFP and FETP, as the proportion attributed to the fibre production here is large. The cellulose content of scutched hemp fibre bundles naturally limits this potential increase in efficiency, because non-cellulosic compounds are removed to free the cellulose fibres. When assuming a non-cellulosic content of 20% (section 2.1.1) the maximum possible impact reduction would be 17%, 13% and 17% for TAP, PMFP and FETP respectively. This would be significant, but still insufficient to have a lower impact than cotton even in those categories. GWP, for example, would only be reduced by 6%, barely changing anything to the situation with cotton.

For many categories, like GWP, FEP, HTP and METP, the degumming process is by far the largest contributor to the impact of degummed hemp. There is an impact of the production of the degumming chemicals but mainly for GWP and FEP it is limited (3-

10% of total) while for HTP and METP it is more significant (19-22% of total). Nonetheless, the impact of (in)direct pollution related to both electricity and water heating is higher for every single impact category. Tackling total energy use in degumming is the environmental hotspot for decreasing the impact of hemp fibre compared to cotton in this stage. Research for alternative degumming methods is being and has been performed (section 2.3.1) and these results only further stress the need for this.

Furthermore, it is clear that the impact is mostly because of (in)direct emissions from coal. Coal is used for heating the degumming liquor and for the major part of Chinese electricity production (section 3.3.1). Because these emissions are very country-dependent, and not very fibre-intrinsic, it would be interesting as well to compare with the degumming of hemp in a European or US energy scenario. This is outside the original scope of this study but provides valuable insights in the results.

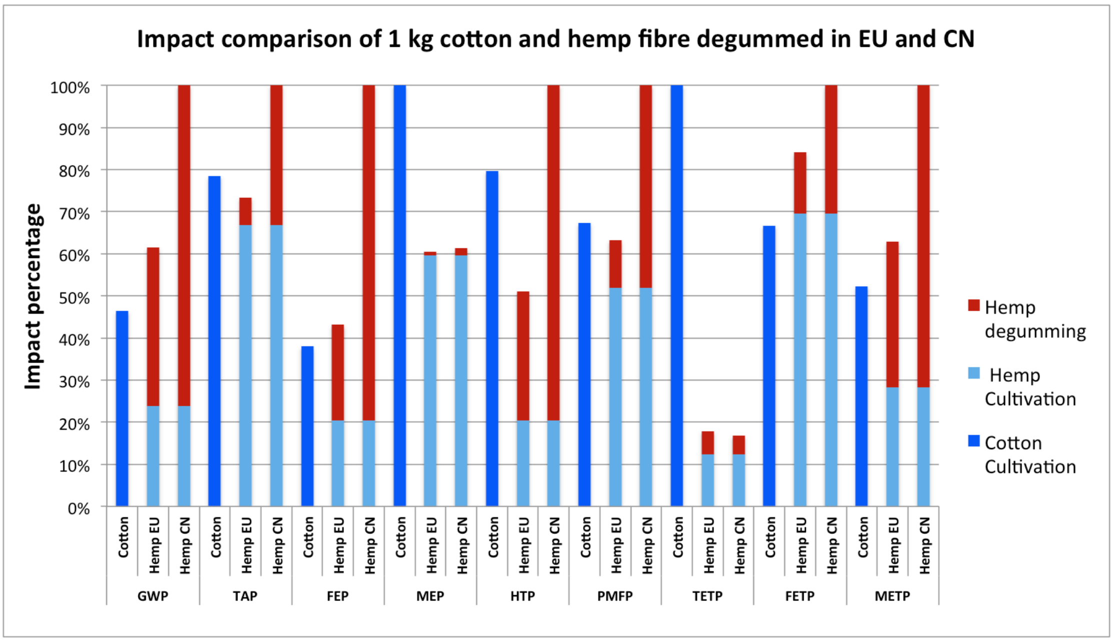

Figure 18: The impact comparison per kg of cotton and degummed hemp fibre.
This figure represents the impact of 1 kg ginned cotton fibre compared to 1 kg degummed hemp fibre with two different degumming scenarios: one in Europe (EU) and one in China (CN). This degumming process requires 1.67 kg of scutched hemp fibre input (produced in China).

Figure 18 presents the results of this exercise in an analogue way to Figure 15. The only difference between the degumming scenario in Europe (Hemp EU) and the degumming scenario in China (Hemp CN) is that the equivalent Belgian electricity mix from Ecoinvent v3.1 (2015) replaced the Chinese electricity mix and that gas was used for heating instead of coal. This figure clearly shows the impact reduction achieved solely by moving one step to another country. Of course this deals with a major simplification. But in total, nine out of eighteen impact categories show a significant reduction of up to even 57% for TA. On the other hand only one greatly increases (IR, because of the proportion of nuclear energy).

Figure 18 actually touches difficult but very relevant matter: The more sustainable, more efficient European infrastructure and methods turn out in less environmental impact but at a certain economic cost, be it for companies paying more for energy or remediation technologies or governments for infrastructure, etc. On the other hand, this extra cost does not incur in Chinese production, resulting in more pollution. This cost to society is hard to monetize at the moment and is thus not included in the price or production cost.

To summarize, first and foremost energy requirements of the degumming process should be lowered significantly to be environmentally competitive in the categories of CC, FE, HT, PMF and MET. Additionally, the sources of energy used are equally important. Increasing the material efficiency of the degumming process would be a serious step towards a lower impact for TA and FET. And for ME and TET hemp is performing significantly better than cotton.

Put in a wider scope it should be mentioned that Figure 15 and Figure 18 compare a highly developed crop with specialized machinery like cotton to a niche crop with barely any recent technological development and limited breeding efforts. By focussing breeding efforts on increased fibre yield and quality at high biomass levels and developing more efficient separation techniques serious efficiency gains could still be realised in favour of hemp. Furthermore, this analysis is focussed on cotton from the YRR and hemp from Heilongjiang province. This should be compared to other cotton and hemp cultivation regions as well. In China alone, the cotton production in Xinjiang province is more input-intensive, which would result in a higher impact as well (Barnes et al. 2012).

Biogenic carbon in textile fibres

An important aspect in the LCAs of renewable materials is carbon accounting. As stated in section 3.2.1 above, the biogenic carbon, sequestered in the hemp and cotton fibres, is not taken into account as a negative emission of CO_2. The back-of-the-envelope calculations in Table 99 (Appendix 10.1) estimate the negative emission per kg fibre that can be taken into account. For hemp and cotton that is 3.76 kg CO_2 and

3.21 kg CO_2 kg^{-1} fibre respectively. This estimation does not take into account the fates of any plant residues or wastes and assumes that the harvest is dry matter. If this negative emission were to be included in the analysis, both hemp and cotton fibre would have a negative GWP of -2.79 kg CO_2 and -0.06 kg CO_2 kg^{-1} fibre respectively. Taking into account the material efficiency of degumming, the fibre alone would reduce the impact of degumming with 4.7 kg CO_2, hereby minimizing the difference in GWP between cotton fibres and degummed hemp fibres.

However, this reasoning is incomplete if we look at the entire life cycle of the material. For renewable materials and biofuels the carbon neutrality assumption is very important. This assumption states that the amount of CO_2 sequestered by the plant is equal to the amount of CO_2 that is ultimately returned back to the environment, or the net GWP effect is zero (McKechnie et al. 2011). If this assumption holds then the sequestered CO_2 should not be taken into account. There is reason to believe however that for textiles this assumption is not entirely correct. Recent studies, by Kendall et al. (2009) among others, suggest that there is a time-dependent effect of biogenic CO_2. First applied to biofuels, this means that the time between the release of CO_2 by using biofuels and the sequestration of that CO_2 in new plant material matters for the GWP of that biogenic CO_2. Cherubini et al. (2011) quantified this effect relative to fossil CO_2 for time horizons of 1 to 100 years suggesting that the longer the biogenic CO_2 remains in the atmosphere the higher the GWP. When inverted, that same time-dependent effect can be applied to renewable materials like natural fibres. If the textile life span is short and the textiles are incinerated at the end-of-life the carbon neutrality assumption holds. If the life span is very long or if part of the waste is landfilled (and the CO_2 remains partially captured) then the time-dependent effect will cause the material to have a lowering effect on GWP because all that time the CO_2 has not been in the atmosphere, warming the planet. In that case it is important to know the exact material streams and fates of all biogenic carbon reservoirs, which is not the case in this study. Therefore it is better omitted.

Comparison to previous LCAs

Some results of the first CP scenario comparison look rather similar to the previously assessed LCAs (section 2.4.2). GWP_{hemp} falls within the 0.95-1.6 kg CO_2-eq range with an average of 1.4 kg CO_2-eq as described before. GWP_{cotton} is also comparable to LCAs in section 2.4.2 with an average GWP of 2.6 kg CO_2-eq (Figure 4). The distribution of the GWP among different processes follows the same trends: a major part is due to fertilizer production and emissions (Table 4). Furthermore irrigation is a significant contributor for cotton. Fibre separation in hemp contributed up to 25% (section 2.4.2) and also in this LCA this amounts to 23% of GWP. A remarkable difference is the minor share of emissions from on-farm fuel consumption for both hemp and cotton: Some previous studies report this to be as high as 20% of GWP (Table 4). One explanation might be that these studies apply to highly mechanized agricultural system in Australia and Europe, which are incomparable to Chinese agricultural methods. A slight increase could be expected for hemp in case the turning during and picking up after retting would have been included (see section 3.3.1 on On-farm fuel use). This, however, would only cause a minor change, as fuel use is no sensitive parameter (Table 22).

Looking at acidification, however, the results show a larger discrepancy. The LCIA results for hemp and cotton are a factor 4 to 9 higher than those summarized in Figure 5. The relative distribution on the other hand, with more than 80% attributed to fertilizer emissions, does correspond (Table 4). A potential explanation is a difference in the LCIA methodology or in the emission factors and models used to complete the LCI. This stresses the importance of assessing the scenarios in parallel LCAs where the exact same methodology, boundaries and factors are used. Additionally, it can partly be due to less nutrient-efficient agricultural practices in general, resulting in more fertilizer emissions.

Eutrophication potential is completely incomparable because of methodological differences. The ReCiPe method splits nitrogen and phosphor emissions with its characterization factors into marine and freshwater eutrophication, according to the element generally limiting algal growth in the respective environment (Goedkoop et al. 2013). The methodologies used by the summarized LCAs only include one eutrophication category, implying that characterization factors for both nitrogen and phosphor emissions are used to calculate EP in PO_4-eq. Moreover, FE in the ReCiPe method is expressed in P-eq.

The scenario that takes degumming into account cannot be compared, as this is the first LCA dealing with this stage. Turunen & van der Werf (2008) do include bleaching, but it is not very clear what the exact impact of this particular process is.

4.2.2 Scenario R, A, B and C

Scenario R and A

Because scenario R and A have the exact same functional unit they are in the best position to compare the environmental performance of hemp and cotton. In any impact category as described in section 4.1.2 the difference between scenario R and A for spinning and weaving is very small. It can thus be presumed from this analysis that there is no significant technical or environmental difference between the actual spinning of cotton yarn and blended yarn using the same equipment. This can be expected looking at the respective LCIs: they have approximately the same electricity consumption, heat consumption and material efficiency. This means that most of the discrepancy between scenario R and A will come from fibre production and degumming.

In five of the important impact categories the impact of scenario R is lower than that of scenario A. In other words, in these categories the addition of hemp to the fabric fails to lower the environmental impact and could even increase it. These categories are CC, FE, FET, MET and FD. The increase in impact ranges from 4% (FD) to 15% (FET). In CC, FE, MET and FD a rather small proportion of the impact is attributed to fibre production. In any of these cases the total impact of fibre production in scenario A is lower than for cotton. But degumming more than compensates this. And because spinning and weaving are very similar degumming thus causes the most important discrepancy. For FET the fibre production has an equal and much bigger impact. But again the impact of degumming makes up most of the difference.

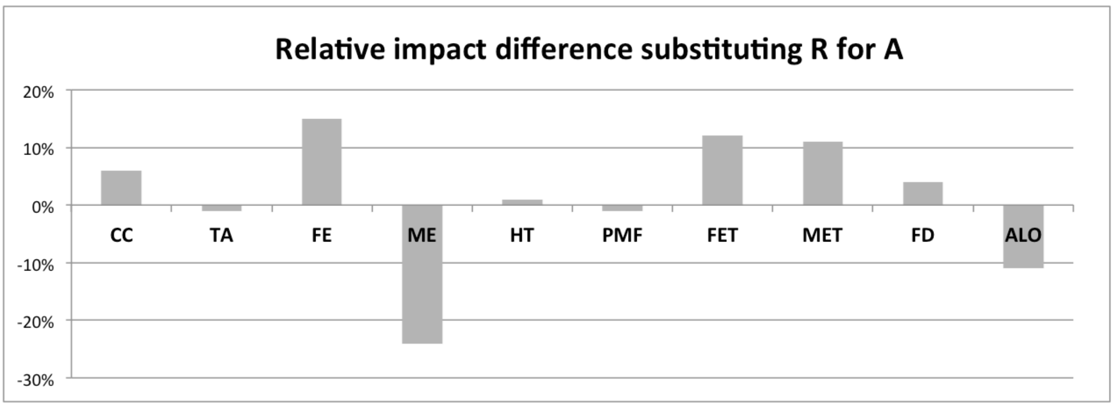

Figure 19: The relative impact difference of substituting scenario R for A.
This figure graphically presents the difference in impact per impact category when substituting fabric of scenario R for fabric of scenario A. This figure is based on data from Table 95 and Table 96 in Appendix 9.2.

TA, HT and PMF have a very insignificant difference in impact. For TA the impact of spinning, weaving and fibre production are all slightly smaller so that the limited impact of degumming doesn't nullify that. Because we now assume that there is no real difference between spinning and weaving for hemp and cotton the slight decrease might as well be a slight increase. For HT, however, the majority of impact of degumming is compensated by the extremely low impact of hemp. While for PMF both fibre production and spinning compensate it.

ME and ALO are unique in the way that all (or most) of the impact is caused by fibre production only. It was already discussed in section 4.2.1 that the actual cultivation of hemp is more sustainable. Even with the increased use of hemp fibre compared to cotton the impact is still generally lower and this is definitely so for ME and ALO.

In total, these two scenarios prove that adding hemp to cotton yarn at the moment makes no significant improvements to the environmental impact of textiles, except in marine eutrophication and agricultural land occupation. As mentioned in the before (section 2.4.2) marine eutrophication is a severe problem without any improvement in sight so far, also for the YRR. Hemp could help remediate this problem if it were to be used on a much larger scale. Furthermore, the Chinese government plans to replace cotton acreage on fertile land by food crops and replace the cotton by hemp production in less fertile regions. Also for this goal hemp textiles are suitable as it is more land-efficient and thus more food could be produced.

Issues with hemp textiles, however, are mainly because of the degumming stage. This makes the production slightly more energy-intensive (FD) and GHG-intensive. These effects are amplified in FE, HT and MET by indirect emissions from energy production. In all other categories the impact is similar and further reduction is possible as well. Economically feasible degumming methods with far lower energy use and higher fibre efficiency are needed to lower the impact below that of cotton. Incremental efficiency gains in this process will not suffice. Only radically innovative methods, like biodegumming without the use of hot water, will have potential for hemp in textile application.

Another suggestion in order to fully understand the intrinsic environmental differences between hemp and cotton is to compare these results with the same analysis where only direct emissions and impacts are included. This would not represent the total impact of the fabric, but only the impact attributed to the textile value chain itself. The findings from such a study would also be valid in more global sense because they would not be dependent that much on a certain energy infrastructure. It is expected that the contribution of fibre production would be significantly higher and that the potential environmental benefits of hemp would be greater.

At the moment, hemp textiles produced in China do not live up to their presumed potential as a more sustainable alternative to cotton. But which natural fibres might? As mentioned in section 2.3.1 above, textile fibres need high aspect ratios, preferably higher than 10^3. Cotton, hemp and flax (linen) fibres have an aspect ratio in this range (Eder & Burgert 2010). Eder & Burgert (2010) also state that the previously mentioned kenaf and jute have significantly lower aspect ratios. Moriana et al. (2014) seem to contradict this, but they use unrealistic fibre lengths suggesting that this does not deal with textile grade cotton, hemp and flax fibres. Hemp and flax are very alike so it can be assumed that similar processes are needed to achieve cottonized fibres. Another potential candidate is the oldest man-made fibre, viscose (Lord 2003c). Originally made from wood, this fibre is produced by treating a cellulose source with sodium hydroxide and carbon disulphide to form cellulose xanthate. This is then dissolved in sodium hydroxide to form a viscous solution and extruded into yarn (Lord 2003c). The same process is possible with hemp as a source of cellulose. Zhang (2008) claims that 1 kg of viscose requires 3 kg of hemp shivs. Given the many processing steps that also involve heat, it is dubious, however, that viscose will be more environmental friendly than normal hemp or cotton fibre. Muthu (2014b) for example reports viscose to have high energy requirements and that carbon disulphide is seriously environmentally hazardous. Comparing hemp and cotton to man-made fibres is an entirely different question. We suggest further research to compare natural fibres with man-made fibres as well.

Anyhow, the results from this LCA are not entirely in line with those of Beton et al. (2012). This study performed by the Joint Research Centre of the European Commission identifies hemp as an opportunity for improving sustainability in the European textile industries. They calculated a significantly reduced impact in ALO, ME, FE, TET, FET and MET compared to only ALO and ME for this study. This for one could be a consequence of the difference between the European and Chinese industry. But on the other hand it seems as if they did not include any degumming process for hemp fibres into the analysis. As proved in this LCA, this is the most important environmental hotspot and cannot be left out of the picture.

Scenario B and C

Scenario B and C are not entirely comparable with scenario R and A and are therefore discussed separately. They do provide some further insights in the environmental impact of hemp and textiles processes (Figure 17). First of all, scenario B confirms the conclusions from section 2.4 that the energy use and impact of weaving is inversely related to yarn count. Scenario B involves a 16 Nm yarn, which is thicker than the 36 Nm yarn in scenario A. It requires less energy and has less impact to produce 1 kg of the former compared to the latter. The same should be true for spinning, but this is not reflected in the results of this LCA.

Spinning and weaving in scenario C in general have a larger impact as well. For spinning this proves that wet ring spinning is more energy-intensive and thus more impactful than dry ring spinning, as already stated in section 2.3.1. The higher impact of weaving is also due to higher electricity use. The cause here, however, is the use of old and less efficient weaving machinery. This means that by using older machinery, the impact of a completely comparable fabric could exhibit the same sort of variance in impact. This implies that data from several textile mills should be averaged when assessing different fibre types with the goal to uncover fibre-intrinsic differences. Else the discrepancies might as well be mill-specific.

We can actually compare the fibre production and degumming in scenario B with scenario R and A. It is clear that even though the impact of fibre production itself further decreases by using hemp, the impact of degumming increases the impact even more than in scenario A in eight out of nine relevant impact categories. In total, more fibre has to be degummed and this makes the impact of this process almost double. Looking at scenario C, on the other hand, the impact of fibre production is higher because even more hemp fibre is used. But here the impact of the bleaching is significantly lower compared to scenario B. This only stresses the importance of developing new, energy-efficient degumming techniques even more.

Parameter sensitivity and data quality

The data quality of scenario R and A is also assessed with a sensitivity and uncertainty analysis (Table 23-24 and Table 74-80). For scenario R the material efficiency and energy use are rather sensitive parameters. The material efficiency luckily has a low uncertainty but the energy use has a much higher uncertainty. A very strong assumption was made on the energy-intensity of the Chinese compared to the European textile industry. Also in scenario A electricity use is a highly sensitive parameter which is also rather uncertain. The data were gathered in China by a third party and not many details are known on how they got these results. The material efficiency is also sensitive and uncertain in scenario A. This all depends on whether everything was correctly interpreted both by us as the Chinese partners. Gathering the data in person or with less language barriers should improve that. Finally, the efficiency of the degumming process is another sensitive parameter, mainly for TA, ME, FET and ALO. This parameter is equally uncertain.

4.2.3 Limitations to the LCA

Both this study in particular and the LCA methodology has limitations. They will be shortly discussed below.

On the LCA of hemp and cotton fibre production

Firstly, only secondary data were used in the construction of the LCI on fibre production. Ideally this should be combined with sources like farmer surveys on inputs and agricultural practices or soil analysis for nutrient modelling. It can be questioned to what extent scientific literature actually represents average field practices or accurately models site-specific processes. Definitely for highly sensitive parameters like fertilizer use, pesticides and yield, accuracy is needed.

A large limitation to the accuracy of the LCA is the frequent use of rather generic, empirical tier 1 models. In case the same model is used to compare two situations, these are comparable relatively to each other. But the question remains how accurate the absolute impact of both is.

Another limitation of this LCA is the inability to assess water use. For cotton only estimations were made on the amount of irrigation. Hemp was found to grow rain-fed, so in that view, hemp would be better in this region. More recent and accurate global studies are necessary on water use in cotton cultivation. The ReCiPe method, however, includes even the water that runs through turbines in hydroelectric plants as water depletion, making it irrelevant and useless. This impact category was therefore left out of the discussion.

Also, carbon accounting remains an important question in LCAs of biomaterials and biofuels. How this is included in the system boundaries and how this is interpreted has a major effect on the LCA. The importance of such LCAs and carbon accounting will only increase with rising interests in renewable industry resources. Definitely when results are used in popular literature, it is important to be aware of misinterpretations and false conclusions.

Finally, there is a pressing need for statistics on hemp in China. Both data on total production, total yields and fibre yields are scarce, variable and unreliable. Perhaps such data are available in Chinese literature on hemp, but even in this case they are unavailable for any non-Sino scientist.

On the LCA about scenario R-C

Firstly, it should be kept in mind that this is a comparison between hemp and cotton fabric made in China from Chinese cultivated fibre. This seriously limits the extent to which conclusions from this study can be generalized in a more global context.

Also, the reference scenario is based on the average Chinese cotton industry and the scenarios on data from one Chinese textile mill. This is important for several reasons:

- Big differences in between textile mills can appear depending the level of technology used and practices applied in the manufacturing process. This was minimized by excluding further finishing of the textiles, but even in spinning and weaving large discrepancies are possible. Using data from several mills allows for the use of averages and lowers the impact of outliers and would thus lower the uncertainty on the result.
- There is also a high degree of uncertainty involved in the reference scenario. The energy-intensity of the entire textile sector was used and it is unknown to what extent that corresponds with the energy-intensity of cotton manufacturing.
- Using averages with accompanying variances also allows for statistical sensitivity analysis like the Monte Carlo analysis. This should give a better view on the robustness of the assessment.

Furthermore the accuracy of the energy data in scenario A-C is rather uncertain. Because the data weren't personally gathered or calculated and some serious language barriers exist, we can only hope that everything happened according to plan and that all data were interpreted correctly. Ideally the LCA practitioner should have control over the quality of data collection in the field. If practically impossible, the practitioner should be provided with as much and as detailed raw data as possible. He is then to determine how and what will be calculated and used in the LCI.

Lastly, there is a need for benchmarking the actual environmental impact of textile manufacturing in China with accurate industry data. Van Der Velden et al. (2014) provide a solid example of how this could be done. Due to the very high impact of energy in the entire LCA, such a benchmarking study is needed to get a better view on how much more polluting this industry actually is compared to European textile manufacturers.

5 CONCLUSION

Are hemp textiles or hemp/cotton blends that are currently produced in China more environmentally sustainable than comparable cotton textiles?

It can be concluded that the currently produced hemp textiles do not have an overall lower environment impact than regular cotton textiles. The use of old machinery and out-dated technology, as still occurs for hemp textiles, is detrimental for the environmental performance. Adding 55% hemp fibre to textiles produced with the same technologies does lower marine eutrophication impact (-24%) and agricultural land occupation (-12%). Trade-offs occur, however, for climate change (+6%), freshwater eutrophication (+15%), freshwater ecotoxicity (+12%), marine ecotoxicity (+11%) and fossil depletion (+4%). This is mainly because the contribution of fibre production to these impact categories is limited and there is a huge impact of energy-related emissions and pollution. There is uncertainty on these results but they definitely do not support many claims made about hemp textiles today.

Can the environmental performance of the textile industry potentially be improved with the use of hemp fibres as an alternative to cotton?

Hemp does, however, have potential to improve the environmental performance of the textile and other industries. The cultivation of hemp has effectively less environmental impact compared to cotton (-50% to -90% for all impact categories). Even with improved fertilization methods hemp remains better. This in itself should be an environmental incentive to use hemp in technical fibre applications instead of cotton. For textiles, however, the degumming phase remains the most important hurdle. This increases the impact of degummed hemp fibres to above that of cotton for all impact categories except for marine eutrophication and terrestrial ecotoxicity. If economically feasible new methods can be developed for degumming hemp fibres without the same level of energy use then, and only then, will hemp textiles have a significantly lower impact than cotton. The difference will still be limited, however, because of the small contribution of fibre production to the total environmental impact. The analysis did show, however, the important impact of energy use on environmental performance. The use of clean energy sources for electricity and heat production should be prioritized in the quest for a more sustainable textile industry. In the end this will increase the relative contribution of fibre production to the total environmental impact, further increasing the potential benefits of hemp.

What are the main differences between hemp fibres and cotton fibres in textile manufacturing both from technical and environmental point of view?

The study shows that the technical difference between hemp and cotton are rather limited. High quality hemp can be spun with the same technology resulting in an equal environmental impact. The main difference, however, is the need for degumming hemp fibres and is thus a real fibre-intrinsic property. Because of the big direct and indirect impact from energy, this extra process of degumming currently nullifies all environmental benefits achieved in the hemp fibre production. Hemp production is definitely more environmental friendly because of a higher fertilizer-efficiency and the use of fewer pesticides. Hemp textiles currently are not the environmental miracle they are presumed to be, but from an environmental point of view, there is potential help the textile industry become more environmentally sustainable.

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PERSONAL COMMUNICATION

E-mail conversation with Dr. Bijay Ghosh of Indian Industrial Hemp Association, on October 8th 2014.

E-mail conversation with microbiology professor Chris Michiels on March 26th 2015.

E-mail conversation with LCA expert Martha Barth of Nova-Intitute, Köln, on March 27th 2015.

E-mail conversation with hemp expert Stefano Amaducci on March 26th 2015.

E-mail conversation with Chinese cotton expert Tian Changyan on November 24th 2014.

E-mail conversation with water treatment experts Bart Van der Bruggen and Ilse Smets on April 3rd 2015.

Interview over the phone with hemp textile expert Robert Hertel on December 29th 2014.

Appendix 1 Textile life cycle assessments

Table 22: Overview of previous sustainability assessments of both cotton and hemp grouped per comparable functional units.

Fibre	Source	Assessment	Functional unit	System boundaries	Allocation	Special remarks
Cotton	Barnes et al. (2012)	LCA-MP/EP	1 t of cotton fibre	Fibre production	EA: 84/16	Weighted average of US, China and India
	Bevilacqua et al. (2014)	GWP LCA-EP	1 kg of cotton fibre	Fibre production	EA: 90/10	Production at best practice farm in Xinjiang, China
	Khabbaz (2010)	CED/GWP	1 kg of cotton fibre	Fibre production Transport	/	Production in Australia Field to port
	Matlock et al. (2008)	CED	1 kg of cotton fibre	Fibre production	/	Weighted average of US, Australia and Asia
	Reed & Barnes (2009)	CED/GWP	1 kg of cotton fibre	Fibre production	/	Production in US
	Turunen & V. d. Werf (2006)	CED LCA-MP	1 kg of fibre	Fibre production	/	No details
	Yilmaz et al. (2005)	CED	1 ha cotton production	Fibre production	TA	Manually harvested production in Turkey 3,112 kg seed cotton ha^{-1}
Hemp	González-García et al. (2010)	CED LCA-MP	1 t of hemp fibre entering paper mill	Fibre production	EA	Spanish production data Low quality fibre
	Turunen & v. d. Werf (2006)	CED LCA-MP	1 kg of hemp fibre	Fibre production	/	No details
	V. d. Werf (2004)	CED LCA-MP	1 ha of hemp production	Fibre production	TA	Production in France 6,750 kg stem ha^{-1}
Cotton	Cherret et al. (2005)	CED/GWP	1 t of spun fibre	Fibre production Processing and spinning Transport	TA	Energy-intensive production in USA 1,350 kg ha^{-1}
	Cherret et al. (2005)	CED/GWP	1 t of spun fibre	Fibre production Processing and spinning Transport	TA	Energy extensive production in Punjab, India 1,350 kg ha^{-1}
Hemp	Cherret et al. (2005)	CED/GWP	1 t of spun fibre	Fibre production Processing and spinning Transport	TA	Hemp traditional method in UK
	Cherret et al. (2005)	CED/GWP	1 t of spun fibre	Fibre production Processing and spinning Transport	TA	Hemp green decortication in UK
	V. d. Werf & Turunen (2008)	CED LCA-MP	100 kg of 26 Nm (385dtex) yarn	Fibre production Processing and spinning	EA	Hungarian method with wet ring spinning 8,000 kg ha^{-1} and 236 kg yarn ha^{-1}
Cotton	Van Der Velden et al. (2014)	CED/GWP LCA-EP	1 kg greige fabric from 150 dtex (67 Nm) yarn	Fibre production Textile manufacturing	/	Benchmarking study on textile LCA 1% cut-off
	Kalliala & Nousiainen (1999)	LCA-MP	1 kg of finished, woven sheet	Fibre production Textile manufacturing	TA	100% cotton, fabric mass of 155 g m^{-2} Comparison of cotton and polyester

Cotton	Lehmann-Pollheimer (2006)	GWP	1 t-shirt	Fibre production Textile manufacturing Transport	/	No details
	Levi Strauss & Co (2008)	CED LCA-MP	1 pair of jeans	Fibre production Textile manufacturing	/	Average of 11 different types of jeans
	Blackburn & Payne (2004)	CED	600 g towel washed 100 times	Cradle-to-grave	/	Min 13.3% material loss in production 100 washes over lifetime
	QUT (2009)	GWP	1 T-shirt	Cradle-to-grave	/	No details
	Steinberger et al. (2009)	LCA-MP	Cotton T-shirt worn 100 days, washed every 2 wearings	Cradle-to-grave	/	T-shirt is 0.25 kg Production in India Consumption in Germany
	Laursen et al. (2007)	CED LCA-EP	1 cotton T-shirt used and washed 50 times	Cradle-to-grave	TA	T-shirt is 0.25 kg No absolute results
	Levi Strauss & Co (2009)	CED/GWP	1 pair of jeans	Cradle-to-grave	/	Full life cycle of jeans in Levi Strauss & Co (2008)
	Yuan et al. (2013)	LCA-EP Ga2Ga	10,000 m dyed fabric of 2,000 kg	Treatment Dyeing Disposal	/	Chinese processing facility Normalized results without further information

LCA-MP/LCA-EP = Life cycle assessment with midpoint/endpoint analysis
CED/GWP = Cumulative energy demand/global warming potential
EA/TA = Economic/total allocation

Appendix 2 LCIA impact categories

Table 23: Summary of all impact categories and characterization factors of the ReCiPe method.

	Impact category (Abbr.)	Indicator	Unit	Characterization factor (Abbr.)	Unit
Midpoint	Climate change (CC)	Infra-red radiative forcing	$W*yr\ m^{-2}$	Global warming potential (GWP)	kg CO_2-eq
	Ozone depletion (OD)	Stratospheric ozone concentration	ppt*yr	Ozone depletion potential (ODP)	kg CFC-11
	Terrestrial acidification (TA)	Base saturation	$yr*m^2$	Terrestrial acidification potential (TAP)	kg SO_2-eq
	Freshwater eutrophication (FE)	Phosphorus concentration	$yr*kg\ m^{-3}$	Freshwater eutrophication potential (FEP)	kg P-eq
	Marine eutrophication (ME)	Nitrogen concentration	$yr*kg\ m^{-3}$	Marine eutrophication potential (MEP)	kg N-eq
	Human toxicity (HT)	Hazard-weighted dose	/	Human toxicity potential (HTP)	kg 1,4-DB-eq
	Photochemical oxidant formation (POF)	Photochemical ozone concentration	kg	Photochemical oxidant formation potential (POFP)	kg NMVOC
	Particulate matter formation (PMF)	PM10 intake	kg	Particulate matter formation potential (PMFP)	kg PM_{10}-eq
	Terrestrial ecotoxicity (TET)	Hazard-weighted concentration	m^2*yr	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DB-eq
	Freshwater ecotoxicity (FET)	Hazard-weighted concentration	m^2*yr	Freshwater ecotoxicity potential (FETP)	kg 1,4-DB-eq
	Marine ecotoxicity (MET)	Hazard-weighted concentration	m^2*yr	Marine ecotoxicity potential (METP)	kg 1,4-DB-eq
	Ionizing radiation (IR)	Absorbed dose	man*Sv	Ionizing radiation potential (IRP)	kg U_{235}-eq
	Agricultural land occupation (ALO)	Occupation	m^2*yr	Agricultural land occupation potential (ALOP)	m^2*yr
	Urban land occupation (ULO)	Occupation	m^2*yr	Urban land occupation potential (ULOP)	m^2*yr
	Natural land transformation (NLT)	Transformation	m^2	Natural land transformation potential (NLTP)	m^2
	Water depletion (WD)	Amount of water	m^3	Water depletion potential (WDP)	m^3
	Mineral resource depletion (MRD)	Grade decrease	kg^{-1}	Mineral resource depletion potential (MRDP)	kg Fe-eq
	Fossil resource depletion (FD)	Lower heating value	MJ	Fossil resource depletion potential (FDP)	kg oil-eq
Endpoint	Damage to human health (HH)	Disability-adjusted loss of life years	yr		
	Damage to ecosystem diversity (ED)	Loss of species during a year	yr^{-1}		
	Damage to resource availability (RA)	Increased cost	$		

Appendix 3 LCI calculations for subsystem 1A

Appendix 3.1 Output: yield and allocation

Table 27: Calculation of the average ginning output.

Gin location	Lint (% gin input)	Waste (% of gin input)
Turkey[1]	38.31	4
China[2]	38.4	/
China[2]	38.3	/
China[2]	38.7	/
China[2]	38.9	/
China[2]	39.4	/
Average	**38.67**	**4**

[1] Adanacioglu & Olgun (2011)

[2] Zhang (2007)

Table 28: Calculation of seedcotton yield.

SCY = LY + SY + WA

SCY = LY / FRAC(lint)

WA = SCY * FRAC(waste)

SCY	=	Total seedcotton yield
	=	3,843 kg per hectare
LY	=	Lint yield
	=	1,486 kg per hectare
SY	=	Seed yield
	=	2,203 kg per hectare
WA	=	Ginning waste
	=	154 kg per hectare
FRAC(lint)	=	Fraction of lint output of total ginning input
	=	0.387
FRAC(waste)	=	Fraction of waste output of total ginning input
	=	0.04

Table 29: Calculation of the economic allocation between cotton fibre and seed.

EAi = ((Pi*Yi) / (Σ(i) (Pi*Yi))) * 100%

EAi		=	Economic allocation of environmental impact (i = fibre, seed)
	For i	=	Fibre: 71.2%
		=	Seed: 28.8%
Pi[1]		=	Market price of commodity i
	For i	=	Fibre: USD 1.54 per kg
		=	Seed: USD 0.42 per kg
Yi		=	Yield of commodity i
	For i	=	Fibre: 1,486 kg per hectare
		=	Seed: 2,203 kg per hectare

[1] USDA (2015a; 2015b)

Appendix 3.2 Input: pesticides

Table 30: Calculation of the pesticide use in cotton cultivation.

Product (kg ha-1)	Bevilacqua et al. (2014)	USDA (2006)	**Average**
Parathion (OP)	0.50	0	0.25
Malathion (OP)	0	4.3	2.15
Aldicarb (C)	0	0.75	0.38
Pyrethroid (P)	0.50	0	0.25
Acephate (OP)	0	0.96	0.48
Organophosphorus (OP)	0.50	0	0.25
Trifluralin (DNA)	0	1.01	0.50
Fluormetron (PU)	0.94	0	0.47
Glyphosate	0.91	1.78	1.35
Prometryn (T)	0.74	0.89	0.82
Total active ingredient	4.07	9.70	6.89

OP = organophosphates, C = carbamates, P = pyrethroids,
DNA = dinitroaniline, PU = phenylurea, T = triazine

Appendix 3.3 Input: fertilizers

Table 31: Calculation of the fertilizer input in cotton cultivation.

TFi = FY * (FEi/YE)

TFi	=	Total amount of fertilizer (i = urea, N-compound, P2O5-compound, K2O-compound)		
for i	=	Kg per hectare	GAP scenario	CP scenario*
		Urea-N:	106	168
		N-compound:	85	135
		P2O5-compound:	85	85
		K2O-compound:	85	85
FY	=	Fibre yield		
	=	1,486 kg per hectare		
FEi[1]	=	Good agricultural practice fertilizer use in experiment		
for i	=	Urea-N: 101 kg per hectare		
		N-compound: 81 kg per hectare		
		P2O5-compound: 81 kg per hectare		
		K2O-compound: 81 kg per hectare		
YE[1]	=	Yield of cotton lint in experiment		
	=	1,430 kg per hectare		

* For the CP scenario the same amounts are assumed as the GAP scenario but with a total N-application of 303 kg ha^{-1} instead of 191 kg ha^{-1} (Lemon et al. 2009; Bevilacqua et al. 2014; Dai & Dong 2014)

[1] Dai et al. (2014)

Appendix 3.4 Input: irrigation

Table 32: Comparison of the YRR climate with that of southeastern US cotton-growing regions.

Location	Rain[2] (mm)	Temperature[2] (°C)					
(% production[1])	May-Oct	May	June	July	August	Sept	Oct
Shaanxi (3.2)	446	20.5	25.6	27.6	26.1	20.4	14.8
Shanxi (4.3)	359	18.3	22.4	24.8	22.8	17.4	10.5
Henan (18.6)	503	21.6	26.8	28.2	26.4	21.6	15.8
Hebei (31.9)	458	20.9	25.7	26.9	25.4	20.6	14.1
Shandong (38.3)	537	21.9	26.5	27.7	26.5	21.9	15.9
Tianjin (3.7)	494	19.9	24.4	26.5	25.7	20.9	14.1
YRR weighted average	493.4	21.3	26.0	27.3	25.9	21.2	15.0
Memphis, Tennessee	548	21.3	25.6	27.4	26.4	22.8	16.9
Montgomery, Alabama	593	22.3	26.0	27.3	26.9	24.3	18.2

[1] Barnes et al. (2012)
[2] Climate data (2014)

Table 33: Calculation of the minimum irrigation used in YRR cotton cultivation.

IR = ((ET-RF) / FFE) * A

IR	=	Total amount of irrigation
	=	1,512 m3 per hectare
ET[1]	=	Evapotranspiration of cotton in warm and humid climate
	=	637 mm
RF	=	Average rainfall during the cotton growing season
	=	493 mm
FFE[2]	=	Factor incorporating efficiency of Flood-and-furrow irrigation
	=	0.4
A[3]	=	Percentage of cotton area irrigated in YRR
	=	0.42

[1] Suleiman et al. (2007) & Perry et al. (2012)
[2] Bevilacqua et al. (2014)
[3] Barnes et al. (2012)

Appendix 3.5 Input: seed

Table 34: Calculation of the average seed use in cotton cultivation.

Source	Amount seed (kg ha^{-1})	Average (kg ha^{-1})
Dai & Dong (2014)	35-45	40
Barnes et al. (2012)	15-30	22.5
Personal communication Tian Changyan	45	45
Total		**35.8**

Appendix 3.6 Input: plastic mulch

Table 35: Calculation of the low-density polyethylene film used in cotton production.

LDPE = A * TH * D(LDPE) * MF		
LDPE	=	Total amount of low density polyethylene film used
	=	41.3 kg per hectare
A[1]	=	Area per hectare covered in plastic mulch
	=	8,000 m^2
TH[2]	=	Average thickness of LPDE film
	=	8 µm
D(LDPE)[3]	=	Density of low density polyethylene film
	=	922 kg per m^3
MF[2]	=	Mulching factor that corrects for farmers not using the technique
	=	0.7

[1] Zhou et al. (2012)

[2] Dai & Dong (2014)

[3] Exxon Mobil (2014)

Appendix 3.7 Input: on-farm fuel use

Table 36: Calculation of the total average mechanization in YRR.

TAM = Mean(AWA(tillage) + AWA(sowing))

Province of YRR	**Production (%)**	**Mechanization percentage**	
		Tillage (%)	**Sowing (%)**
Shaanxi	3.2	88	34
Shanxi	4.3	100	88
Henan	18.6	25	0.5
Hebei	31.9	100	98
Shandong	38.3	88	69
Area-weighted averages (AWA)		80.2	57.9
Total average mechanization (TAM)		69.05	

Source: Dai & Dong (2014)

Table 37: Comparison of a hand tractor with a normal tractor.

Factor	**Hand tractor (HT)**[1]	**Tractor (T)**[2]	**Ratio HT/T**
Weight (kg)	318	3,000	0.106
Power (HP)	8.8	80	0.110
Fuel consumption ($l\ h^{-1}$)	2.04	16	0.127
Mean ratio			0.117

[1] Tractordata (2014)

[2] Turunen & van der Werf (2006)

Table 38: Calculation of on-farm fuel use in cotton cultivation.

FU = Σ(i) (Ni * Ti * HFU * TAM)

Ti = Area/width*V

FU	=	Total fuel use				
	=	93.3 l per hectare				
Ni	=	Number of application of operation i				
Ti	=	Time needed per operation i				
		Operation (i)[1]	N[1]	Area (m^2)*	Width (m)**	T (h)
		Tillage	2	10,000	0.5	8
		Intertillage	7	5,000	0.5	4
		Sowing	1	10,000	0.5	8
		Fertilizing	3	10,000	1	4
		Mulching	1	5,600	1	2.24
HFU[2]	=	Average hourly fuel use				
	=	2.04 l per hour				
TAM	=	Total average mechanization in YRR				
	=	0.69				

* *The application area of intertillage is assumed at half a hectare because this happens in between the rows of cotton. The area for mulching is calculated from the area per hectare that is actually mulched (See Dai & Dong (2014)).*

** *The width is an estimate from the width of a hand tractor and plough (Tractordata 2014). Fertilizer is assumed to have a wider spraying range and mulching plastic is assumed at a width of 1 meter.*

[1] Dai & Dong (2014)

[2] Tractordata (2014)

Appendix 3.8 Input: Ginning

Table 39: Calculation of the electricity consumption in cotton ginning.

ECgin = AEC * FY

ECgin	=	Electricity consumption of ginning	
	=	2095 MJ per hectare	
AEC	=	Average electricity consumption of gins	
	=	Australia[1]:	0.86 MJ per kg
	=	US[2]:	1.69 MJ per kg
	=	US[3]:	1.68 MJ per kg
	=	**Average:**	**1.41 MJ per kg**
FY	=	Fibre yield	
	=	1,486 kg per hectare	

[1] Ismail et al. (2011)
[2] Reed & Barnes (2009)
[3] Barnes et al. (2012)

Table 40: Calculation of the gas consumption in cotton ginning.

GCgin = AGC * FY		
GCgin	=	Gas consumption of ginning
	=	681 MJ per hectare
AGC	=	Average gas consumption of 6 Australian gins
	=	0.459 MJ per kg
FY	=	Fibre yield
	=	1,486 kg per hectare
[1] Ismail et al. (2011)		

Appendix 3.9 Output: fertilizer emissions

Table 41: Calculation of the NMVOC emissions from cotton cultivation.

NMVOC = FE(NMVOC)		
NMVOC	=	Emissions of non-methane volatile organic compounds
	=	0.86 kg per hectare
FE(NMVOC)	=	Fixed emission of NMVOC
	=	0.86 kg per hectare
[1] Hutchings et al. (2013)		

Table 42: Calculation of the ammonia emissions from cotton cultivation.

NH3 = (((EF(urea1)*N(urea)) + (EF(com)*N(com))) * F(pH)) * (1-EF(N2O1))			
NH3	=	Emissions of ammonia	
		GAP	CP
	=	28.48 kg per hectare	45.32 kg per hectare
EF(urea1)[1]	=	Emission factor for ammonia from urea fertilizer (pH-independent)	
	=	0.243 kg NH3 per kg N from urea fertilizer	
N(urea)	=	Amount of N applied per hectare from urea fertilizer	
		GAP	CP
	=	105.5 kg per hectare	167.9 kg per hectare
EF(com)[1]	=	Emission factor for ammonia from compound fertilizer (pH-independent)	
	=	0.037 kg NH3 per kg N from compound fertilizer	
N(com)	=	Amount of N applied per hectare from compound fertilizer	
		GAP	CP
	=	84.7 kg per hectare	135.2 kg per hectare
F(pH)[1]	=	pH-dependent factor from the tier 2 model	
	=	1 (because both EFs are pH-independent)	
EF(N2O1)[2]	=	Emission factor for indirect nitrous oxides from ammonia emissions	
	=	0.01	
[1] Hutchings et al. (2013)			
[2] De Klein et al. (2006)			

Table 43: Calculation of the nitric oxides emissions from cotton cultivation.

$NOx = (EF(tot1)*N(tot)) * (1-EF(N2O2))$

NOx	=	Emissions of nitrogen oxides	
		GAP	CP
	=	10.49 kg per hectare	16.66 kg per hectare
EF(tot1)[1]	=	Emission factor for nitrogen oxides from total nitrogen fertilizer	
	=	0.026 kg NOx per kg N from fertilizer	
N(tot)	=	Amount of N applied per hectare from all nitrogen fertilizer	
		GAP	CP
	=	190.2 kg per hectare	303.1 kg per hectare
EF(N2O2)[2]	=	Emission factor for indirect nitrous oxides from nitrogen oxide emissions	
	=	0.01	

[1] Hutchings et al. (2013)

[2] De Klein et al. (2006)

Table 44: Calculation of the nitrate emissions from cotton cultivation.

$NO3 = ((EF(tot3)*N(tot)) * (1-EF(N2O3))) * W(NO3)$

NO3	=	Leached nitrate emissions	
		GAP	CP
	=	250.81 kg per hectare	398.22 kg per hectare
EF(tot3)[1]	=	Emission factor for nitrates from total nitrogen fertilizer	
	=	0.3 kg NO3-N per kg N from fertilizer	
N(tot)	=	Amount of N applied per hectare from all nitrogen fertilizer	
		GAP	CP
	=	190.2 kg per hectare	303.1 kg per hectare
EF(N2O3)[2]	=	Emission factor for indirect nitrous oxides from leached nitrates	
	=	0.0075 kg N2O-N per kg N from NO3 emissions	
W(NO3)	=	Factor for multiplying NO3-N weight to NO3 weight	
	=	62/14	

[1] Mosier et al. (1998)

[2] De Klein et al. (2006)

Table 45: Calculation of the nitrous oxide emissions from cotton cultivation.

N2O = N2O(direct) + N2O(indirect)

N2O(direct) = (EF(tot2)*N(tot)) * W(N2O)

N2O(indirect) = (EF(N2O1)*N(NH3)) + (EF(N2O2)*N(NOx)) + (EF(N2O3)*N(NO3))

N2O	=	Total emissions of nitrous oxides	
		GAP	CP
	=	4.11 kg per hectare	6.48 kg per hectare
N2O(direct)	=	Direct nitrous oxide emissions	
		GAP	CP
	=	2.99 kg per hectare	4.76 kg per hectare
N2O(indirect)	=	Indirect nitrous oxide emissions	
		GAP	CP
	=	1.12 kg per hectare	1.72 kg per hectare
EF(tot2)[1]	=	Emission factor for nitrous oxides from total nitrogen fertilizer	
	=	0.01 kg N2O-N per kg N from fertilizer	
N(tot)	=	Amount of N applied per hectare from all nitrogen fertilizer	
	=	190.2 kg per hectare	
W(N2O)	=	Factor for multiplying N2O-N weight to N2O weight	
	=	44/28	
EF(N2O1)[1]	=	Emission factor for indirect nitrous oxides from ammonia emissions	
	=	0.01 kg N2O-N per kg N from NH3 emissions	
N(NH3)	=	Amount of nitrogen in NH3 emissions	
	=	NH3/(17/14)	
		GAP	CP
	=	23.69 kg per hectare	37.70 kg per hectare
EF(N2O2)[1]	=	Emission factor for indirect nitrous oxides from nitrogen oxide emissions	
	=	0.01 kg N2O-N per kg N from NOx emissions	
N(NOx)	=	Amount of nitrogen in NOx emissions	
	=	NOx/(30/14)*	
		GAP	CP
	=	4.95 kg per hectare	7.85 kg per hectare
EF(N2O3)[1]	=	Emission factor for indirect nitrous oxides from leached nitrates	
	=	0.0075 kg N2O-N per kg N from NO3 emissions	
N(NOx)	=	Amount of nitrogen in leached NO3	
	=	NO3/(62/14)	
		GAP	CP
	=	57.06 kg per hectare	90.60 kg per hectare

* For weight only NO is assumed.
[1] De Klein et al. (2006)

Table 46: Calculation of the phosphate emissions from cotton cultivation.

PO4 = PO4(leach) + PO4(runoff)

PO4(leach) = FE(PO4) * W(PO4)

PO4(runoff) = (AF * (1+(0.0025*P(tot)))) * W(PO4)

PO4	=	Total phosphate emissions
	=	0.86 kg per hectare
PO4(leach)	=	Phosphate emissions from leaching
	=	0.21 kg per hectare
PO4(runoff)	=	Phosphate emissions from field runoff
	=	0.65 kg per hectare
FE(PO4)[1]	=	Fixed emission estimate for arable land
	=	0.07 kg PO4-P per hectare
W(PO4)	=	Factor for multiplying PO4-P weight to PO4 weight
	=	95/31
AC[1]	=	Arable land constant
	=	0.175 kg PO4-P per hectare
P(tot)	=	Amount of P2O5 applied per hectare from all phosporus fertilizer
	=	84.7 kg per hectare

[1] Nemecek (2013)

Table 47: Calculation of the carbon dioxide emissions from cotton cultivation.

CO2 = EF(urea2) * N(urea) * W(CO2)

CO2	=	Emission of CO2 from urea fertilizer	
		GAP	CP
	=	165.8 kg per hectare	264.9 kg per hectare
EF(urea2)[1]	=	Emission factor of carbon from urea fertilizer	
	=	0.43 kg CO2-C per kg of urea-N	
N(urea)	=	Amount of N applied per hectare from urea fertilizer	
		GAP	CP
	=	105.5 kg per hectare	167.9 kg per hectare
W(CO2)	=	Factor for multiplying CO2-C weight to CO2 weight	
	=	44/12	

[1] De Klein et al. (2006)

Table 48: Calculation of the heavy metal emissions from cotton cultivation.

HMi = HMi(fert) - HMi(cot)

HMi(fert) = Σ(j) (MCji*TOTj)

HMi(cot) = ((MCFi*FY) + (MCSi*SY))

HMi	=	Net heavy metal i emission to soil (i = Cd, Cu, Zn, Pb, Ni, Cr)			
		GAP		CP	
For i	=	Cd: 4.2 g per ha		4.2 g per ha	
		Cu: 5.8 g per ha		8.4 g per ha	
		Zn: 37.5 g per ha		51.2 g per ha	
		Pb: 1.1 g per ha		1.7 g per ha	
		Ni: 3.4 g per ha		5.3 g per ha	
		Cr: 56.2 g per ha		57.1 g per ha	
HMi(fert)	=	Amount of heavy metal i added to the soil by fertilizers			
MCji[1]	=	Mean content of heavy metal i (mg per kg j) in j-fertilizer (j = N, P2O5, K2O)			
	=	i/j	N	P2O5	K2O
		Cd	0.21	51.32	0.11
		Cu	22.25	118.22	6.17
		Zn	121.43	751.32	70.33
		Pb	5.37	49.42	7.88
		Ni	17.17	100.46	7.52
		Cr	7.81	589.46	88.54
TOTj	=	Total amount of j-fertilizer			
			GAP	CP	
For j	=	N:	190.2 kg per ha	303.1 kg per ha	
		P2O5:	84.7 kg per ha	84.7 kg per ha	
		K2O:	84.7 kg per ha	84.7 kg per ha	
HMi(cot)	=	Amount of heavy metal i accumulated in cotton fibre and seed			
MCFi/MCSi[1,2]	=	Mean content for metal I in cotton fibre and cotton seed			
	=		Fibre (mg kg^{-1})	Seed (mg kg^{-1})	
		Cd	0.07	0.05	
		Cu	1.1	3.3	
		Zn	11.5	17.3	
		Pb	2.5	0.5	
		Ni*	2.44		
		Cr*	0.73		
FY/SY	=	Fibre/seed yield			
	=	1,486/2,203 kg per ha			

* *Specific values for cotton are only available for Cd, Cu, Zn and Pb (Angelova et al. 2004). Estimates for Ni and Cr were made by averaging heavy metal contents of grass, potatoes and soybeans as reported by Freiermuth (2006). These averages for Cd, Cu, Zn and Pb were in the correct order of magnitude so the estimate is assumed as solid.*

[1] Freiermuth (2006)

[2] Angelova et al. (2004)

Appendix 3.10 Output: pesticide emissions

Table 49: Comparison of assumed environmental fates of pesticides in cotton cultivation.

Pesticide emissions	Vapor pressure (mPa)	Fraction to air	Soil mobility	Fraction to soil[4]	Solubility (g l^{-1})	Fraction to water
Parathion[1]	5	0.50	none	0.50	negligible	0
Malathion[2]	16.6	0.95	high	0	0.145	0.05
Aldicarb[1]	10	0.50	high	0	9	0.50
Pyrethroid[2]	low	0.01	none	0.99	negligible	0
Acephate[2]	2.3	0.50	high	0	790	0.50
Organophosporus[3]	/	0.50	high	0.50	/	0
Trifluralin[1]	15	0.95	none	0.05	0.0024	0
Fluormeturon[1]	0.066	0.05	high	0	0.1	0.95
Glyphosate[2]	negligible	0.05	none	0.95	10	0
Prometryn[1]	0.16	0.15	low	0.85	0.033	0

[1] PMEP (2015)

[2] NPIC (2015)

[3] PIO (2015)

[4] Webb et al. (2013)

Table 50: Calculation of the pesticide emissions from cotton cultivation.

Emissions	Air (kg ha^{-1})	Water (kg ha^{-1})	Soil (kg ha^{-1})
Parathion	0.125	0	0.125
Malathion	2.0425	0.1075	0
Aldicarb	0.19	0.19	0
Pyrethroid	0.0025	0	0.2475
Acephate	0.24	0.24	0
Organophosporus	0.125	0	0.125
Trifluralin	0.475	0	0.025
Fluormeturon	0.0235	0.4465	0
Glyphosate	0.0675	0	1.2825
Prometryn	0.123	0	0.697

Appendix 3.11 Output: fuel use emissions

Table 51: Calculation of the emissions from fuel use in cotton cultivation.

FUEi = EFi * FU * W(fuel)				
FUEi	=	Emission from fuel use for component i		
EFi[1]	=	Emission factor for component i		
FU	=	Total on-farm fuel use		
	=	93.3 l per hectare		
W(fuel)	=	Weight of diesel		
	=	0.835 kg per liter		
for i	=	Component	EFi (mg kg^{-1})	FUEi (g ha^{-1})
		CO2	3,120,000	243,065
		SO2	1,010	78.68
		CH4	129	10.05
		C6H6	7.3	0.569
		Cu	1.7	0.132
		N2O	120	9.35
		Zn	1	0.078
		NH3	20	1.56
		Penanthene	2.5	0.195
		NOx	35,043	2,730
		PM	1,738	135.4
		NMVOC	3,366	262.2

[1] Nemecek & Kägi (2007) & Winther et al. (2013)

Appendix 4 LCI calculations for subsystem 1B

Appendix 4.1 Output: yield and allocation

Table 52: Comparison of hemp yields with distribution of fibre and shivs.

Source	Location	Total stem yield (t DM ha^{-1})	Fibre content (%)	Shivs content (%)
Amaducci et al. (2014)	*China*	6.6 - 10.9	/	/
Clarke 1(995)	*China*	8 - 12	/	/
Zheng et al. (2013)	*China*	/	22.3	/
Barth & Carus (2015)	*Europe*	7 - 9	28	55
Assumed	*Heilongjiang*	10	22	55

Table 53: Calculation of hemp yield in Heilongjiang province.

FY = TSY - RL - SY - SW

FY	=	Fibre yield after scutching
	=	2,200 kg per hectare
TSY	=	Total stem yield before retting and scutching
	=	10,000 kg per hectare
RL[1]	=	Retting loss of stem biomass
	=	0.1 * TSY
	=	1,000 kg per hectare
SY	=	Shivs yield after scutching
	=	5,500 kg per hectare
SW	=	Scutching waste
	=	1,300 kg per hectare

[1] Turunen & van der Werf (2006)

Table 54: Calculation of the economic allocation between hemp fibre and shivs.

EAi = ((Pi * Yi) / (Σ(i) (Pi * Yi))) * 100%

EAi	=	Economic allocation of environmental impact (i = fibre, seed)
For i	=	Fibre: 52.8%
	=	Shivs: 47.2%
Pi[1]	=	Market price of commodity i
For i	=	Fibre: EUR 0.70 per kg
	=	Shivs: EUR 0.25 per kg
Yi	=	Yield of commodity i
For i	=	Fibre: 2,200 kg per hectare
	=	Shivs: 5,500 kg per hectare

[1] Personal communication Martha Barth (March 27th 2015)

Appendix 4.2 Input: pesticides

Table 55: Calculation of the pesticide use in hemp cultivation.

AI = AR * C * D		
AI	=	Total amount of active ingredient metolachlor
	=	2,145 g per hectare
AR[1]	=	Application rate
	=	3 L per hectare
C[1]	=	Concentration of emulsion
	=	65% metolachlor per liter
D[2]	=	Density of metolachlor
	=	1.1 kg per liter

[1] Amaducci et al. (2014)

[2] NPIC (2015)

Appendix 4.3 Input: fertilizer

Table 56: Comparison of the fertilizer input in GAP and CP hemp cultivation scenarios.

Scenario	**Urea-N (kg ha^{-1})**	**P2O5 (kg ha^{-1})**	**K2O (kg ha^{-1})**
GAP[1]	*90*	100	80
CP[2]	*200*	75	150

[1] Song et al. (2012)

[2] Liu (2013)

Appendix 4.4 Input: seeds

Table 57: Calculation of the seed used in hemp cultivation.

IS = (SR / SY) * IHH		
IS	=	Impact of seed
	=	0.0485*IHH
SR[1]	=	Seed rate of fibre hemp
	=	80 kg per hectare
SY[2]	=	Average seed yield in China
	=	1,650 kg per hectare
IHH	=	Impact hectare hemp production
	=	Fertilizer, pesticide, fuel use and emissions from LCI

[1] Liu (2013)

[2] Yunnan Industrial Hemp (2015)

Appendix 4.5 Input: on-farm fuel use

Table 58: Calculation of the on-farm fuel use in hemp cultivation.

FU = Σ(i) (Ni * Ti * HFU * TAM)						
Ti = Area/width*V						
FU	=	Total fuel use				
	=	69.4 l per hectare				
Ni	=	Number of application of operation i				
Ti	=	Time needed per operation i				
		Operation[1]	N	Area (m^2)*	width (m)**	T (h)
		Tillage	2	10,000	0.5	8
		Sowing	1	10,000	0.5	8
		Fertilizing/ pesticide	3	10,000	1	4
		Harvesting	1	10,000	1	2.24
HFU[2]	=	Average hourly fuel use				
	=	2.04 l per hour				
TAM	=	Total average mechanization in Heilongjiang				
	=	0.85				

* *As opposed to cotton, all operations are applied to the entire field area.*

** *The with is an estimate from the width of a hand tractor and plough (Tractordata 2014). Fertilizing and pesticide application is assumed to have a wider spraying range.*

[1] Liu (2013)

[2] Tractordata (2014)

Appendix 4.6 Input: scutching

Table 59: Calculation of the electricity consumption of hemp scutching.

ECscutch = AEC * FY			
ECgin	=	Electricity consumption of scutching	
	=	3,146 MJ per hectare	
AEC	=	Average electricity consumption of scutching machines	
	=	Hungary[1]:	1.65 MJ per kg
	=	Spain[2]:	1.21 MJ per kg
	=	**Average:**	**1.43 MJ per kg**
FY	=	Fibre yield	
	=	2,200 kg per hectare	

[1] Turunen & van der Werf (2006)

[2] González-García et al. (2010)

Appendix 4.7 Output: fertilizer emissions

Table 60: Calculation of the NMVOC emissions from hemp cultivation.

NMVOC = FE(NMVOC)		
NMVOC	=	Emissions of non-methane volatile organic compounds
	=	0.86 kg per hectare
FE(NMVOC)	=	Fixed emission of NMVOC
	=	0.86 kg per hectare

[1] Hutchings et al. (2013)

Table 61: Calculation of the ammonia emissions from hemp cultivation.

NH3 = (((EF(urea1)*N(urea)) + (EF(com)*N(com))) * F(pH)) * (1-EF(N2O1))			
NH3	=	Emissions of ammonia	
		GAP	CP
	=	21.87 kg per hectare	48.11 kg per hectare
EF(urea1)[1]	=	Emission factor for ammonia from urea fertilizer (pH-independent)	
	=	0.243 kg NH3 per kg N from urea fertilizer	
N(urea)	=	Amount of N applied per hectare from urea fertilizer	
		GAP	CP
	=	90 kg per hectare	200 kg per hectare
EF(com)[1]	=	Emission factor for ammonia from compound fertilizer (pH-independent)	
	=	0.037 kg NH3 per kg N from compound fertilizer	
N(com)	=	Amount of N applied per hectare from compound fertilizer	
	=	0 kg per ha	
F(pH)[1]	=	pH-dependent factor from the tier 2 model	
	=	1 (because both EFs are pH-independent)	
EF(N2O1)[2]	=	Emission factor for indirect nitrous oxides from ammonia emissions	
	=	0.01	

[1] Hutchings et al. (2013)

[2] De Klein et al. (2006)

Table 62: Calculation of the nitric oxides emissions from hemp cultivation.

NOx = (EF(tot1)*N(tot)) * (1-EF(N2O2))			
NOx	=	Emissions of nitrogen oxides	
		GAP	CP
	=	4.96 kg per hectare	11.03 kg per hectare
EF(tot1)[1]	=	Emission factor for nitrogen oxides from total nitrogen fertilizer	
	=	0.026 kg NOx per kg N from fertilizer	
N(tot)	=	Amount of N applied per hectare from all nitrogen fertilizer	
		GAP	CP
	=	90 kg per hectare	200 kg per hectare
EF(N2O2)[2]	=	Emission factor for indirect nitrous oxides from nitrogen oxide emissions	
	=	0.01	

[1] Hutchings et al. (2013)

[2] De Klein et al. (2006)

Table 63: Calculation of the nitrous oxide emissions from hemp cultivation.

N2O = N2O(direct) + N2O(indirect)			
N2O(direct) = (EF(tot2)*N(tot)) * W(N2O)			
N2O(indirect) = (EF(N2O1)*N(NH3)) + (EF(N2O2)*N(NOx)) + (EF(N2O3)*N(NO3))			
N2O	=	Total emissions of nitrous oxides	
		GAP	CP
	=	2.05 kg per hectare	4.56 kg per hectare
N2O(direct)	=	Direct nitrous oxide emissions	
		GAP	CP
	=	1.41 kg per hectare	3.14 kg per hectare
N2O(indirect)	=	Indirect nitrous oxide emissions	
		GAP	CP
	=	0.64 kg per hectare	1.42 kg per hectare
EF(tot2)[1]	=	Emission factor for nitrous oxides from total nitrogen fertilizer	
	=	0.01 kg N2O-N per kg N from fertilizer	
N(tot)	=	Amount of N applied per hectare from all nitrogen fertilizer	
	=	190.2 kg per hectare	
W(N2O)	=	Factor for multiplying N2O-N weight to N2O weight	
	=	44/28	
EF(N2O1)[1]	=	Emission factor for indirect nitrous oxides from ammonia emissions	
	=	0.01 kg N2O-N per kg N from NH3 emissions	
N(NH3)	=	Amount of nitrogen in NH3 emissions	
	=	NH3/(17/14)	
		GAP	CP
	=	18.01 kg per hectare	40.02 kg per hectare
EF(N2O2)[1]	=	Emission factor for indirect nitrous oxides from nitrogen oxide emissions	
	=	0.01 kg N2O-N per kg N from NOx emissions	
N(NOx)	=	Amount of nitrogen in NOx emissions	
	=	NOx/(30/14)*	
		GAP	CP
	=	2.34 kg per hectare	5.20 kg per hectare
EF(N2O3)[1]	=	Emission factor for indirect nitrous oxides from leached nitrates	
	=	0.0075 kg N2O-N per kg N from NO3 emissions	
N(NOx)	=	Amount of nitrogen in leached NO3	
	=	NO3/(62/14)	
		GAP	CP
	=	27.00 kg per hectare	59.55 kg per hectare

* For weight only NO is assumed.
[1] De Klein et al. (2006)

Table 64: Calculation of the nitrate emissions from hemp cultivation.

NO3 = ((EF(tot3)*N(tot)) * (1-EF(N2O3))) * W(NO3)			
NO3	=	Leached nitrate emissions	
		GAP	CP
	=	118.67 kg per hectare	263.72 kg per hectare
EF(tot3)[1]	=	Emission factor for nitrates from total nitrogen fertilizer	
	=	0.3 kg NO3-N per kg N from fertilizer	
N(tot)	=	Amount of N applied per hectare from all nitrogen fertilizer	
		GAP	CP
	=	90 kg per hectare	200 kg per hectare
EF(N2O3)[2]	=	Emission factor for indirect nitrous oxides from leached nitrates	
	=	0.0075 kg N2O-N per kg N from NO3 emissions	
W(NO3)	=	Factor for multiplying NO3-N weight to NO3 weight	
	=	62/14	

[1] Mosier et al. (1998)

[2] De Klein et al. (2006)

Table 65: Calculation of the phosphate emissions from hemp cultivation.

PO4 = PO4(leach) + PO4(runoff) **PO4(leach) = FE(PO4) * W(PO4)** **PO4(runoff) = (AF * (1+(0.0025*P(tot)))) * W(PO4)**			
PO4	=	Total phosphate emissions	
		GAP	CP
	=	0.88 kg per hectare	0.85 kg per hectare
PO4(leach)	=	Phosphate emissions from leaching	
		GAP	CP
	=	0.21 kg per hectare	0.21 kg per hectare
PO4(runoff)	=	Phosphate emissions from field runoff	
		GAP	CP
	=	0.67 kg per hectare	0.64
FE(PO4)[1]	=	Fixed emission estimate for arable land	
	=	0.07 kg PO4-P per hectare	
W(PO4)	=	Factor for multiplying PO4-P weight to PO4 weight	
	=	95/31	
AC[1]	=	Arable land constant	
	=	0.175 kg PO4-P per hectare	
P(tot)	=	Amount of P2O5 applied per hectare from all phosporus fertilizer	
		GAP	CP
	=	100 kg per hectare	75 kg per hectare

[1] Nemecek (2013)

Table 66: Calculation of the carbon dioxide emissions from hemp cultivation.

CO2 = EF(urea2) * N(urea) * W(CO2)			
CO2	=	Emission of CO2 from urea fertilizer	
		GAP	CP
	=	141.9 kg per hectare	315.3 kg per hectare
EF(urea2)[1]	=	Emission factor of carbon from urea fertilizer	
	=	0.43 kg CO2-C per kg of urea-N	
N(urea)	=	Amount of N applied per hectare from urea fertilizer	
		GAP	CP
	=	90 kg per hectare	200 kg per hectare
W(CO2)	=	Factor for multiplying CO2-C weight to CO2 weight	
	=	44/12	

[1] De Klein et al. (2006)

Table 67: Calculation of the heavy metal emissions from hemp cultivation.

HMi = HMi(fert) - HMi(cot)					
HMi(fert) = Σ(j) (MCji * TOTj)					
HMi(cot) = ((MCFi*FY) + (MCSi*SY))					
HMi	=	Net heavy metal i emission to soil (i = Cd, Cu, Zn, Pb, Ni, Cr)			
		GAP		CP	
For i	=	Cd: 2.3 g per ha		1 g per ha	
		Cu: -14.3 g per ha		-14.4 g per ha	
		Zn: -10.2 g per ha		-10.7 g per ha	
		Pb: -17.3 g per ha		-17.4 g per ha	
		Ni: -12.2 g per ha		-12.3 g per ha	
		Cr: 59.4 g per ha		51.8 g per ha	
HMi(fert)	=	Amount of heavy metal i added to the soil by fertilizers			
MCji[1]	=	Mean content of heavy metal i (mg per kg j) in j-fertilizer (j = N, P2O5, K2O)			
	=	i/j	N	P2O5	K2O
		Cd	0.21	51.32	0.11
		Cu	22.25	118.22	6.17
		Zn	121.43	751.32	70.33
		Pb	5.37	49.42	7.88
		Ni	17.17	100.46	7.52
		Cr	7.81	589.46	88.54
TOTj	=	Total amount of j-fertilizer			
			GAP	CP	
For j	=	N:	90 kg per ha	200 kg per ha	
		P2O5:	100 kg per ha	75 kg per ha	
		K2O:	80 kg per ha	150 kg per ha	
HMi(cot)	=	Amount of heavy metal i accumulated in hemp fibre and residual stem			
MCFi/MCSi[1,2]	=	Mean content for metal I in hemp fibre and residual stem			
	=		Fibre ($mg\ kg^{-1}$)	Stems ($mg\ kg^{-1}$)	
		Cd	0.15	0.33	
		Cu	1.3	3.3	
		Zn	1.3	12.7	
		Pb	2.1	2.4	
		Ni*	2.44		
		Cr*	0.73		
FY/SY	=	Fibre/residual stem yield			
	=	2,200/7,800 kg per ha			

* *Specific values for cotton are only available for Cd, Cu, Zn and Pb (Angelova et al. 2004). Estimates for Ni and Cr were made by averaging heavy metal contents of grass, potatoes and soybeans as reported by Freiermuth (2006). These averages for Cd, Cu, Zn and Pb were in the correct order of magnitude so the estimate is assumed as solid.*

[1] Freiermuth (2006)

[2] Angelova et al. (2004)

Appendix 4.8 Output: pesticide emissions

Table 68: Comparison of assumed environmental fates of pesticides in hemp cultivation.

Pesticide emissions	Vapor pressure (mPa)	Fraction to air	Soil mobility	Fraction to soil[4]	Solubility ($g\ l^{-1}$)	Fraction to water
Metolachlor[1]	1.73	0.50	high	0	0.53	0.5

[1] (NPIC 2015)

Table 69: Emissions from pesticides in hemp cultivation.

Emissions	Air ($kg\ ha^{-1}$)	Water ($kg\ ha^{-1}$)	Soil ($kg\ ha^{-1}$)
Metolachlor	1.073	1.073	0

Appendix 4.9 Output: fuel use emissions

Table 70: Calculation of emissions from fuel use in hemp cultivation.

FUEi = EFi * FU * W(fuel)

FUEi	=	Emission from fuel use for component i		
EFi[1]	=	Emission factor for component i		
FU	=	Total on-farm fuel use		
	=	69.4 l per hectare		
W(fuel)	=	Weight of diesel		
	=	0.835 kg per liter		
for i	=	Component	EFi ($mg\ kg^{-1}$)	FUEi ($g\ ha^{-1}$)
		CO2	3,120,000	180,696
		SO2	1,010	58.94
		CH4	129	7.47
		C6H6	7.3	0.423
		Cu	1.7	0.098
		N2O	120	6.95
		Zn	1	0.058
		NH3	20	1.16
		Penanthene	2.5	0.145
		NOx	35,043	2,029.5
		PM	1,738	100.7
		NMVOC	3,366	194.9

[1] Nemecek & Kägi (2007) & Winther et al. (2013)

Appendix 4.10 Output: retting emissions

Table 71: Calculation of the nitrogen emissions from hemp retting.

REi = RL * NC * EFi		
REi	=	Emissions from retting (i = N2O, NH3 and NOx)
For i	=	N2O: 448 g per hectare
	=	NH3: 950 g per hectare
	=	NOx: 988 g per hectare
RL	=	Retting loss of stem biomass
	=	1,000 kg per hectare
NC[1]	=	Average N-content of hemp plant material
	=	0.0095 kg N per kg hemp stem
EFi[2,3]	=	Emission factor for N from decomposing organic matter (most conservative)
For i	=	N2O: 0.047 kg N2O per kg N
	=	NH3: 0.1 kg NH3 per kg N
	=	NOx: 0.104 kg NOx per kg N

[1] Liu (2013)
[2] De Klein et al. (2006)
[3] Hutchings et al. (2013)

Appendix 5 LCI of subsystem 1A and 1B

Appendix 5.1 LCI of subsystem 1A: Cotton scenario

Table 72: LCI of two scenarios for one hectare cotton production.

Type	Category	Compound	Quantity*: GAP	CP	Unit	Comp.**
Ouptut	Product	Ginned cotton lint	1,486		kg	
Output	By-product	Ginned cottonseed	2,203		kg	
Output	Waste	Ginning waste	154		kg	Waste
Input	Insecticide	Parathion (OP)	0.25		kg	
Input	Insecticide	Malathion (OP)	2.15		kg	
Input	Insecticide	Aldicarb (C)	0.38		kg	
Input	Insecticide	Pyrethroid (P)	0.25		kg	
Input	Insecticide	Acephate (OP)	0.48		kg	
Input	Insecticide	Organophosphorus (OP)	0.25		kg	
Input	Herbicide	Trifluralin (DNA)	0.50		kg	
Input	Herbicide	Fluormetron (PU)	0.47		kg	
Input	Herbicide	Glyphosate	1.35		kg	
Input	Herbicide	Prometryn (T)	0.82		kg	
Input	Fertilizer	N from ammonium in compound fertilizer	84.7	133.7	kg	
Input	Fertilizer	N from urea fertilizer	105.5	167.8	kg	
Input	Fertilizer	P2O5 from compound fertilizer	84.7	84.7	kg	
Input	Fertilizer	K2O from compound fertilizer	84.7	84.7	kg	
Input	Irrigation	Pumping of irrigation water	1,512		m^3	
Input	Seed	Cotton seed for sowing	35.8		kg	
Input	Mulching	Low-density polyethylene mulch	41.3		kg	
Input	Fuel use	On-farm fuel use	93.3		l	
Input	Ginning	Electricity consumption	2,095.3		MJ	
Input	Ginning	Heating energy from natural gas	681.5		MJ	
Output	Fertilizer	Non-methane volatile organic compounds	0.86	0.86	kg	Air
Output	Fertilizer	Ammonia	28.48	45.32	kg	Air
Output	Fertilizer	Nitrogen oxides	10.49	16.66	kg	Air
Output	Fertilizer	Nitrous oxides	4.11	6.48	kg	Air
Output	Fertilizer	Nitrates	250.81	398.22	kg	Water
Output	Fertilizer	Phosphates	0.86	0.86	kg	Water
Output	Fertilizer	Carbon dioxide	165.80	264.88	kg	Air
Output	Fertilizer	Cadmium	4.2	4.2	g	Soil
Output	Fertilizer	Copper	6.0	8.4	g	Soil
Output	Fertilizer	Zinc	37.5	51.2	g	Soil
Output	Fertilizer	Lead	1.0	1.7	g	Soil
Output	Fertilizer	Nickel	3.4	5.3	g	Soil
Output	Fertilizer	Chrome	56.2	57.1	g	Soil
Output	Insecticide	Parathion (OP)	125		g	Air
Output	Insecticide	Parathion (OP)	125		g	Soil
Output	Insecticide	Malathion (OP)	2,043		g	Air
Output	Insecticide	Malathion (OP)	108		g	Water
Output	Insecticide	Aldicarb (C)	190		g	Air
Output	Insecticide	Aldicarb (C)	190		g	Water
Output	Insecticide	Pyrethroid (P)	2.5		g	Air
Output	Insecticide	Pyrethroid (P)	248		g	Soil
Output	Insecticide	Acephate (OP)	240		g	Air
Output	Insecticide	Acephate (OP)	240		g	Water
Output	Insecticide	Organophosphorus (OP)	125		g	Air
Output	Insecticide	Organophosphorus (OP)	125		g	Soil
Output	Herbicide	Trifluralin (DNA)	475		g	Air
Output	Herbicide	Trifluralin (DNA)	25		g	Soil
Output	Herbicide	Fluormeturon (PU)	34		g	Air
Output	Herbicide	Fluormeturon (PU)	447		g	Water
Output	Herbicide	Glyphosate	68		g	Air
Output	Herbicide	Glyphosate	1,283		g	Soil
Output	Herbicide	Prometryn (T)	123		g	Air
Output	Herbicide	Prometryn (T)	697		g	Soil
Output	Fuel use	Carbon dioxide	243.1		kg	Air
Output	Fuel use	Sulfur dioxide	78.68		g	Air
Output	Fuel use	Methane	10.05		g	Air
Output	Fuel use	Benzene	0.569		g	Air
Output	Fuel use	Nitrous oxide	9.35		g	Air
Output	Fuel use	Zinc	0.078		g	Air

Output	Fuel use	Ammonia	1.56		g	Air
Output	Fuel use	Penanthene	0.195		g	Air
Output	Fuel use	Nitrogens oxids	2,730		g	Air
Output	Fuel use	Particulate matter	135.4		g	Air
Output	Fuel use	Non-methane volatile organic compounds	262.2		g	Air

* Table contains LCI before economic allocation between cotton fibre and seed.
** Comp. = Compartment

Appendix 5.2 LCI of subsystem 1B: Hemp scenario

Table 73: LCI of two scenarios for one hectare hemp production.

Type	Category	Compound	Quantity*: GAP	CP	Unit	Comp.
Ouptut	Product	Scutched hemp fibre	2,200		kg	
Output	By-product	Hemp shivs	5,500		kg	
Output	Waste	Scutching waste	1,300		kg	Waste
Input	Herbicide	Metolachlor	2.15		kg	
Input	Fertilizer	N from urea fertilizer	90	200	kg	
Input	Fertilizer	P2O5 from compound fertilizer	100	75	kg	
Input	Fertilizer	K2O from compound fertilizer	80	150	kg	
Input	Seed	Hemp seed for sowing	80		kg	
Input	Fuel use	On-farm fuel use	69.4		l	
Input	Scutching	Electricity consumption	3,146		MJ	
Output	Fertilizer	Non-methane volatile organic compounds	0.86	0.86	kg	Air
Output	Fertilizer	Ammonia	21.65	48.11	kg	Air
Output	Fertilizer	Nitrogen oxides	4.96	11.03	kg	Air
Output	Fertilizer	Nitrous oxide	2.05	4.56	kg	Air
Output	Fertilizer	Nitrates	118.67	263.72	kg	Water
Output	Fertilizer	Phosphates	0.88	0.85	kg	Water
Output	Fertilizer	Carbon dioxide	141.9	315.3	kg	Air
Output	Fertilizer	Cadmium	2.3	1.0	g	Soil
Output	Fertilizer	Copper	-14.3	-14.4	g	Soil
Output	Fertilizer	Zinc	-10.2	-10.7	g	Soil
Output	Fertilizer	Lead	-17.3	-17.4	g	Soil
Output	Fertilizer	Nickel	-12.2	-12.3	g	Soil
Output	Fertilizer	Chrome	59.4	51.8	g	Soil
Output	Herbicide	Metolachlor	1,073		g	Air
Output	Herbicide	Metolachlor	1,073		g	Water
Output	Fuel use	Carbon dioxide	180.7		kg	Air
Output	Fuel use	Sulfur dioxide	58.49		g	Air
Output	Fuel use	Methane	7.47		g	Air
Output	Fuel use	Benzene	0.423		g	Air
Output	Fuel use	Nitrous oxide	6.95		g	Air
Output	Fuel use	Zinc	0.058		g	Air
Output	Fuel use	Ammonia	1.16		g	Air
Output	Fuel use	Penanthene	0.145		g	Air
Output	Fuel use	Nitrogen oxides	2,029.5		g	Air
Output	Fuel use	Particulate matter	100.7		g	Air
Output	Fuel use	Non-methane volatile organic compounds	194.9		g	Air
Output	Scutching	Nitrous oxide	448		g	Air
Output	Scutching	Ammonia	950		g	Air
Output	Scutching	Nitrogen oxides	988		g	Air

* Table contains LCI before economic allocation between hemp fibre and shivs.
** Comp. = Compartment

Appendix 6 Data quality assessment

Appendix 6.1 Quality of hemp LCI data

Table 74: Summary of the uncertainty ranking of the data in the hemp LCI.

Phase	Data	Source	Uncertainty
Cultivation	Yield	Secondary Literature-based estimate	Medium
	Economic allocation	Secondary Expert communication	Medium
	Pesticide production	Secondary Literature	Low
	Fertilizer production	Secondary Literature	Medium
	Seed	Secondary Literature average	Low
	Fuel use	Secondary Literature-based estimate	High
	Scutching	Secondary Literature	Medium
	Pesticide emissions	Secondary Literature and expert communication	High
	Fertilizer emissions	Secondary Literature	Medium
	Fuel emissions	Secondary Literature	Low
Spinning and weaving	Degumming agents	Primary Chinese textile manufacturer[1]	Medium
	Degumming emissions	Secondary Expert communication	High
	Energy	Primary Chinese textile manufacturer[1]	High
	Material efficiency	Primary Chinese textile manufacturer[1]	High
	Sizing agent	Primary Chinese textile manufacturer[1]	Medium

[1] The manufacturer wishes for remain anonymous

Appendix 6.2 Quality of cotton LCI data

Table 75: Summary of the uncertainty ranking of the data in the cotton LCI.

Phase	Data	Type	Uncertainty
Cultivation	Yield	Secondary Databases and literature	Low
	Economic allocation	Secondary Databases	Low
	Pesticide production	Secondary LCI and database	Medium
	Fertilizer production	Secondary Literature	Low
	Irrigation	Secondary Literature-based estimate	Medium
	Seed	Secondary Literature average	Medium
	Mulching	Secondary Literature and expert communication	Low
	Fuel use	Secondary Literature-based estimate	High
	Ginning	Secondary Literature	Low
	Pesticide emissions	Secondary Literature and expert communication	High
	Fertilizer emissions	Secondary Literature	Medium
	Fuel emissions	Secondary Literature	Low
Spinning and weaving	Energy	Secondary Literature-based estimate	High
	Material efficiency	Secondary Literature	Low
	Sizing agent	Primary Chinese textile manufacturer	Medium

[1] The manufacturer wishes for remain anonymous

Appendix 7 LCI calculations for subsystem 2 R

Appendix 7.1 Inputs and outputs of spinning process

Table 76: Calculation of the electricity consumption in cotton yarn spinning.

EC(spin) = F(cn/eu) * EC(eus)		
EC(eus) = 0.3627 * YC + 0.0427		
EC(spin)	=	Electricity consumption in fibre preparation and spinning process of 36 Nm yarn
	=	24 MJ per kg yarn
F(cn/eu)	=	Factor for correcting European EU to Chinese EU in textile industry
	=	2.97/1.62
	=	1.83
EC(eus)[1]	=	European electricity consumption benchmark for spinning of 36 Nm yarn
	=	13.1 MJ per kg yarn
YC	=	Yarn count
	=	36 Nm
[1] Van Der Velden et al. (2014)		

Table 77: Calculation of the material flows in cotton yarn spinning.

YO = FI * ME(prep) * ME(spin)		
YO = FI - W		
YO	=	Yarn output of spinning
	=	1 kg
FI	=	Fibre input in the form of ginned cotton fibre
	=	1.182 kg
ME(prep)[1]	=	Material efficiency during fibre preparation
	=	94%
ME(spin)[1]	=	Material efficiency during yarn spinning
	=	90%
W	=	Fibre waste
	=	0.182 kg
[1] Blackburn & Payne (2004)		

Appendix 7.2 Outputs of sizing process

Table 78: Calculation of the COD removed in treatment and emitted from cotton sizing.

COD(tot) = CODC(st) * SC		
COD(tot) = COD(treat) + COD(env)		
COD(tot)	=	Total COD in wastewater
	=	90 g per kg yarn
CODC(st)[1]	=	COD-content for starch
	=	1 g per g
SC	=	Starch consumption
	=	90 g per kg yarn
COD(treat)[2]	=	COD removed by treatment
	=	82.8 g per kg yarn
COD(env)	=	COD not removed and emitted to environment
	=	7.2 g per kg yarn

[1] IPPC (2003)
[2] Yuan et al. (2013)

Appendix 7.3 Inputs and outputs of weaving process

Table 79 Calculation of the electricity consumption in cotton fabric weaving.

EC(we) = F(cn/eu) * EC(euw)		
EC(euw) = 0.5328 * YC – 0.0311		
EC(we)	=	Electricity consumption in sizing and weaving process of 36 Nm yarn
	=	35 MJ per kg fabric
F(cn/eu)	=	Factor for correcting European EU to Chinese EU in textile industry
	=	1.83
EC(euw)[1]	=	European electricity consumption benchmark for weaving of 36 Nm yarn
	=	19.1 MJ per kg yarn
YC	=	Yarn count
	=	36 Nm

[1] Van Der Velden et al. (2014)

Table 80: Calculation of the material flows in cotton fabric weaving.

FO = YI * ME(we) **FO = YI(weft) + YI(warp) - W**		
FO	=	Fabric output of weaving
	=	1 kg
YI(weft)	=	Yarn input of weft yarn
	=	0.5 kg per kg fabric
YI(warp)	=	Yarn input of warp yarn
	=	0.57 kg per kg fabric
ME(we)[1]	=	Material efficiency during weaving
	=	94%
W	=	Fibre waste
	=	0.07 kg

[1] ITMF (2012)

Appendix 8
LCI calculations for subsystem 2 A, B and C

Appendix 8.1 Material efficiencies

Table 81: Calculation of the material flow in the spinning process of scenario A.

W = FI - SFO + LFO **SFO = HC / ME(spin)**		
W	=	Waste from carding process
	=	0.059 kg per kg yarn
FI	=	Degummed fibre input in carding process*
	=	0.849 kg per kg yarn
SFO	=	Short fibre output of carding process
	=	0.594 kg per kg yarn
LFO	=	Long fibre output of carding process**
	=	0.33 * SFO
	=	0.196 kg per kg yarn
HC	=	Hemp content of scenario A yarn
	=	0.550 kg per kg yarn
ME(spin)	=	Material efficiency of spinning process
	=	92.5%

* The textile mill uses 849 grams of degummed hemp fibre per kg blended yarn.
** This ratio of 1/3 LFO/SFO is provided as well.

Table 82: Calculation of the material efficiency in the hemp carding process in scenario A and B.

ME(cardAB) = (FI-W) / FI * 100%		
ME(cardAB)	=	Material efficiency of carding in scenario A and B
	=	93%
W	=	Waste from carding process
	=	0.196 kg per kg yarn
FI	=	Degummed fibre input in carding process
	=	0.849 kg per kg yarn

Table 83: Calculation of the material flow in the spinning process of scenario C.

W = FI - SO + TO **SO = HY / ME(spin) / ME(bleach)**		
FI	=	Scutched fibre input in carding process*
	=	3.3 kg per kg yarn
SO	=	Sliver output of carding process
	=	1.44 kg per kg yarn
TO	=	Tow output of carding process**
	=	0.5 * FI
	=	1.65 kg per kg yarn
W	=	Waste from carding process
	=	0.21 kg per kg yarn
HY	=	Amount of hemp yarn
	=	1 kg
ME(spin)	=	Material efficiency of spinning process
	=	92.5%
ME(bleach)	=	Material efficiency of bleaching process
	=	75%

* The textile mill used 3.3 kg scutched hemp fibre per kg scenario C yarn.
** The tow output is provided by the mill as well.

Table 84: Calculation of the material efficiency in the hemp carding process in scenario C.

ME(cardC) = (FI-W) / FI * 100%		
ME(cardAB)	=	Material efficiency of carding in scenario A and B
	=	94%
W	=	Waste from carding process
	=	0.21 kg per kg yarn
FI	=	Scutched fibre input in carding process
	=	3.3 kg per kg yarn

Appendix 8.2 Inputs and outputs of degumming or bleaching process

Table 85: Calculation of the heating energy used in hemp degumming and bleaching.

HE = (ΔT * M(water) * C) * (1 + LF)

HE	=	Heating energy from burning coal	
		Scenario A, B	Scenario C
	=	17.3 MJ per kg degummed fibre	10.4 MJ per kg bleached fibre
ΔT[1]	=	Water temperature difference of before and after heating*	
	=	75°C	
M(water)	=	Mass of water being heated	
		Scenario A, B	Scenario C
	=	50 kg	30 kg
C	=	Specific heat capacity of water	
	=	4.2 kJ $(kg\ K)^{-1}$	
LF	=	Loss factor accounting for heating inefficiencies	
	=	0.1	

* A starting temperature of 15°C is assumed.
[1] Turunen & van der Werf (2006)

Table 86: Calculation of the material flow in hemp degumming and bleaching.

FO = FI * ME(proc)
FO = FI - W

FO	=	Fibre ouput from degumming/bleaching process	
	=	1 kg	
FI	=	Scutched fibre input in degumming/bleaching process	
		Scenario A, B	Scenario C
	=	1.67 kg	1.33 kg
ME(degum)	=	Material efficiency of degumming/bleaching process	
		Scenario A, B	Scenario C
	=	60%	75%
W	=	Waste from degumming process dissolved in degumming/bleaching liquor	
		Scenario A, B	Scenario C
	=	0.67 kg	0.33 kg

Table 87: Calculation of the COD removed in treatment and emitted from the degumming.

COD(tot) = CODC(W) * W **COD(tot) = COD(treat) + COD(env)**			
COD(tot)	=	Total COD in wastewater	
		Scenario A, B	Scenario C
	=	0.67 kg per kg degummed fibres	0.33 kg per kg degummed fibres
CODC(W)[1]	=	COD-content for degummed organic waste material	
	=	1 g per g	
W	=	Organic waste from degumming process dissolved in degumming liquor	
		Scenario A, B	Scenario C
	=	0.67 kg per kg degummed fibres	0.33 kg per kg degummed fibres
COD(treat)	=	COD removed by treatment	
	=	92% * COD(tot)	
		Scenario A, B	Scenario C
	=	0.615 kg per kg yarn	0.306 kg per kg yarn
COD(env)	=	COD not removed and emitted to environment	
		Scenario A, B	Scenario C
	=	0.053 g per kg yarn	0.027 kg per kg yarn

[1] Assumption that results from a discussion with water treatment experts Bart Van der Bruggen and Ilse Smets.

Appendix 8.3 Economic allocation in carding

Table 88: Calculation of the economic allocation of the hemp carding process.

EAi = ((Pi * Yi) / (Σ(i) (Pi * Yi))) * 100%				
EAi		=	Economic allocation of environmental impact (i = short, long fibre/sliver, tow)	
			Scenario A, B	Scenario C
	For i	=	Short: 75%	Sliver: 65.2%
		=	Long: 25%	Tow: 34.8%
Pi[1]		=	Market price of commodity i	
			Scenario A, B	Scenario C
	For i	=	/	Sliver: EUR 0.75 per kg
		=	/	Tow: EUR 0.35 per kg
Yi		=	Process yield of commodity i	
			Scenario A, B	Scenario C
	For i	=	Short: 0.75 kg per kg output	Sliver: 0.53 kg per kg output
		=	Long: 0.25 kg per kg output	Tow: 0.47 kg per kg output

[1] Personal communication Martha Barth (March 27th 2015)

Appendix 8.4 Outputs of sizing process

Table 89: Calculation of the COD removed in treatment and emitted from sizing wastewater.

COD(tot) = CODC(st) * SC **COD(tot) = COD(treat) + COD(env)**		
COD(tot)	=	Total COD in wastewater
	=	80 g per kg yarn
CODC(st)[1]	=	COD-content for starch
	=	1 g per g
SC	=	Starch consumption
	=	80 g per kg yarn
COD(treat)	=	COD removed by treatment
	=	92% * COD(tot)
	=	73.6 g per kg yarn
COD(env)	=	COD not removed and emitted to environment
	=	6.4 g per kg yarn

[1] (IPPC 2003)

Appendix 8.5 Inputs of weaving process

Table 90: Calculation of the electricity consumption in weaving in scenario A, B and C.

EC(kg) = EC(m) / WI / W(fabric)				
EC(kg)	=	Electricity consumption per kg		
		Scenario A	Scenario B	Scenario C
	=	31.35 MJ	17.56 MJ	49.98 MJ
EC(m)	=	Electricity consumption per kg		
		Scenario A	Scenario B	Scenario C
	=	6.12 MJ	5.76 MJ	9.72 MJ
WI	=	Width of the fabric		
	=	1.6 m		
W(fabric)	=	Weight of the fabric		
		Scenario A	Scenario B	Scenario C
	=	0.122 kg per m^2	0.205 kg per m^2	0.117 kg per m^2

Appendix 9 Output ReCiPe modeling from Simapro

Appendix 9.1 Fibre production scenarios

Table 91: Characterization output from Simapro of 1 kg scutched hemp fibre in the CP scenario.

Impact category	Unit	Total	Fertilizer production	Fertilizer emissions	Pesticide production	Pesticide emissions	Hempseed	Fuel use	Scutching	Retting emissions
CC	kg CO_2-eq	0.969230243	0.219230348	0.403325182	0.004881627	0	0.032935189	0.05185111	0.224844461	0.032162327
		100%	23%	42%	1%	0%	3%	5%	23%	3%
TA	kg SO_2-eq	0.036019679	0.001703916	0.029883881	0.000156001	0	0.001542046	6.08946E-05	0.001978934	0.000694006
		100%	5%	83%	0%	0%	4%	0%	5%	2%
FE	kg P-eq	0.000183396	7.76841E-05	6.76545E-05	1.51268E-06	0	7.14085E-06	4.28868E-07	2.89752E-05	0
		100%	42%	37%	1%	0%	4%	0%	16%	0%
ME	kg N-eq	0.016690809	7.14955E-05	0.01578241	2.12623E-06	0	0.000768841	1.31597E-06	3.42826E-05	3.03382E-05
		100%	0%	95%	0%	0%	5%	0%	0%	0%
HT	kg 1,4-DB-eq	0.163381438	0.107378705	0.019234534	0.001831498	0.000677201	0.006291676	0.000643877	0.027323946	0
		100%	66%	12%	1%	0%	4%	0%	17%	0%
PMF	kg PM_{10}-eq	0.005899269	0.000573976	0.004293434	3.51353E-05	0	0.000238528	1.70936E-05	0.000615502	0.0001256
		100%	10%	73%	1%	0%	4%	0%	10%	2%
TET	kg 1,4-DB-eq	0.000392729	6.26869E-05	-2.68685E-05	8.63521E-07	0.00033256	1.79618E-05	1.2213E-06	4.30391E-06	0
		100%	16%	-7%	0%	85%	5%	0%	1%	0%
FET	kg 1,4-DB-eq	0.032647738	0.002904104	-4.46857E-06	0.000226475	0.027447176	0.001483199	1.76976E-05	0.000573554	0
		100%	9%	0%	1%	84%	5%	0%	2%	0%
MET	kg 1,4-DB-eq	0.005484846	0.002810302	-2.42153E-06	4.77599E-05	0.00178718	0.000227316	4.55754E-05	0.000569134	0
		100%	51%	0%	1%	33%	4%	1%	10%	0%

Table 92: Characterization output from Simapro of 1 kg ginned cotton fibre in the CP scenario.

Impact category	Unit	Total	Fertilizer production	Fertilizer emissions	Pesticide production	Pesticide emissions	Cotton seed	Irrigation	Plastic mulch	Fuel use	Ginning
CC	kg CO_2-eq	3.1532	1.184524927	1.0521596	0.032596517	0	0.013329337	0.3473927	0.059353617	0.140035	0.323888703
		100%	38%	33%	1%	0%	0%	11%	2%	4%	10%
TA	kg SO_2-eq	0.0706	0.007012216	0.0576708	0.000267334	0	0.000142205	0.0024572	0.000235281	0.000170	0.002663752
		100%	10%	82%	0%	0%	0%	3%	0%	0%	4%
FE	kg P-eq	0.0005	0.000266182	0.0001367	3.87108E-05	0	4.88928E-06	7.601E-05	6.09509E-06	1.21E-06	4.00913E-05
		100%	47%	24%	7%	0%	1%	13%	1%	0%	7%
ME	kg N-eq	0.0468	0.000408568	0.0461914	3.05669E-05	0	5.47196E-05	5.912E-05	6.7218E-06	3.73E-06	4.64224E-05
		100%	1%	99%	0%	0%	0%	0%	0%	0%	0%
HT	kg 1,4-DB-eq	1.0635	0.41387486	0.2029386	0.015954393	0.29017223	0.004263269	0.0915378	0.005104164	0.001829	0.037901611
		100%	39%	19%	2%	27%	0%	9%	0%	0%	4%
PMF	kg PM_{10}-eq	0.0127	0.002096586	0.0087047	8.65126E-05	0	3.68758E-05	0.0009003	8.22963E-05	4.80E-05	0.00082967
		100%	16%	68%	1%	0%	0%	7%	1%	0%	6%
TET	kg 1,4-DB-eq	0.0053	0.000727742	7.071E-05	1.01845E-05	0.003736295	0.00074685	1.491E-05	1.47579E-06	3.33E-06	6.03441E-06
		100%	14%	1%	0%	70%	14%	0%	0%	0%	0%
FET	kg 1,4-DB-eq	0.0523	0.011054093	6.052E-06	0.000394559	0.037359928	0.000232836	0.0022112	0.000187488	5.03E-05	0.000802375
		100%	21%	0%	1%	71%	0%	4%	0%	0%	2%
MET	kg 1,4-DB-eq	0.0169	0.010999804	3.109E-06	0.000383226	0.002154418	0.000100639	0.0022135	0.000169358	0.000128	0.000796925
		100%	65%	0%	2%	13%	1%	13%	1%	1%	5%

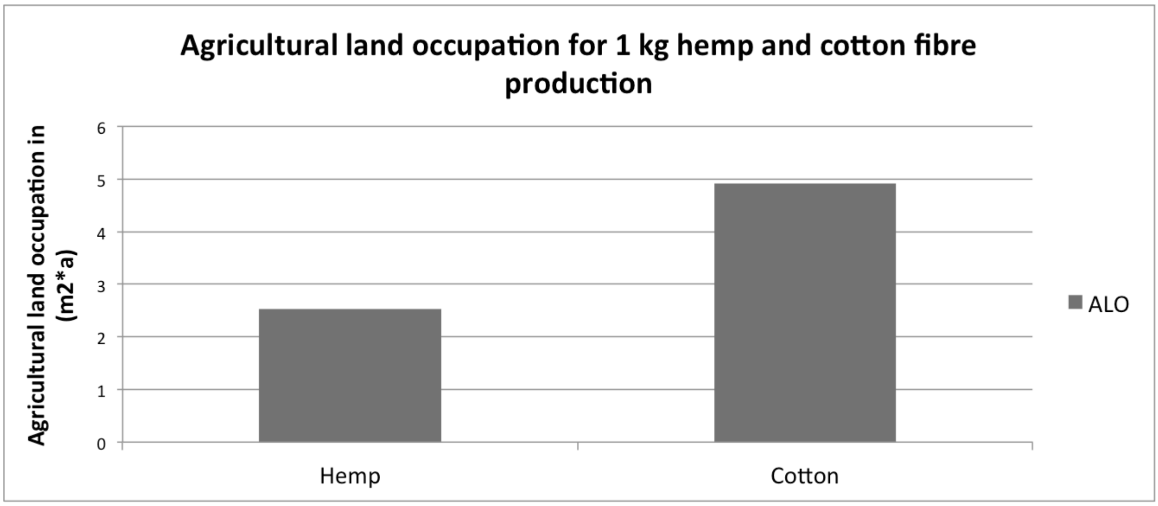

Figure 20: Agricultural land occupation of hemp and cotton.
A graphical representation of the agricultural land occupation for 1 kg of scutched hemp and ginned cotton fibre.

Table 93: Characterization output of 1 kg degummed hemp and ginned cotton fibre.

Impact category	Unit	Hemp total	Hemp cultivation	Hemp degumming	Cotton cultivation
CC	kg CO_2-eq	6.791622176	1.618614501	5.173007675	3.15328095
TA	kg SO_2 eq	0.090030119	0.060152863	0.029877256	0.070619487
FE	kg P eq	0.00150084	0.000306272	0.001194568	0.000569973
ME	kg N eq	0.028681726	0.027873652	0.000808075	0.046801305
HT	kg 1,4-DB eq	1.335919561	0.272847	1.063072562	1.063576076
PMF	kg PM_{10}-eq	0.018993651	0.009851779	0.009141872	0.012785212
TET	kg 1,4-DB eq	0.000893406	0.000655857	0.000237549	0.005317543
FET	kg 1,4-DB eq	0.078411972	0.054521722	0.023890251	0.052298825
MET	kg 1,4-DB eq	0.032418024	0.009159693	0.023258331	0.016949399

Table 94: Characterization output of the degumming of hemp fibre per kg output.

Impact category	Unit	Total	Chemical inputs	Electricity production	Heat from coal	Wastewater treatment
CC	kg CO_2-eq	5.173007663	0.493829159	1.709893067	2.526969316	0.44231612
		100%	10%	33%	49%	9%
TA	kg SO_2-eq	0.029877256	0.002904403	0.015049362	0.011573024	0.000350467
		100%	10%	50%	39%	1%
FE	kg P-eq	0.001194568	0.00020459	0.00022035	0.000769515	1.13021E-07
		100%	17%	18%	64%	0%
ME	kg N-eq	0.000808075	0.00028291	0.000260712	0.000241059	2.33934E-05
		100%	35%	32%	30%	3%
HT	kg 1,4-DB-eq	1.063072558	0.248362567	0.207792652	0.60482471	0.00209263
		100%	23%	20%	57%	0%
PMF	kg PM_{10}-eq	0.009141872	0.001080953	0.00468076	0.00323744	0.000142719
		100%	12%	51%	35%	2%
TET	kg 1,4-DB-eq	0.000237549	0.00014806	3.27303E-05	5.57395E-05	1.01916E-06

		100%	62%	14%	23%	0%
FET	kg 1,4-DB-eq	0.023890251	0.00749127	0.00436175	0.012029877	7.35358E-06
		100%	31%	18%	50%	0%
MET	kg 1,4-DB-eq	0.023258331	0.007050445	0.00432814	0.011869464	1.02818E-05
		100%	30%	19%	51%	0%

Appendix 9.2 Scenario R, A, B and C

Table 95: Characterization output from Simapro of scenario R.

Impact category	Unit	Total	Cotton production	Prep. and spinning	Sizing and weaving
CC	kg CO_2-eq	22.16350336	3.965250781	7.586843003	10.61140958
		100%	18%	34%	48%
TA	kg SO_2-eq	0.247951905	0.088804005	0.066774438	0.092373463
		100%	36%	27%	37%
FE	kg P-eq	0.00305837	0.000716741	0.000977699	0.00136393
		100%	23%	32%	45%
ME	kg N-eq	0.062131064	0.058852641	0.001156785	0.002121639
		100%	95%	2%	3%
HT	kg 1,4-DB-eq	3.542100373	1.337446918	0.921981762	1.282671693
		100%	38%	26%	36%
PMF	kg PM_{10}-eq	0.065542378	0.016077404	0.020768663	0.028696311
		100%	25%	32%	44%
FET	kg 1,4-DB-eq	0.112089344	0.065765773	0.019353204	0.026970367
		100%	59%	17%	24%
MET	kg 1,4-DB-eq	0.067378077	0.02131387	0.019204078	0.026860129
		100%	32%	29%	40%
FD	kg 1,4-DB-eq	4.145632056	0.615645063	1.465090967	2.064896026
			15%	35%	50%

Table 96: Characterization output from Simapro of scenario A.

Impact category	Unit	Total	Hemp production	Cotton production	Degumming or bleaching	Prep. and spinning	Sizing and weaving
CC	kg CO_2-eq	23.4836	1.031260979	1.75007093	3.295205881	6.743526	10.663578
		100%	4%	7%	14%	29%	45%
TA	kg SO_2-eq	0.24512	0.038324938	0.03919381	0.019031812	0.058933	0.0896354
		100%	16%	16%	8%	24%	37%
FE	kg P-eq	0.00353	0.000195133	0.00031633	0.00076094	0.000883	0.0013728
		100%	6%	9%	22%	25%	39%
ME	kg N-eq	0.04738	0.017759021	0.02597472	0.000514744	0.001029	0.0021014
		100%	37%	55%	1%	2%	4%
HT	kg 1,4-DB-eq	3.57217	0.17383785	0.59028472	0.67717722	0.831121	1.2997498
		100%	5%	17%	19%	23%	36%
PMF	kg PM_{10}-eq	0.06532	0.006276822	0.00709579	0.005823373	0.018326	0.0277931
		100%	10%	11%	9%	28%	43%
FET	kg 1,4-DB-eq	0.12448	0.034737193	0.02902585	0.01521809	0.017488	0.0280075
		100%	28%	23%	12%	14%	23%
MET	kg 1,4-DB-eq	0.07466	0.005835876	0.00940692	0.014815557	0.017341	0.0272608
		100%	8%	13%	20%	23%	37%
FD	kg 1,4-DB-eq	4.55755	0.15525471	0.27171611	0.672372796	1.303752	2.1544555
			3%	6%	15%	29%	47%

Table 97: Characterization output from Simapro of scenario B.

Impact category	Unit	Total	Hemp production	Degumming or bleaching	Prep. and spinning	Sizing and weaving
CC	kg CO_2-eq	21.77385852	1.889998975	6.052418965	6.846654631	6.984785945
		100%	9%	28%	31%	32%
TA	kg SO_2-eq	0.220664637	0.070238373	0.034956389	0.059307504	0.05616237
		100%	32%	16%	27%	25%
FE	kg P-eq	0.003570666	0.000357622	0.001397645	0.000914432	0.000900967
		100%	10%	39%	26%	25%
ME	kg N-eq	0.035987228	0.032547078	0.000945447	0.001045103	0.0014496
		100%	90%	3%	3%	4%
HT	kg 1,4-DB-eq	3.277991971	0.318593803	1.243794893	0.858461957	0.857141317
		100%	10%	38%	26%	26%
PMF	kg PM_{10}-eq	0.058009343	0.011503574	0.010695991	0.018437071	0.017372707
		100%	20%	18%	32%	30%
FET	kg 1,4-DB-eq	0.128658149	0.063663088	0.027951593	0.018115717	0.018927751
		100%	49%	22%	14%	15%
MET	kg 1,4-DB-eq	0.073954269	0.01069545	0.027212247	0.01794888	0.018097692
		100%	14%	37%	24%	24%
FD	kg 1,4-DB-eq	4.315557575	0.284536357	1.234970441	1.325595552	1.470455225
		100%	7%	29%	31%	34%

Table 98: Characterization output from Simapro of scenario C.

Impact category	Unit	Total	Hemp production	Degumming or bleaching	Prep. and spinning	Sizing and weaving
CC	kg CO_2-eq	31.8292476	2.18755266	4.78542733	8.708259029	16.14800858
		100%	7%	15%	27%	51%
TA	kg SO_2-eq	0.324304131	0.081296415	0.032575013	0.072383893	0.13804881
		100%	25%	10%	22%	43%
FE	kg P-eq	0.004607833	0.000413925	0.000946904	0.001167378	0.002079627
		100%	9%	21%	25%	45%
ME	kg N-eq	0.042521489	0.037671157	0.000649803	0.001278977	0.002921552
		100%	89%	2%	3%	7%
HT	kg 1,4-DB-eq	4.290639817	0.368751905	0.842215784	1.113564863	1.966107266
		100%	9%	20%	26%	46%
PMF	kg PM_{10}-eq	0.088678095	0.01331465	0.010013861	0.022495718	0.042853866
		100%	15%	11%	25%	48%
FET	kg 1,4-DB-eq	0.15848019	0.073685944	0.018283312	0.024540547	0.041970386
		100%	46%	12%	15%	26%
MET	kg 1,4-DB-eq	0.095180124	0.012379297	0.017905679	0.023761093	0.041134055
		100%	13%	19%	25%	43%
FD	kg 1,4-DB-eq	6.259723017	0.329332594	0.948248665	1.771818582	3.210323177
		100%	5%	15%	28%	51%

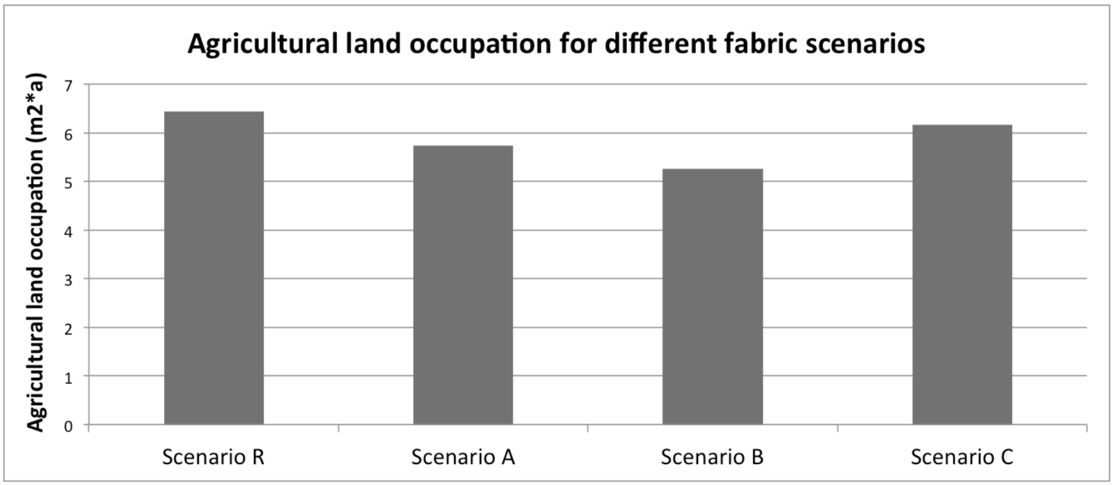

Figure 21: Agricultural land occupation of four fabric scenarios.
This figure presents a graphical representation of the agricultural land occupation for 1 kg fabric in the four different fabric scenarios.

Appendix 10 Biogenic carbon sequestration

Appendix 10.1 Calculation of biogenic carbon content in cotton and hemp

Table 99: Back-of-the-envelope calculations of CO2-sequestration in hemp and cotton fibres.

CO2(i) = CC * TY(i) * W(CO2) * EA(i) / FY(i)				
CO2(i)	=	Biogenic CO2 sequestered per kg of fibre (i = hemp or cotton)		
For i	=	Hemp		Cotton
	=	3.76 kg per kg fibre		3.21 kg per kg fibre
CC	=	Average carbon content of dry biomass		
	=	47.5%		
TY(i)	=	Total harvested dry matter yield		
For i	=	Hemp	Cotton	
	=	9000	3843	
W(CO2)	=	Factor for multiplying CO2-C weight to CO2 weight		
	=	44/12		
EA	=	Economic allocation to the fibre		
For i	=	Hemp	Cotton	
	=	53%	72%	
FY(i)	=	Fibre yield		
For i	=	Hemp	Cotton	
	=	2200 kg per hectare	1486 kg per hectare	