

# Life Cycle Assessment Comparing Ten Sources of Manmade Cellulose Fiber

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*Prepared by:*

**Tobias Schultz** | Manager of Corporate Sustainability Services

**Aditi Suresh** | Corporate Sustainability & Life Cycle Assessment Associate  
Corporate Sustainability Services

*Contact Person:*

Tobias Schultz, +1-510-452-6389, [tschultz@scsglobalservices.com](mailto:tschultz@scsglobalservices.com)



**SCS**global  
SERVICES  
*Setting the standard for sustainability™*

2000 Powell Street, Ste. 600, Emeryville, CA 94608 USA  
+1.510.452.8000 main | +1.510.452.8001 fax

# 1 Executive Summary

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## 1.1 Introduction

This Life Cycle Assessment (LCA) study evaluates the life cycle impact profile of manmade cellulose fibers (MMCF), made from pulp originating from ten different sources. It examines MMCF derived from five completely different material feedstocks (wood from different forest regions, bamboo pulp, cotton linter, flax by-products, recycled clothing), with supply chains stretching across four continents. This study is the first to date which looks at 10 scenarios of MMCF production, with a focus on analyzing impacts associated with fibers from different locations, supply chains, and manufactured using different mill technologies.

The LCA provides information useful in the development of environmentally sustainable sourcing strategies for apparel companies, by evaluating the differences in the relative environmental performance of the different fiber sources considered (particularly in relation to terrestrial and freshwater ecosystem impacts). It also provides quantitative information to identify fiber sources which have improved environmental performance for specific impact categories.

This LCA study was conducted in conformance with ISO 14044<sup>1</sup>, the draft LEO-S 002 standard,<sup>2</sup> and the Product Category Rule Module for Roundwood.<sup>3</sup> This study is a comparative assertion intended to be disclosed to the public. The study has been critically reviewed by a panel of four expert stakeholders representing academia, LCA experts, textile industry experts, and the environmental community.

## 1.2 Goal and Scope of the Study

A key goal of the study is to understand the relative level of impacts on ecosystems associated with the production of each source of MMCF. An additional goal is to understand the unit processes which are the biggest contributors to environmental impacts.

The scope of this LCA is cradle-to-gate, including all relevant impacts involved in raw material extraction, dissolving pulp (DP) production, and production of MMCF (including viscose staple fiber, lyocell staple fiber, and flax fiber). Impacts associated with the use and end-of-life of MMCF are excluded (these stages are similar for all products considered). Due to the potential use of MMCF in various applications (e.g. yarns, embroidery threads, blended fabrics, apparel, and upholstery), a specific functional unit cannot be clearly defined and a declared unit is used; the production of 1,000 tons of staple fiber (MMCF).

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<sup>1</sup> ISO 14044:2006 Environmental management – Life Cycle Assessment – Requirements and guidelines

<sup>2</sup> LEO-SCS-002 Standard Draft Dated June 2014. Leonardo Academy.  
<http://www.leonardoacademy.org/programs/standards/life-cycle.html>

<sup>3</sup> PCR Module for Roundwood Production:  
[https://www.scsglobalservices.com/files/resources/pcr\\_final\\_wood-products\\_101816.pdf](https://www.scsglobalservices.com/files/resources/pcr_final_wood-products_101816.pdf)

The geographical and technological scope including ten different scenarios for MMCF made in different regions are presented in Table 1 below.

**Table 1.** Scope of the LCA study including 10 different scenarios of MMCF production.

Scenario Name	Type of Manmade Cellulose Fiber (MMCF)	Type and Source of Dissolving Pulp	Location of Dissolving Pulp (DP) Mill	Location of Staple Fiber (MMCF) Mill
1. German Production from Swedish Managed Forest Pulp	Viscose staple fibers	Softwood pulp from Sweden	Sweden	Germany
2. Asian Production from Canadian Boreal Forest Pulp <sup>4,5</sup>	Viscose staple fibers	Softwood pulp from Canada	Canada	China
3. Chinese Production from Indonesian Rainforest Pulp <sup>5</sup>	Viscose staple fibers	Mixed tropical hardwood pulp from Indonesia	Indonesia	China
4. Chinese Production from Indonesian Plantation Pulp <sup>5</sup>	Viscose staple fibers	Eucalyptus pulp from Indonesia	Indonesia	China
5. German Production from Recycled Pulp	Viscose staple fiber	Recycled pulp from clothing inputs	Sweden	Germany
6. Chinese Production from Chinese Bamboo Pulp	Viscose staple fiber	Bamboo pulp from China	China	China
7. Chinese Production from Indian Cotton Linter Pulped in China	Viscose staple fibers	Cotton linter* sourced from India and pulped in China	China	China
8. Chinese Production from South African Plantation Pulp	Viscose staple fibers	Eucalyptus pulp from South Africa	South Africa	China
9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	Lyocell fibers	Mix of beechwood and eucalyptus pulp from Austria	Austria/ South Africa	Austria
10. Belgian Flax Production	Flax fibers*	Not Applicable**	Not Applicable	Belgium

\* Scenario 7 and Scenario 10 consider co-products of cotton (cotton linter) and flax fibers (short fibers from combings and card waste) respectively.

\*\*Scenario 10 (Belgian Flax Production) does not involve any pulping process. The flax fibers are chemically processed using proprietary technology to produce fibers that are functionally equivalent to MMCF

The dissolving pulp mills and MMCF mills were identified carefully, based on characteristics including location of the mill, current supply chain of the MMCF mills and production capacities, and overall representativeness of local industry in the considered scenario. The mills included were reviewed in consultation with experts and thus serve as representations adequate to achieve the goals of the study, but it should be recognized use of different mills could affect results. The temporal scope includes production of MMCF in 2016.

<sup>4</sup> Scenario 2 considers sourcing of pulp from a hypothetical dissolving pulp mill located in Canada, which is projected to be transformed from a pulp/paper mill to a dissolving grade pulp mill.

<sup>5</sup> The forests in Scenarios 2 and 3 from which timber is extracted are “ancient and endangered forests” as defined by the [CanopyStyle](#) initiative (see Section 3.1.1 for more detail); Scenario 4 includes plantations which are present in regions where such forests were cleared recently.

### 1.3 Methodology Summary

A life cycle inventory (LCI) analysis was conducted in conformance with ISO 14044, draft LEO-S-002 and the Roundwood PCR<sup>6</sup>. The openLCA software<sup>7</sup> was used to model and analyze the complete set of inputs and outputs associated with all production stages in each product system, by unit process. The complete set of inputs and outputs is called the LCI for each product system. The LCI of product systems are modeled based on primary data of dissolving pulp mills and staple fiber mills for three of the ten scenarios, and supplemented with site-level data from third party databases such as RISI and Chinese market research firms for other scenarios. Representative data from the Ecoinvent v3.1 database was used to model background processes (See Table 16, Table 17 and Table 18 for more details).<sup>8</sup> Data for category indicators assessed for Terrestrial Ecosystem Impacts is sourced from government forest inventories and threatened species lists, the NatureServe Explorer Database,<sup>9</sup> IUCN Red list species,<sup>10</sup> and literature.

It is important to note that this is a cradle-to-gate study, which ends at the MMCF production facility and is subject to certain key assumptions and limitations discussed in Section 4.3 of the main LCA report. Furthermore, it is to be noted that impacts during downstream processing (e.g. weaving, knitting, dyeing, finishing, etc.), use and waste management stages may differ depending on the source of MMCF. Refer to Section 4.3 of the LCA report for details on the assumptions and limitations of this study.

In conformance with ISO 14044, a sensitivity analysis was performed (see Section 5.4) for the climate change impact category, using a 100-year time horizon, to test the sensitivity of the indicator. The result of this analysis showed that the relative positioning of the different scenarios studied does not evolve.

### 1.4 Results Summary

The number of selected impact categories is intended to comprehensively reflect all impacts relevant to MMCF production. The LCA methodology contains a relatively larger number of impact categories (over twenty impact categories considered in five groups) than previous LCAs of MMCF. Some new impact categories include:

- Effects on the Climate Hot Spots present in Indonesia, East Asia (China), and Africa. In these regions, ambient pollution from the aerosols, mostly driven by black carbon and sulfate aerosols, has greatly disrupted regional climates.

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<sup>6</sup> PCR LCIA Methodology:

[https://www.scsglobalservices.com/files/resources/pcr\\_final\\_lcia-methodology\\_101816.pdf](https://www.scsglobalservices.com/files/resources/pcr_final_lcia-methodology_101816.pdf)

<sup>7</sup> openLCA modeling software, version 1.5.beta1 By GreenDelta.

<sup>8</sup> Ecoinvent v3.1 Swiss Center for Life Cycle Inventories, 2014. The system model used is based on the recycled content cut-off method. <http://www.ecoinvent.org>

<sup>9</sup> NatureServe Explorer: An Online Encyclopedia of Life. <http://explorer.natureserve.org/>

<sup>10</sup> IUCN Red List Species database; <http://www.iucnredlist.org/>

- An in-depth evaluation, using site-specific data, of impacts on Terrestrial and Freshwater Ecosystems, which are of major concern for most sources of MMCF. This considers quantitatively, the ecological conditions of forest ecosystems, compared with undisturbed conditions. It evaluates the implications of differing land use management regimes, the potential consequences in the absence of harvest and the "opportunity cost" of ongoing harvests.<sup>11</sup> Furthermore, it also considers the threatened, endangered, and vulnerable species affected negatively by local land use management practices.
- Ocean acidification, referred to by some as the "evil twin" of Global Climate Change.<sup>12</sup> After emission, roughly 25% of CO<sub>2</sub> is absorbed by the oceans,<sup>13</sup> fundamentally changing the chemistry of seawater in a mechanism parallel to climate change.<sup>14</sup>

While there are a number of impact categories in the scope, this LCA does not use numerical weighting or any other approach to indicate any priority or importance of any impact category over any other.

The relative performance of each scenario is illustrated in Figure 1. The results are provided for the production of 1,000 tons of MMCF, for all ten scenarios, by impact category indicator in Section 4.2 of the LCA report (see Figure 5 through Figure 18).

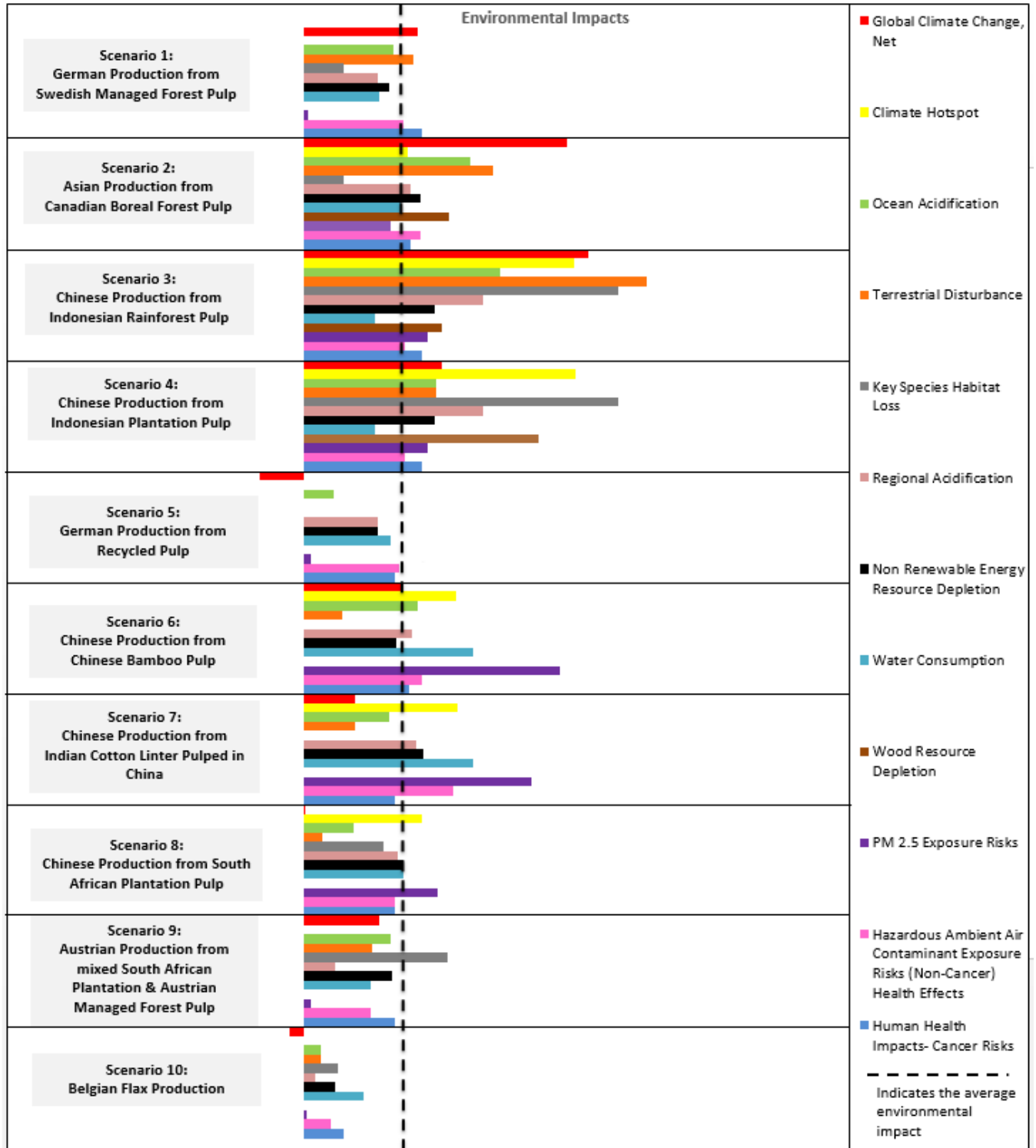
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<sup>11</sup> Across the scenarios, the socio-economic implications of avoiding harvests will be different. For example, the socio-economic implications of regenerating forests in Europe, are very different from forgoing harvesting in forests in Indonesia or Canada's Boreal. These socio-economic considerations are outside the scope of this LCA.

<sup>12</sup> United Nations University. Climate Change's 'Evil Twin': Ocean Acidification. 2013. See <https://ourworld.unu.edu/en/climate-changes-evil-twin-ocean-acidification>

<sup>13</sup> National Oceanic and Atmospheric Administration. Ocean Acidification: The Other CO<sub>2</sub> Problem. <http://www.pmel.noaa.gov/co2/story/Ocean+Acidification>

<sup>14</sup> The inclusion of ocean acidification anticipates a trend to include this impact category in other LCAs. See Bach, V., et al. Characterization model to assess ocean acidification within life cycle assessment. The International Journal of Life Cycle Assessment. April 2016.



**Figure 1.** Summary chart shows the relative environmental performance, by scenario and by impact category. Results were normalized based on the average environmental impact (indicated as a dash line in the figure). Impact bars which cross the dash line suggest that the scenario has above average impacts, whereas impact bars below the dash line indicate that the scenario has impacts which is below the average.

## 1.5 Summary of Key Findings

Based on the results presented above, the following key findings can be derived:

### **Variation in Impacts of MMCF from Different Sources:**

There is a very wide variability in impacts associated with MMCF sourcing, resulting not only from differences in material feedstocks, but also the region where the fiber inputs originate, the land use management practices involved in raw material feedstock extraction, the location of the supply chain operations and the type of mill technology being used. This LCA makes it clear that it is critical to understand not just the type of material used in MMCF production, but also the source of material.

### **Key Drivers of Environmental Performance:**

For most scenarios, a few unit processes at similar stages in the life cycle drive most of the resulting impacts. This includes the following processes:

*Land use management, including logging and agriculture.*<sup>15</sup> For Global Climate Change and Ocean Acidification, this accounts for a significant level of impact for all scenarios (due to forest carbon storage losses from harvesting wood/agricultural inputs); and for Terrestrial and Freshwater Ecosystem Impacts, it is the sole driver. The inherently local effects of different land use management regimes on distinct ecosystems in various regions, result in different effects on terrestrial disturbance, key species, and biogenic carbon storage

*Production of dissolving pulp.*<sup>16</sup> The use and purchase of energy leads to air emissions which contribute to multiple impact categories; for Global Climate Change, dissolving pulp production is the first or second most important contributor to results for all scenarios, and is a very significant contributor to PM2.5 Exposure Risks and Regional Acidification as well.

*Operations at MMCF mills.* The use and purchase of energy leads to air emissions which contribute to multiple impact categories; for Global Climate Change, it contributes between 9-37%. It is the dominant contributor (accounting for over 50% of results) to Regional Acidification in nearly all scenarios, and contributes to at least 25% of total impacts across all scenarios.

*Sodium hydroxide production and sulfuric acid production.* These processes, including the upstream production of these materials used at MMCF mills, make up important contributions to several impact categories in selected scenarios, including Global Climate change (for Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production), Climate Hot Spots (for all scenarios where this impact is relevant), Non-renewable energy resource depletion, Regional Acidification, and PM2.5 Exposure Risks.

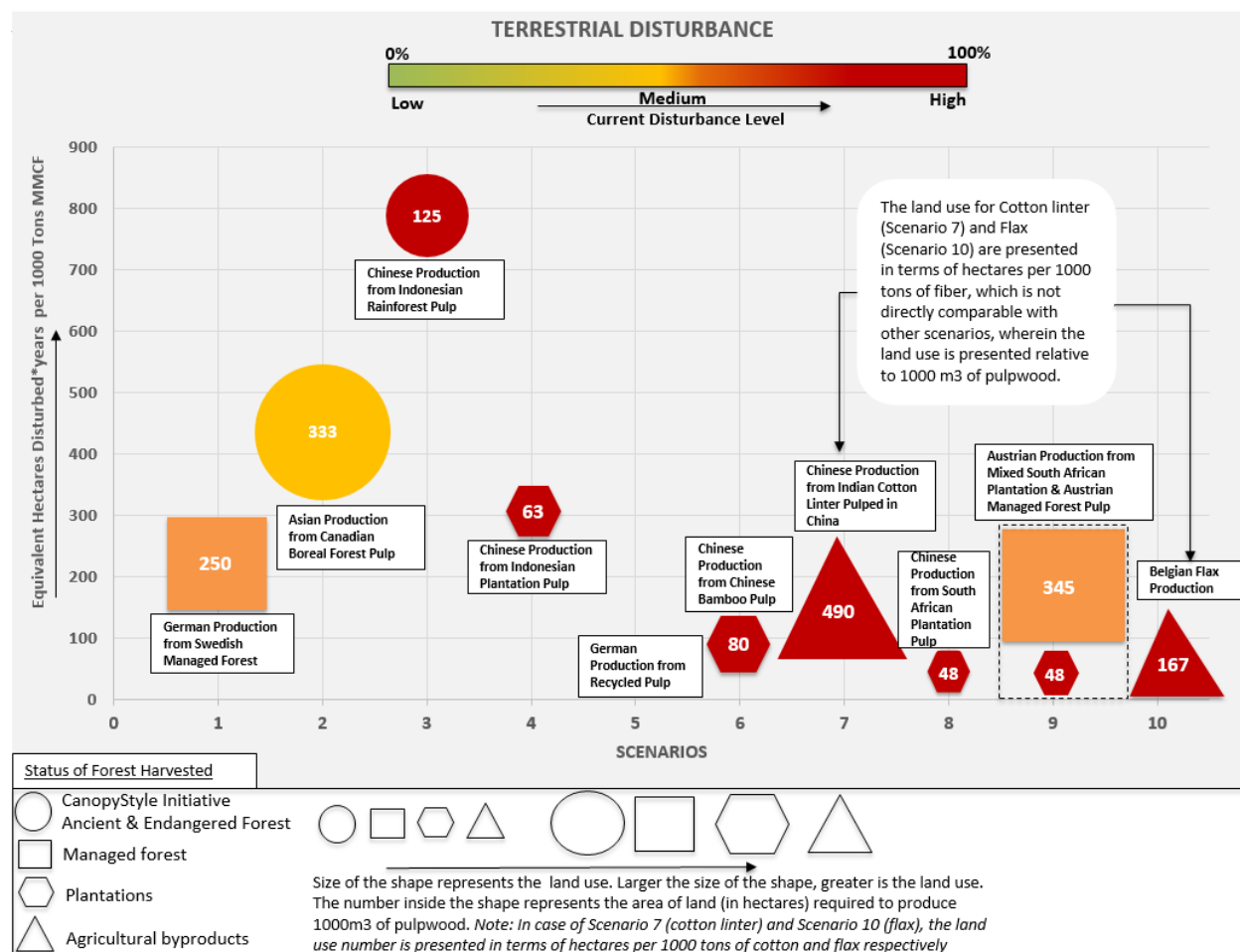
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<sup>15</sup> Not relevant for Scenario 5: German Production from Recycled Pulp.

<sup>16</sup> Not relevant for Scenario 10: Belgian Flax Production.

## Variations in Terrestrial and Freshwater Ecosystem Impacts

The Terrestrial and Freshwater Ecosystem Impacts vary widely (as illustrated in the chart below) and are mainly driven by logging and agriculture (depending on the raw material from which the fiber is manufactured).



**Figure 2.** Terrestrial disturbance chart portraying the following information for each source of MMCF: (i) number of hectares disturbed to produce MMCF; (ii) the status of forest harvested by scenario (i.e. plantations or agricultural byproducts); (iii) land use is the area required to produce 1,000m<sup>3</sup> pulpwood or 1,000 tons of agricultural by-product (applicable to cotton linter and Scenario 10: Belgian Flax Production); and (iv) the color of the shape indicates the current terrestrial disturbance level (i.e. green color indicates low disturbance, orange indicates medium disturbance and red indicates high disturbance). Refer to the main LCA for detailed interpretation of results. See Section 3.1.1 in the LCA report for the definition of “ancient and endangered” forest as used in the CanopyStyle initiative.

The terrestrial disturbance impacts are dependent on the site productivity in a given region; the volume of fiber which can be extracted from a given area over an extended period of time. Although some forests, such as those in Scenario 3: Chinese production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian plantation pulp, and Scenario 8: Chinese production from South African plantation pulp, are in a very high state of disturbance because of transition from native forests or grasslands to exotic plantations, forests in these regions are extremely productive. Conversely,



Sweden, Canada and Austria do not experience the high state of disturbance, however require significantly more area to be managed for harvest to produce the same amount of material.

In Indonesia, forest conversion has been extremely rapid, with forests being converted from a largely undisturbed state 20 years ago to a fully disturbed state today. At the current trend, there will be essentially no undisturbed forest remaining in the Indonesian region in 10-20 years. This LCA finding is consistent with independent evaluations completed for Indonesian forests by organizations such as WWF.<sup>17</sup> These trends in forest disturbance are factored into the analysis and is one of the reasons for the relatively high result of terrestrial disturbance for dissolving pulp sourced from Indonesia.

In addition to physical alterations resulting in terrestrial disturbance, wood extraction, intensive agriculture and land transformation activities, can also have a negative influence on the species habitat, causing a decline in species population. Refer to Section 5 for detailed discussion of results and key findings.

## 1.6 Conclusions

It can be concluded that the choice of the MMCF raw material input is a critical one with overarching effects on life cycle analysis of impacts. While there is no source of MMCF which is unambiguously environmentally preferable across all impact categories, Scenario 10: Belgian Flax Production seems favorable across majority of the impact categories, followed by Scenario 5: German Production from Recycled Pulp. Table 2 below provides a relative comparison of the ten scenarios across each impact category and identifies the best, worst and mid-range performer(s) in the same.

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<sup>17</sup> Terrdaily, 2005. WWF Warns that Borneo's Forests Could be Destroyed within a Decade.  
<http://www.terradaily.com/news/terradaily-05f.html>

**Table 2.** Color coded matrix to distinguish the best and worst performers amongst the ten scenarios, by impact category, on the basis of LCA results presented in Section 1.4. Refer to the legend provided in the table below.

Impact Categories by Group		1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	10. Belgian Flax Production
<b>Biotic/Abiotic Resource Depletion Impacts</b>											
Nonrenewable Energy Resource Depletion										*	
Net Freshwater Consumption			*	*	*		*	*	*	*	
Wood Resource Depletion							*				
<b>Global and Regional Climate System Impacts</b>											
Global Climate Change, Net										*	
Regional Climate Impacts			*	*	*		*	*	*		
<b>Ocean Ecosystem Impacts</b>											
Ocean Acidification				*	*		*	*	*	*	
Ocean Warming											
<b>Terrestrial &amp; Freshwater Ecosystem Impacts (from Emissions)</b>											
Regional Acidification							*	*		*	
Freshwater Eutrophication											
<b>Terrestrial &amp; Freshwater Ecosystem Impacts (from Land Use and Conversion)</b>											
Terrestrial Disturbance							*	*	*		
Freshwater Disturbance											
Wetland Disturbance											
Threatened species Habitat Disturbance											
<b>Human Health Impacts (from Chronic Exposure to Hazardous Chemicals)</b>											
PM 2.5 Exposure Risks							*	*		*	
Hazardous Ambient Air Contaminant Exposure Risks – Respiratory (Non-Cancer) Health Effects		*	*	*	*	*	*	*	*	*	*
Human Health Impacts- Cancer Risks		*	*	*	*	*	*	*	*	*	*
Ground Level Ozone Exposure Risks											
Legend		*	Indicates Low Data Quality								
			Impact category is relevant but could not be evaluated due to lack of consistent data across all scenarios								
		Best performer(s) amongst the ten scenarios <sup>18</sup>									
		Worst performer(s) amongst the ten scenarios									
		Mid-range performer (better than some scenarios, worse than others)									

<sup>18</sup> Impact category indicator results for the best and worst performers which are within ~±15% are denoted in the same color. This is within a reasonable margin of error. As a result, some scenarios have multiple best and worst performers, indicating there was not sufficient accuracy in results to differentiate these scenarios.

All raw material inputs of MMCF have benefits and disadvantages environmentally. However, some sources of fiber have more benefits, and fewer disadvantages, than others. The following can be noted from the relative comparison of the ten different scenarios across each impact category:

- MMCF from Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production have lowest impacts and Scenario 2: Asian Production from Canadian Boreal Forest Pulp, Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian Plantation Pulp and Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China should be avoided. These findings should be reconciled with existing corporate policies and commitments related to forests while making procurement decisions.
- Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian Plantation Pulp are the worst performers in multiple categories, including Global Climate Change, Climate Hotspot, Ocean Acidification (applies to Scenario 3 only), Terrestrial Disturbance (applies to Scenario 3 only), Regional acidification, Non-renewable resource depletion and Human Health impacts. These two scenarios are also the worst performers in terms of number of species affected by habitat loss. This is due to the rapid and large scale conversion of forests in this region, as well as the highly diverse nature of local ecosystems.
- Impacts to Terrestrial and Freshwater Ecosystem are a major driver for many impact categories, with the exception of Scenario 5: German Production from Recycled Pulp. There is wide variation in the level of impacts on forest ecosystems as described below.
  - Wood resource depletion impacts are only relevant for Scenario 2: Asian Production from Canadian Boreal Forest Pulp, and Scenario 3: Chinese Production from Indonesian Rainforest Pulp. These are the only regions where a depletion in valuable wood resources is occurring.
  - Scenario 3: Chinese Production from Indonesian Rainforest Pulp, exhibits the highest terrestrial disturbance, followed by Scenario 2: Asian Production from Canadian Boreal Forest Pulp. Of note, Scenario 2 is the 2<sup>nd</sup> worst performer for Global Climate Change, faring better only than Scenario 3, where carbon loss is very high. These are the worst performing options across all potential sources of MMCF by a wide margin.

The main body of the LCA report provides more depth on the results and key findings described above, as well as the methodology and data sources used to derive the results.

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## Terminology Used in this Report

Term	Definition
Background Unit Processes (or Background System)	Unit processes not specific to the product system under study, including those processes upstream and/or downstream where many suppliers are involved.
Biotic Resource	A resource deriving recently from living biomass.
Black carbon	The light-absorbing component of carbonaceous aerosols. Black carbon contributes to roughly 1 W/m <sup>2</sup> of global radiative forcing, and is the second most important forcing agent after carbon dioxide.
Black liquor	A by-product of wood pulping, which can be combusted to generate electricity in integrated virgin pulp and paper mills.
Category Indicator	Quantifiable representation of an impact category [Ref. ISO-14044] (Also referred to as “Impact Category Indicator,” or simply, “Indicator.”)
Climate Forcer	An emission or activity which can be linked to positive or negative climate forcing (i.e., both warming and cooling are considered).
Comparative Assertion	Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function. [Ref: ISO 14044]
Core Impact Category	An impact category in which at least one unit process in the product system under study contributes measurably to observed midpoints or endpoints in the stressor-effects network. Defined independently by product system.
Cradle-to-gate	A scope which includes the life cycle stages from raw material extraction through production of a product.
Cradle-to-grave	A scope which includes all life cycle stages from raw material extraction through end-of-life.
Data Quality	Characteristics of data that relate to their ability to satisfy stated requirements [Ref: ISO 14044].
Dissolving pulp	Pulp processed from wood species or cotton linters, containing high chemical purity (cellulose content > confidence in) compared to paper grade pulp.
Disturbance	Average deviation in overall ecological conditions in a terrestrial ecoregion biome, when compared to undisturbed conditions (i.e., unaffected by anthropogenic activities since the pre-industrial era) and fully disturbed conditions (i.e., representing maximally disturbed areas) in an area within the same biome ecoregion type.
Effect	A change to human health or the environment.
Endpoint	Attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern [ISO-14044]
Environmental Characterization Data	Data used in the characterization model to establish the relevant characterization factors for category indicators.
Environmental Data	See environmental characterization data.
Environmental Mechanism	System of physical, chemical, radiological, and biological processes for a given impact category, linking stressor(s) to midpoints and to category endpoints. [Based on 14044]
Environmental Relevance	The degree of linkage between a category indicator result and the category endpoint(s). [Ref. ISO 14044, § 4.4.2.2.2]
Exceedance of threshold	For a given impact category, represents the surpassing of a threshold (defined below).
Fiber Basket	Region supplying pulpwood to each dissolving pulp mill.
Foregone growth	The forest growth avoided as a result of ongoing harvests. In terms of carbon or forest condition, this is the “opportunity cost” associated with ongoing harvests.
Forest Analysis Unit	An area of timberland used to represent forest ecosystem impacts resulting from forestry operations within a region.
Forest Inventory	Forest inventory is an accounting of trees and their related characteristics of interest over a well-defined land area.

Term	Definition
Forest Type	A classification of forest land based on the species that form a plurality of live-tree basal-area stocking. <sup>19</sup>
Forestland	Land that is at least 10 percent stocked with trees of any size, or that formerly had such tree cover and is not currently developed for a nonforest use. The minimum area for classification of forest land is one acre. The components that make up forest land are timberland and all noncommercial forest land. <sup>20</sup>
Freshwater ecosystem	An interconnected biotic community, including watercourses, lakes, wetlands, and adjacent riparian areas, within specific watershed boundaries, defined by: salinity; turbidity; water temperature; sedimentation rates; sediment size distribution; flow rates; depths; channel contours; hydrology and hydraulics; water quality; watershed area; tributary areas; stream lengths; presence of large woody debris; riparian canopy cover; riparian zone vegetative species composition; climate; and geology.
Functional Unit	Quantified performance of a product system for use as a reference unit. [Ref: ISO 14044].
Grid mix	The mix of sources used to generate electricity consumed at a specific unit process.
Impact	An effect on human health or the environment.
Impact Category	Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned [Ref: ISO-14044]. The issues of concern are represented in a distinct environmental mechanism, which can be modeled with a stressor-effects network made up of observable stressors, midpoints, and endpoints.
Impact Group	Impact categories with similar endpoints and environmental mechanisms.
Impact Profile	See LCIA Profile. (Also referred to as “profile” or “eco-profile.”)
Indicator	See Category Indicator.
Input	Product, material or energy flow that enters a unit process. [Ref: ISO 14044].
Key unit process or key unit operation	A unit process (or unit operation) contributing over 10% to any indicator result.
LCIA Profile	A discrete compilation of the LCIA category indicator results for different impact categories. [Ref: ISO 14044, §4.4.2.5]
Life Cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation from providing environment to final disposal.
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs and the environmental and human health impacts of a product system throughout its life cycle. [Based on ISO 14044]
Life Cycle Impact Assessment (LCIA)	Phase of life cycle assessment aimed at determining the magnitude and significance of the environmental and human health impacts for a product system throughout the life cycle of the product. [Based on ISO 14044]
Life Cycle Interpretation	Phase of life cycle assessment in which findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations. [Ref: ISO 14044]
Life Cycle Inventory (LCI)	Phase of a life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. [Ref: ISO 14044]
Managed forest	A forest composed of species native to the region, which is actively managed to produce timber for various purposes.
Manmade cellulose fiber	Chemical processing of fibers by extracting cellulose from wood pulp and other sources and regenerating fibers by precipitation in chemical reagents.
Midpoint Characterization Factor (M-CF)	A factor which characterizes the actual effect on the receiving environment of emissions, resource uses, or land uses. Multiplied with Potency Potential Characterization Factors (PP-CFs) to calculate results.
Midpoints	A distinct node in a stressor-effects network representing an observed chemical, physical, radiological or biological impact that is linked to the final category endpoint(s).
Node	The modeled representation of an observed chemical, physical, radiological, or biological impact within a distinct stressor-effects network.

<sup>19</sup> USFS. Northeastern Forest Inventory & Analysis, Methodology: Common Definitions Used in FIA. [http://www.fs.fed.us/ne/fia/methodology/def\\_ah.htm](http://www.fs.fed.us/ne/fia/methodology/def_ah.htm)

<sup>20</sup> Ibid.

Term	Definition
Organic carbon	The scattering component of carbonaceous aerosols, these emissions lead to a modest cooling effect globally due to their negative radiative forcing.
Output	Product, material or energy flow that leaves a unit process. [Ref. ISO 14044].
Plantation	An intensively managed area of land, which is regularly planted with tree species (native or non-native) subject to even-aged forest management.
Post-consumer material	Material generated by households, commercial, or institutional, facilities in their role as end-users of the product which can no longer be used for its intended purpose.
Potency Potential Characterization Factor (PP-CF)	A factor which characterizes the relative potency of emissions, resource uses, or land uses, in causing impacts. Multiplied with Midpoint Characterization Factors (M-CFs) to calculate results.
Pre-consumer material	Material that was discarded before it was ready for consumer use. Pre-consumer waste is the reintroduction of manufacturing scrap (such as trimmings from paper production, defective aluminum cans, etc.) back into the manufacturing process.
Product	Any goods or service. [Ref: ISO 14025].
Product system	Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product. [Ref. ISO 14044]
Providing Environment	The environment from which raw materials are extracted.
Pulpwood	Refers to woody inputs to pulping mills, used to produce pulp. Includes roundwood, chips, and other mill residues.
Radiative Forcing	It is the net change in the energy balance of the Earth system due to some imposed perturbation, typically expressed in watts per square meter. Can be expressed as a global or regional mean.
Receiving Environment	The environment affected by stressor(s) including emissions, land use, or wastes.
Resource Depletion	The degree to which the net consumption of a resource results in a reduction in its reserve base, taking into account the extent of reserve base and projected consumption.
Roundwood	A length of cut tree generally having a round cross-section, such as a log or bolt. <sup>21</sup>
Sensitivity Analysis	Systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study. [Ref. ISO-14044]
Short ton	Imperial unit of 2,000 pounds
Staple fiber	Discontinuous lengths of fiber which can be spun into yarn or incorporated as fillings or other non-woven applications.
Stressor	Any life cycle inventory input, output, or other activity associated with a unit process that can be linked to observable midpoints and endpoints in a defined environmental mechanism.
Stressor-Effects Network	A model used to represent an environmental mechanism, beginning with stressor(s) associated with a given unit process, which lead to midpoint(s) and eventually category endpoint(s) within an impact category. (Also referred to as "Cause-Effect Chain")
System	See product system.
Technically recoverable reserve base	The technically recoverable reserve base includes "the part of an identified resource reserve that could be commercially extracted at a given time". The technically recoverable reserve base may encompass those parts of a resource that have a reasonable potential for becoming economically recoverable within planning horizons that extend beyond those which assume proven technology and current economics <sup>22</sup> .
Terrestrial ecoregion/ forest ecoregion	A biotic community in a specific terrestrial area, which is defined by conditions such as prevailing vegetation structure, leaf types, plant spacing, vegetative species composition, vegetative compositional structure, vegetative age structure, presence of large living trees and snags (if relevant), presence of biomass (above and below ground), soil conditions, connectivity, landscape heterogeneity, fragmentation, climate, and topography.

<sup>21</sup> Stokes, Bryce J.; Ashmore, Colin; Rawlins, Cynthia L.; Sirois, Donald L. 1989. Glossary of Terms Used in Timber Harvesting and Forest Engineering. Gen. Tech. Rep. SO-73. New Orleans, LA: U.S. Dept. of Agriculture, Forest Service, Southern Forest Experiment Station. 33 p.

<sup>22</sup> LEO-SCS-002 Standard Draft Dated June 2014. Leonardo Academy.  
<http://www.leonardoacademy.org/programs/standards/life-cycle.html>



Term	Definition
Threshold	A recognized environmental condition that, when exceeded, is linked to nonlinear changes in impacts to environment or human health.
Timberland	Forest land producing or capable of producing crops of industrial wood (more than 20 cubic feet per acre per year) and not withdrawn from timber utilization (formerly known as commercial forest land). <sup>23</sup>
Time Horizon	A specified timeframe.
Ton	Metric ton (1,000 kilograms or 2,204.6 pounds).
Ton-kilometer	Unit of transport, representing one metric ton transported one kilometer
Undisturbed Reference Area	<p>Area of forest/other wooded land against which measurements of ecological conditions in a Forest Analysis Unit (FAU) are compared. The Undisturbed Reference Area is chosen to be representative of the forest ecosystem in the Forest Analysis Unit against which it is compared, if significant human interventions were absent for a time period sufficient for mature forest ecosystem characteristics to become established. The Undisturbed Reference Area:</p> <ul style="list-style-type: none"> <li>• Include an area which has not been subject to significant human interventions (i.e., logging, intensive hunting, non-timber extraction, agriculture, mining, or other activities) for the longest time possible, which is not less than 80 years.</li> <li>• Located in a region with similar climate, elevation, rainfall, and soil conditions, to the forest ecosystem in the Forest Analysis Unit against which it is compared.</li> <li>• Located as close as possible to the Forest Analysis Unit against which it is compared, and never farther away than 800 kilometers.</li> <li>• Include the largest possible contiguous area in the region satisfying these requirements, which is no less than 5,000 hectares.</li> </ul>
Unit Process	Smallest element considered in the life cycle assessment for which input and output data are quantified [Ref: ISO 14044].
Watershed or hydro-basin	A watershed is the area of land where all of the water that falls in it and drains off of it goes into the same place. <sup>24</sup>
Wetland ecosystem)	A biotic community in a specific wetland, defined by: salinity; turbidity; water quality; sedimentation rates; sediment size distribution; flow rates; depths; hydrology; vegetative cover; plant structure (if plants are present); bottom particle composition and structure; channel connectivity; channel complexity; tidal action (for saltwater wetlands); wave action (for saltwater wetlands); and climate.

<sup>23</sup> USFS. Northeastern Forest Inventory & Analysis, Methodology: Common Definitions Used in FIA. [http://www.fs.fed.us/ne/fia/methodology/def\\_qz.htm](http://www.fs.fed.us/ne/fia/methodology/def_qz.htm)

<sup>24</sup> USGS: What is a Watershed? <http://water.usgs.gov/edu/watershed.html>

## Acronyms

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AGWP	Absolute Global Warming Potential
AGWP-20, 100	Absolute Global Warming Potential over 20, 100 years
C	Carbon
CF	Characterization factor
CH <sub>4</sub>	Methane
CO	Carbon monoxide
CO <sub>2</sub>	Carbon Dioxide
d.b.h.	Diameter at breast height
DP	Dissolving Pulp
Eq.	Equivalent
EU	European Union
FAU	Forest Analysis Unit
GHG	Greenhouse gas
GJ	Gigajoule
GLO	Ground level ozone
GWP	Global Warming Potential
GWP-100	Global Warming Potential, calculated over a 100 year time horizon
H <sub>2</sub> CO <sub>3</sub>	Carbonic Acid
H <sub>2</sub> S	Hydrogen sulfide
HAAC	Hazardous ambient air contaminant
HEC	Hazardous Environmental Contaminant
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
IAEA	International Atomic Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRIS	Integrated Risk Information System
IUCN	International Union for the Conservation of Nature
kW	kilowatt
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m	meters
m <sup>2</sup>	Square meter
m <sup>3</sup>	cubic meter
M-CF	Midpoint Characterization Factor
MJ	Megajoule
MMBtu	Million British thermal units
MMCF	Man-made cellulose fibers (Staple fibers)
MW	Megawatts

mW	milli-Watts
MWh	Megawatt-hours
N <sub>2</sub> O	Nitrous oxide
NAAQS	National Ambient Air Quality Standards
NATA	National Air Toxics Assessment
ND	No Data
NEI	National Emissions Inventory
NO <sub>x</sub>	Nitrogen oxides
O <sub>3</sub>	Ozone
OECD	Organization for Economic Cooperation and Development
PEFC	Programme for the Endorsement of Forest Certification
PM	Particulate matter
PM <sub>10</sub>	Particulate matter 10
PM <sub>2.5</sub>	Particulate matter 2.5
ppb	parts per billion
PP-CF	Potency Potential Characterization Factor
ppm	parts per million
RDF	Resource Depletion Factor
RF	Radiative Forcing
RfC	Reference Concentration
RfD	Reference Dose
SA	South Africa
SO <sub>2</sub>	Sulfur dioxide
TCF	Totally chlorine free
TDF	Terrestrial Disturbance Factor
Tg	Teragram
Thous.	Thousand
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
URA	Undisturbed reference area
V	Viscose
VOC	Volatile organic compound
WHO	World Health Organization
yr	Year

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## 2 Introduction

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In 2014, manmade cellulose fibers constituted approximately 6.4% of global fiber market consumption of 93 million tons<sup>25</sup>. Over the past decade, the market share of manmade cellulose fibers has nearly doubled and demand for these fibers is forecasted to increase further in the next few years. Manmade cellulose fibers have various applications such as apparel, home textile, industrial sectors, etc., of which apparel sector accounted for the largest share of the cellulose fiber market.

Questions have been raised by many stakeholders regarding the environmental performance of different sources of manmade cellulose fiber (MMCF). LCA is a tool which can be used to assess the environmental impacts associated with the supply chain of manmade cellulose fiber production, including all stages of production. LCA provides a unique, quantified approach for comparing the environmental performance of different sources of fiber.

This LCA study provides a comprehensive accounting of the impacts associated with the production of MMCF, made from pulp originating from ten different sources. This comparative LCA study was evaluated, using a methodology conforming to ISO 14044<sup>26</sup>, the draft LEO-S-002 standard,<sup>27</sup> and the Product Category Rule Module for Roundwood (hereafter referred to as Roundwood PCR).<sup>28</sup> The requirements of the draft LEO-S-002 standard ensure that LCA results are as complete, environmentally relevant, and accurate as possible.

### 2.1 Structure and Format of this Report

LCA reports are typically structured and formatted based on four fundamental stages of LCA: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment and (4) Interpretation. The current LCA report includes all the four LCA stages listed above; however, these stages are presented in a different structure and sequence. Figure 3 presents a map of the relevant sections in the current LCA report, where information can be found for each of the four LCA stages.

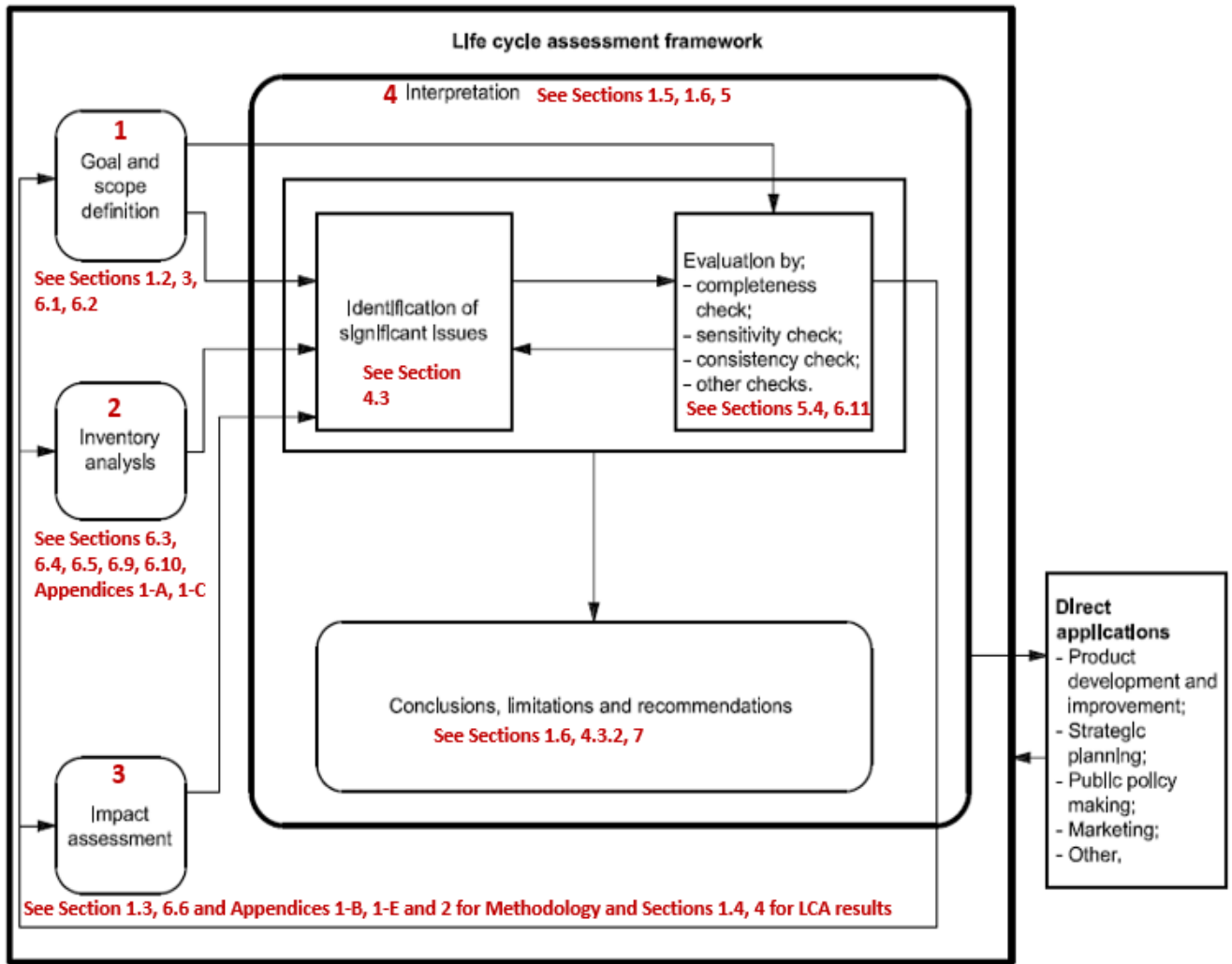
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<sup>25</sup> CIRFS; [www.cirfs.org](http://www.cirfs.org)

<sup>26</sup> ISO 14044:2006 Environmental management – Life Cycle Assessment – Requirements and guidelines

<sup>27</sup> LEO-SCS-002 Standard Draft Dated June 2014. Leonardo Academy.  
<http://www.leonardoacademy.org/programs/standards/life-cycle.html>

<sup>28</sup> PCR Module for Roundwood Production:  
[https://www.scsglobalservices.com/files/resources/pcr\\_final\\_wood-products\\_101816.pdf](https://www.scsglobalservices.com/files/resources/pcr_final_wood-products_101816.pdf)



**Figure 3.** Adapted from Figure 4 of ISO 14044:2006 standard<sup>29</sup> and modified in red text for the purpose of mapping the structure of this LCA report according to the four fundamental LCA stages prescribed by ISO 14044. Relevant sections of the LCA report and Appendices are referenced in red text for each of the 4 LCA stages.

<sup>29</sup> Figure 4- Relationships between elements within the interpretation phase with other phases of LCA from ISO 14044:2006 Environmental management – Life Cycle Assessment – Requirements and guidelines

### 3 Goal and Scope of the Study

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The intended use of this LCA is to support decisions made regarding MMCF sourcing for apparel companies, by quantitatively evaluating the environmental performance of ten different sources of MMCF. The LCA provides information useful in the development of environmental sustainability sourcing strategies for apparel companies, by evaluating the differences in the relative environmental performance of the different fiber sources considered (particularly in relation to terrestrial and freshwater ecosystem impacts).

This LCA also provides quantitative information to identify fiber sources which have improved environmental performance for specific impact categories. An additional goal is to understand the unit processes which are the biggest contributors to environmental impacts.

The intended audience of this LCA are procurement officials at clothing brands, sustainability managers at fiber companies, LCA practitioners, and other stakeholders interested in the environmental performance of different sources of MMCF.

The scope of this LCA is cradle-to-gate. Impacts linked to the production of staple fibers (MMCF) are assessed, while impacts associated with the use and end-of-life of MMCF are excluded, as these life cycle stages are similar for all products considered. The geographical and technological scope includes ten different scenarios, for MMCF made in different regions. The ten sources of MMCF are listed in Table 3, with the locations of the dissolving pulp and fiber mills shown in Figure 4. The dissolving pulp (DP) mills and staple fiber (MMCF) mills included in each of the ten scenarios were identified based on research and in consultation with experts. These mills were selected carefully to represent MMCF production more broadly and the selection criteria was based on geographic location, capacity and grade of MMCF products produced. The temporal scope includes production of MMCF in 2016. The latest available data were used in all cases (see Section 6.5 for summary of data sources).

**Table 3.** Types of manmade cellulose fiber, source of pulp and list of mills considered for each scenario.

Scenario	Type of Manmade Cellulose Fiber (MMCF)	Type and Source of Pulp	Dissolving Pulp (DP) Mill	Staple Fiber (MMCF) Mill
			Country	Country
1. German Production from Swedish Managed Forest Pulp	Viscose staple fibers <sup>30</sup>	Pulp from Sweden	Sweden	Germany
2. Asian Production from Canadian Boreal Forest Pulp <sup>31</sup>	Viscose staple fibers	Pulp from Canada	Canada	China
3. Chinese Production from Indonesian Rainforest Pulp <sup>31</sup>	Viscose staple fibers	Mixed tropical hardwood pulp from Indonesia	Indonesia	China
4. Chinese Production from Indonesian Plantation Pulp <sup>32</sup>	Viscose staple fibers	Eucalyptus pulp from Indonesia	Same as Scenario 3	Same as Scenario 3
5. German Production from Recycled Pulp	Viscose staple fiber	Recycled pulp from clothing inputs	Sweden	Germany
6. Chinese Production from Chinese Bamboo Pulp	Viscose staple fiber <sup>30</sup>	Bamboo pulp from China	China	China
7. Chinese Production from Indian Cotton Linter Pulped in China	Viscose staple fibers	Cotton linter* sourced from India and pulped in China	China	China
8. Chinese Production from South African Plantation Pulp	Viscose staple fibers	Eucalyptus pulp from South Africa	South Africa	China
9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	Lyocell fibers	Mix beechwood and eucalyptus pulp from Austria	Austria/ South Africa	Austria
10. Belgian Flax Production	Flax fibers*	Not Applicable**	Not Applicable	Belgium

\* Scenario 7 and Scenario 10 consider co-products of cotton (cotton linter) and flax fibers (short fibers from combings and card waste) respectively.

\*\*Scenario 10 (Belgian Flax Production) does not involve any pulping process. The flax fibers are chemically processed using proprietary technology to produce fibers that are functionally equivalent to MMCF.

While the Chinese MMCF mills listed for Scenarios 3, 4, 7 and 8 are sourcing from multiple dissolving pulp (DP) mills, for representative purposes, the focus of this study is on dissolving pulp sourced from regions specified in the above table. Scenario 2 considers a hypothetical dissolving pulp mill located in Canada, which is projected to be transformed from a pulp/paper mill to a dissolving grade pulp mill.

<sup>30</sup> In case of Scenario 1: German Production from Swedish Managed Forest Pulp and Scenario 6: Bamboo, data was collected from companies producing viscose filament yarn and not staple fiber. Since highest energy consumption occurs in spinning machines during yarn manufacturing, the energy associated with yarn manufacturing was neglected. The facility energy data for Scenario 1: German Production from Swedish Managed Forest Pulp and Scenario 6 was adjusted (20% of total energy use) based on average energy consumption data relative to 1 ton of staple fiber produced, across all the MMCF mills considered in this study.

<sup>31</sup> These two scenarios are defined as “ancient and endangered” forests under the CanopyStyle initiative. Refer to Section 3.1.1 for more detail.

<sup>32</sup> This scenario is covered by pledges under the CanopyStyle initiative. Refer to Section 3.1.1 for more detail.





**Figure 4.** Location of dissolving pulp (DP) mills and staple fiber (MMCF) mills by scenario. The number assigned to each DP mill and MMCF mill corresponds to the Scenarios included in this study.

Ten different scenarios were considered for manmade cellulose fibers in this assessment:

- **Scenario 1 (“German Production from Swedish Managed Forest Pulp”):** Viscose fibers produced in Germany, originating from a dissolving pulp mill in Sweden.
- **Scenario 2 (“Asian Production from Canadian Boreal Forest Pulp”):** Viscose fibers produced in Asia, made from pulp originating in boreal forests in Canada. Dissolving pulp mill in Ontario, Canada supplies pulp to MMCF mill in China.
- **Scenario 3 (“Chinese Production from Indonesian Rainforest Pulp”):** Viscose fibers produced in China, made from pulp originating from mixed tropical hardwoods in Indonesia. Dissolving pulp mill in Indonesia, supplies pulp to two viscose fiber mills in Fujian and Jiangxi provinces in China.
- **Scenario 4 (“Chinese Production from Indonesian Plantation Pulp”):** Viscose fibers produced in China, made from pulp originating from eucalyptus plantations in Indonesia. Dissolving pulp mill in Indonesia, supplies pulp to two viscose fiber mills in Fujian and Jiangxi provinces in China.
- **Scenario 5 (“German Production from Recycled Pulp”):** Viscose fibers produced in Germany, made from pulp originating from recycled clothing inputs. Recycled pulp plant is located in Sweden.
- **Scenario 6 (“Chinese Production from Chinese Bamboo Pulp”):** Viscose fibers produced in China, made from bamboo pulp originating in China. Dissolving pulp mill located in Hebei province in China, supplies bamboo pulp to viscose fiber mill in Jilin, China.

- **Scenario 7 (“Chinese Production from Indian Cotton Linter Pulped in China”):** Viscose fibers produced in China, made from cotton linter pulp manufactured in China. Cotton linters are assumed to be imported from India to the cotton linter pulp mill in Xinjiang, China.
- **Scenario 8 (“Chinese Production from South African Plantation Pulp”):** Viscose fibers produced in China, made from pulp originating in eucalyptus plantations in South Africa. Dissolving pulp mill in Mpumalanga, South Africa, supplies pulp to viscose fiber mill in Zhejiang, China.
- **Scenario 9 (“Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp”):** Lyocell fibers produced in Austria, made from pulp originating in eucalyptus plantations in South Africa and beechwood sourced from Austria.
- **Scenario 10 (“Belgian Flax Production”):** Flax fibers produced in Belgium, made from by-products of linen industry (e.g. combings and card waste).

This study is a comparative assertion intended to be disclosed to the public. The study was critically reviewed according to ISO 14044, by a panel of four expert stakeholders representing academia, LCA experts, textile industry experts, and the environmental not-for-profit experts, including:

- Neva Murtha (Chair), Senior Campaign Manager, Canopy
- Olivier Muller, PwC Stratégie, Développement Durable, PricewaterhouseCoopers Advisory
- Dr. Richard Condit, Smithsonian Tropical Research Institute
- Dr. Li Shen, Assistant Professor, Copernicus Institute of Sustainable Development, Utrecht University

### 3.1.1 Connection to CanopyStyle Policies

The environmental not-for-profit Canopy, working with numerous stakeholders, scientific supporters and GIS experts, has developed a criteria to define "ancient and endangered forests".<sup>33</sup> Canopy worked with these stakeholders to subsequently identify forest regions to be categorized as "ancient and endangered" according to their definition.

As part of Canopy's CanopyStyle<sup>34</sup> initiative, a number of companies and MMCF fiber producers<sup>35</sup> have committed not to source from these forests.<sup>36</sup> Several scenarios in this LCA report were selected in part to represent the forests included in the CanopyStyle policies. The scenarios which would be covered by policies under this initiative are listed below, for reference:

- Scenario 2 -Chinese Production from Canadian Boreal Forest Pulp
- Scenario 3 - Chinese Production from Indonesian Rainforest Pulp

Also contained within these CanopyStyle policies is a commitment not to source from plantations converted from "ancient and endangered" rainforests after 1994, which would apply to:

- Scenario 4 - Chinese Production from Indonesian Plantation Pulp

These CanopyStyle policies also clarify active support for lower impact non-wood fiber inputs, a commitment that this LCA can provide clarity on (see Figure 1 in Section 1.4).

While this connection to CanopyStyle provides context for companies which have made commitments under this initiative, it is important to note that determining whether MMCF sourced from a specific mill does not originate from wood harvested from CanopyStyle-defined "ancient and endangered" forests requires verification of chain-of-custody across the supply chain.

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<sup>33</sup> The definition used by companies participating in this CanopyStyle initiative is: Ancient and endangered forests are defined as intact forest landscape mosaics, naturally rare forest types, forest types that have been made rare due to human activity, and/or other forests that are ecologically critical for the protection of biological diversity. Ecological components of endangered forests are: Intact forest landscapes; Remnant forests and restoration cores; Landscape connectivity; Rare forest types; Forests of high species richness; Forests containing high concentrations of rare and endangered species; Forests of high endemism; Core habitat for focal species; Forests exhibiting rare ecological and evolutionary phenomena. As a starting point to geographically locate ancient and endangered forests, maps of High Conservation Value Forests (HCVF), as defined by the Forest Stewardship Council (FSC), and of intact forest landscapes (IFL), can be used and paired with maps of other key ecological values like the habitat range of key endangered species and forests containing high concentrations of terrestrial carbon and High Carbon Stocks (HCS). (The Wye River Coalition's Endangered Forests: High Conservation Value Forests Protection – Guidance for Corporate Commitments. This has been reviewed by conservation groups, corporations, and scientists such as Dr. Jim Stritholt, President and Executive Director of the Conservation Biology Institute, and has been adopted by corporations for their forest sourcing policies). Key endangered forests globally are the Canadian and Russian Boreal Forests; Coastal Temperate Rainforests of British Columbia, Alaska and Chile; Tropical forests and peat lands of Indonesia, the Amazon and West Africa.

<sup>34</sup> See <http://www.canopystyle.org/>

<sup>35</sup> [www.canopyplanet.org](http://www.canopyplanet.org)

<sup>36</sup> Based on electronic communication received from Canopy on 6/15/2017 at 9:55PM Pacific time.

## 4 Results

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### 4.1 Interpretation of LCA results

The results of this LCA are presented in this section for 1,000 tons of MMCF produced. For each impact category, the following information is provided:

- Results for each scenario illustrated by impact group (refer to Figure 1 in Section 1.4)
- Contribution analysis for each scenario, showing the process contribution, in percent, of the “key” unit processes (i.e., most significant contributors), to each scenario.

This LCA contains a relatively larger number of impact categories than previous LCAs of MMCF. These impact categories are associated with five groups of endpoints: Climate System Impacts, Ocean Ecosystem Impacts, Terrestrial and Freshwater Ecosystem Impacts, Resource Depletion Impacts, and Human Health Impacts. The number of impact categories within these groups which are relevant, varies from 12 to 18, depending on the source of MMCF. The number of selected impact categories is intended to comprehensively reflect all impacts relevant to MMCF production.

While there are a number of impact categories in the scope, this LCA does not use numerical weighting or any other approach to indicate any priority or importance of any impact category over any other. For impact categories with effects on very different endpoints, there is no objective basis for weighting; considerations such as the scale of impact, irreversibility, stakeholders affected, and contribution to local impacts associated with MMCF, all must be factored in making these weightings. For example, whether Global Climate System Impacts should be given a greater weight than Terrestrial Disturbance, requires the counter-balancing of spatial scale of impact (much larger for Global Climate Impacts) and contribution from MMCF; while MMCF production has a trivial influence on Global Climate Impacts, it can have a major effect on Terrestrial Disturbance. This means that while policies aimed at minimizing Global Climate Impacts from MMCF cannot have any major effect on Global Climate Change, policies intended to reduce Terrestrial Disturbance could have measurable improvements in local conditions.

For impact categories with similar endpoints, weighting and aggregation of impact categories is not possible due to a lack of data of sufficient accuracy. For example, both PM2.5 Exposure Risks and Hazardous Ambient Air Pollutants Emissions result in human health endpoints; but making an aggregate estimate of a factor such as Disability Adjust Life Years (DALYs) would require numerical evaluations of dose-response of selected populations, comparison of potentially very different human health effect, and other factors, preventing a scientific and objective weighting to be completed.

Weighting and prioritization involves value choices and subjective considerations which vary user-by-user and even within a given decision making context, and are outside the scope of this LCA.

## 4.2 LCA Results

This LCA study includes an extensive amount of detailed information across ten scenarios of MMCF production and many impact categories. This section includes the following:

- A summary of the type and number of relevant impact categories, by scenario, is provided (summarized in Table 4).
- Results summarized for all ten scenarios, by impact group category indicator (see Table 5).
- Results presented by impact category group and the accompanying contribution analyses for impact category results (Figure 5 through Figure 18).

This structure allows for focus on key impact categories of concern where desired.

### **Summary of Relevant Impact Categories, by Scenario**

Following LEO-S-002 requirements, results for distinct impact categories are reported whenever distinct environmental impacts linked to MMCF production are observed. Conversely, LCA results for scenarios (e.g. Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production) for which no impacts are observed, are not included. This ensures that LCA results are fully transparent, yet focused only on impacts which are actually linked to staple fiber (MMCF) production.

The “core” impact categories relevant to the production of each of the ten scenarios of MMCF production were identified by reviewing the default list of impact categories in Table 3 of LEO-S-002. For some impact categories, multiple impacts were observed; in these cases, multiple category indicators were defined for each impact, and multiple results reported. The core impact categories, and number of relevant impacts in each category, are shown in Table 4 for each scenario of MMCF production. Note that results for few impact categories (indicated as ‘ND= No Data’ in Table 4) could not be evaluated, due to a lack of comparable information across all scenarios.

**Table 4.** Number of relevant impacts considered by impact category for each of the ten scenarios. ND = No data.

Impact Categories by Group	Relevant Impacts considered by Scenario									
	1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian Managed	10. Belgian Flax Production
<b>Biotic/Abiotic Resource Depletion Impacts</b>										
Nonrenewable Energy Resource Depletion	1	1	1	1	1	1	1	1	1	1
Net Freshwater Consumption	1	1	1	1	1	1	1	1	1	1
Wood Resource Depletion	1	1	1	1	0	1	0	1	1	0
<b>Global and Regional Climate System Impacts</b>										
Global Climate Change	1	1	1	1	1	1	1	1	1	1
Regional Climate 'Hotspot' Impacts	0	0	1	1	0	1	1	1	0	0
<b>Ocean Ecosystem Impacts</b>										
Ocean Acidification	1	1	1	1	1	1	1	1	1	1
Ocean Warming	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
<b>Terrestrial &amp; Freshwater Ecosystem Impacts (from Emissions)</b>										
Regional Acidification	1	1	1	1	1	1	1	1	1	1
Freshwater Eutrophication	1	ND	ND	ND	ND	ND	ND	ND	ND	ND
<b>Terrestrial &amp; Freshwater Ecosystem Impacts (from Land Use and Conversion)</b>										
Terrestrial/Forest Disturbance	1	1	1	1	0	1	1	1	1	1
Freshwater Disturbance	ND	ND	ND	ND	0	ND	ND	ND	ND	ND
Wetland Disturbance	ND	ND	ND	ND	0	ND	ND	ND	ND	ND
Threatened species Habitat Disturbance	See Appendix 1-C for detailed list of species impacted in each Scenario.									
<b>Human Health Impacts (from Chronic Exposure to Hazardous Chemicals)</b>										
Ground Level Ozone Exposure Risks	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PM 2.5 Exposure Risks	1	1	1	1	1	1	1	1	1	1
Hazardous Ambient Air Contaminant Exposure Risks - Respiratory (Non-Cancer) Health Effects	1	1	1	1	1	1	1	1	1	1
Human Health Impacts- Cancer Risks	1	1	1	1	1	1	1	1	1	1
Health Impacts from Exposure to Toxic Herbicides	ND	ND	ND	ND	0	ND	ND	ND	ND	ND

## Results Summary

The results are provided for the production of 1,000 tons of MMCF, for all ten scenarios, by impact group category indicator (see Table 5).

**Table 5.** LCA results for 1000 tons of MMCF, by impact category, by scenario. (ND= No Data)

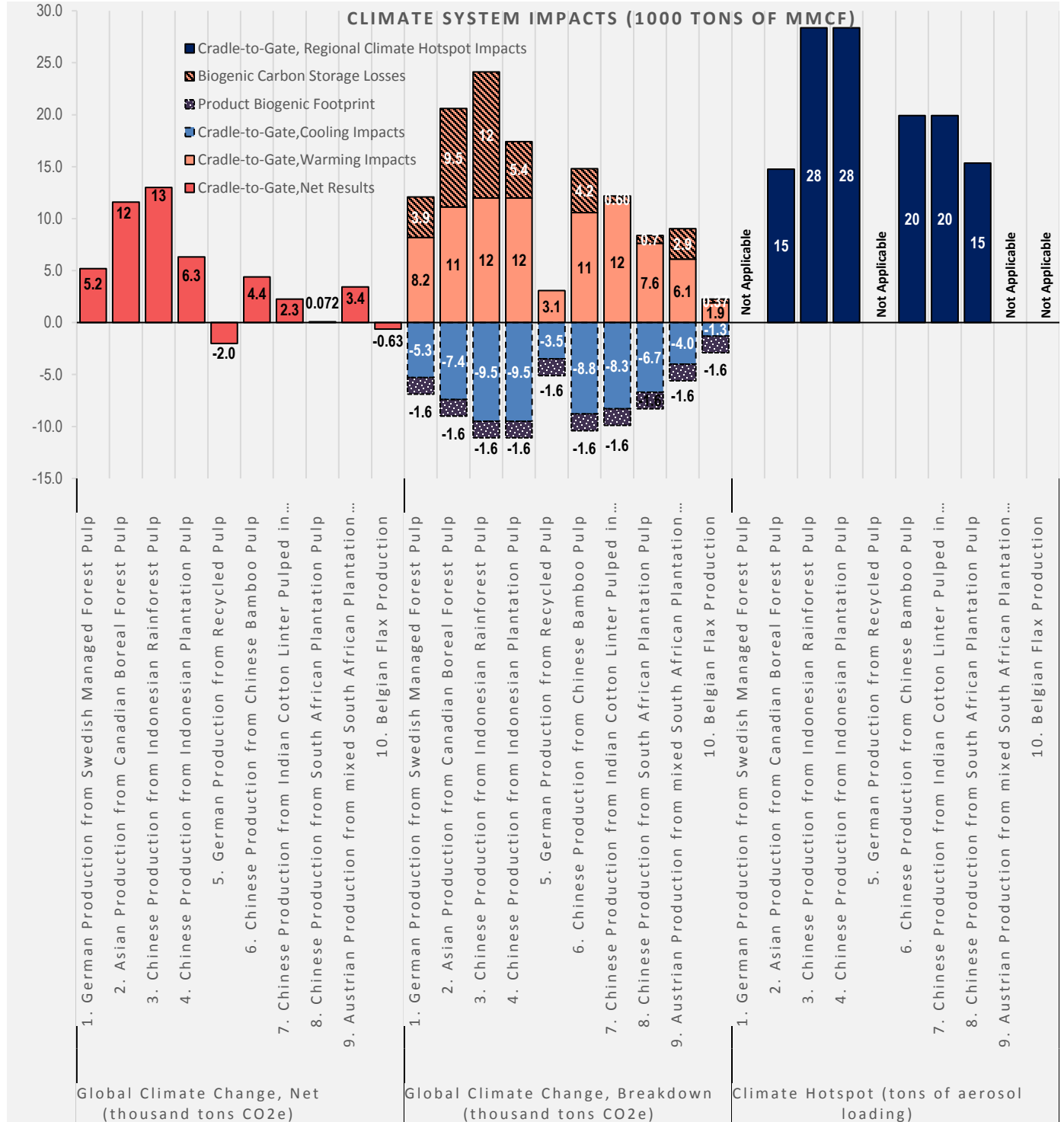
Impact Categories by Group	Units	1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	10. Belgian Flax Production
<b>Biotic/Abiotic Resource Depletion Impacts</b>											
Nonrenewable Energy Resource Depletion	thousand GJ eq	22	33	37	37	21	26	34	28	25	9
Net Freshwater Consumption	thousand m <sup>3</sup>	327	422	310	310	377	738	740	432	290	262
Wood Resource Depletion	thousand m <sup>3</sup>	No Impact	5.5	5.2	No Impact	No Impact	No Impact	No Impact	No Impact	No Impact	No Impact
<b>Global and Regional Climate System Impacts</b>											
Global Climate Change, Net	thousand ton CO <sub>2</sub> eq	5.2	12	13	6.3	-2.0	4.4	2.3	0.072	3.4	-0.63
Regional Climate Impacts	ton aerosol loading	No Impact	15	28	28	No Impact	20	20	15	No Impact	No Impact
<b>Ocean Ecosystem Impacts</b>											
Ocean Acidification	thousand ton H <sub>2</sub> CO <sub>3</sub> eq	3.4	6.3	7.4	5.0	1.1	4.3	3.2	1.9	3.3	0.60
Ocean Warming	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
<b>Terrestrial &amp; Freshwater Ecosystem Impacts (from Emissions)</b>											
Regional Acidification	ton SO <sub>2</sub> eq	33	46	80	80	33	48	50	42	14	5
Freshwater Eutrophication	ton NO <sub>3</sub> eq	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
<b>Terrestrial &amp; Freshwater Ecosystem Impacts (from Land Use and Conversion)</b>											
Terrestrial Disturbance	eq hectares disturbed* yrs.	250	435	787	304	No Impact	89	116	41	158	40
Freshwater Disturbance	eq hectares disturbed* yrs.	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Wetland Disturbance	eq hectares disturbed* yrs.	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Threatened species Habitat Disturbance	number of species	7	7	55	55	No Impact	ND	ND	14	25	6
<b>Human Health Impacts (from Chronic Exposure to Hazardous Chemicals)</b>											
PM 2.5 Exposure Risks	persons*hrs* μg PM2.5 eq/m <sup>3</sup>	7,800	162,888	244,372	244,372	13,116	507,578	451,109	164,947	13,980	4,300
Hazardous Ambient Air Contaminant Exposure Risks – Respiratory (Non-Cancer) Health Effects	kg acrolein eq	5.5	6.6	5.6	5.6	5.3	6.6	8.3	5.1	3.7	1.5
Human Health Impacts- Cancer Risks	kg Cr VI eq	0.9	0.8	0.9	0.9	0.7	0.8	0.7	0.7	0.7	0.3
Ground Level Ozone Exposure Risks	persons*hrs* kg O <sub>3</sub> eq/m <sup>3</sup>	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Exposure to Toxic Herbicides	N/A	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

## **Results and Contribution Analyses, by Impact Category**

Results and accompanying contribution analyses are presented below, by group of impact categories (see Figure 5 through Figure 18). A detailed description of the methodology used in this report is found in Section 6 of this report, while Appendix 2 contains the detailed approach used in the LCIA methodology.

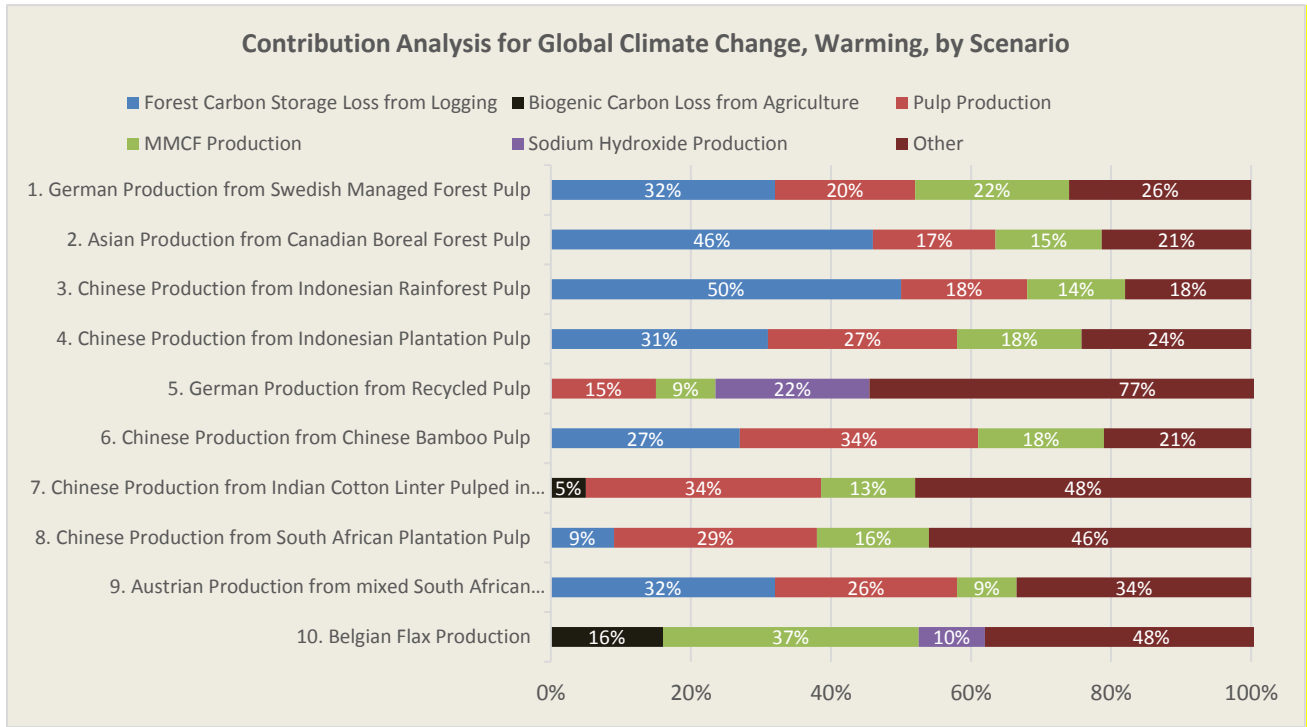


Climate System Impacts

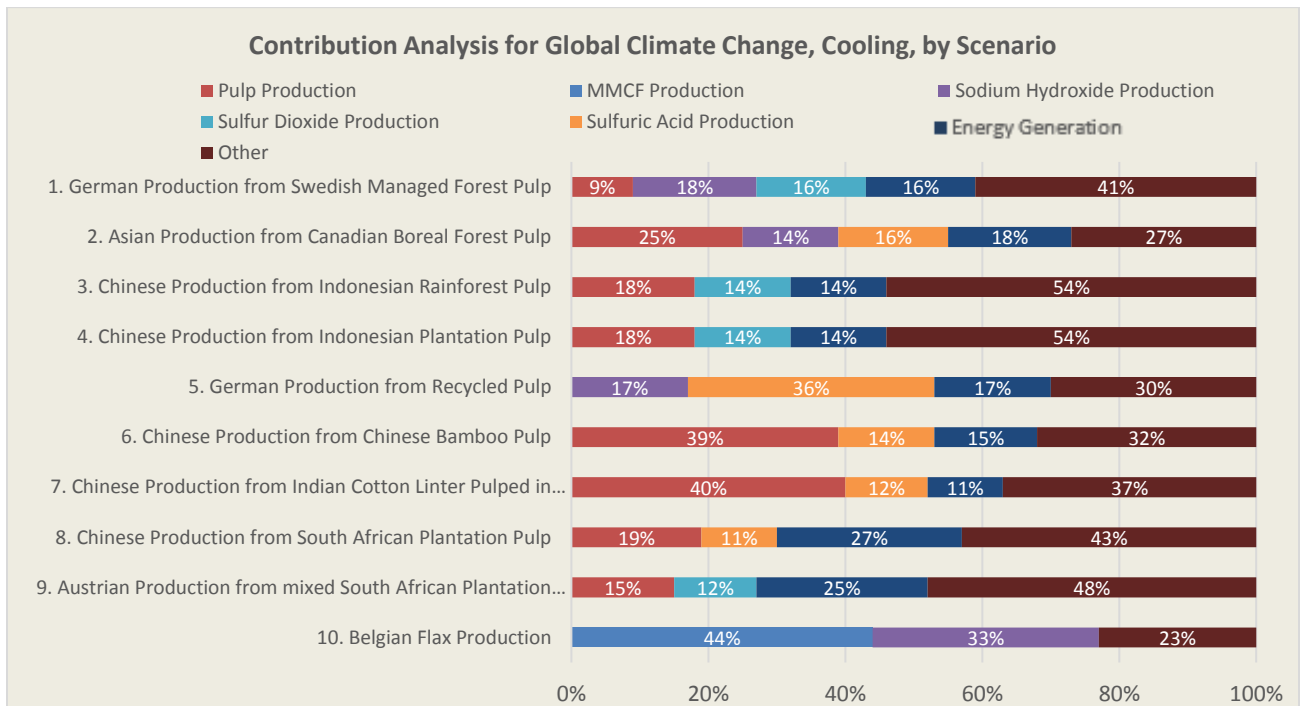


**Figure 5.** Results for Global Climate Change and Climate Hotspot Impact categories. A breakdown of the Global Climate Change, Net results has been provided. The net results for Global Climate Change includes forest carbon storage impacts, warming impacts, cooling impacts and the embodied carbon stored in the product. See Appendix 2 for calculation details and Section 5.2.2 for interpretation of results.

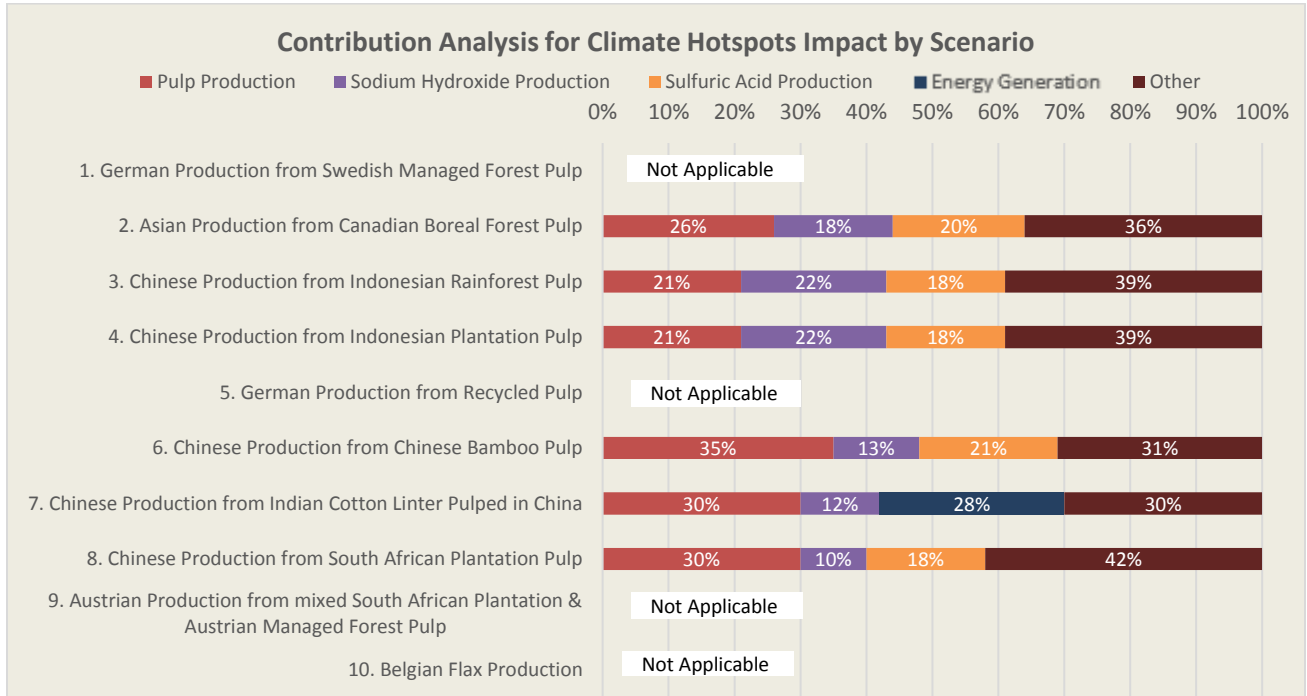
**Contribution Analysis for Climate System Impacts**



**Figure 6.** % Contribution analysis by Scenario for Global Climate Change, Warming impact category. *Note:* Product biogenic carbon stored in the product is not included in this contribution chart. See Figure 2 for estimates of carbon stored in the MMCF products.

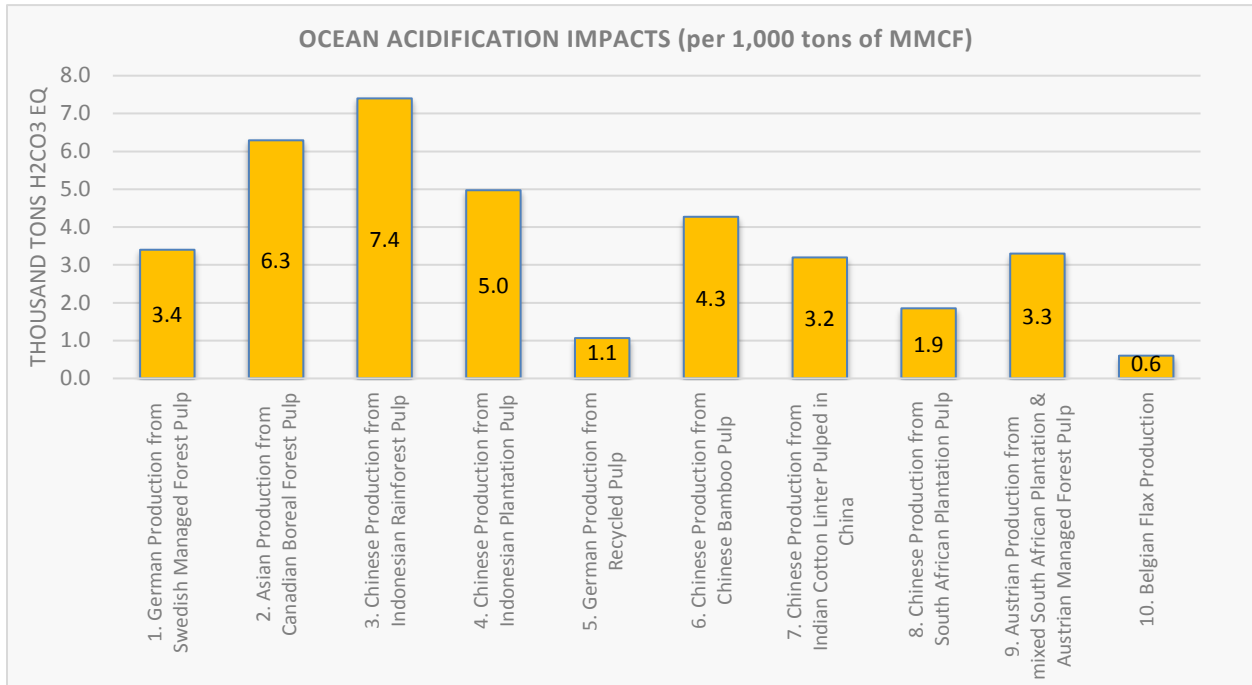


**Figure 7** % Contribution analysis by Scenario for Global Climate Change, Cooling impact category.



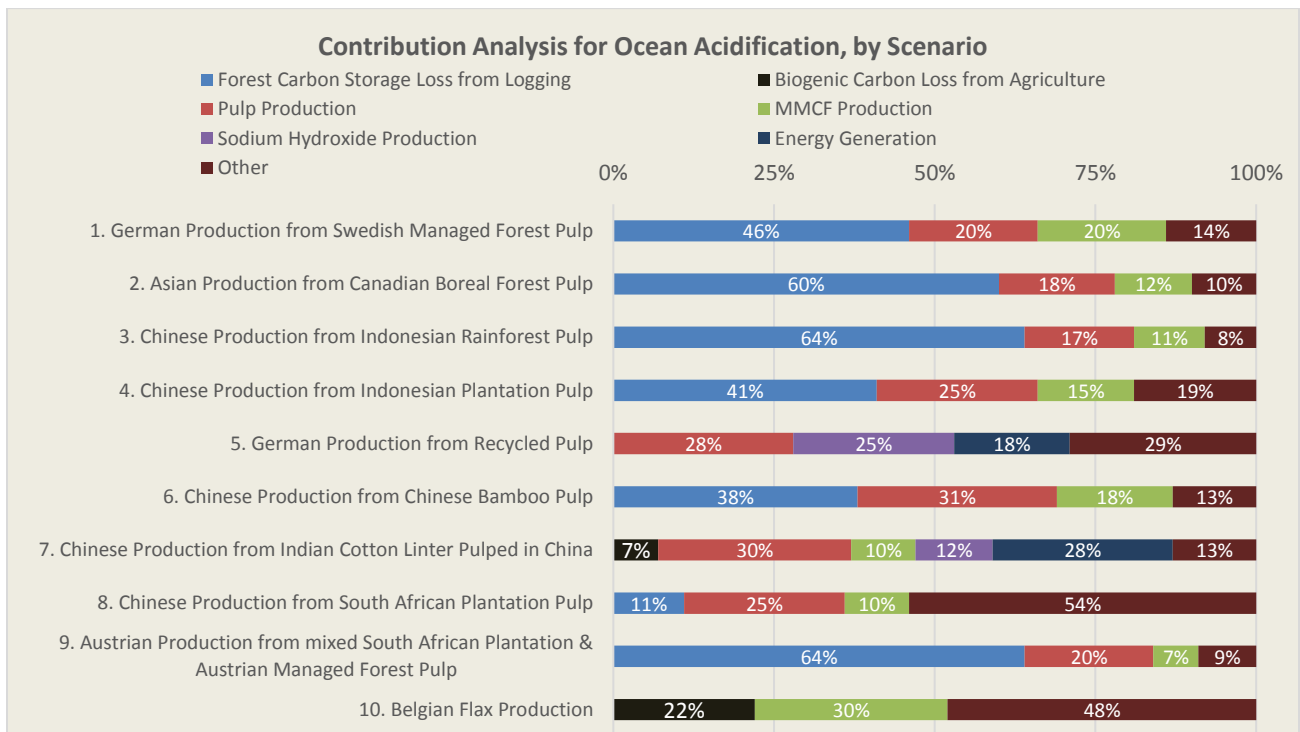
**Figure 8** % Contribution analysis by Scenario for Climate Hotspot impact category.

**Ocean Ecosystem Impacts**



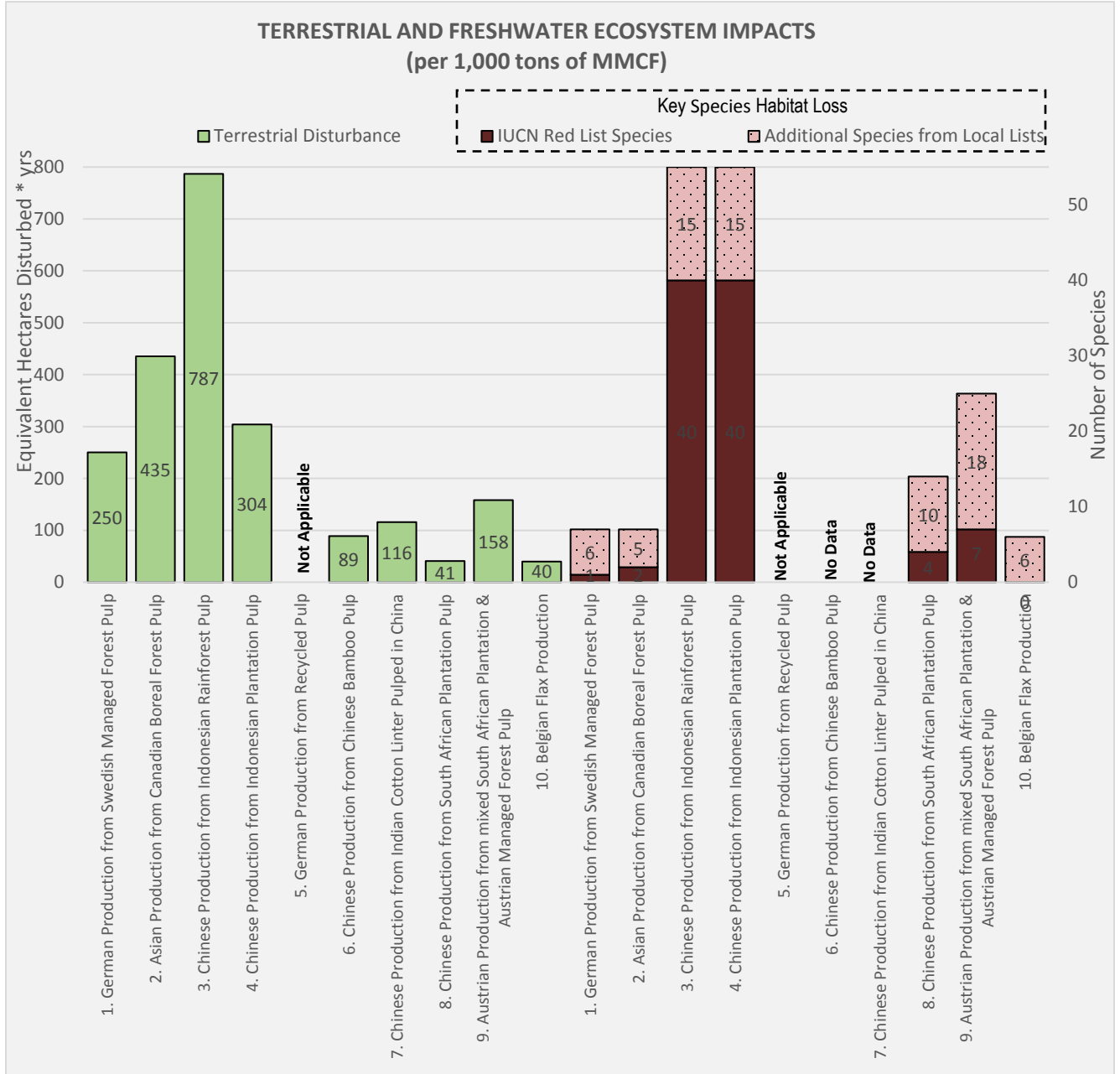
**Figure 9.** Results for Ocean Acidification. See Appendix 2 for calculation details and Section 5.2.3 for interpretation of results.

**Contribution Analysis for Ocean Acidification Impacts**



**Figure 10.** % Contribution analysis by Scenario for Ocean Acidification.

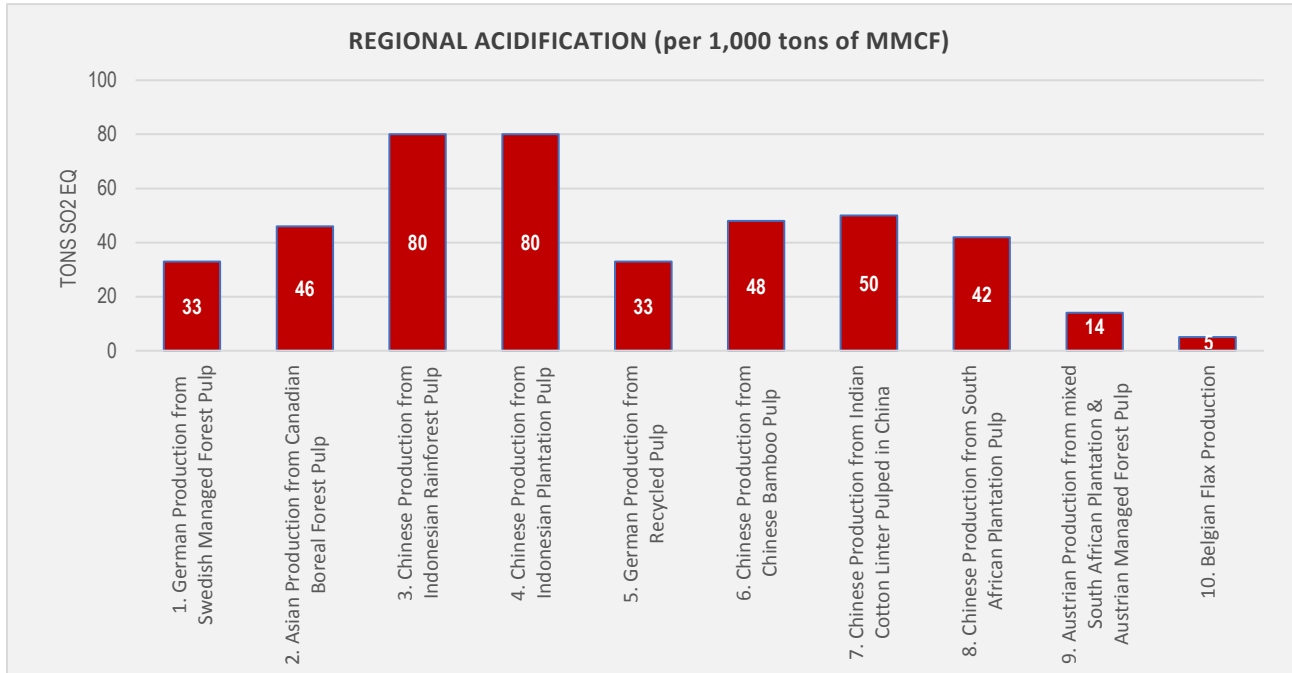
**Terrestrial and Freshwater Ecosystem Impacts (from Land Use and Conversion)**



**Figure 11.** Results for Terrestrial Disturbance and Key Species Habitat Loss<sup>37</sup> impact categories; an extended timeframe of 20 years is considered to capture temporal aspects of ecosystem impacts relevant to pulpwood production (which is the main raw material for MMCF). See Appendix 2 for calculation details and Section 5.2.5 for interpretation of results.

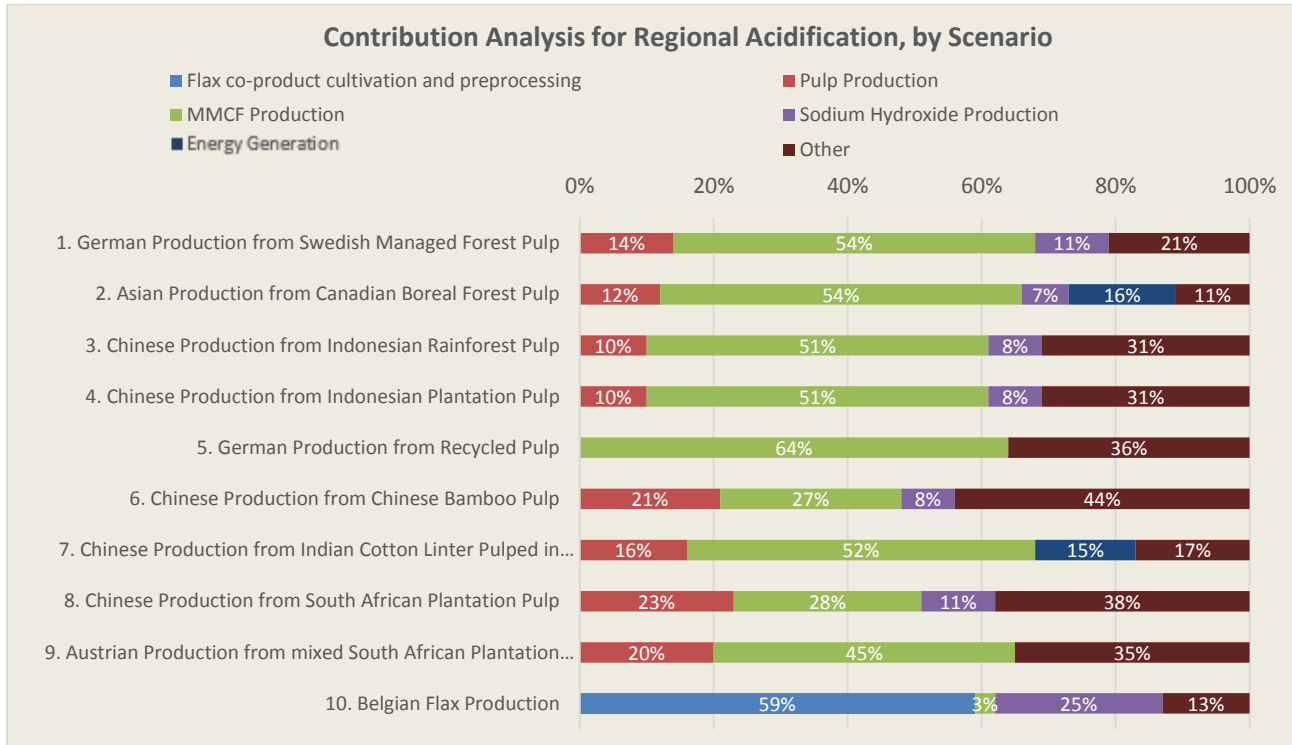
<sup>37</sup> This indicator includes threatened (includes Vulnerable, Endangered and Critically Endangered status) species from two lists for applicable scenarios: (1) IUCN Red List Species, which is a global-level species list and (2) Additional species from local lists (evaluated by local governments).

**Regional Environmental Impacts from Emissions**



**Figure 12.** Results for Regional Acidification; See Appendix 2 for calculation details and Section 5.2.4.1 for interpretation of results.

**Contribution Analysis for Regional Acidification**



**Figure 13.** % Contribution Analysis by Scenario for Regional Acidification

Resource Depletion Impacts

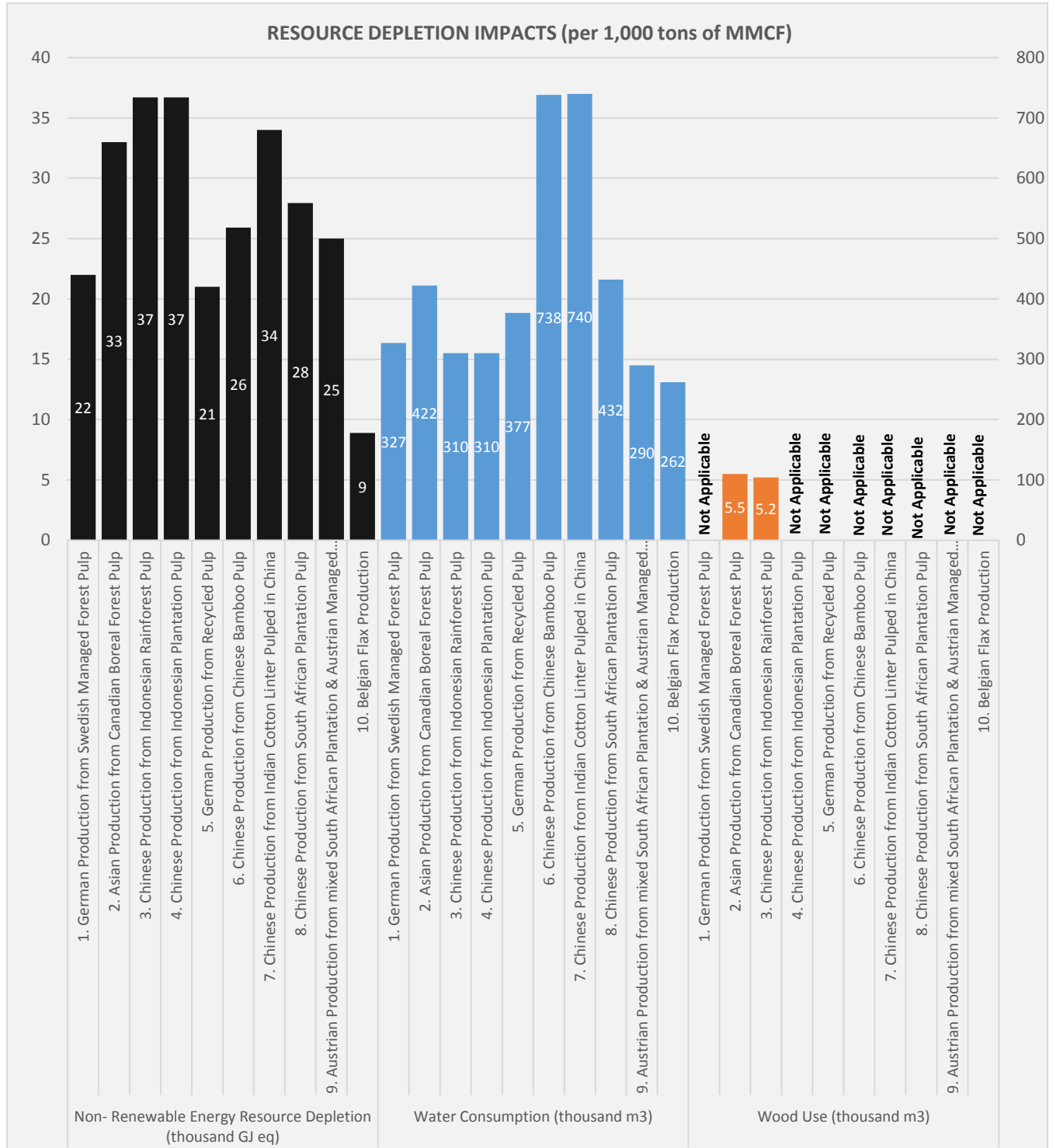
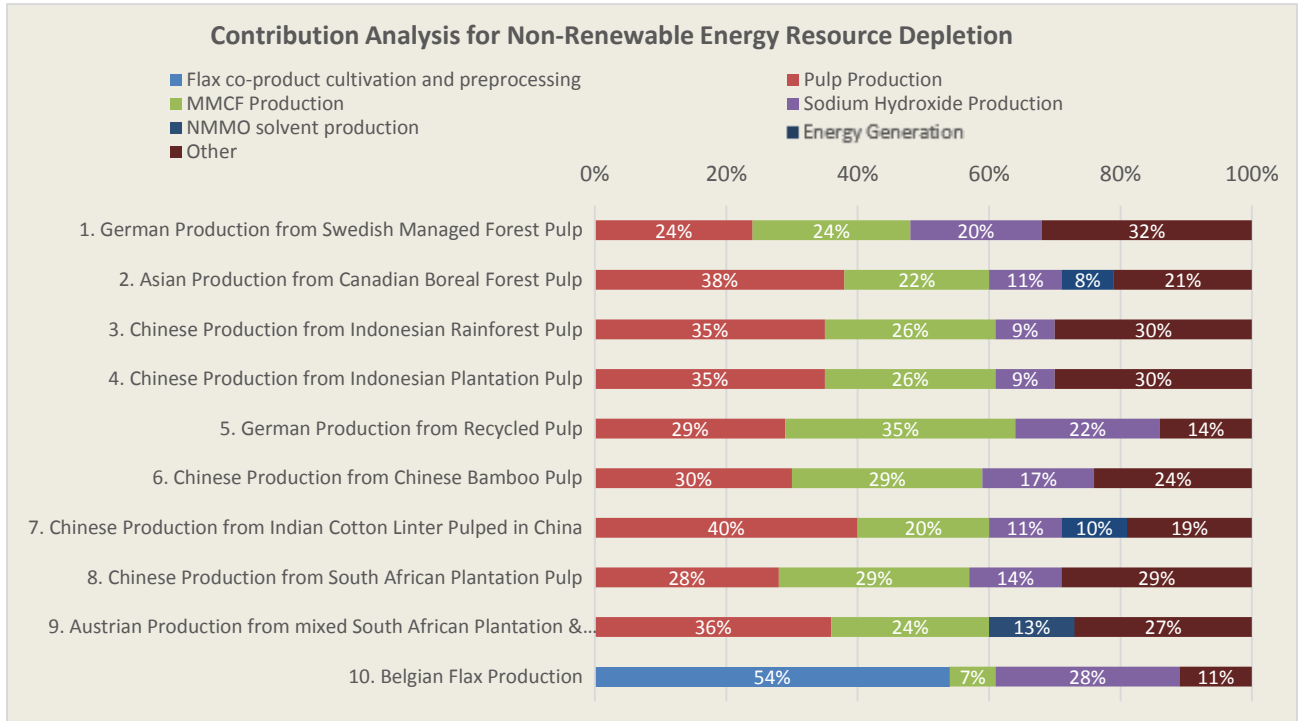
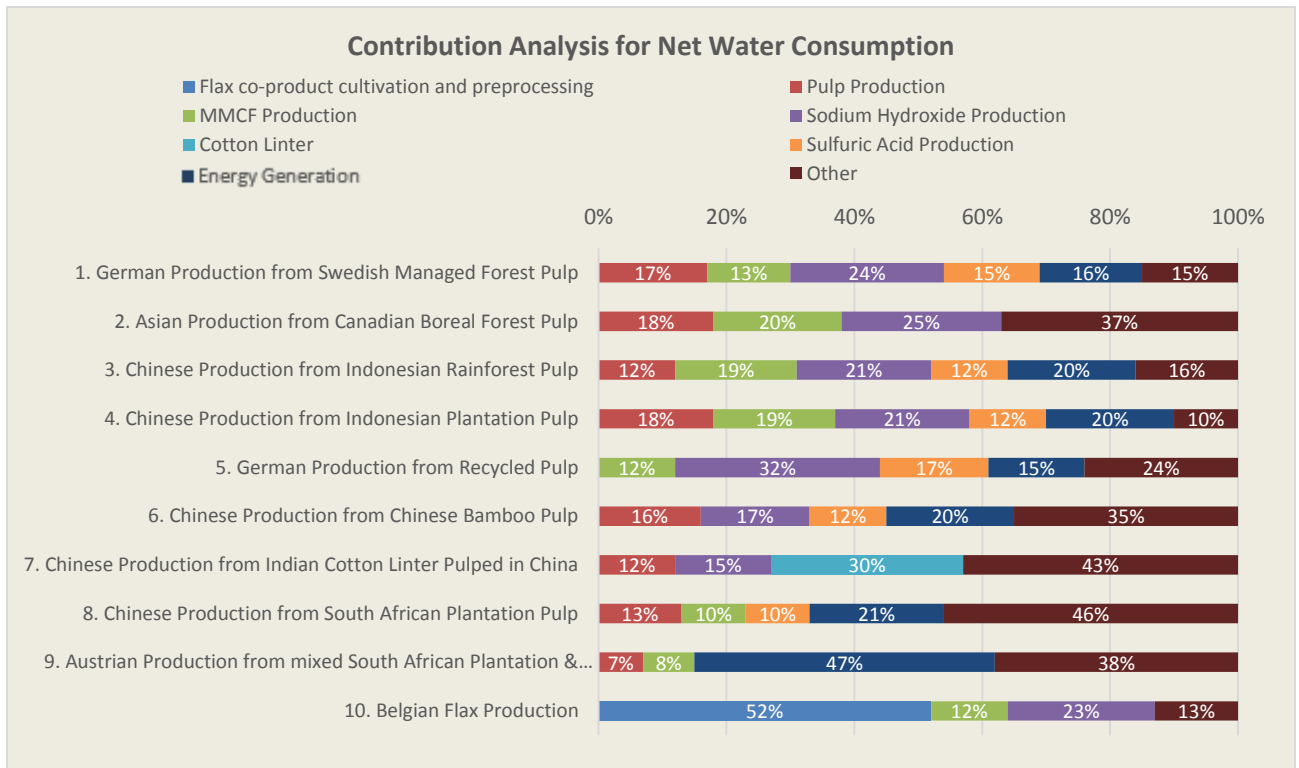


Figure 14. Results for Non-Renewable Energy Resource Depletion, Water Consumption and Wood Resource Depletion impact categories. See Appendix 2 for calculation details and Section 5.2.1 for interpretation of results.

**Contribution Analysis for Resource Depletion Impacts**



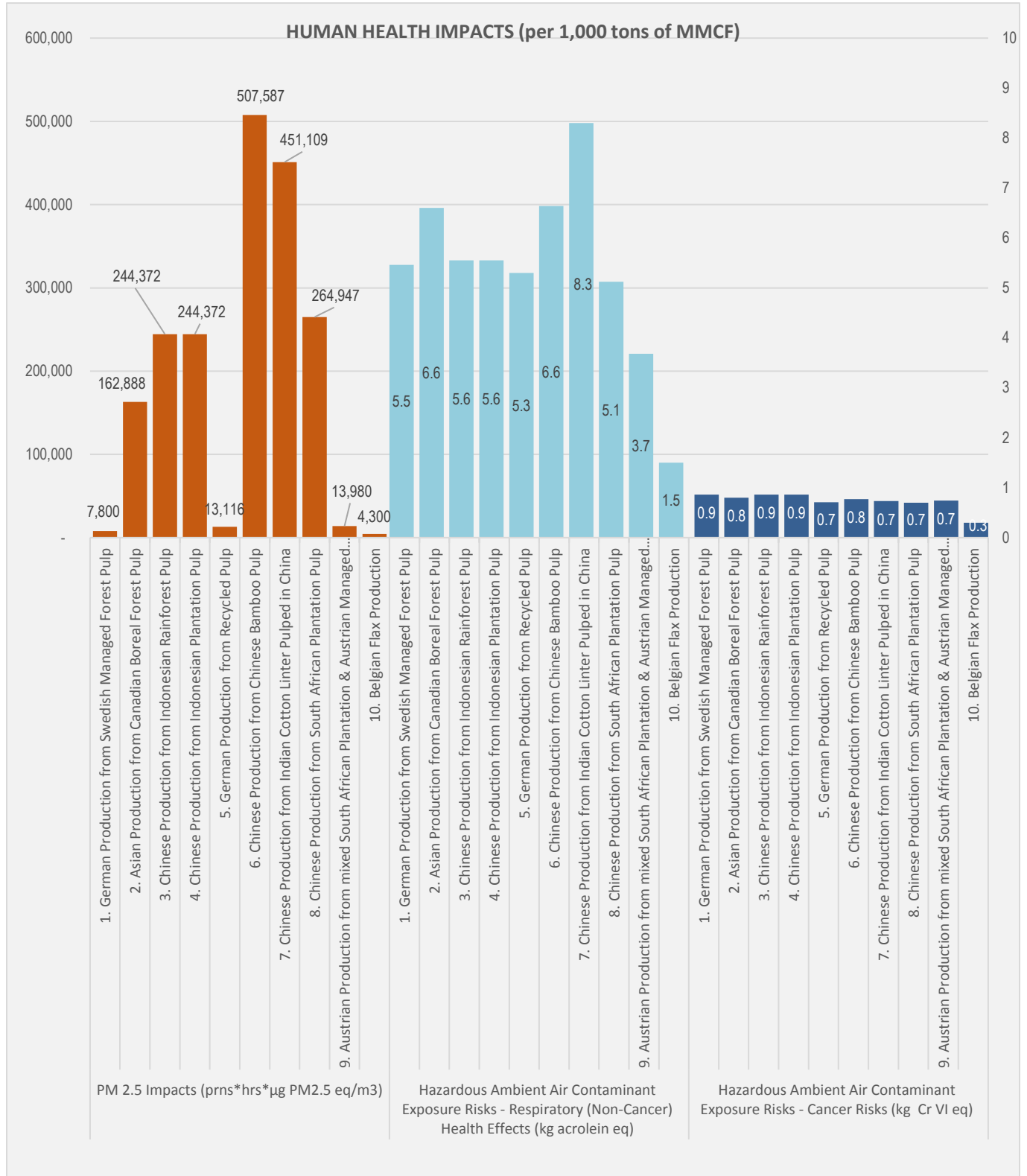
**Figure 15.** % Contribution Analysis by Scenario for Renewable Energy Resource Depletion.



**Figure 16.** % Contribution Analysis by Scenario for Net Water Consumption.

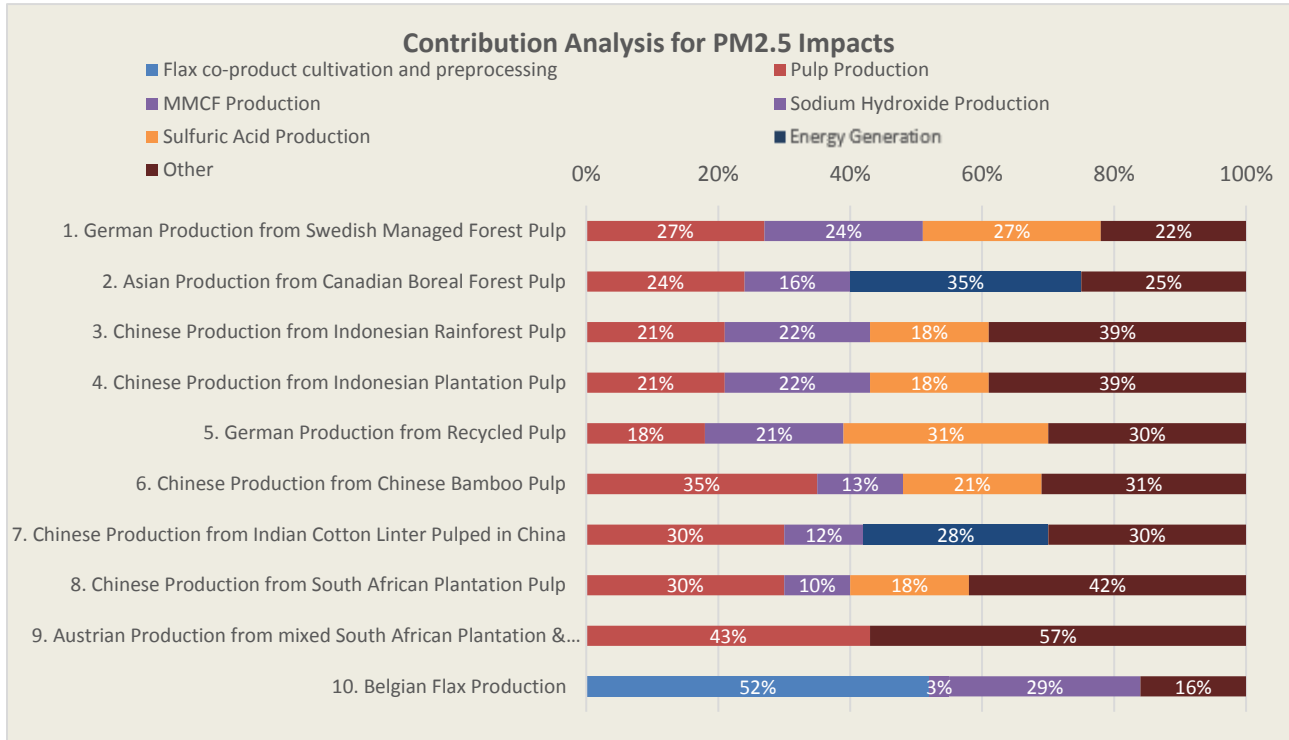


**Human Health Impacts from Emissions**



**Figure 17.** Results for PM 2.5 Exposure Risks, Hazardous Ambient Air Contaminant Air Exposure Risks (Non-Cancer and Cancer Risks). See Appendix 2 for calculation details and Section 5.2.6 for interpretation of results.

**Contribution Analysis for PM2.5 Impacts**



**Figure 18.** % Contribution Analysis by Scenario for PM2.5 Impacts

**Data Quality Analysis**

The data quality analysis accounts for the cumulative effects of input uncertainty, data variability and model imprecision. It considers the data quality of inventory data and the LCIA method, considering the data quality parameters such as temporal coverage, geographic coverage, technology coverage, precision, completeness, uncertainty and reproducibility (refer to Table 28 in Appendix 1-G for more detail). The overall data quality was evaluated for the LCI data relevant to each indicator and the LCIA method (i.e. the data relevant in calculating each indicator). The overall data quality of the indicator result is the lower quality of those two parameters. The data quality (by source), are described in Table 6. See Appendix 1-G for more information.

**Table 6.** The data quality in combined data quality in final results, by indicator result. H = High, M = Medium, L = Low, N/A=Not Applicable

Indicator	1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	10. Belgian Flax Production
Non-Renewable Energy Resource Depletion	H	M	M	M	M	M	M	M	L	H
Water Consumption	M	L	L	L	M	L	L	L	L	M
Wood Resource Depletion	M	M	L	L	N/A	L	N/A	N/A	M	N/A
Terrestrial Disturbance	H	H	M	M	N/A	L	L	L	M	M
Global Climate Change	H	M	M	M	M	M	M	M	L	H
Regional Climate Hot Spot Impacts	N/A	L	L	L	N/A	L	L	L	N/A	N/A
Ocean Acidification	M	M	L	L	M	L	L	L	L	M
Regional Acidification	H	M	M	M	M	L	L	M	L	H
PM2.5 Exposure Risks	H	M	M	M	M	L	L	M	L	H
HAAC Exposure Risks	L	L	L	L	L	L	L	L	L	L

### 4.3 Key Limitations and Assumptions

#### 4.3.1 Assumptions

A number of assumptions were made as a result of data limitations or for other reasons. These assumptions are important to understand, as some result in study limitations (discussed in Section 4.3.2). The assumptions with the most important effects on final results are as follows:

- Several assumptions were made in order to determine the fiber basket for all the ten scenarios (except Scenario 5: German Production from Recycled Pulp). Refer to 'Forestry in Mill Fiber Basket' described for each scenario in Section 6.9 for a description of the process used for each. The fiber baskets and areas studied within each were carefully selected so as to represent a large area, which is representative of practices in the region as a whole.
- It is assumed that all chemical inputs required for producing dissolving pulp and MMCF are manufactured in the same region in which the mills are located. This assumption was made in order to apply regional factors for certain impact categories. Results do not strongly depend on this assumption, as it is likely that most chemical inputs are sourced in the same region, and variations due to transportation and different production mixes would not have a significant effect on final results, given the materiality of these production steps on final results.
- In identifying the threatened species impacted by forestry in each fiber basket, several simplifying assumptions were made, as discussed in Appendix 2.
- In the assessment of Climate Change and Ocean Acidification Impacts, which result from effects of forest carbon storage by forestry in the fiber baskets of the integrated mills, several simplifying assumptions are made (see Appendix 2).
- The MMCF mills considered in Scenario 1: German Production from Swedish Managed Forest Pulp and Scenario 6: Chinese Production from Chinese Bamboo Pulp produce viscose filament yarn and not manmade cellulose fiber. Primary data on facility energy use included the energy consumed during yarn formation processes as well. However, the scope of this study only includes staple fiber (MMCF). Hence, the facility energy use was adjusted based on the average energy consumption data relative to 1 ton of staple fiber produced, across all the MMCF mills considered in this study. The total adjustment was 20% of total energy use, and since facility energy use accounts for no more than 19% of any indicator result, results do not strongly depend on this assumption.
- Scenario 2: Asian Production from Canadian Boreal Forest Pulp explores a hypothetical scenario of a dissolving pulp mill operating in the boreal region in Ontario, Canada; supplying dissolving pulp to an MMCF mill in China. This scenario is based on the impending conversion of many pulp and paper mills currently operating in the boreal region into dissolving grade pulp mills. A representative mill where this conversion is planned in the near future was selected for this study. It is assumed that pulpwood from boreal forests will be sourced by the mill for dissolving pulp production. Representative inventory data for dissolving pulp production was used in the LCA model.

- Data on transport distances for chemical inputs were not available for many of the scenarios. To avoid any bias, the same road freight transport of 200 miles was assumed as a default distance for all scenarios (see Section 6.10). Transportation was no more than 1% of any indicator result and so the results do not strongly depend on this assumption.
- In the case of Scenario 5: German Production from Recycled Pulp, it was not possible to determine the MMCF mill that would consume the recycled pulp produced by Recycled DP Mill. This is because Recycled DP Mill is in the process of scaling up its recycling technology and the manufacturing facility is currently under construction. Thus, for the purpose of this study, it is assumed that recycled pulp is delivered to MMCF mill in Germany.
- During logging, decay and/or combustion of aboveground logging residues (i.e., “slash”) and carbon stored in tree roots were assumed to occur immediately, with all of the carbon assumed to be converted into emissions of CO<sub>2</sub> (this is applicable to all scenarios except 5, 7 and 10). It is assumed that slash left on the site is 25% of the harvest volume. Belowground roots are assumed to have a carbon mass same as in slash. These fractions are considered typical of most forestry practices, and have been used in past LCAs.<sup>38</sup> In case of Scenario 6: Chinese Production from Chinese Bamboo Pulp and Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China, it is assumed that residues left on the field make a negligible contribution to emissions.
- It was not possible to determine whether all unit processes in all ten scenarios were in regions experiencing water scarcity, mainly due to the fact that the locations of background unit processes could not be determined. To be conservative, the water resources used for these unit processes were assumed to be exploited and an M-CF of 1 was applied to account for all the upstream water consumption in the product systems considered.

#### 4.3.2 Limitations and Significant Data Gaps

There are several key study limitations, resulting from limitations in the methodology used and data gaps, as well as assumptions made. The main limitations in the study are as follows:

- **Data not provided by manufacturers.** For scenarios 2, 3, 4, 6, 7, 8, 9 primary data were not provided by manufacturers. This is applicable to the DP mills in the Indonesian scenario (Scenario 3 and 4), dissolving pulp production in Austria (Scenario 9), and MMCF production in China (Scenarios 2, 3, 4, 6, 7 and 8). This data gap was overcome by using mill-level data developed by third parties like RISI Mill Asset database for the specific mills selected in this study. Data from RISI Mill Asset database and Chinese MMCF production database provided by a market research company in China were used in this study. Data from the RISI Mill Asset database did not include waste outputs, water use and amount of chemical inputs; these gaps were filled using background data on pulp production in Ecoinvent v3.1 and primary data

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<sup>38</sup> SCS Global Services, October 2015. Life Cycle Assessment of Reincarnation 100 Coated Freesheet Compared to Virgin Paper Products.

obtained for Scenario 1 and Scenario 10. Data for the MMCF fiber mills obtained from Chinese database did not include data on facility fugitive air emissions, water emissions, and other auxiliary chemical inputs; these gaps were filled using primary data obtained for German MMCF mill and background data on viscose production in Ecoinvent v3.1.

- **Limitations resulting from scope of the study.** The study was cradle-to-gate, ending at the production of MMCF. Impacts associated with the use and end-of-life of MMCF are excluded.
- **Use of different mills in a given scenario could influence results.** The dissolving pulp mills and MMCF mills were identified carefully, based on characteristics including location of the mill, current supply chain of the MMCF mills and production capacities, and overall representativeness of local industry in the considered scenario. The mills included were reviewed in consultation with experts and so serve as representations adequate to achieve the goals of the study, but it should be recognized use of different mills could affect results.
- **Lack of geographic specificity of impacts to hazardous ambient air contaminant exposure risks and mercury emissions.** These LCA results have limited relevance to environmental performance, as the results presented here have a weak correlation to observed impacts. Depending on the location and timing of emissions of these pollutants, the resulting impacts have high variability in severity. However, no data were available to evaluate site-specific results.
- **Lack of data to calculate Ground Level Ozone Exposure Risk, Ocean Warming, and Exposure to Toxic Herbicides.** Production of MMCF from all ten sources results in impacts relevant to these impact categories. However, consistent data on emissions and/or algorithms for assessment of impacts were not available to assess impacts from all mills. These impacts are all relevant to MMCF production and of major importance, but results could not be assessed in a way which would provide a fair comparison.
- **Lack of data to calculate Freshwater and Wetland disturbance.** The freshwater and wetland disturbance conditions and trend could not be determined for the ten scenarios due to lack of data. Nor could the specific affected watersheds and wetlands be determined, as there was no data of comparable quality across the scenarios which could be suitably used. For some scenarios, these impacts could be significant, as land use management can lead to many types of impacts, as described in Sections 6.6.2.2 and 6.6.2.3.
- **Lack of data to calculate freshwater depletion impacts due to logging in some regions.** For some scenarios, such as pulpwood production in South Africa (Scenario 8), freshwater depletion could be occurring due to land use management practices. This is not a relevant issue for all scenarios; for example, in Scenario 1: German Production from Swedish Managed Forest Pulp, local water resources are not classified as scarce. For other scenarios, the effect of harvest on water resource depletion is unclear, as harvesting and decrease in forest cover could decrease

evapotranspiration, leading to increased water availability. No data were available to quantify this water impact. This is a limitation in results.

- **Lack of data to calculate Freshwater Eutrophication.** Production of MMCF from all ten sources results in Eutrophication impacts. However, data on water emissions discharged to impaired water bodies from the dissolving pulp mills and MMCF mills was available only for one scenario. Emissions data of comparable quality were not available for other scenarios. Due to this limitation, evaluating results for this one scenario would have led to results which could not be fairly compared. Therefore, results for eutrophication were not evaluated for any scenario. These impacts are relevant and so results are reported as “No data.”
- **There may be additional ecoregions and key species affected by fiber produced in some scenarios.** For Scenario 1, 6, 7,<sup>39</sup> 8 and 9, there may be additional ecoregions and key species impacted by pulpwood production which is occurring outside the defined Forest Analysis Units (FAUs), which were used as the basis of the study. The FAUs were selected carefully to represent the major sources of pulpwood or other fiber source, but did not cover every potential source of material to mills in the scope. For the fiber basket of Scenario 6 and 7, there was insufficient information on the specifics of the regions from which bamboo and cotton were sourced and it was unclear which species were affected negatively by bamboo and cotton grown in the fiber basket. Results for Scenario 6 and 7 could not be evaluated and are reported as “no data”.
- **Lack of data to estimate soil carbon storage changes for most scenarios.** Soil organic carbon was only assessed for Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 10: Belgian Flax Production due to availability of data for cotton and flax production, and the importance of soil carbon to the final results for these scenarios. Soil carbon release occurs at a very slow rate in forest systems, possibly over several decades. The magnitude and direction of changes in soil carbon changes related to logging activities is open to active debate and scientific research.<sup>40</sup> These changes in soil carbon can vary based on soil moisture content, temperature, and many other factors, and have high levels of uncertainty and variability, precluding their inclusion in the analysis. As there is no data available to quantify soil carbon losses for any other scenario relying on woody fiber sources, changes in soil carbon are not included.<sup>41</sup> However the magnitude of losses in soil carbon are unlikely to

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<sup>39</sup> For the Cotton Linter Scenario, a hypothetical scenario was used to define the geographical boundaries of cotton production as being within India. This does not include cotton produced in China, and used in the DP mill in this scenario. See Section 6.9.7.1 for a discussion.

<sup>40</sup> See Achat, et al. Forest soil carbon is threatened by intensive biomass harvesting. Scientific Reports 5, Article number: 15991 (2015). doi:10.1038/srep15991

<sup>41</sup> For the German Production from Swedish Managed Forest Pulp scenario, this is consistent with the approach used in other estimates of total carbon stock changes associated with logging in the boreal zone. For example, Greenpeace estimated a loss of 40 tons of carbon per hectare due to logging in the boreal zone, which excluded soil carbon stock changes. The data for the management units included in this report is 28 tons of carbon lost per hectare, within a similar range to this estimate. See <http://www.greenpeace.org/canada/Global/canada/report/2009/10/turninguptheheat.pdf>

significantly affect the comparison of results. This is due to the fact that over the timeframe considered, they are unlikely to be large compared to aboveground carbon loss or the industrial processes leading to climate pollutant emissions included in the scope (see Section 5).

- **Use of “pilot” plant operational data for Scenario 5: German Production from Recycled Pulp (Scenario 5).** In the case of Scenario 5: German Production from Recycled Pulp, it should be noted that the data provided by Recycled DP Mill are based on estimates for scaling up pilot operations to an expected full-scale production capacity. Scaling up manufacturing capacity will invariably result in deviations from the estimated data. For example, Recycled DP Mill anticipates that process chemicals will be recycled during full-scale operations. As Recycled DP Mill optimizes the efficiency of its operations, it is likely that the estimated data may prove to be larger than actual full-scale production data.

Some other significant data gaps are described in Table 7.

**Table 7.** The significant data gaps in the study not discussed above.

Product System	Data Gaps
<b>All product systems</b>	<ul style="list-style-type: none"> <li>• For many key unit processes, no specific data were available regarding inputs and outputs, and representative data from Ecoinvent v3.1 were used. These datasets may have limitations in terms of geographical and/or temporal representativeness. These datasets included: sulfur dioxide production; liquid oxygen production; sodium hydroxide production; sulfuric acid production; carbon disulfide production; electricity production: forest management and timber harvest (including operation of logging equipment).</li> <li>• In assessment of terrestrial disturbance, there are indirect impacts on continuity and connectance of local forests which result from logging activities, relevant for terrestrial disturbance calculations. Impacts from fragmentation were not included due to a lack of data.</li> </ul>
<b>Scenario 9</b>	<ul style="list-style-type: none"> <li>• Primary data was not shared by producer for lyocell fiber production. Best available estimates were used from literature. Assumptions on upstream production of NMMO solvent and amount of NMMO solvent required for lyocell production were adopted from literature. Average energy input data for viscose fiber production was used to estimate energy consumption for lyocell fiber.</li> </ul>



## 5 Discussion of Results

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This LCA evaluates a complete set of impacts associated with the production of MMCF. It examines the impacts associated with ten potential sources of fiber, considering production of MMCF derived from five completely different material feedstocks (wood, bamboo pulp, cotton linter, flax by-products, recycled clothing), with supply chains stretching across four continents. From this information, several key findings can be derived, discussed in depth in Section 5.1. A discussion of how to interpret the results for these impact categories and others are provided in Section 5.2.

To properly understand the breadth of these impacts, effects on over twenty impact categories (not all relevant to each source of fiber) were considered in five groups. Many of these impact categories have not been included in previous LCA studies on MMCF. These new impact categories include:

- Effects on the Climate Hot Spots present in Indonesia, East Asia (China), and Africa. In these regions, ambient pollution from the aerosols, mostly driven by black carbon and sulfate aerosols, has greatly disrupted regional climates. Over India, this disruption to the regional climate has even weakened the monsoon cycle, affecting the water supplies impacting hundreds of millions of people.<sup>42</sup> Mill operations in several scenarios contribute to these hot spots, and it is important to understand their effects on these impacts.
- Ocean acidification, referred to by some as the “evil twin” of Global Climate Change.<sup>43</sup> After emission, roughly 25% of CO<sub>2</sub> is absorbed by the oceans,<sup>44</sup> fundamentally changing the chemistry of seawater in a mechanism parallel to climate change.<sup>45</sup>
- An in-depth evaluation, using site-specific data, of impacts on Terrestrial and Freshwater Ecosystems, which are of major concern for most sources of MMCF. This considers quantitatively, the terrestrial conditions of these ecosystems, compared with undisturbed conditions. It also includes consideration of threatened, endangered, and vulnerable species affected negatively by local land use management practices.

This LCIA methodology has not previously been applied to MMCF. In order to understand the implications of this new method and how it presents results differently from other LCIA methods, a sensitivity analysis was conducted, comparing the LCA results for the ten scenarios using this LCIA methodology, with results using the CML method<sup>46</sup>. This sensitivity analysis is discussed in Section 5.3.

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<sup>42</sup> See Appendix 2 for full description of this impact category.

<sup>43</sup> United Nations University. Climate Change’s ‘Evil Twin’: Ocean Acidification. 2013. See <https://ourworld.unu.edu/en/climate-changes-evil-twin-ocean-acidification>

<sup>44</sup> National Oceanic and Atmospheric Administration. Ocean Acidification: The Other CO<sub>2</sub> Problem. <http://www.pmel.noaa.gov/co2/story/Ocean+Acidification>

<sup>45</sup> The inclusion of ocean acidification anticipates a trend to include this impact category in other LCAs. See Bach, V., et al. Characterization model to assess ocean acidification within life cycle assessment. The International Journal of Life Cycle Assessment. April 2016.

<sup>46</sup> CML- Baseline; April 2013; <http://cml.leiden.edu/software/data-cmlia.html>

The differences between the findings in this study and a previous LCA on MMCF are also examined in this section.

Finally, the climate change impact category result is based on a 20-year time horizon. Previous LCAs for MMCFs have used a 100-year time horizon. In order to understand implications on climate change results, a sensitivity analysis of these two time horizons is provided in Section 5.4.

## 5.1 Key Findings

Inclusion of such a breadth of impact categories provides a tremendous amount of information. From this information, several key findings can be derived:

1. There is a very wide variability in impacts associated with MMCF, resulting not only from differences in material feedstocks, but also the region where the fiber inputs originate, the land use management practices involved in raw material feedstock extraction, the location of the supply chain operations and the type of mill technology being used. This LCA makes it clear that it is critical to understand not just the type of material used in MMCF, but also the source of material.
2. The impacts to Terrestrial and Freshwater Ecosystem Impacts vary widely. This is driven by the inherently local effects of different land use management practices on distinct ecosystems in various regions, resulting in different effects on terrestrial disturbance, key species, and biogenic carbon storage.
3. A summary of current terrestrial disturbance levels (see Table 8) across all scenarios indicate that for forest harvests in the fiber basket of the DP mills in Canada (Scenario 2) and Indonesia (Scenarios 3 and 4), local forest disturbance levels have been rising. The trend in disturbance also has implications on threatened species, albeit in different ways.
4. For most scenarios, a few unit processes at similar stages in the life cycle drive most of the resulting impacts.

The sections below provide detailed discussion of these key findings.

### 5.1.1 Key Finding 1: Variation in Impacts of MMCF from Different Sources

This examination of a breadth of different sources of MMCF, highlights the wide variability in impacts. Across the ten scenarios of MMCF production considered, the number of relevant impact categories varies by nearly a factor of two – only 12 relevant impacts for Scenario 5: German Production from Recycled Pulp, and up to 18 for Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian Plantation Pulp, Scenario 6: Chinese Production from Chinese Bamboo Pulp, Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 8: Chinese Production from South African Plantation Pulp.

Furthermore, there is wide variation across the impact categories considered. This is evident in Figure 1, which highlights the variability in impacts. For production of 1000 tons of MMCF:

- Global Climate Change results vary by a factor of 8, from -2.0 thousand tons CO<sub>2</sub>e for Scenario 5: German Production from Recycled Pulp, to 13 thousand tons of CO<sub>2</sub>e for Scenario 3: Chinese Production from Indonesian Rainforest Pulp (see Figure 5).
- Ocean acidification impacts vary from 0.6 thousand tons H<sub>2</sub>CO<sub>3</sub>e for Scenario 8: Chinese Production from South African Plantation Pulp (resulting from the increased absorption of carbon in this scenario – see Section 5.2.3.1) to 7.4 thousand tons H<sub>2</sub>CO<sub>3</sub>e for Scenario 3: Chinese Production from Indonesian Rainforest Pulp (see Figure 9).
- Terrestrial Disturbance resulting from MMCF production varies from 0 in Scenario 5: German Production from Recycled Pulp (which does not involve any land use in MMCF production), to 787 disturbed hectares \* years for Scenario 3: Chinese Production from Indonesian Rainforest Pulp. There is a 10-fold difference observed between different sources of fiber, while for one scenario (i.e. Scenario 5: German Production from Recycled Pulp), impacts are not relevant at all (see Figure 11).
- The number of species affected varies significantly – again 0 for recycled MMCF, to over 55 for the Indonesian Scenarios (Scenario 3: Chinese Production from Indonesian Rainforest Pulp and Scenario 4: Chinese Production from Indonesian Plantation Pulp).
- For PM<sub>2.5</sub> Exposure Risks, results vary by a factor of nearly 120. This is linked to the extremely poor ambient air quality in the scenarios involving DP and MMCF production in Asia. See Appendix 2 for details on air quality models used to assess this impact category.

Given this variability, it is critical to understand not just the type of material composition used in MMCF, but also the source of material.

### **5.1.2 Key Finding 2: Variations in Terrestrial and Freshwater Ecosystem Impacts**

A key goal of the study is to understand the relative level of impacts on ecosystems associated with the production of each source of MMCF. A second key finding is that, the driver of impacts across Terrestrial and Freshwater Ecosystem Impacts are logging and agriculture (depending on the raw material from which the fiber is manufactured). Logging and agriculture also have effects on Global Climate Change, and Ocean Acidification, resulting from effects on the biogenic carbon storage capability of local ecosystems.

In order to appropriately and accurately evaluate these impacts in this LCA, a sophisticated and integrated approach for assessing ecosystem disturbances is used to assess results, based on approaches commonly used in field ecology. Four distinct impact categories are measured: terrestrial disturbance; freshwater disturbance; wetland disturbance; and threatened species habitat disturbance. These four components provide a holistic understanding of ecosystem impacts.

The level of data available precluded a quantitative assessment of disturbances to freshwater and wetland systems; but data were available for a detailed evaluation of terrestrial disturbances in all scenarios. The assessment is based upon the consideration of the “foregone growth” for each scenario, based on the area of pulpwood sourced in the terrestrial ecoregion. In each affected terrestrial ecoregion, ecosystems, if no longer subject to harvest, would recover over time. The methodology looks at the implications for differing land use management regimes and what could happen in the absence of harvest, evaluating the “opportunity cost” of ongoing harvests.<sup>47</sup> From this perspective, even land use conversions happening decades or centuries in the past matter, if the ecosystem could begin recovering today.

For example, in Scenario 10: Belgian Flax Production, the agricultural land (in Belgium) used to produce feedstocks was converted from forests decades or perhaps centuries in the past. However, if agriculture were to halt in this part of Belgium, the land would almost certainly return to a forested state within a few decades. This is the case in other parts of Belgium and Europe where farmland has been abandoned; in Belgium, the amount of forest cover area has increased over the past 15 years<sup>48</sup>. Since 1900, forest cover in Europe has increased by 56%, due to a decreasing trend in forest harvests. The European economy increasingly relied on fossil fuels in lieu of wood, which allowed the ecosystems to gradually recover. Based on this evidence, there is every reason to expect that the flax fields, if unharvested, would return to a forested state and contribute to the overall trend of forest recovery in Belgium and Europe.

The calculation of terrestrial disturbance considers this “opportunity cost” involved in continued harvest of flax, wood for pulp, cotton, and bamboo, required for production of the different feedstocks. This “opportunity cost” is evaluated over the next 20 years, a minimum timeframe required to observe changes in terrestrial ecosystems. (See Appendix 2 for a further discussion of how terrestrial disturbance is calculated.) Yet in order to fully and transparently understand the conditions of terrestrial components of ecosystems, it is important to also consider the current level of disturbance, as well as the area subjected to harvest. Figure 2 in Section 1.5 includes all of this information, allowing for a holistic understanding of the terrestrial disturbance resulting from the production of each source of fiber. The following inferences can be made from Figure 2:

- The terrestrial disturbance impacts are dependent on the site productivity in a given region; the volume of fiber which can be extracted from a given area over an extended period of time. Although some forests, such as those in Scenario 3: Chinese production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian plantation pulp, and Scenario 8: Chinese production from South African plantation pulp, are in a very high state of disturbance because of transition from native forests or grasslands to exotic plantations, forests in these

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<sup>47</sup> Across the scenarios, the socio-economic implications of avoiding harvests will be different. For example, the socio-economic implications of regenerating forests in Europe, are very different from forgoing harvesting in forests in Indonesia or Canada’s Boreal. These socio-economic considerations are outside the scope of this LCA.

<sup>48</sup> World Bank, Food and Agricultural Organization. Forest land area, (% of land area).

<http://data.worldbank.org/indicator/AG.LND.FRST.ZS?end=2015&locations=BE&start=2000&view=chart>

regions are extremely productive. Conversely, Sweden, Canada and Austria do not see the high state of disturbance, however require significantly more area to be managed for harvest to produce the same amount of material.

- The land use results for Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 10: Belgian Flax Production cannot be directly compared to the other scenarios, because, the results are estimated in terms of mass of cotton or flax fibers required to produce MMCF and not in terms of volume of wood required for MMCF. A high level of disturbance is determined for both scenarios as a result of historical transformation of desert scrubland and native forests to agriculture for Scenario 7 and Scenario 10 respectively.
- Scenario 3: Chinese Production from Indonesian Rainforest Pulp, exhibits the highest terrestrial disturbance, followed by Scenario 2: Asian Production from Canadian Boreal Forest Pulp. The current level of disturbance in the boreal region is medium, showing there is opportunity to conserve intact forests. However, there is an increasing trend in the disturbance in this region (5% per decade)<sup>49</sup>. Furthermore, these forests are in northern latitudes and relatively unproductive in terms of their yield, and therefore have a high land area requirement compared to other scenarios. These factors combined lead to a higher level of foregone growth, and therefore, results are higher than other scenarios. Foregone Growth and the importance of forest conversion and recovery trends is discussed further in Section 5.1.3.
- In addition to physical alterations resulting in terrestrial disturbance, wood extraction, intensive agriculture and land transformation activities, can also have a negative influence on the species habitat, causing a decline in species population. The threatened species habitat disturbance indicator assesses the count of key species losing habitat in a specific fiber basket. This indicator is assessed based on IUCN Red List Species database, which assesses conservation status and classifies threatened species (i.e. species at high risk of global extinction) at a global-level. A global-level assessment of species risk may not be robust enough to reflect the relative threats encountered by species at a local level. For example, the European tree frog is enlisted as “Vulnerable” in the Flanders region by the government of Belgium. However, at a global scale, this species is considered to be of “Least Concern” status by IUCN. Many species that appear in local lists may not be enlisted as threatened (includes Vulnerable, Endangered and Critically Endangered status) by IUCN. Furthermore, in many instances, species in local lists overlapped with IUCN red list species. Hence, to improve robustness of results, this indicator includes threatened species from two lists: (1) IUCN Red List Species, which is a global-level species list and (2) Additional species from local lists (evaluated by local governments).

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<sup>49</sup> Lee P. 2007. Recent Anthropogenic Changes within the Boreal Forests of Ontario and Their Potential Impacts on Woodland Caribou (A Global Forest Watch Canada Report). Edmonton, Alberta: Global Forest Watch Canada. 51 pp.

### 5.1.3 Key Finding 3: Foregone Growth and the Importance of Forest Conversion/Recovery Trends

In the evaluation of terrestrial ecosystem impacts, it is important to understand not only the current state of disturbance, but also the trend in time of disturbance on the site, which determines an effective “opportunity cost” of the effect of harvesting on both the local ecosystem integrity and capacity to store carbon.<sup>50</sup>

For many scenarios, data on local terrestrial disturbance conditions was available over an extended period of time, allowing direct measurement of changes in ecosystem quality going back 20 years or more. For others, data was limited, but reasonable assumptions could be made considering the nature of the harvest operation and overall trend. The current disturbance level and disturbance trend, by scenario, is listed in the table below. The trends are evaluated based on past trends.

**Table 8.** Summary of current disturbance level and trend over the past one or two decades, by scenario.

Scenario	Current Disturbance Level	Current Disturbance Trend
German Production from Swedish Managed Forest Pulp	52%	Recovering, ~4% per decade
Asian Production from Canadian Boreal Forest Pulp	45%	Increasing, 5% per decade
Chinese Production from Indonesian Rainforest Pulp	80%	Increasing, 45% per decade
Chinese Production from Indonesian Plantation Pulp	81%	Increasing, 45% per decade
German Production from Recycled Pulp	No impact	N/A
Chinese Production from Chinese Bamboo Pulp	80%	Limited data – assumed stable
Chinese Production from Indian Cotton Linter Pulped in China	80%	Limited data – assumed stable
Chinese Production from South African Plantation Pulp	80%	Limited data – assumed stable
Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	47%	Recovering, ~1% per decade
Belgian Flax Production	80%	Limited data – assumed stable

This table illustrates that for forest harvests in the fiber basket of the DP mills in Canada and Indonesia, local forest disturbance levels have been rising. In Indonesia, this conversion has been extremely rapid, with forests being converted from a largely undisturbed state 20 years ago to an essentially fully disturbed state today. At the current trend, there will be essentially no undisturbed forest remaining in the Indonesian region in 10-20 years. This LCA finding is consistent with independent evaluations completed for Indonesian forests by organizations such as WWF.<sup>51</sup> As a result of this high rate of forest conversion, the government of Indonesia has attempted to halt deforestation, though with limited success.<sup>52</sup> These trends in forest disturbance are factored into results and is one of the reasons for the relatively high result for DP sourced from Indonesia.

<sup>50</sup> The approach used to calculate results considering this “foregone growth” is described in Section 5.2.5.1 and Appendix 2.

<sup>51</sup> Terradaily, 2005. WWF Warns that Borneo’s Forests Could be Destroyed within a Decade.

<http://www.terraily.com/news/terraily-05f.html>

<sup>52</sup> The Guardian, May 26, 2013. The Sumatran rainforest will mostly disappear within 20 years.

<https://www.theguardian.com/world/2013/may/26/sumatra-borneo-deforestation-tigers-palm-oil>

The trend in disturbance also has implications on threatened species, albeit in different ways. The species considered inhabit not only the sites being considered, but are present across a range in the region of each fiber basket. Some species have large ranges, and if a single site is disturbed, will migrate to other portions of their habitat. This means that the condition and trend in disturbance in the regions surrounding the fiber basket are just as important as the conditions within the fiber basket (sometimes even more so). This has several implications on the number of threatened species relevant in each scenario:

- Generally, scenarios present in developed regions have higher levels of threatened species, regardless of the overall trend in disturbance in the fiber basket. In these regions, local habitats in the vicinity of the fiber basket are fragmented as a result of many land uses, including not only forestry and agriculture but also unrelated stressors like urban development. In these regions, species displaced from a specific site in the fiber baskets considered, have no habitat to which they can migrate. This is the reason the scenarios where harvest activities have presumably occurred for an extended amount of time (specifically, Belgium, Austria, and Sweden), have relatively high levels of threatened species. The local regions are relatively highly developed and the threatened species present in the fiber basket have lost a substantial amount of local habitat across the entire region. Effects from harvesting in the fiber baskets considered are one stressor of many contributing to these regional habitat impacts.
- Similarly, increasing disturbance trends in the vicinity of a fiber basket can threaten species, even if disturbance trends are relatively static at the site of harvest. For example, in Belgium, the threats to the Northern Lapwing include “land-use intensification” and “loss of field margins and semi-natural habitat.” This implies that in the vicinity of the fiber basket, there is ongoing removal of habitat favorable to this species, due to agriculture. This implies that indirectly, increased flax cultivation is threatening this species’ existing habitat.
- Indonesia stands out as a region with high current disturbance levels and an increasing trend in disturbance within the fiber basket, as well as in the vicinity of the fiber basket. In addition, as it exists in a tropical region, there are significantly more species present in the region than in any other scenario. These factors can be attributed to the very high result for threatened species in Indonesia.
- Although not nearly as high as the negative trend in Indonesia, the increasing disturbance trend in the boreal forest of Canada could eventually lead to larger numbers of threatened species being affected in this region over time. However, data in this LCA is not sufficiently detailed to make this determination, which would require projections of forest disturbance trends across a large swath of forests in the region of this scenario’s fiber basket.

The inclusion of these considerations in these LCA results gives an accurate and robust “snapshot” of ecosystem impacts across the fiber baskets for each scenario.

#### 5.1.4 Key Finding 4: Key Drivers of Environmental Performance

A fourth key finding is that, for most scenarios, few unit processes at similar stages in the life cycle drive most of the resulting impacts. This includes the following processes:

- *Land use management, including logging and agriculture.*<sup>53</sup> For Global Climate Change and Ocean Acidification, this accounts for a significant level of impact for all scenarios; and for Terrestrial and Freshwater Ecosystem Impacts, it is the sole driver.
- *Production of dissolving pulp.*<sup>54</sup> The contribution analysis chart in Figure 15 indicates that 24-40% of the Non-Renewable Energy Resource Depletion impact is associated with the process energy used at the dissolving pulp mills across all the scenarios (except Scenario 10: Belgian Flax Production). This use and purchase of energy leads to air emissions which contribute to multiple impact categories; for Global Climate Change, dissolving pulp production is the first or second most important contributor to results for all scenarios, and is a very significant contributor to PM2.5 Exposure Risks and Regional Acidification as well.
- *Operations at MMCF mills.* The contribution analysis chart in Figure 15 indicates that 20-35% of the Non-Renewable Energy Resource Depletion impact is associated with the process energy used at the MMCF mills across all the scenarios (except Scenario 10: Belgian Flax Production). This use and purchase of energy leads to air emissions which contribute to multiple impact categories; for Global Climate Change, it contributes between 9-37%. MMCF production at MMCF mills is the dominant contributor (accounting for over 50% of results) to Regional Acidification in nearly all scenarios, and contributes to at least 25% of total impacts across all scenarios.
- *Sodium hydroxide production and sulfuric acid production.* These processes, including the upstream production of these materials used at MMCF mills, make up important contributions to several impact categories in selected scenarios, including Global Climate change (for Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production), Climate Hot Spots (for all scenarios where this impact is relevant), Non-renewable energy resource depletion, Regional Acidification, and PM2.5 Exposure Risks.

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<sup>53</sup> Not relevant for Scenario 5: German Production from Recycled Pulp.

<sup>54</sup> Not relevant for Scenario 10: Belgian Flax Production.



## 5.2 Interpretation of Results for the Impact Categories in this LCA

### 5.2.1 Interpretation of Biotic/Abiotic Resource Depletion Impacts

#### 5.2.1.1 Non-Renewable Energy Resource Depletion

##### *Significance of Impact Category*

This impact category refers to the depletion of non-renewable energy resource reserve bases, including coal, petroleum, natural gas, uranium, as well as consumption of any wood resources in a non-sustainable fashion (where harvest rates exceed regrowth). “Non-renewable” consumption of a resource is defined as a case where the consumption rate of the resource exceeds the accretion rate.

##### *Calculation Approach*

This impact category was calculated based on the energy content of the resources (using lower heating value) and the energy consumption was weighted based on the projected scarcity of different non-renewable resources. Refer to Appendix 2 for more details on the methodology.

##### *Interpretation of Results*

The following conclusions can be drawn:

- Figure 14 shows that Scenario 10: Belgian Flax Production has the least non-renewable energy resource depletion impacts compared to other scenarios. This significant decrease is observed because the processing of flax fibers does not involve any pulping process and is less energy intensive compared to the production of regenerated cellulose products.
- The cradle-to-gate energy consumption for MMCF production in Asia (Indonesian Scenarios<sup>55</sup>, Scenario 6: Chinese Production from Chinese Bamboo Pulp, Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 8: Chinese Production from South African Plantation Pulp ) is greater than the energy consumption for MMCF produced in Europe (Scenario 1: German Production from Swedish Managed Forest Pulp, Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production). The process efficiency of the mills and the energy mix of the electricity grid in China is the main factor distinguishing the scenarios.
- The contribution analysis chart in Figure 15 indicates that 40-60% of the impacts is associated with the process energy used at the DP mill and MMCF mills across all the scenarios, except Scenario 10: Belgian Flax Production. The energy required to produce sodium hydroxide (9-28%) also contributes measurably to this impact category for all scenarios except Scenario 9: Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp. In

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<sup>55</sup> Indonesian Scenario includes Scenario 3: Chinese Production from Indonesian Rainforest Pulp and Scenario 4: Chinese Production from Indonesian Plantation Pulp Scenarios.

case of Scenario 9, the chemical input requirements are different compared to conventional MMCF products. The cradle-to-gate energy requirement for NMMO solvent has notable impacts.

### 5.2.1.2 Net Freshwater Consumption

#### ***Significance of Impact Category***

This impact category considers the net consumption of freshwater. In general, net freshwater consumption includes the water withdrawn from surface water or groundwater source and not directly returned.<sup>56</sup> Consumption of saltwater is not included. Water scarcity of regions is also not factored in this impact category.

#### ***Calculation Approach***

This impact category provides an aggregate of net freshwater consumed from cradle-to-gate for MMCF production.

#### ***Interpretation of Results***

The following conclusions can be drawn:

- Figure 14 shows that Scenario 10: Belgian Flax Production consumes the least amount of water compared to other scenarios. This significant decrease is observed because of fewer processing steps involved in transformation of raw flax co-products into finished flax fibers.
- Overall, the net freshwater consumption at the pulp and MMCF mills account for less than 20% of the final results. The contribution analysis chart in Figure 16 suggests that majority of the water consumption results from the embedded water requirements associated with the production of chemical inputs such as sodium hydroxide, sulfuric acid and energy generation; all unit processes which are upstream of the supply chain.

### 5.2.1.3 Wood Resource Depletion

#### ***Significance of Impact Category***

This impact category assesses the depletion of wood resources resulting from pulpwood harvesting. Wood resource depletion is only considered relevant if harvest rates exceed recovery rates, and is only relevant for Scenario 2: Asian Production from Canadian Boreal Forest Pulp, and Scenario 3: Chinese Production from Indonesian Rainforest Pulp. It should be noted that effects on forest ecosystems are treated in the impact category group of Terrestrial and Freshwater Ecosystem Impacts (i.e., Forest, Freshwater, Wetland, and Species impacts) and forest carbon loss is treated in the impact category of Global Climate Change and Ocean

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<sup>56</sup> King, C. W., & Webber, M. E. (2008). Water intensity of transportation. *Environmental Science & Technology*, 42(21), 7866-7872.

Acidification. These impact categories are all linked to losses of wood resources but nevertheless are distinct categories of impact.

### ***Calculation Approach***

The calculation approach incorporates the amount of wood used to produce 1000 tons of MMCF. Refer to Appendix 2 for more details on the methodology.

### ***Interpretation of Results***

The following conclusions can be drawn:

- Figure 14 shows that this impact category is not applicable to most scenarios. Due to the fact that harvest rates exceed regrowth, the impact is relevant only for, Scenario 2: Asian Production from Canadian Boreal Forest Pulp, and Scenario 3: Chinese Production from Indonesian Rainforest Pulp.

## **5.2.2 Interpretation of Climate System Impacts**

Conventional LCA studies only include impacts from GHG emissions to evaluate climate change impacts for different products. However, the current study applies new metrics, focusing on two impact categories to account for regional variability and includes climate effects of additional pollutants such as black carbon, organic carbon, and sulfur dioxide and nitrogen oxides. While Global Climate Change impact category addresses both long lived greenhouses gases and short-lived climate pollutants (SLCPs), the Climate 'Hotspot' impact category is a new impact category which is introduced in this study to address impacts of aerosols in regional climate hot spots around the world.

### **5.2.2.1 Global Climate Change**

#### ***Significance of Impact Category***

This impact category considers Global Climate Change, Warming and Global Climate Change, Cooling, based on the radiative forcing metrics and the timeframe of analysis is 20 years. The 20 year time horizon is used for consistency with the goals of the Paris Climate Agreement, and to minimize the uncertainty in calculation. See Section 5.4 for discussion on use of the 20 year time horizon and exploration of a sensitivity analysis comparing results when a 100 year timeframe is used instead.

#### ***Global Climate Change, Warming:***

This refers to the effects of GHGs and other climate forcers (such as black carbon and nitrogen oxides) on positive radiative forcing, leading to global temperature increases. The results for Global Climate Change, Warming in this LCA consider not only the effect of emissions occurring in the production of fiber; but also the effect on the climate from foregone growth, which is the carbon that would have been sequestered in the forest had it not been harvested (see Appendix 2 for description of how this is calculated).

In the fiber baskets of the mills included in the scope of the study, forestry and agricultural activities have, over many decades, led not only to ecosystem disturbances and key species impacts, but also reductions in stored forest carbon, when compared to undisturbed forestlands. According to the IPCC,<sup>57</sup> historic CO<sub>2</sub> emissions from land use changes are responsible for approximately 33% of the additional CO<sub>2</sub> burden in the atmosphere from anthropogenic activities, leading to roughly 0.5 W/m<sup>2</sup> of radiative forcing in 2011. Most of the terrestrial ecoregions considered, if left unharvested, would re-absorb a large portion of this CO<sub>2</sub>. IPCC estimates, for example, that afforestation and reforestation could sequester 40-70 billion tons of carbon,<sup>58</sup> indicating the large potential of allowing disturbed ecosystems to re-sequester carbon that has been lost to the atmosphere. The effect on ongoing harvest therefore *suppresses the rate of forest carbon storage recovery in most scenarios.*<sup>59</sup>

#### Global Climate Change, Cooling:

This refers to the effects of sulfur dioxide (SO<sub>2</sub>) forming sulfate aerosols and other coolants (such as organic carbon) on negative radiative forcing, offsetting some positive forcing caused by GHGs and other forcers. While CO<sub>2</sub> is retained in the atmosphere after emissions, the impacts accumulate over time. If emissions decrease or stop after 20 years, there is still a retained “legacy” impacts of global warming that is attributable to the product. Conversely, aerosols do not accumulate, and if emissions stopped after 20 years, the impact would dissipate completely in just few weeks. The global cooling effect from all coolants is measured by scientists to be -1 to -2 W/m<sup>2</sup>,<sup>60</sup> offsetting a significant amount of the warming impact. Reduction in cooling effects will have immediate increase in forcing and temperature. However, the pollutants causing cooling are not desirable, as they also, in parallel, contribute to impacts on Regional Acidification and exposure to particulate matter. It occurs in specific regions, in distinct parts of the atmosphere, and has a different effect compared to positive radiative forcing.

#### **Calculation Approach**

The calculation approach considers climate forcers causing warming and cooling, using radiative forcing, which expresses the average heat increase per square meter of the Earth’s surface. This radiative forcing is made relative to the emission of a ton of carbon dioxide (CO<sub>2</sub>) in the next

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<sup>57</sup> Intergovernmental Panel on Climate Change. Working Group I Contribution to the IPCC Fifth Assessment Report. *Climate Change 2013: The Physical Science Basis. Summary for Policymakers.*

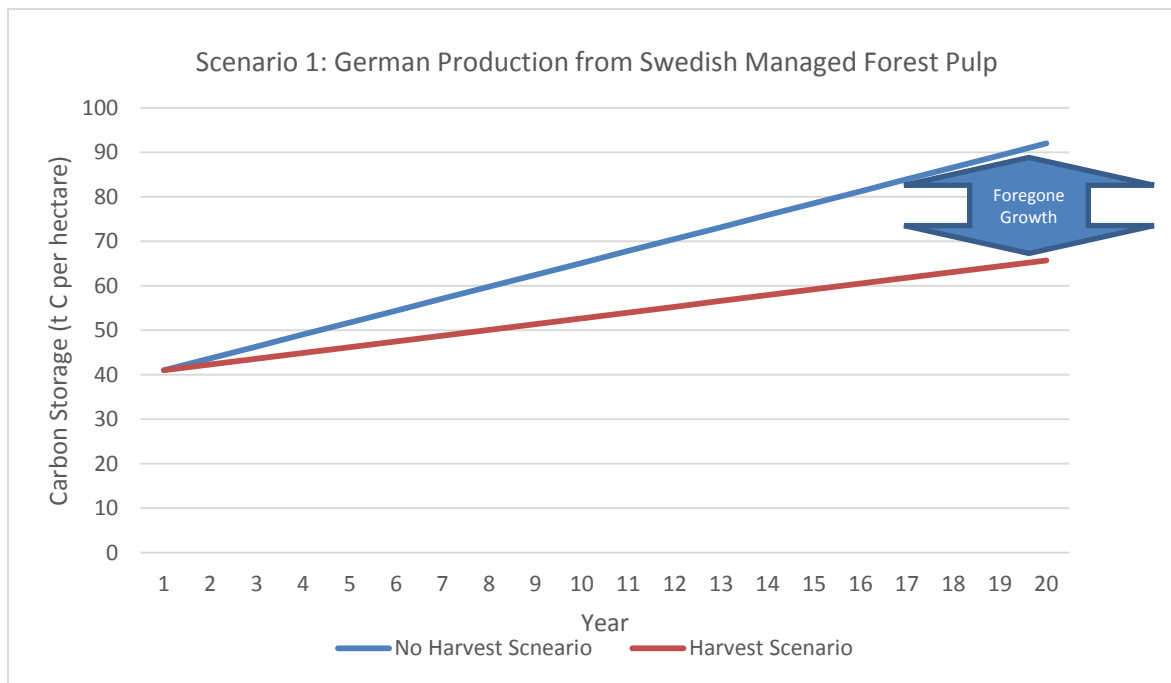
<sup>58</sup> IPCC Fifth Assessment Report. Table 6.1.5. 2013.

<sup>59</sup> Across the scenarios, the socio-economic implications of avoiding harvests will be different. For example, the socio-economic implications of regenerating forests in Europe, are very different from forgoing harvesting in forests in Indonesia or Canada’s Boreal. These socio-economic considerations are outside the scope of this LCA.

<sup>60</sup> Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Chapter 8, Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

year, putting results in standard units of carbon dioxide equivalent (CO<sub>2</sub>e). A 20-year time horizon is used for calculation.

The foregone growth was calculated in conformance with the Roundwood PCR<sup>61</sup>. To do so, the rate of change of carbon storage per hectare in each FAU was assumed to continue over the next 20 years, and then compared after 20 years, to a conservatively high estimate of rate of recovery (assuming that the forest will fully recover all lost carbon within 50 years). For example, in Scenario 1, data from the Swedish Forest Inventory indicated that forest carbon had increased at a rate of 1.3 tons of carbon per hectare over the past 20 years. In a no-harvest scenario, it was estimated that recovery would be 2.7 tons of carbon per hectare. The “foregone growth” for Scenario 1: German Production from Swedish Managed Forest Pulp was the carbon not absorbed over this 20-year timeframe, which leads to radiative forcing due to the excess CO<sub>2</sub> remaining in the atmosphere. The effect of this radiative forcing is integrated over 20 years to provide results in integrated radiative forcing, with units equivalent to metric for calculating Global Warming Potential values, a commonly method calculate LCA results.

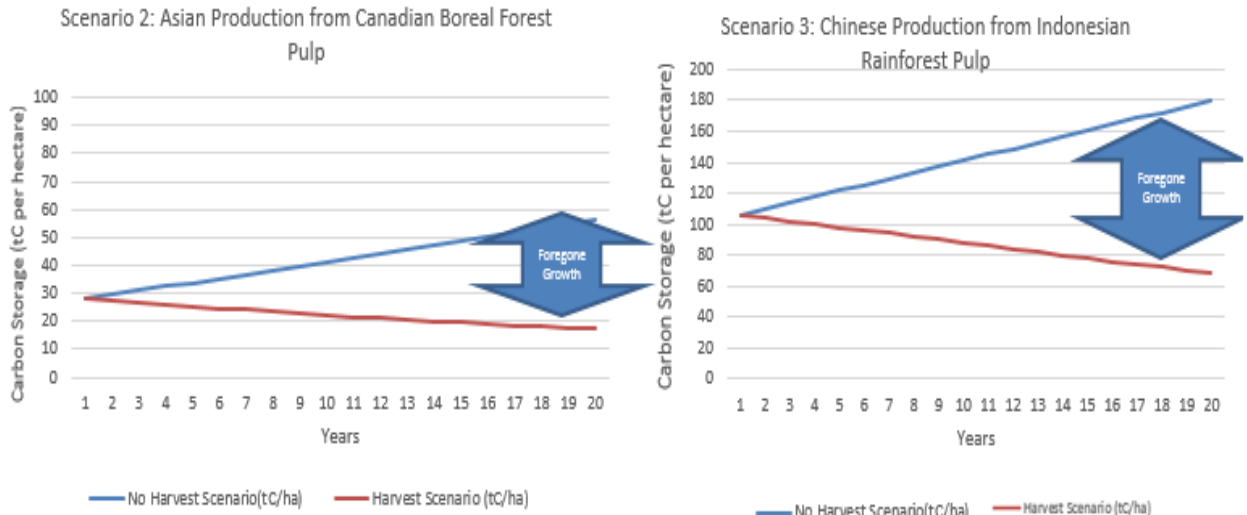


**Figure 19.** The trend in carbon absorption in the FAUs of Scenario 1: German Production from Swedish Managed Forest Pulp, in the Harvest and No Harvest Scenarios. Foregone growth is shown with the arrow. (Note: It is assumed that the forest will fully recover all lost carbon within 50 years.)

Some forests may never recover the lost carbon. However, this study only considers a 20 year time horizon, and does not consider long term carbon storage losses beyond that time horizon.

<sup>61</sup> PCR Module for Roundwood Production:  
[https://www.scsglobalservices.com/files/resources/pcr\\_final\\_wood-products\\_101816.pdf](https://www.scsglobalservices.com/files/resources/pcr_final_wood-products_101816.pdf)

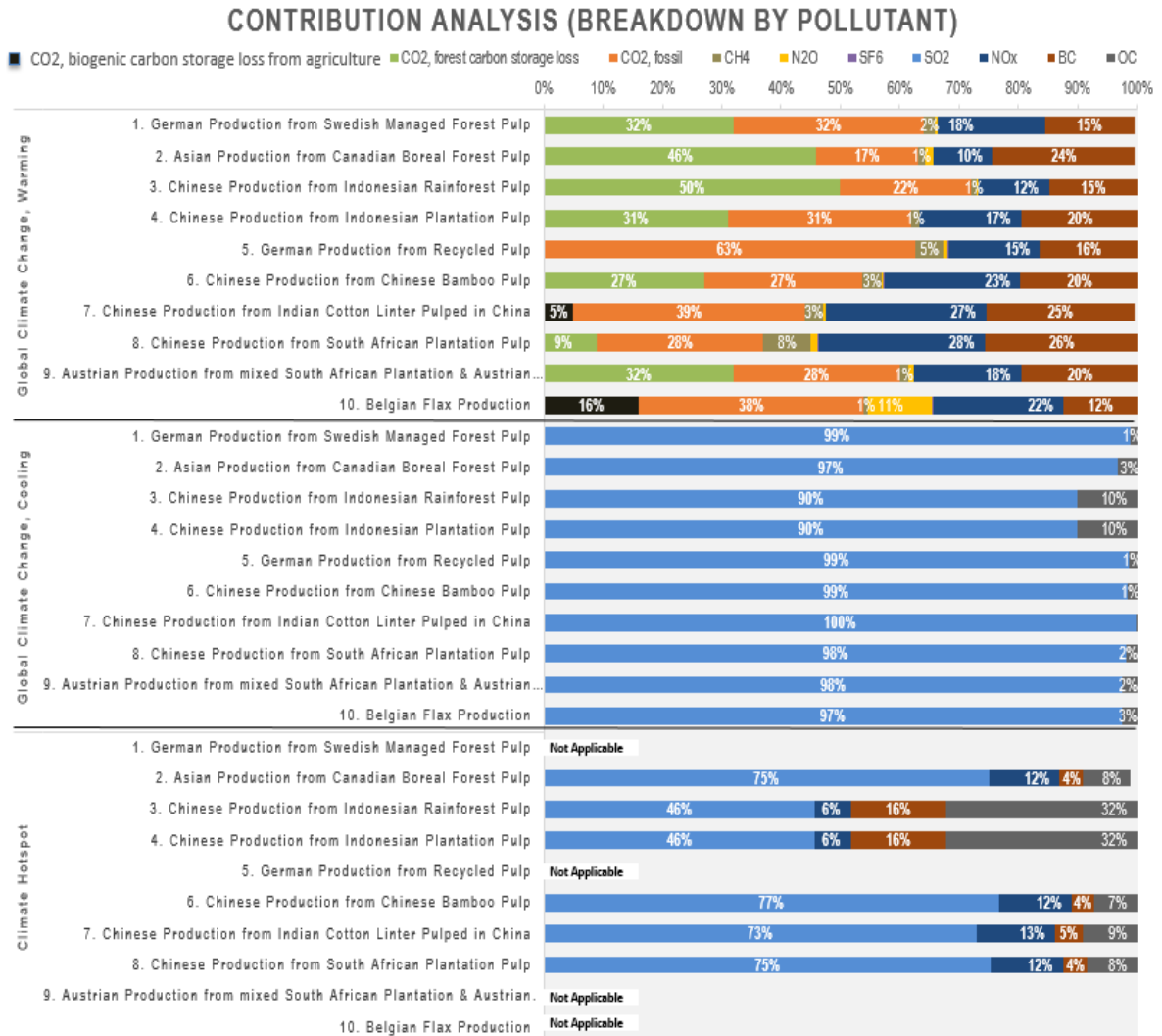
Contrary to Scenario 1: German Production from Swedish Managed Forest Pulp (where there is a gradual increase in carbon storage as the forests are recovering), a decreasing trend in forest carbon storage is observed in boreal forests in Canada (Scenario 2) and Indonesian rainforests (Scenario 3) due to intensive logging and high disturbance in forests. As illustrated in Figure 20, due to a decreasing trend in forest carbon storage, the foregone growth is much higher for Scenarios 2 and 3 compared to Scenario 1. The forest carbon storage losses for Scenario 2 and Scenario 3 account for 46% and 50% of total climate warming impacts respectively.



**Figure 20.** . The trend in carbon absorption in the FAUs of Scenario 2 and Scenario 3, in the Harvest and No Harvest Scenarios. Foregone growth is shown with the arrow. (Note: It is assumed that the forest will fully recover all lost carbon within 50 years.)

**Interpretation of Results**

In addition to the summary results and process contribution charts presented in Figure 5 through Figure 8, the following chart provides a contribution analysis by pollutant for climate system impacts.



**Figure 21.** % Contribution Analysis by pollutant for impact categories in Climate System Impact group. The results differ by scenario, and only the relative contribution is shown here. The absolute results, by impact category, are shown in Figure 5.

The following conclusions can be drawn:

- Figure 5 in Section 4.2 shows that Scenario 5: German Production from Recycled Pulp has the least Global Climate Change warming and cooling impacts compared to other scenarios, closely followed by Scenario 10: Belgian Flax Production and Scenario 8: Chinese Production from South African Plantation Pulp. This significant decrease for Scenario 10 is observed because the processing of flax fibers does not involve any pulping process and only uses co-products of flax plants. The refining of flax co-products into fibers is less energy and chemical intensive compared to the production of regenerated cellulose products.

- Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 2: Asian Production from Canadian Boreal Forest Pulp, Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 4: Chinese Production from Indonesian Plantation Pulp have the largest warming and cooling impacts compared to other scenarios. Overall, the warming impacts in particular for Scenario 3, are almost twofold high compared to other scenarios. 50% of the warming impacts are attributed to the forest carbon storage losses occurring due to logging of mixed tropical hardwood in the Indonesian rainforests. Black carbon pollutant contributes measurably to the warming impacts in the Indonesian scenario, as a results of high particulate matter emissions from upstream energy generation and pulp production.
- Overall, CO<sub>2</sub> emissions from forest carbon storage losses from logging operations are a dominant contributor to the Global Climate Change, warming impacts across all the scenarios, except for Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production. Impacts associated with process energy (mainly fossil fuels and purchased electricity from public grids) used for dissolving pulp and MMCF production are significant contributors to both warming and cooling impacts.
- It should be noted that in some scenarios, carbon storage has changed very little or actually increased. For example, in Scenario 8: Chinese Production from South African Plantation Pulp, eucalyptus plantations have replaced native grasslands. Although this results in a high level of disturbance on the site, these eucalyptus plantations actually *increase* the carbon storage on site, which is reflected in the lower CO<sub>2</sub> impacts from forest carbon storage (9% of climate impacts attributed to carbon storage loss) compared to carbon storage losses occurring in boreal forests and Indonesian rainforests (27%-52%).
- Sulfur dioxide (SO<sub>2</sub>) emissions is the main contributor to the Global Climate Change, Cooling impact category. It is emitted at pulp mills and is also emitted during production of chemicals such as sulfuric acid. Additionally, it is primarily emitted by coal fired plants and is linked to upstream electricity generation activities. Countries which predominantly rely on coal power generation, have greater SO<sub>2</sub> emissions. Chinese and Indonesian energy production relies more on fossil fuels (77% hard coal in China and 41% lignite in Indonesia) compared to countries like Sweden, which rely more on hydropower (43%) for power generation. Hence coolant emissions for MMCF produced in Asia (Scenario 2, Scenario 3, Scenario 4, Scenario 6, Scenario 7 and Scenario 8) are higher compared to other scenarios where MMCF is produced in Europe.



### 5.2.2.2 Climate 'Hotspot' Impact

#### ***Significance of Impact Category***

This impact category addresses impacts of aerosols and their precursors (i.e., black carbon, organic carbon, sulfur dioxide, and nitrogen oxides), that have an atmospheric lifetime of at most a few weeks. Since these aerosols have such a short atmospheric residence time, they are not evenly distributed in the global atmosphere and concentrations vary regionally, depending on the local degree of emission and ambient atmospheric conditions. This means that the same mass of aerosols emitted from different locations can have markedly distinct climate effects.

These aerosols therefore behave very differently than GHGs and have different impacts. Unlike GHGs, aerosols do not remain well-mixed in the atmosphere; aerosol particles remain suspended in the air until they settle back on the surface, or are washed out by rain. Black carbon absorbs energy, trapping heat and warming the climate more intensely than CO<sub>2</sub> over a short time frame (few weeks). Although black carbon has a short residence time in the atmosphere, over a 20 year span, one ton of black carbon likely has an impact of nearly 4,000 tons of CO<sub>2</sub>. While radiative forcing estimates for black carbon have wide ranges of uncertainty, there is growing evidence that black carbon is a key driver of warming impacts in certain hotspots and it is pertinent to include these emissions. The sources of black carbon in developing countries are significantly different from those in North America and Europe, with majority of black carbon emissions originating from residential heating and cooking, and industrial sources. Black carbon is co-emitted with other forms of particulate matter (PM) such as organic carbon, which have a cooling effect.

Regional climate impacts in certain regions arise because these absorbing and scattering aerosols block solar radiation so that it does not hit the Earth's surface, causing surface dimming<sup>62</sup>. This means that in some regions, these pollutants can even lead to surface cooling. In addition to other local impacts on the climate, this leads to reduction in evaporation of water vapor from the surface, impacting the hydrological cycle and (in some regions) reducing precipitation. For example, studies have shown that over the last few decades, precipitation in the monsoon regions in Asia has been largely altered due to increased aerosol loading within climate "hot spots"<sup>63,64,65</sup>. These regional impacts are independent of the greenhouse effect and would occur even in the absence of elevated GHG concentrations.

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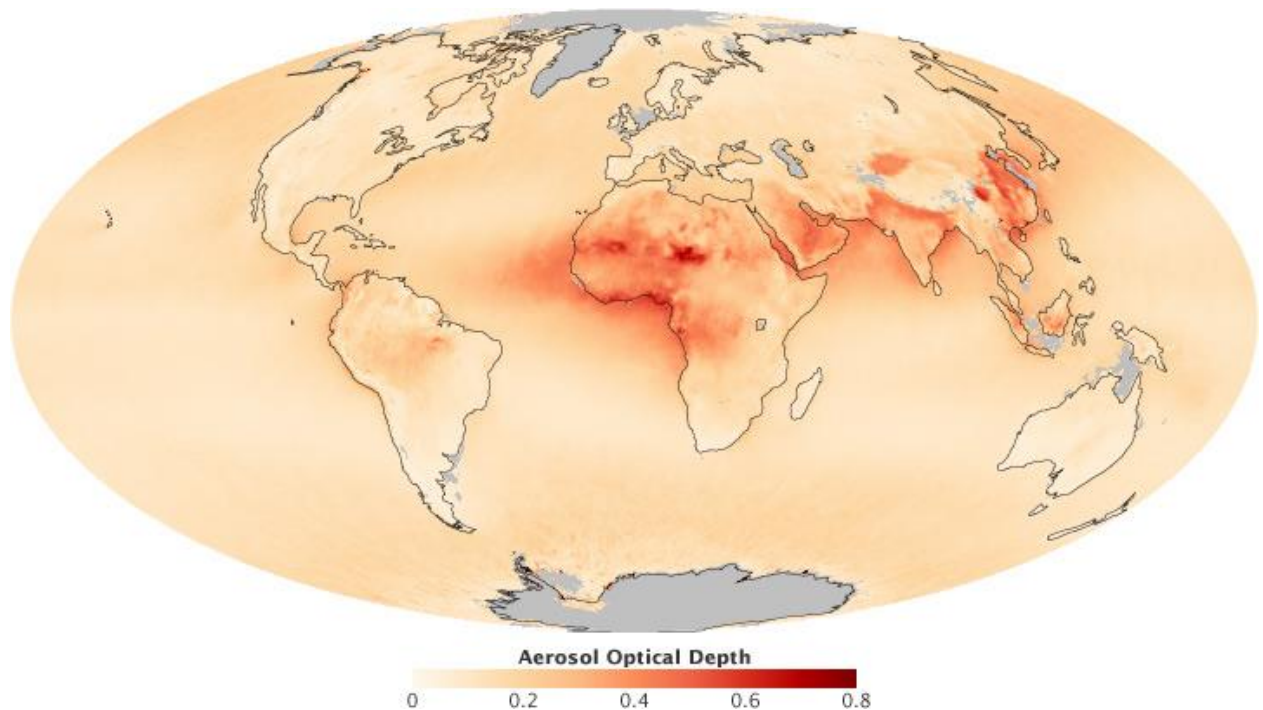
<sup>62</sup> Ramanathan, V., et al., (2008), Atmospheric Brown Clouds: Regional Assessment Report with Focus on Asia. Published by the United Nations Environment Programme, Nairobi, Kenya.

<sup>63</sup> Das, S., Dey, S., & Dash, S. K. (2016). Direct radiative effects of anthropogenic aerosols on Indian summer monsoon circulation. *Theoretical and Applied Climatology*, 124(3-4), 629-639.

<sup>64</sup> Bollasina, M. A., Ming, Y., & Ramanathan, V. (2011). Anthropogenic aerosols and the weakening of the South Asian summer monsoon. *Science*, 334(6055), 502-505.

<sup>65</sup> Burney, J., & Ramanathan, V. (2014). Recent climate and air pollution impacts on Indian agriculture. *Proceedings of the National Academy of Sciences*, 111(46), 16319-16324

In this study, only emissions of aerosols and their precursors which transport to and lead to impacts within regional climate hot spots are considered. The hot spots are those identified by the United Nations Environment Program (UNEP) in its report on the topic,<sup>66</sup> with additional hot spots identified through examination of satellite data provided by NASA in its AQUA/MODIS satellite system.<sup>67</sup> A satellite image of aerosol concentration globally from NASA is shown in the figure below.



**Figure 22.** Aerosol optical depth, the fundamental measurement of quantity and distribution of aerosols. This map shows the average distribution of aerosols from June 2000 through May 2010, measured by the Multi-angle Imaging Spectroradiometer. Red indicates high concentrations of aerosols, beige indicates low concentrations. *Source: NASA.*<sup>68</sup>

The climate impacts within “hot spots” are distinct in nature and would still occur, even in the absence of increased GHG concentrations and radiative forcing and therefore Climate “Hotspot” Impacts are accounted for in separate indicators.

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<sup>66</sup> UNEP. Atmospheric Brown Clouds: Regional Assessment Report with Focus on Asia. 2008.

<http://www.unep.org/pdf/ABCsummaryFinal.pdf>

<sup>67</sup> NASA Earth Observatory. Aerosol Optical Thickness (AQUA/MODIS).

[http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MYDAL2\\_M\\_AER\\_OD](http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MYDAL2_M_AER_OD)

<sup>68</sup> <http://earthobservatory.nasa.gov/Features/Aerosols/page5.php>

### ***Calculation Approach***

The “hot spots” relevant in this scope are in East Asia (China), Africa, and Indonesia, applicable to Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian Plantation Pulp, Scenario 6: Chinese Production from Chinese Bamboo Pulp, Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 8: Chinese Production from South African Plantation Pulp. However, the impacts are highly localized, and not all scenarios contribute. Results in this impact category reflect the distinct nature of the hot spot impacts and report only emissions transporting and affecting these hot spots, in terms of tons of black carbon equivalent.

### ***Interpretation of Results***

- Figure 21 illustrates that sulfur dioxide (SO<sub>2</sub>) is the main contributor to regional climate hotspot impacts. As discussed in the previous section, the embedded impacts from energy generation (mainly coal or lignite) and production of chemical inputs such as sulfur dioxide and sulfuric acid are the main drivers of climate ‘hotspot’ impacts within the MMCF life cycle.
- Scenario 3: Chinese Production from Indonesian Rainforest Pulp and Scenario 4: Chinese Production from Indonesian Plantation Pulp have the largest impacts compared to other applicable scenarios. Black carbon was not a large driver of results for this impact category.

## **5.2.3 Interpretation of Ocean Ecosystem Impacts**

This impact group generally deals with effects on ocean ecosystems. The only relevant impact category is Ocean Acidification.

### **5.2.3.1 Ocean Acidification**

#### ***Significance of Impact Category***

This impact category represents the degree to which CO<sub>2</sub> emissions lead to decrease in the pH of the oceans through the formation of carbonic acid, negatively impacting coral reefs and other marine life by lowering both the aragonite and calcite saturation levels. This refers to increased acidity and altered chemistry of oceans caused by carbon dioxide emissions. This impact category is treated separately from Global Climate Change, as the impact categories are linked but represent parallel environmental mechanisms. While CO<sub>2</sub> retained in the atmosphere affect the climate, the portion (roughly 25%) which is absorbed by the oceans increases ocean acidity. Furthermore, the non-CO<sub>2</sub> climate forcers do not affect ocean acidification. This approach is similar to other published LCA papers which have provided characterization models for ocean acidification.<sup>69</sup> Results consider the effect of CO<sub>2</sub> emitted during MMCF production on ocean acidification, as well as the effect of foregone growth in logged forests (which do not recover as

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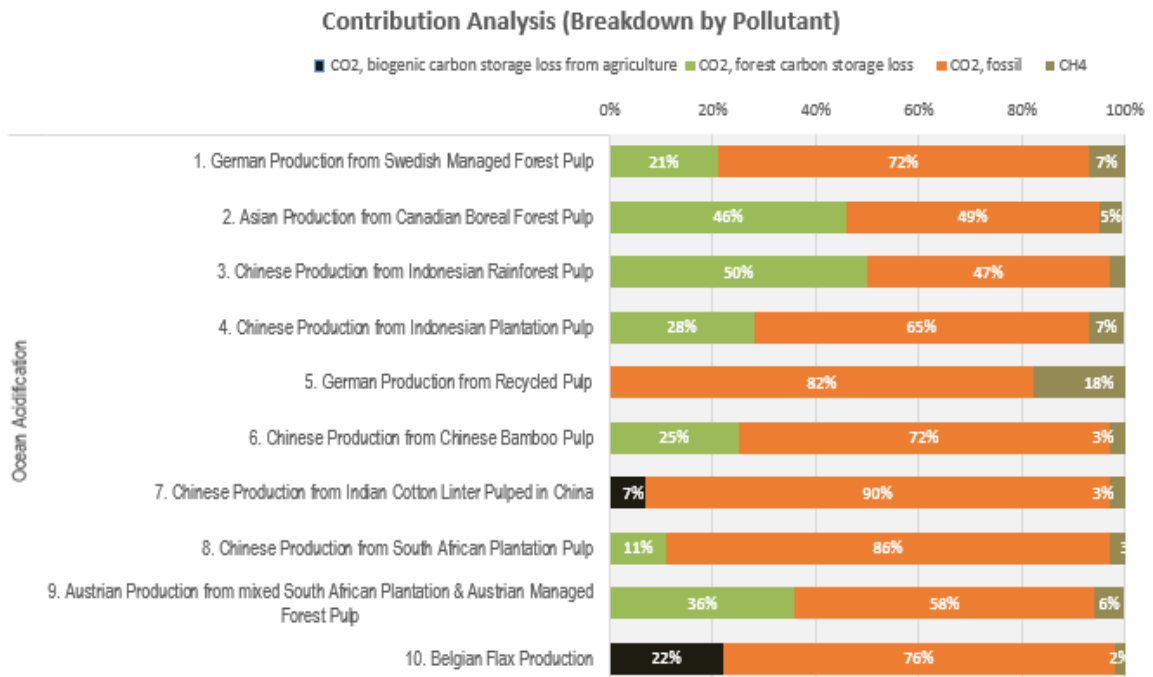
<sup>69</sup> Bach, V., Möller, F., Finogenova, N. et al. Int J Life Cycle Assess (2016) 21: 1463. doi:10.1007/s11367-016-1121-x.

quickly due to ongoing harvests). As with Global Climate Change, a 20 year time horizon is used to characterize impacts, assuming continuous harvesting of wood from forests, for use in MMCF over this time period.

**Calculation Approach**

Only carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) emissions are considered. The conversion of these substances into carbonic acid (H<sub>2</sub>CO<sub>3</sub>) in the world’s oceans is considered. There are two sources of oceanic H<sub>2</sub>CO<sub>3</sub> to be considered, depending on the product system: (1) The emissions of CO<sub>2</sub> and CH<sub>4</sub> occurring from MMCF production, and (2) carbon storage losses resulting from foregone growth resulting from logging (e.g., net forest regrowth, decomposition of belowground biomass). Refer to Appendix 2 for more details on the methodology.

**Interpretation of Results**



**Figure 23.** % Contribution Analysis by pollutant for Ocean Acidification. The absolute results, by impact category, are shown in Figure 9.

The following conclusions can be drawn:

- The contribution chart presented above indicates that overall, CO<sub>2</sub> emissions from forest carbon storage losses from logging operation is a dominant contributor for most of the scenarios, except for Scenario 5: German Production from Recycled Pulp. Scenario 3: Chinese Production from Indonesian Rainforest Pulp has the largest impact owing to 50% of CO<sub>2</sub> emissions from forest carbon storage losses, closely followed by Scenario 2: Asian Production from Canadian Boreal Forest Pulp (46% of CO<sub>2</sub> emissions from forest carbon storage losses).

- Figure 9 in Section 4.2 shows that Scenario 5: German Production from Recycled Pulp, Scenario 10: Belgian Flax Production and Scenario 8: Chinese Production from South African Plantation Pulp have the least ocean acidification impact compared to other scenarios. This significant decrease is observed because in South Africa, native grasslands were transformed to eucalyptus plantations, resulting in a net *increase* the carbon storage on site, which is reflected in the lower contribution of CO<sub>2</sub> impacts from forest carbon storage (11%) compared to forest carbon storage losses in other scenarios (21-50%).
- Similar to Climate System Impacts, the CO<sub>2</sub> emissions associated with process energy (mainly fossil fuels and purchased electricity from public grids) used for dissolving pulp and MMCF production are significant contributors.

### 5.2.3.2 Ocean Warming

This impact category refers to increased ocean temperatures caused by GHGs and positive climate forcers. Although this impact is important and relevant to emissions and foregone growth from logging, no algorithm is available to calculate results. Reflecting the critical nature of this impact category, it is reported as relevant to fiber production, although results cannot be evaluated.

## 5.2.4 Interpretation of Terrestrial and Freshwater Ecosystem Impacts (from Emissions)

### 5.2.4.1 Regional Acidification

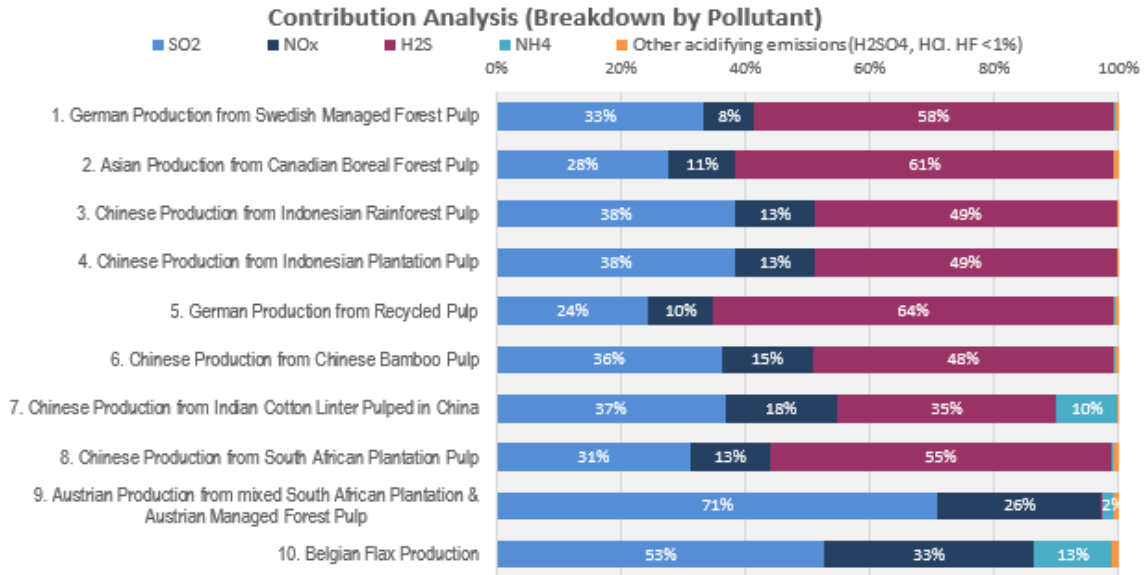
#### ***Significance of Impact Category***

This impact category addresses impacts caused primarily from acid rain on terrestrial and freshwater ecosystems. Some regions are much more sensitive to acid deposition than others. The indicator characterizes the fraction of acidifying emissions which deposit into sensitive soils.

#### ***Calculation Approach***

The results were calculated based on the potential release of hydrogen ions per kg of acidifying emissions and the fraction of acidifying emissions which deposit into sensitive soils. The fraction of emission which deposits into sensitive regions is determined from dispersion plumes and differs by location for unit processes across the supply chain. Refer to Appendix 2 for more details.

**Interpretation of Results**



**Figure 24** % Contribution Analysis by pollutant for Regional Acidification. The absolute results, by impact category, are shown in Figure 12.

Overall, sulfur dioxide (SO<sub>2</sub>) and hydrogen sulfide (H<sub>2</sub>S) emissions are the key drivers of regional acidification impacts across all scenarios except for Scenario 9: Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp and Scenario 10: Belgian Flax Production. A large share of SO<sub>2</sub> emissions arise from pulp mills, which are mainly emitted from oxidation of reduced sulfur compounds in the recovery furnace of the mills. Furthermore, as indicated in the process contribution chart (Figure 13), sodium hydroxide, which is the primary chemical input used in the production of dissolving pulp as well as MMCF also contributes measurably to this impact category. The MMCF production is the main source of H<sub>2</sub>S emissions because relies on the use of carbon disulfide as one of the solvents for processing MMCF, of which at least 70% is recovered and the remaining is emitted along with hydrogen sulfide. Scenarios 9 and 10 do not require carbon disulfide for processing and are in general less chemical intensive compared to the other scenarios. Thus, the results for Scenarios 9 and 10 are much lower compared to other scenarios. Figure 9 in Section 4.2 shows that the Indonesian scenarios have the largest regional acidification impacts, which is nearly twice that of other scenarios.

#### 5.2.4.2 Freshwater Eutrophication

##### *Significance of Impact Category*

This impact category addresses eutrophication impacts to aquatic systems. Emissions at the dissolving pulp and MMCF production facilities are linked to eutrophication in the watersheds. Forestry associated with pulpwood production can also result in increased sediment loading in the fiber baskets of the dissolving pulp mills considered in the study. Quantifying eutrophication impacts was challenging due to overly coarse spatial resolution of data and lack of direct local linkages between water effluent discharged from the facility and impairment of local water bodies. Due to lack of consistent data for establishing and characterizing category indicators for eutrophication linked to ten product systems, no results are assessed for eutrophication. This is a study limitation.

In order to provide context on the significance of these impacts, a qualitative summary of water quality status has been provided for all ten scenarios based on a collaborative study on river biodiversity conducted by multiple global institutions<sup>70</sup>. The study published a dataset mapping water quality parameters on a global scale<sup>71</sup>. It provided data on 23 environmental drivers effecting water quality on a 0.5° grid across the world, essentially providing regional average values on water quality issues globally. For the current LCA study, four drivers were considered to determine the water quality status for the ten scenarios: nitrogen loading, phosphorus loading, organic loading, and total suspended solids. Based on spatial data on these factors from this published study, the water quality status was determined to be “low”, “medium” or “high” for all the scenarios in Table 9, with “low” corresponding to regions with the worst relative water quality. Refer to Appendix 2 for more detail on the applied methodology.

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<sup>70</sup> Global threats to human water security and river biodiversity. C.J. Vorosmarty, P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C. Reidy Liermann, and P.M. Davies  
Nature 467, 555-561 (30 September 2010) doi:10.1038/nature09440

<sup>71</sup> <http://www.riverthreat.net/maps/>

**Table 9.** Water quality status summary for dissolving pulp (DP) mills and MMCF mills, by scenario, factoring in nitrogen loading, phosphorus loading, organic loading, and total suspended solids. The evaluation is based on regional averages of water quality in the region of each MMCF and DP mill.

Parameter	1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	10. Belgian Flax Production
DP Mill Location	Sweden	Canada	Indonesia	Indonesia	Sweden	China	China	South Africa	South Africa+Austria	Not Applicable
DP Mill Water Quality Status	High	High	Low	Low	High	Low	Low	Medium	Medium	Not Applicable
MMCF Mill Location	Germany	China	China	China	Germany	China	China	China	Austria	Belgium
MMCF Mill Water Quality Status	Medium	Low	Low	Low	Medium	Low	Low	Low	Medium	High

Refer to water quality status section in Appendix 2 for details on mapping water quality status as low, medium or high.

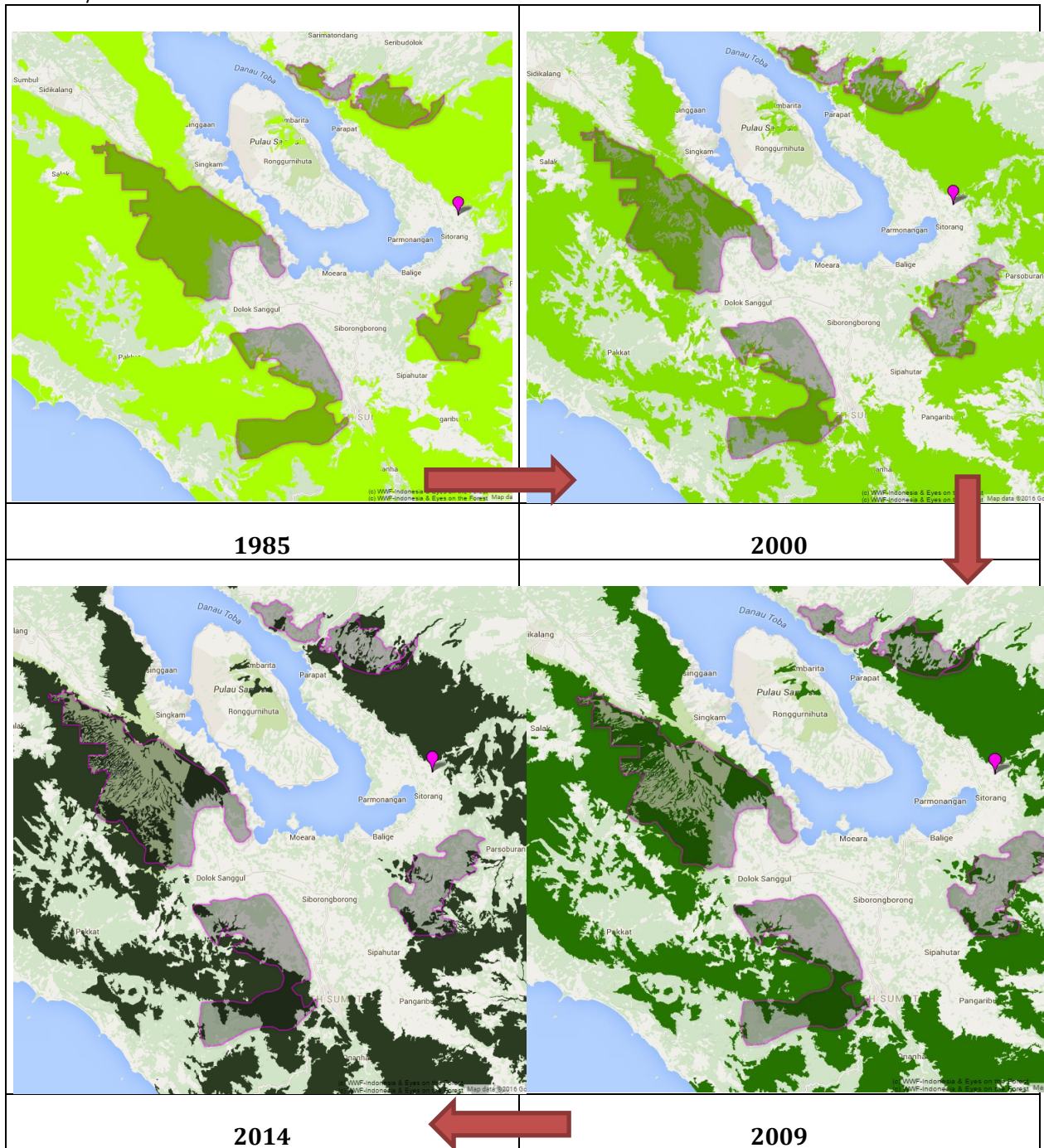
### 5.2.5 Interpretation of Impacts on Terrestrial and Freshwater Ecosystems (from Land Use and Conversion)

The group of impacts titled “Terrestrial and Freshwater Ecosystem Impacts from Land Use” accounts for land-use related activities that can lead to physical disturbance, which eventually lead to impacts to local or regional ecosystems in terrestrial and freshwater settings. These impacts are inherently local, though the scale of effects, both direct and indirect, can vary broadly.

Impacts to terrestrial and freshwater ecosystems from land-use activities around the world have consequences on many scales. Impacts of concern to many stakeholders include loss of biodiversity, changes in biosphere integrity, loss of endangered species, and more. In the production of MMCF, the main contributing activity is logging and agriculture, depending on the raw material from which the fiber is manufactured. These activities directly alter ecological conditions in terrestrial and freshwater ecosystems (i.e., lead to disturbances), which are measurable within ecosystems at many different scales. It is critical to understand these impacts at the landscape scale, understanding not only the impacts from direct harvest, but effects from fragmentation on adjacent forests. For example, the image below in Table 10 shows the conversion of natural forests to eucalyptus plantations in Sumatra, Indonesia (Scenario 4: Chinese Production from Indonesian Plantation Pulp). Sumatra lost 55% of its natural forest cover over 29 years, which is clearly evident in the pulpwood concession areas. This highlights the dramatic change occurring in the forests of this region.



**Table 10.** Natural Forest Cover Maps<sup>72 73</sup> for Sumatra, Indonesia from 1985 to 2014. Region in green is the natural tropical hardwood forests. The areas outlined in pink represent the pulpwood concession areas designated by the Indonesian Ministry of Forestry



<sup>72</sup>Eyes on the Forest; <http://maps.eyesontheforest.or.id/>

In other regions, it is just as important to understand the scale of effects on a holistic level, due to differing forest management practices and history of land management.

In this LCA, a sophisticated and integrated approach for assessing ecosystem disturbances is used to measure these impacts, based on approaches commonly used in the field ecology, which include systematic, practical, and cost effective measurements for assessment of ecosystem characteristics. Balancing the need for a meaningful assessment of ecosystem disturbances with the level of data usually available in LCA, four distinct impact categories are measured in this study. These four components provide a holistic understanding of ecosystem impacts, yet can be assessed in a practical fashion in LCA. The four impact categories include terrestrial disturbance, freshwater disturbance, wetland disturbance, and threatened species habitat disturbance. All comparisons consider the implications of ongoing harvest practices with a scenario where harvests were halted (“no harvest scenario”). For some scenarios, this “no harvest scenario” leads to forest recovery, or for the scenarios in Canada (Scenario 2: Asian Production from Canadian Boreal Forest Pulp) and Indonesia (Scenario 3: Chinese Production from Indonesian Rainforest Pulp), halts the increase in forest disturbance. The only exceptions are any forest conversions occurring after 2011; for these cases, comparisons are against the intact forest state, which is assumed to be the no-harvest representation. (No forests considered have begun conversion since 2011.)

#### **5.2.5.1 Terrestrial disturbance.**

##### ***Significance of Impact Category***

Terrestrial disturbance impact quantifies the number of hectares disturbed as a result of forest harvest or agriculture activities, to produce 1000 tons of MMCF annually, over a period of 20 years. The impacts calculated are consequential in nature, accounting for foregone growth of forest ecosystems, after 20 years; which is the difference in the disturbance condition under continuing harvests, when compared to the disturbance condition where forests are not being harvested. This consideration of the temporal timeframe is essential in understanding the impacts to forest ecosystems.

This is important to understand in terms of the “opportunity cost” of forest recovery suppression, which is salient both in understanding the effect of current forest management on future disturbance levels, but also the possible carbon storage which could be accrued in the forest (discussed in the next section). Even in settings where an ecosystem is improving, ongoing harvests can suppress forest recovery.

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<sup>73</sup> Natural forest 1985-2008/2009: [WWF Indonesia \(2010\) Sumatra’s Forests, their Wildlife and the Climate. Windows in Time: 1985, 1990, 2000 and 2009.](#)

This LCA provides data on the *current* conditions of these impacts, within each fiber basket for each scenario. However, a critical component to understand ecosystem impacts is also the duration and trend in forest conditions. Terrestrial and freshwater ecosystems, after significant and persistent disturbance, can take decades to fully recover; and conversely, intact ecosystems can take long periods of time to be converted into a highly disturbed state. For these reasons, it is critical to understand whether the forest is improving or being further degraded in addition to the current state. Each affected forest, if no longer subject to harvest, would recover over time.

### ***Calculation Approach***

Terrestrial systems are defined using the WWF Wildfinder database for ecoregions. Within each terrestrial system, average ecological conditions such as average tree diameter, tree species composition, and biomass, are measured in specific Forest Analysis Units (FAUs) and compared to undisturbed conditions (URAs). The deviation in ecological conditions is averaged to evaluate current terrestrial disturbance level, which provides a holistic and quantitative measure of understanding the severity of effects on local terrestrial ecosystems. The site productivity is another parameter, which has a very important effect on the embedded impact of fiber from different sources. For additional context, potential recovery, which could be realized in forest ecosystems, is also provided. High quality data was available to evaluate terrestrial disturbance for fiber sourced in nearly all scenarios.

The foregone recovery of forest ecosystem was calculated in conformance with the Roundwood PCR. Based on the trend of disturbance (increasing, decreasing or recovering trend) determined from historic data, the current level of terrestrial disturbance in the FAU was assumed to continue with the same trend over the next 20 years, and then compared after 20 years to a conservatively high estimate of rate of recovery (assuming that the forest system will recover by 2% every year if the forests had not been harvested). Refer to Section 1.3.1 in Appendix 2 for more details on equations and methodology.

For example, in Scenario 1: German Production from Swedish Managed Forest Pulp, data from the Swedish Forest Inventory provided in Table 1 in Appendix 1-C indicated that the current disturbance level is 52%. The time-integrated difference between the terrestrial disturbance in “harvest” scenario and a “no harvest” scenario in this forest is considered; that is, the difference between the disturbance conditions under continuing harvests, when compared to the disturbance condition in a “no harvest” condition.

***No Harvest Scenario:*** Under “no harvest” scenario, it is assumed that the forest will recover at ~2% per year. After 20 years, under a “no harvest” scenario, the terrestrial disturbance level is expected to recover from 52% to 14%.

***Harvest Scenario:*** Historic data from Sweden Forest Inventory indicates that under continuing harvests, actual forest recovery is around 0.25% per year. So after 20 years, under a harvest scenario, the terrestrial disturbance is expected to recover from 52% to 47%.

Foregone recovery for 1000 tons of MMCF= The difference between the “harvest” scenario and “no harvest” scenario is calculated for each year of producing MMCF, the results are integrated over 20 years and normalized for 1000 tons of MMCF.

For example, in year 20, the foregone recovery=  $47\% - 14\% = 33\%$

From Table 2 in Appendix 1-C, based on the land use data, which is 250 hectares per 1000m<sup>3</sup> of timber, land use for 1000 tons of MMCF in a year= 1500 hectares.

For example in year 20, terrestrial disturbance results for MMCF in Scenario 1: German Production from Swedish Managed Forest Pulp in year 20=  $33\% * 1500 = 500$  eq. hectares. Similarly, results are calculated for each year from year 1 to year 20. The results are aggregated over 20 years and normalized for 1000 tons of MMCF to obtain the final results of 250 eq hectares disturbed\* yrs. .

### ***Interpretation of Results***

The following inferences can be made from Figure 2 in Section 1.5:

- The Indonesian tropical rainforests exhibit the highest terrestrial disturbance, followed by the boreal forest regions. As evident in Table 10, the rainforests in Indonesia are being transformed into eucalyptus plantation, resulting in the highest terrestrial disturbance. The current level of disturbance in the boreal region is medium (approximately 45% as presented in Table 5 in Appendix 1-C), showing there is opportunity to conserve local forests. However, there is an increasing trend in the disturbance (5% per decade). Such persistent increase in disturbance will gradually cause these intact ecosystems to transition to a disturbed terrestrial ecosystem.
- The terrestrial disturbance impacts are dependent on the site productivity in a given region; the volume of fiber which can be extracted from a given area over an extended period of time. Although some forests, such as those in the scenarios specifying Indonesian and South African logging (Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian Plantation Pulp and Scenario 8: Chinese Production from South African Plantation Pulp), are in a very high state of disturbance because of transition from native forests or grasslands to exotic plantations, plantations in these regions are extremely productive. This means that although local forest conditions are highly negative compared to regions such as Sweden, Canada or Austria, significantly less area is required to produce the same amount of fiber.
- Production of 1000 cubic meters of pulpwood from eucalyptus plantations in South Africa requires only 20% of the land area to produce the same amount of pulpwood in Sweden. Thus, due to high productivity, the South African scenario appears to be more favorable compared to other pulpwood sources.
- Scenario 1: German Production from Swedish Managed Forest Pulp, which is the baseline scenario, is a mid-range performer compared to other scenarios (better than some scenarios, worse than other). The current level of disturbance in Sweden is medium

(approximately 52% as presented in Table 2 in Appendix 1-C) and historical data on gradual increase in forest stands suggest that the forest conditions are recovering, although at a slow rate of around 2% per decade. This indicates that the forests are managed to steadily increase forest carbon stocks as well as produce a sustained yield of timber in these forest ecosystems.

- The land use results for Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 10: Belgian Flax Production cannot be directly compared to the other scenarios, because, the results are estimated in terms of mass of cotton or flax fibers required to produce MMCF and not in terms of volume of wood required for MMCF. A high level of disturbance is determined for both scenarios as a result of historical transformation of desert scrubland and native forests to agriculture for Scenario 7 and Scenario 10 respectively. The number of hectares disturbed to produce MMCF from agricultural byproducts is less than disturbance caused by sourcing wood from forests.

#### **5.2.5.2 Freshwater disturbance.**

##### ***Significance of Impact Category***

This impact category refers to the degree to which activities involved in production of manmade cellulose fibers impact rivers, streams and creeks affect flora and fauna and the purpose is to evaluate the disruption of sensitive ecosystems that have evolved over millennia.

##### ***Calculation Approach and Interpretation***

There was insufficient data of comparable quality to identify affected freshwater systems across the global scope of this study. Results could not be evaluated. For some scenarios, these impacts could be significant, as land use management can lead to many types of impacts, as described in Appendix 2.

#### **5.2.5.3 Wetland disturbance.**

##### ***Significance of Impact Category***

This impact category refers to the degree to which activities involved in production of MMCF can impact wetlands and the purpose is to evaluate the disruption of sensitive ecosystems that have evolved over millennia.

##### ***Calculation Approach and Interpretation***

There was insufficient data of comparable quality to identify affected wetlands across the global scope of this study. Results could not be evaluated. However, for some scenarios, these impacts could be significant, as land use management can lead to many types of impacts, as described in Appendix 2.

#### 5.2.5.4 Threatened species habitat disturbance.

##### ***Significance of Impact Category***

This impact category refers to activities involved in production of manmade cellulose fibers affecting habitats of threatened species. Species sensitive to logging operations in the fiber basket are included in the assessment.

##### ***Calculation Approach***

Included are all threatened categories of species affected by pulpwood harvested for dissolving pulp production, based upon the definition of the “threatened categories” according to the IUCN Red List Categories and Criteria Version 3.1 Second Edition<sup>74</sup>. This includes species (mammals, amphibians, reptiles and birds) meeting the categories of Critically Endangered, Endangered, or Vulnerable in the IUCN Red List database<sup>75</sup>. Only those species with habitats and/or populations negatively affected by logging and/or agriculture in the region (depending on the fiber source) were included. Justification for species inclusion is provided for applicable scenarios in Appendix 1-C, based on correlation of logging threats assessed by IUCN and the fiber basket of dissolving pulp mills.

It is to be noted that IUCN assesses conservation status and classifies threatened species (i.e. species at high risk of global extinction) at a global-level. A global-level assessment of species risk may not be robust enough to reflect the relative threats encountered by species at a local level. The robustness of data quality associated with the IUCN Red list species is low for some regions, particularly Indonesia. In these regions, not all species may be catalogued sufficiently, let alone being categorized into threatened or endangered status. This is likely to result in an underestimation of number of threatened species in Indonesia. Developed countries like Canada and Sweden provide a detailed list of locally threatened species.

For example, the European tree frog is enlisted as “Vulnerable” in the Flanders region by the government of Belgium. However, at a global scale, this species is considered to be of “Least Concern” status by IUCN. Furthermore, in many instances, species in local lists overlapped with IUCN red list species. IUCN also partners with many regional institutions and local governments for species research and assessments. Hence, where applicable, this indicator includes threatened (includes Vulnerable, Endangered and Critically Endangered status) species from two lists: (1) IUCN Red List Species, which is a global-level species list and (2) Additional species from local lists (evaluated by local governments).

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<sup>74</sup> IUCN Red List; <http://www.iucnredlist.org/>

<sup>75</sup> IUCN Red List; <http://www.iucnredlist.org/>

It is to be noted that for most scenarios (except Scenario 6 and 7), local governments conduct regional assessment of species by following the IUCN Red List criteria to determine species status. Hence, the data quality for this indicator was improved by inclusion of both IUCN and local government lists.

### ***Interpretation of Results***

Results for key species habitat loss provided in Section 4.2 indicate that the number of threatened species is greatest for the Indonesian scenarios (Scenario 3 and Scenario 4), which is seven to thirteen times the number of species impacted in other scenarios. Although there are limitations in results, particularly due to paucity of data in scenarios such as Indonesia, the ranking of the scenarios is not expected to change because of the fact that biodiversity in the tropics is the greatest across all scenarios and most subjected to threats from logging. This means that while the number of threatened species in Indonesia may be underestimated, a more accurate result would not affect the outcome of the comparison. Scenario 5: German Production from Recycled Pulp is the best performer as it does not involve any pulpwood extraction for MMCF production, and therefore does not affect any threatened species.

#### **5.2.5.5 Evaluation of Other LCA Methodologies Approach to Evaluating Ecosystem Disturbances**

Many approaches for assessing disturbances to terrestrial and freshwater ecosystems exist, and have been presented and discussed widely in the field of ecology over many decades.<sup>76,77,78,79</sup> In LCA, generally, impacts are evaluated using generic measures of “land use”, or using an endpoint measure of “partially disappeared fraction of species” (PDF) which is intended to indicate the total reduction of biodiversity in a region. These approaches were not used in this LCA, as they can be both impractical and very misleading, portraying an inaccurate or incomplete picture of disturbance on the ground. There are several reasons that the measures of “land use” or “PDF” are problematic:

- Measures solely of “land use” only examine measures of site productivity, overlooking what could be high-intensity disturbance in some regions. Using just the measure of “land use”, the best-performing scenarios would involve production of pulpwood from eucalyptus plantations in Indonesia and South Africa. These scenarios also have the highest level of current disturbance of any scenario, a fact overlooked when reporting solely on measures of “land use”.

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<sup>76</sup> Ecosystem health and integrity? D. Wicklum, Ronald W. Davies. Canadian Journal of Botany, 1995, 73:997-1000, 10.1139/b95-108.

<sup>77</sup> Schaeffer, D. J., et al. Ecosystem health: I. Measuring ecosystem health. Environmental Management, July 1988, Volume 12, Issue 4, pp 445-455.

<sup>78</sup> Lindenmayer, D.B., J.F. Franklin, and J. Fischer. General management principles and a checklist of strategies to guide forest biodiversity conservation. Biological Conservation 131 (2006) 433-445.

<sup>79</sup> Michael A. Schroeder, Rex C. Crawford, F. Joseph Rocchio, D. John Pierce, and Matt Vander Haegen. Ecological Integrity Assessments: Monitoring and Evaluation of Wildlife Areas in Washington (Draft). Washington Department of Fish and Wildlife, August 2011. <http://wdfw.wa.gov/publications/01314/>

- For PDF, the measure of “biodiversity loss” in practice is very difficult to define and measure. At any given site, the number of species present will be enormous, when considering organisms such as soil microbes and bacteria. For some taxa, species counts are very difficult. For example, censuses of migratory birds is very challenging logistically. Any type of comprehensive measure of biodiversity loss will be very difficult in practice and necessarily have high uncertainty. Yet in most LCAs, PDF is measured using site-generic databases based on limited inputs, usually using vascular plant data as a proxy. This is inappropriate when considering the highly site variable and greatly complex nature of biodiversity changes.
- Even in principle, the measure of PDF overlooks the varied effects on an ecosystem, not only to measure changes in biodiversity, but also on effects to vegetative composition, tree sizes, and landscape connectivity. A tally of the number of species does not consider the species which are there, neglecting to account for the replacement of endemic species by exotics, or situations where a disturbance favors aggressive native species which proliferate, resulting in the decline of other native species. In fact, PDF, by reflecting only biodiversity, could report a better performing value because biodiversity can actually increase with disturbance. This can occur when a disturbance event allows new species to colonize a site, adding to the total number of species which are present. Even using site data in the PDF measure could therefore give a misleading understanding of on-the-ground conditions.

For these reasons, these existing LCA approaches were not used in the study.

## **5.2.6 Interpretation of Human Health Impacts (from Chronic Exposure to Hazardous Chemicals)**

### **5.2.6.1 Ground Level Ozone Exposure Risks**

#### ***Significance of Impact Category***

Emissions of NO<sub>x</sub> and certain volatile organic compounds (VOCs) undergo a complex series of photochemical reactions that lead to the formation of ozone (O<sub>3</sub>). Human health impacts are widely recognized to occur when ozone near the Earth’s surface (ground level ozone, or “GLO”) is found at concentrations above critical threshold concentrations, especially for prolonged periods of time. Specific regional data regarding the conversion rates of ozone precursors were not available for the regions considered in this study.

### **5.2.6.2 PM 2.5 Exposure Risks**

#### ***Significance of Impact Category***

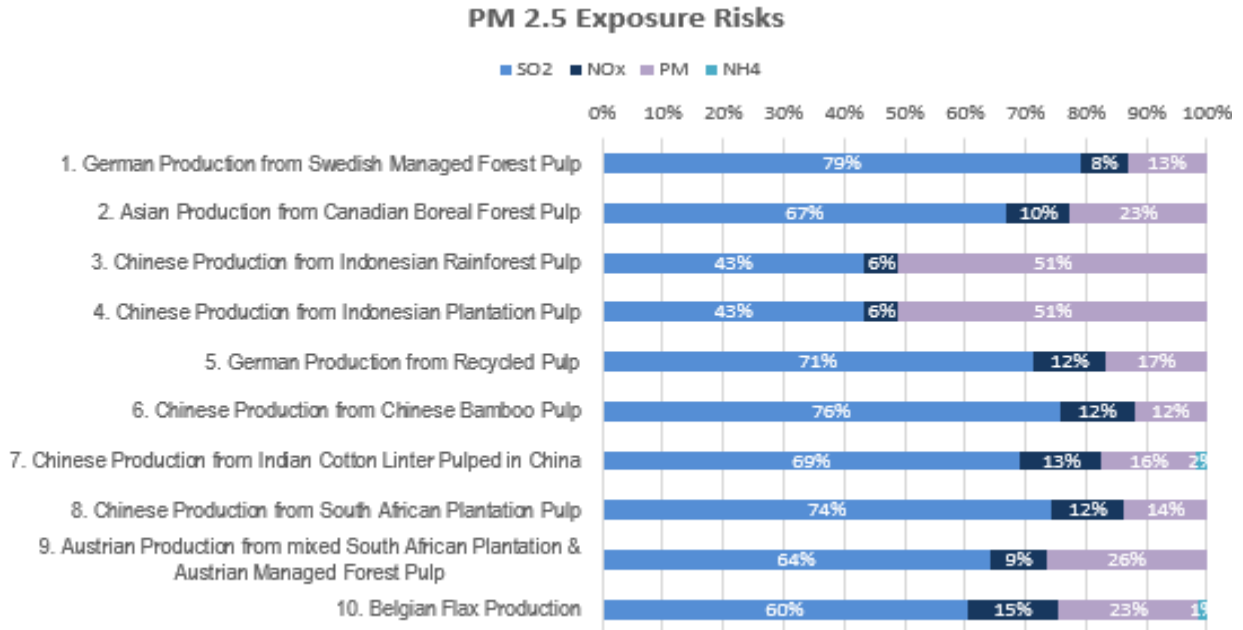
This impact category considers health risks from inhalation of particles less than 2.5 microns in diameter (PM<sub>2.5</sub>). This refers to human exposure to particulates smaller than 2.5 microns at levels above human health thresholds. For indicator results, all primary particulate emissions are included, as well as emissions which can convert into particulate matter in the atmosphere to form secondary particulates.



**Calculation Approach**

This impact category characterizes the mass of PM<sub>2.5</sub> transported into the atmosphere as the result of an emission and characterizes the exposure of humans to fine particulate matter, considering the local severity of health impacts linked to elevated levels of PM<sub>2.5</sub>. Results are calculated using air dispersion modeling of particulate emissions plumes in different regions.

**Interpretation of Results**



**Figure 25.** % Contribution Analysis by pollutant for PM<sub>2.5</sub> Exposure Risks. The absolute results, by impact category, are shown in Figure 7.

Scenario 10: Belgian Flax Production has the least PM<sub>2.5</sub> exposure impacts compared to all the scenarios and it is closely followed by Scenario 1: German Production from Swedish Managed Forest Pulp, Scenario 5: German Production from Recycled Pulp and Scenario 9: Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp. The results for MMCF produced in Asia vary by an order of magnitude. The main factor for this increase results from (i) the particulate emissions associated with energy generation in Asia and (ii) population exposure to particulate emissions above human health thresholds. Overall, sulfur dioxide (SO<sub>2</sub>) and particulate matter emissions (PM<sub>2.5</sub>) are the key drivers of PM<sub>2.5</sub> impacts across all scenarios. The contribution analysis chart (refer to Figure 18) suggests that pulp production is a relevant contributor to this impact category, accounting for 18%-43% of total impacts across all scenarios. Typically, particulate emissions occur largely from the recovery furnace and combustion of fuels such as natural gas, coal, oil, wood waste, etc. for steam generation at the pulp mills. A large share of SO<sub>2</sub> emissions arise from pulp mills, which are mainly emitted from oxidation of reduced sulfur compounds in the recovery furnace of the mills.

Furthermore, sodium hydroxide and sulfuric acid production, which are primary chemical inputs for MMCF production, also contribute measurably to this impact category.

### 5.2.6.3 Hazardous Ambient Air Contaminant Exposure Risks

#### ***Significance of Impact Category***

This impact category considers hazardous ambient air contaminants (HAACs) emitted to air which, if inhaled, may lead to toxic effects in humans. The only substances considered are those which contribute to the contamination of ambient air at concentrations over safe thresholds, which could subsequently expose humans through inhalation. Results are separately assessed for two indicators, characterization HAAC emissions with respiratory health impacts, and emissions of carcinogens.

#### ***Calculation Approach***

The calculation approach is based on HAAC emissions and the inhalation toxicity of each chemical relative to a reference chemical, based on the Reference Concentration (RfC). Refer to Appendix 2 for more detail.

#### ***Interpretation of Results***

Figure 17 in Section 4.2 indicates that Scenario 10: Belgian Flax Production has the least HAAC impacts compared to all the scenarios. The results for other scenarios are more or less similar, except for Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China, which is nearly 25% greater than other scenarios. This is probably because of the upstream production of fertilizers used in cotton cultivation.

## 5.3 Comparison to LCIA Profile Using CML

A sensitivity analysis was conducted, comparing the LCA results for the ten scenarios, using the CML method<sup>80</sup>, and the framework of the draft LEO-S-002 standard. The intention of this sensitivity analysis is to understand the effect on the comparison of the LCA results for each scenario when different LCA methodologies are applied. For comparison purposes, Table 11 presents results calculated using CML method for 1 ton of MMCF with the LCIA method used as a default in the current study.

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<sup>80</sup>CML- Baseline; April 2013; <http://cml.leiden.edu/software/data-cmlia.html>

**Table 11.** Results for 1 ton of MMCF calculated using CML method. Note that these results include a uniform credit of 1.6ton CO<sub>2</sub>e of biogenic carbon stored in the product across all the scenarios.

LCIA Method	Impact Category	1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	10. Belgian Flax Production
CML	Acidification potential (kg SO <sub>2</sub> eq)	36	44	65	65	21	64	64	48	20	8.2
CML	Climate change – GWP100 (ton CO <sub>2</sub> eq)	4.1	7.2	8.3	8.3	1.6	6.8	7.4	3.3	4.5	0.20
CML	Depletion of abiotic resources – elements, ultimate reserves (ton antimony)	4.4E-05	9.8E-05	3.4E-05	3.4E-05	2.2E-05	5.1E-05	3.6E-05	3.0E-05	1.1E-05	1.6E-05
CML	Depletion of abiotic resources – fossil fuels (thousand MJ)	28	26	41	41	14	15	18	14	22	8.3
CML	Eutrophication (ton PO <sub>4</sub> -eq)	4.2E-03	4.9E-03	5.3E-03	5.3E-03	3.1E-03	6.4E-03	6.7E-03	5.2E-03	3.7E-03	1.8E-03
CML	Freshwater aquatic ecotoxicity (ton 1, 4-dichlorobenzene eq.)	2.4E-02	2.2E-02	3.4E-02	3.4E-02	2.4E-02	2.0E-02	3.1E-02	2.5E-02	8.1E-02	2.6E-03
CML	Human toxicity (kg 1, 4-dichlorobenzene eq.)	0.78	1.1	1.1	1.1	0.86	1.2	1.4	1.4	0.69	0.40
CML	Marine aquatic ecotoxicity (ton 1, 4-dichlorobenzene eq.)	1.6	2.4	2.5	2.5	1.1	2.9	3.0	3.4	2.7	0.7
CML	Ozone layer depletion (ton CFC-11 eq.)	1.1E-07	9.9E-07	1.1E-06	1.1E-06	1.0E-06	9.6E-07	9.8E-07	7.8E-07	6.9E-07	5.2E-07
CML	Photochemical oxidation (ton ethylene eq.)	1.8E-03	2.1E-03	2.9E-03	2.9E-03	1.0E-03	2.5E-03	2.4E-03	2.0E-03	9.0E-04	3.6E-04
CML	Terrestrial ecotoxicity (ton 1, 4-dichlorobenzene eq.)	2.0E-3	2.0E-3	2.5E-3	2.5E-3	1.5E-3	1.5E-3	0.243	1.7E-3	1.3E-3	2E-04

Using the CML approach, although there is no source of fiber which is unambiguously environmentally preferable across all impact categories, Scenario 10: Belgian Flax Production and Scenario 5: German Production from Recycled Pulp seem favorable across majority of the impact categories. This is similar to the result for the LEO-S-002 approach. As in the LEO-S-002 approach, all sources of fiber have benefits and disadvantages environmentally. However, some sources of fiber have more benefits, and fewer disadvantages, than others.

- For CML, Scenario 10: Belgian Flax Production has the least climate impact compared to other scenarios, closely followed by Scenario 5: German Production from Recycled Pulp. On the other hand, for the LEO-S-002 approach, Scenario 5 has the least climate impact compared to other scenarios. When accounting for climate impacts using the LEO-S-002 approach, Scenario 10 appears slightly less favorable compared to Scenario 5. This is because the LEO-S-002 climate impact includes carbon storage losses occurring due to flax harvest, whereas, this is irrelevant for Scenario 5 as it requires only recycled clothing inputs.
- For CML, Scenario 3: Chinese Production from Indonesian Rainforest Pulp and Scenario 4: Chinese Production from Indonesian Plantation Pulp are the worst performers in multiple impact categories. This conclusion is similar to the findings of the current study presented in Table 1 using the LEO-S-002 approach.
- Scenarios 2: Asian Production from Canadian Boreal Forest Pulp and Scenario 6: Chinese Production from Chinese Bamboo Pulp, are not the worst performers in any category. Nor are they the best performers in any impact category. Under the LEO-S-002 approach, these scenarios appear worse, with Scenario 2 being one of the worst performers in climate and ocean impact categories, and Scenario 6 being one of the worst performers in the human health impact categories. This is because, for Scenario 2, the carbon storage losses occurring in the boreal forests in Canada are high, resulting in larger climate impact and ocean acidification impacts. In case of Scenario 6, human health impacts are higher because the population exposure is greater for the mill located in China compared to Europe. Hence, Scenario 2 and Scenario 6 look worse under the LEO-S-002 approach.
- For CML, Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China is the worst performer in 2 impact categories. Scenario 7 therefore performs similar to the LEO-S-002 approach, where it is the worst performer in 2 impact categories, and the second/third worst performer in multiple categories.
- For CML, Scenario 5: German Production from Recycled Pulp, is the second-best performer across all impact categories. Under LEO-S-002, it is the best performer in over five (due to its lack of effect on ecosystems).
- Scenario 10: Belgian Flax Production is the best performer in most categories. This conclusion is the same between the two approaches.

Based on this discussion above, it is clear that results between CML and LEO-S-002 bear several important differences. As it addresses fewer impact categories, and does not differentiate whether impacts are relevant for each scenario, CML does not pick up the same magnitude of difference as LEO-

S-002. Furthermore, a key goal of this study was the evaluation of ecosystem impacts resulting from land intensive harvesting activities, required to produce MMCF. As CML does not include these vectors of impact directly, it does not record the wide variability in impacts, including effects on fundamentally different types of forest ecosystems and key species.

### Comparison of LCA results with other published LCA studies

The climate change results calculated using CML method<sup>81</sup> presented in Table 11 were compared to existing LCA studies, in particular, a study published by Lenzing in 2010<sup>82</sup> (hereafter, referred to as the Lenzing LCA), which assessed the environmental impacts of MMCFs produced in Asia and Europe. The Lenzing LCA reported a cradle-to-gate GWP of 3.8tCO<sub>2</sub>e and -0.25 tCO<sub>2</sub>e for 1 ton of MMCF produced in Asia and Europe respectively. These results cannot be compared to the current LCA study's main results, presented in Section 4 because the climate change impact reported in the Lenzing LCA does not include cooling effects or forest carbon storage losses. However, use of the same indicators means that results from the Lenzing LCA can be compared with results from Table 11. Furthermore, the dissimilarity in the scope of the two studies prevents a meaningful side-by-side comparison between the two studies. For example, while in both LCA studies, MMCF produced in Asia has higher impacts compared to MMCF produced in Europe, the Lenzing LCA did not consider MMCF produced from boreal forest pulp, Indonesian rainforest and plantation pulp, recycled pulp, flax, cotton linter, or bamboo, and so conclusions for those scenarios cannot be evaluated.

For the scenarios which do bear similarities, reviewing the results for the Lenzing LCA with those in Table 11, it is clear there are some important differences. For example, Scenario 1: Scandinavian Managed Forest, involving production in Europe, has a GWP result of 4.1 tCO<sub>2</sub>e, whereas the Lenzing LCA had a result of -0.25 tCO<sub>2</sub>e. While differences are expected, as the MMCF is produced at different mills, and the LCA results calculated using different datasets; these differences were significant enough to warrant review. SCS reviewed the reasons behind the differences found in Table 11, and are summarized below:

- **Life Cycle Inventory Data:** The deviation in LCA results is largely observed due to the underlying inventory data used to model the results. The processing efficiency of dissolving pulp and MMCF varies by mill and by location. An integrated pulp and fiber mill operates more efficiently and may be self-sufficient in terms of energy use, compared to non-integrated production of pulp and MMCF. All the scenarios evaluated in this study consider non-integrated production of pulp and MMCF; whereas the Lenzing LCA considers a mix of market pulp and Lenzing pulp produced at Lenzing pulp mill, as well as integrated pulp/fiber production in Austria, resulting in lower results for viscose produced in Austria.

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<sup>81</sup> CML- Baseline; April 2013; <http://cml.leiden.edu/software/data-cmlia.html>

<sup>82</sup>[http://www.lenzing.com/fileadmin/template/pdf/konzern/lenzinger\\_berichte/ausgabe\\_88\\_2010/LB\\_88\\_2010\\_paper\\_1.pdf](http://www.lenzing.com/fileadmin/template/pdf/konzern/lenzinger_berichte/ausgabe_88_2010/LB_88_2010_paper_1.pdf)

- **Allocation Procedure:** The Lenzing LCA used the system expansion method as the default approach, thereby assigning credits to by-products obtained from dissolving pulp production and viscose fiber production. According to Lenzing LCA, credits from by-products represent at least a third of fossil CO<sub>2</sub> emissions for viscose fibers. The current LCA study uses a mass-based allocation approach as a default, wherein all the impacts are assigned based on the mass of dissolving pulp or MMCF produced at the mill.

#### 5.4 Sensitivity Analysis Comparing Results using 100-year timeframe for Global Warming

In this study, CO<sub>2</sub>e results are calculated using the integrated radiative forcing (IRF) over 20 years (see Appendix 2 for more information). Although most past LCA studies have used the 100-year time horizon, in this study, two compelling reasons motivated use of the 20-year timeframe:

- 1) The Paris Agreement, the international consensus agreement on combating climate change, has set a goal of limiting global temperatures to 2°C, and preferably 1.5°C. However, without a significant reduction in GHG emissions, 2°C could be reached in 30-40 years, and 1.5°C in just 20 years.<sup>83</sup> By 2030, radiative forcing, a measure which includes all non-CO<sub>2</sub> forcers, could exceed 2.6 W/m<sup>2</sup>, at which point the world will be committed irreversibly to 2°C.<sup>84</sup> An analysis by the United Nations Environment Program (UNEP) reinforces the urgent need for action in the near term. In November 2016, it stated that 2030 GHG emissions must be reduced an additional 25% beyond the Paris pledges to meet the 2°C goal, and that emissions levels projected in 2030 “will, even if the Paris pledges are fully implemented, place the world on track for a temperature rise of 2.9 to 3.4 degrees this century.”<sup>85</sup> Additionally, most of the Intended Nationally Determined Contributions, containing GHG reduction commitments of Paris Agreement country signatories, do not extend beyond 2035. Given the needed timeframe of mitigation (before 2030, according to UNEP), and the timeframe of mitigation policies agreed to by Paris Agreement signatories, use of the 20-year timeframe is justified for this report. A sensitivity analysis is also completed, examining the effect on results of the 100-year time horizon (see Section 5.4).

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<sup>83</sup> Based on temperature projections of the IPCC Fifth Assessment Report RCP6.0.

<sup>84</sup> See Figure 12.4 of Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

<sup>85</sup> UNEP, Nov. 3, 2016: “World must urgently up action to cut a further 25% from predicted 2030 emissions, says UN environment report.”

<http://wedocs.unep.org/bitstream/handle/20.500.11822/10014/Emission%20Gap%202016%20press%20release.docx?sequence=1&isAllowed=y>

- 2) The dynamic changes in ecosystems mean that predicting implications on climate change and ecosystem quality more than 20 years in the future are highly uncertain. Therefore, including a result focused solely on the 100-year time frame would lead to a result with very low data quality. GWP-100 values are 50-100% higher in uncertainty than GWP-20 values; furthermore, the assumptions made to calculate foregone growth over a 100-year timeframe have significant uncertainty, as trends in forest recovery and harvest past 20 years have exponentially increasing uncertainty levels.

For these reasons, the 100-year time horizon should not be used as the basis of comparison. However, in order to provide context, a sensitivity analysis is completed comparing the use of the 20-year and 100-year timeframe, in order to provide context to results when compared to other LCAs.

In this sensitivity analysis, GWP-100 values were used in lieu of GWP-20 values, and the timeframe of the foregone growth calculation was extended to 100 years. In this approach, the trend of forest recovery under the no-harvest condition results in full recovery of all unharvested regions within 50 years; and the trend in change in the actual forest carbon storage level as well for 100 years (although forests on a recovering trajectory are assumed to sequester at a maximum 80% of the undisturbed state, while forests on a worsening trajectory do not achieve less than 0 tons of carbon storage per hectare). This result was then integrated over 100 years and normalized to the AGWP-100.

One additional adjustment was made to the results. Using the results over 20 and 100 years cannot be directly compared, as each are respectively divided by two different values: the AGWP-20 and AGWP-100 of CO<sub>2</sub>, which IPCC reports respectively have values of 0.0249 and 0.0923 mW Tg<sup>-1</sup> m<sup>-2</sup> yrs. In order to ensure results are directly comparable, the results calculated over 100 years are adjusted to use the divisor of the GWP-20; this ensures units are comparable. This was completed by multiplying all results over 100 years by 3.707, which is the ratio of the AGWP-100 and the AGWP-20.

Results of this sensitivity analysis are shown in Table 12 for all scenarios.

**Table 12.** Sensitivity analysis comparing Global Climate Change, Net results calculated over a 100-year time horizon with 20-year time horizon.

Impact Category	Units	1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	10. Belgian Flax Production
Global Climate Change (20 years)	thous. tons CO <sub>2</sub> e	5.2	12	13	6.3	-2.0	4.4	2.3	0.072	3.4	-0.63
Global Climate Change (100 years)	thous. tons CO <sub>2</sub> e	8.6	29	39	17	-1.8	12	8.2	0.060	2.7	0.047
Change from 20 year timeframe	thous. tons CO <sub>2</sub> e	65%	142%	200%	170%	+10%	173%	257%	-17%	-21%	+107%

A few conclusions can be derived from these results:

- Nearly all scenarios dependent upon bio-derived sources have an impact from foregone growth which increases over time with increases ranging from +65% to +200%. This reveals the long-term negative impact of suppressing ecosystem carbon storage increases, a negative effect which increases with time.
- The only exceptions are Scenario 8: Chinese Production from South African Plantation Pulp and Scenario 9: Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp. Both of these scenarios draw wood from eucalyptus plantations in South Africa which *increase* carbon storage compared to native grasslands. This carbon benefit increases over time, as these plantations effectively sequester additional CO<sub>2</sub> from the atmosphere, than would be the case if management ceased and the plantations returned to a grassland condition. However, it should be noted that this carbon benefit comes along with a high level of terrestrial disturbance on-site (see Figure 2).
- The relative ranking does not change for the worst performers, which remain the boreal and two Indonesian scenarios. These scenarios show significant increases that in fact increase the margin of difference between nearly all other scenarios. This accounts for the long term carbon implications of converting high carbon density forests to relatively low carbon density plantations and managed forests.
- Neither does the relative ranking of the best performer change; the recycled textile source remains the best option from a climate perspective.
- The margin between the 2<sup>nd</sup> and 3<sup>rd</sup> best performers (Scenario 10 and Scenario 8) diminish to a level that is within a reasonable margin of error, making these two appear comparable from a climate perspective across a 100-year timeframe. The carbon benefit of the South African



plantations increases over time (discussed above), while the carbon debit from preventing flax fields from restoring to forests works against Scenario 10.

- Scenario 1: German Production from Swedish Managed Forest Pulp shows an increased result over this 100 year timeframe, but the increase is significantly less than the increases associated with other scenarios with foregone growth impacts. This is because the forests are recovering in these regions, a trend which is assumed to continue over the projected timeframe.

Overall, the relative ranking of performance of the different scenario changes very little using this extended timeframe.

## 6 Methodology

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This LCA conforms to ISO 14044 and the draft LEO-S-002 standard<sup>86</sup>, and the Roundwood PCR<sup>87</sup>. The sections below describe the key points of the methodology used to assess LCA results.

### 6.1 Functional Unit

MMCF can be used in multiple applications (e.g. yarns, embroidery threads, blended fabrics, apparel, upholstery, etc.). Due to its potential use in various applications, a specific functional unit cannot be clearly defined. Hence, a declared unit is used, in lieu of a functional unit in this study. The declared unit clearly defines, quantitatively and qualitatively, the reference flow in the study.<sup>88</sup>

The declared unit, used as a basis of comparison for all ten scenarios, is based on 1,000 tons of staple fiber (MMCF) produced.

All MMCF products considered in the scope are staple fibers used in textile clothing. It does not include MMCF grades produced for non-woven and other industrial applications.

### 6.2 System Boundary

The system boundary for this LCA study is cradle-to-gate; including all relevant impacts involved in raw material extraction, dissolving pulp production, and staple fiber production, for ten sources of MMCF. The gate ends at the staple fiber (MMCF) manufacturing facility gate. The ten sources of MMCF are listed in Table 3, with the locations of the dissolving pulp and fiber mills shown in Figure 4. The dissolving pulp mills and MMCF mills will hereafter be referred to as the names indicated in Table 3.

The forests which supply pulpwood to the dissolving pulp mills are the fiber baskets of each mill. The fiber baskets are defined by scenario in Sections 6.9.1 through Section 6.9.10.

It is to be noted that Scenario 5: German Production from Recycled Pulp considers the production of viscose fibers from recycled clothing inputs. The recycled content cut-off approach is used, whereby the impacts from the prior and subsequent life cycles are not included. Hence, impacts to terrestrial and freshwater ecosystems from land use and conversion are not relevant for this product system. The transportation from the textile recycling center to the pulping unit in Sweden is included. See Section 6.9.5.1 for discussion.

In case of Scenario 9: Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp, the technology for fiber production differs compared to conventional viscose fiber

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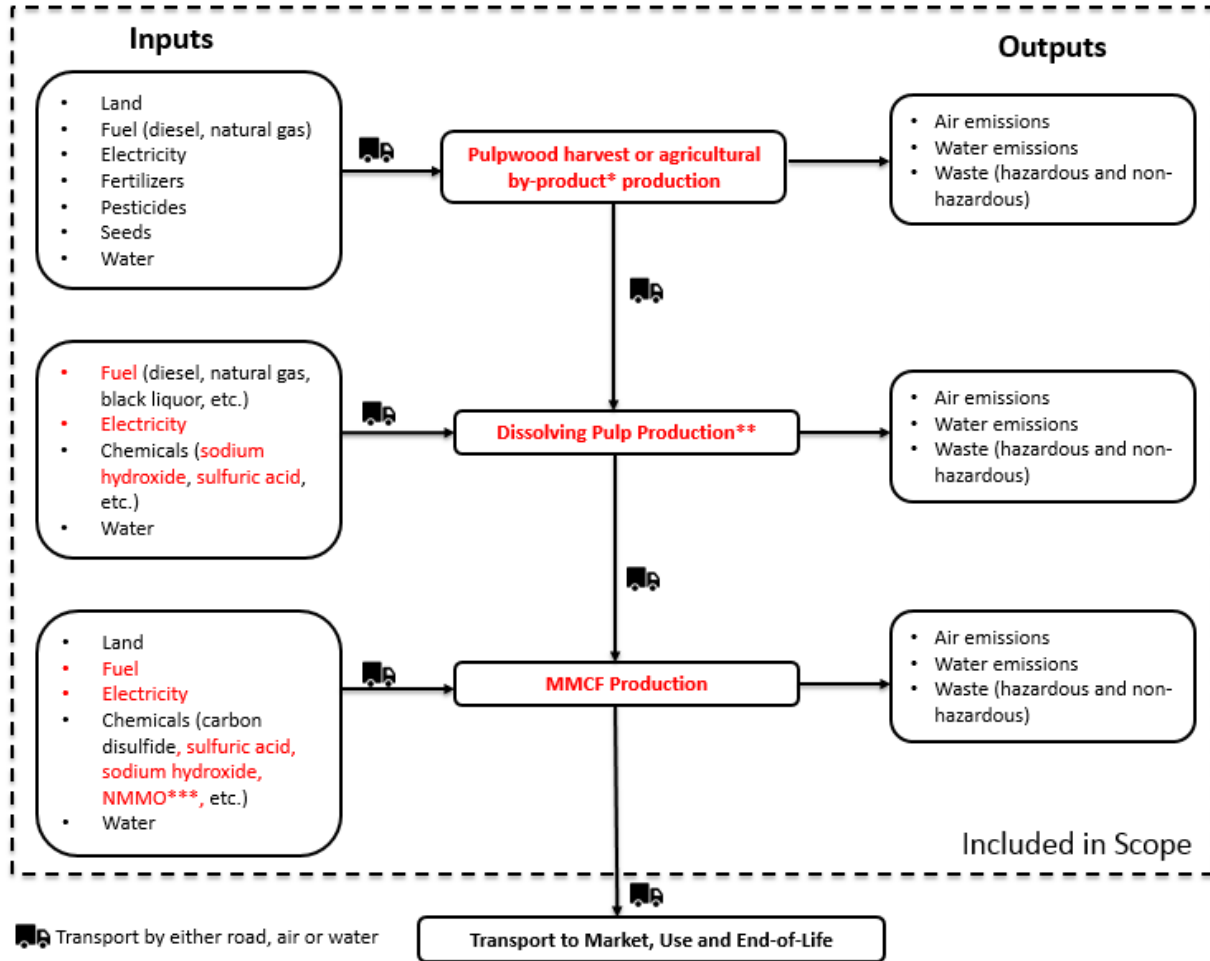
<sup>86</sup> LEO-SCS-002 Standard Draft Dated June 2014. Leonardo Academy.  
<http://www.leonardoacademy.org/programs/standards/life-cycle.html>

<sup>87</sup> PCR Module for Roundwood Production:  
[https://www.scsglobalservices.com/files/resources/pcr\\_final\\_wood-products\\_101816.pdf](https://www.scsglobalservices.com/files/resources/pcr_final_wood-products_101816.pdf)

<sup>88</sup> International Life Cycle Database Handbook: General Guide for Life Cycle Assessment – Detailed Guidance. Section 6.4.6.

production. The main difference lies in the distinct chemistry associated with the production of this regenerated cellulose fiber. Refer to description of lyocell processing technology provided in Appendix 1-D.

The system boundary diagram presented in Figure 26 illustrates the key inputs, outputs and processing steps which were included in the scope of this study. A description of the product systems, LCI analysis, and LCIA, are provided in Sections 6.5, 6.8, and 6.9, including the most important unit processes in the study scope.

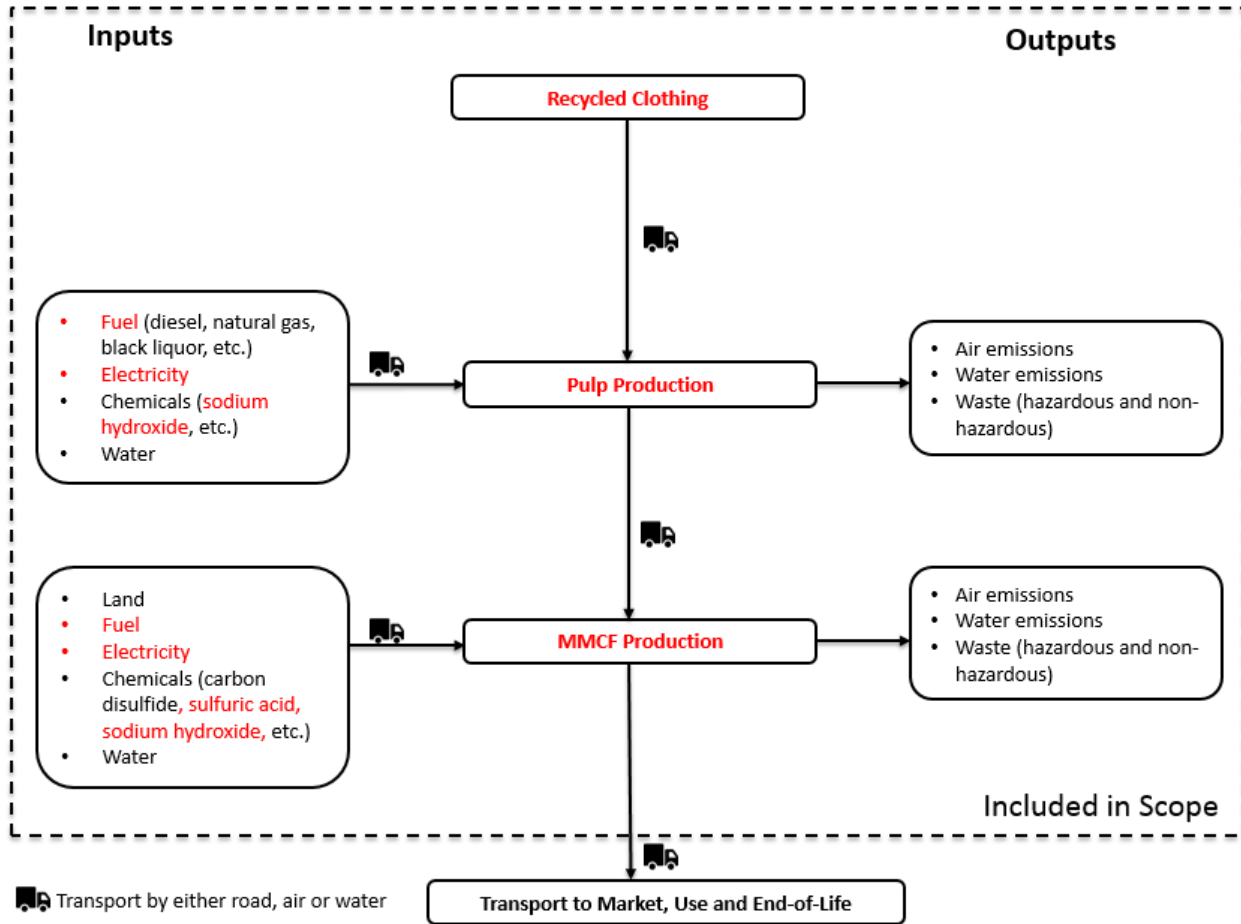


\*Applicable to Scenario 7 and Scenario 10 (short flax fibers).

\*\*Not applicable to Scenario 10. Scenario 5 produces pulp from recycled clothing input.

\*\*\*Applicable only to Scenario 9

**Figure 26.** The flow diagram depicts the key inputs, outputs and processing steps involved in the production of MMCF for all scenario except Scenario 5: German Production from Recycled Pulp (See Figure 27 below). Key unit processes (contributing over 10% to any indicator result) are in highlighted in red. This flow diagram is applicable to all product systems. Not all unit processes involved in the product systems are shown in this figure. Refer to the Figure 27 below for product system of Scenario 5: German Production from Recycled Pulp.



**Figure 27.** The flow diagram depicts the key inputs, outputs and processing steps involved in the production of MMCF for Scenario 5: German Production from Recycled Pulp.

### 6.3 Allocation Procedures

When dealing with useful co-products, this study followed allocation guidelines of ISO 14044, and sought to minimize the use of allocation wherever possible. However, ISO 14044 states that mass-based allocation should be used preferentially if allocation is needed, and for this reason, a mass-based allocation approach was used where necessary.<sup>89</sup> Mass-based allocation takes a physical approach by partitioning impacts based on relative mass of products and co-products generated. System expansion was used in some cases where mass allocation was not possible.

Table 13 presents the useful co-products produced at the major unit processes, and the allocation method used for each, for the ten product systems considered.

<sup>89</sup> Economic allocation would have been impractical, due to a lack of information on prices of co-products sold for all of the mills.

**Table 13.** Useful co-products from the major processes associated with the production of manmade cellulose fibers (MMCF) across all ten scenarios, and method used to allocate impacts to each.

Unit Process	Potential useful co-products	Allocation method
Dissolving Pulp Mill	<ul style="list-style-type: none"> <li>Dissolving pulp of different grades: viscose/rayon, specialty, acetate, etc.</li> <li>Lignin and bio-ethanol*</li> </ul>	For Scenario 1: German Production from Swedish Managed Forest Pulp, system expansion was used, assuming that the bioethanol generated substitutes for conventional gasoline and lignin substitutes for cement <sup>90</sup> (calculated using Ecoinvent v3.1 <sup>91</sup> ). For the other dissolving pulp mills, it was not possible to apply system expansion, due to lack of information on the co-products generated at pulp mills across all the scenarios, and what end uses those products may be used for. For other scenarios involving dissolving pulp production, all impacts were allocated equally to each ton of viscose/rayon grade dissolving pulp produced at the mill.
Staple Fiber Mill (MMCF)	<ul style="list-style-type: none"> <li>Viscose fibers of different grades</li> <li>Glauber's salt, acetic acid, etc.</li> </ul>	All impacts were allocated based on the mass of staple fiber produced.
Cotton fiber production (applicable to Scenario 7)	<ul style="list-style-type: none"> <li>Cotton seeds</li> <li>Cotton linters (<i>input for Scenario 7</i>)</li> <li>Cotton long fiber</li> </ul>	Mass-based allocation; 10% of impacts associated with cotton fiber production were attributed to cotton linters based on % yield data obtained from literature <sup>92</sup> .
Flax long fiber production (applicable to Scenario 10)	<ul style="list-style-type: none"> <li>Flax long fiber (used for linen production)</li> <li>Shives</li> <li>Scutching tow (i.e. short fibers) (<i>input for Scenario 10</i>)</li> <li>Hackling tow (i.e. short fibers) (<i>input for Scenario 10</i>)</li> </ul>	Mass-based allocation; 25% of impacts associated with flax long fiber production were attributed to flax co-products based on the % yield data obtained from literature <sup>93</sup> .
Other unit processes (Chemical inputs)	Processes from Ecoinvent v3.1 database	Mass-based allocation, based on the recycled content cut-off approach.

\*Applicable to products generated from spent liquor at DP mills operating as biorefineries. In this study, these by-products are only applicable to Swedish DP mill, which operates as a biorefinery in Sweden.

<sup>90</sup> <http://biomassmagazine.com/articles/8756/scientists-build-stronger-greener-concrete-with-lignin>

<sup>91</sup> The Ecoinvent3.1 datasets on *petrol production, low-sulfur* and *cement, Portland production* were used to calculate avoided impacts of bioethanol and lignin production respectively.

<sup>92</sup> Central Institute for Research on Cotton Technology. Utilization of cotton seed by-products; <http://www.cicr.org.in/pdf/ELS/ph1.pdf>

<sup>93</sup> Turunen, L., & van der Werf, H. (2006). Life cycle analysis of hemp textile yarn. *INRA, French National Institute for Agronomy Research, France.*

These additional notes apply to allocation used in specific instances for each scenario:

- For the Sumatran DP mill, based on RISI data and publicly available information from the company's financial reports, it was determined that only dissolving grade pulp was being produced at the mill; there was no mention of co-products generated at the mill, and hence there was no reason to apply system expansion or allocation.
- All the dissolving pulp mills generate black liquor as a co-product. This liquor is used for generating process energy at the mills. For at least one dissolving pulp mill (the Swedish DP mill in Scenario 1: German Production from Swedish Managed Forest Pulp), a small portion of black liquor generated was not combusted, and instead was disposed of as waste sludge (green liquor sludge). This waste sludge is not a useful product and was built into the LCA model as a waste, with impacts associated with sludge disposal taken into account.
- In the case of Scenario 5: German Production from Recycled Pulp, pulp is produced from recycled clothing. Hence, a recycled content allocation approach (or cut-off method) was used for this scenario. Using the recycled content allocation approach, system inputs with recycled content do not receive any burden from the previous life cycle other than reprocessing of the waste material. Thus, this scenario only bears the impacts associated with transportation of recycled textile clippings and the process of turning these clippings into recycled pulp. It does not account for any burdens of the activities or processing required for primary production of textile clothing. Furthermore, no credits are granted to the final recycled product leaving the system boundary.
- In case of Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China and Scenario 10: Belgian Flax Production, cotton linters and flax fibers are co-products of cotton and flax fiber processing respectively. Cotton linters are short fibers obtained from delinting of cotton seeds, which are valuable co-products of cotton ginning process. Similarly, scutching and hackling tow are short flax fibers, obtained from processing of long flax fibers which are used in the linen industry. Hence, only a portion of impacts associated with cotton fiber and flax fiber production were allocated to cotton linters and flax co-products (as indicated in Table 13). Impacts across different co-products were allocated on a mass basis, using data on total yield of all products per hectare.

#### **6.4 Data and Data Quality Requirements**

The dissolving pulp mills and fiber mills included in each scenario were identified for each of the ten scenarios based on research and in consultation with experts. These mills were selected based on location, capacity and grade of MMCF products produced. Data Request Forms were sent to these mills (refer to Appendix 1-A for the Data Request Form template), in an effort to collect primary data for each scenario. Completed DRFs were obtained for Scenario 1: German Production from Swedish Managed Forest Pulp, Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production. Complete DRFs could not be obtained from mills considered in the other scenarios. This was supplemented with activity level data on dissolving pulp mills from credible sources (the RISI Mill Asset database). Data on viscose fiber mills located in China, was procured from a market research company based in China.

RISI, the data provider for dissolving pulp mills, works with industry and trade associations to collect information for their databases and is considered to be the leading information provider for pulp/paper industrial sector. RISI data is commonly used in U.S. and global market modeling for the pulp and paper sector. The RISI Mill Asset database consists of data on 80 dissolving pulp mills around the world, including the two mills which provided SCS with primary data. RISI collects consumption data for fiber, energy and chemicals based on mill equipment data, capacity of production as well as spend data for several mills.

To ensure the validity of RISI data, SCS compared the primary data received from two dissolving pulp and MMCF mills with the data in the RISI and Chinese database. Table 14 lists the percent deviation between certain comparable parameters of RISI/Chinese data with the primary data received from DP/MMCF mill. An average deviation of 17% was observed in RISI data compared to primary data. Similarly, comparison of MMCF production data provided by a Chinese market research company to the primary data received from two MMCF mills resulted in an average deviation of 11%.

**Table 14.** Percentage deviation of comparable data points between RISI/Chinese data and primary data.

Comparable Data Points	% Deviation observed between RISI/Chinese data and primary data from DP/MMCF mill
<b>DP Mill</b>	
Pulpwood input	2%
Energy consumption	17%
CO <sub>2</sub> emissions	-19%
NO <sub>x</sub> emissions	-23%
SO <sub>2</sub> emissions	7%
<b>MMCF Mill</b>	
Dissolving pulp input	-6%
Water consumption	31%
Electricity consumption	5%
Steam consumption	-2%
Carbon disulfide consumption	16%
Sodium hydroxide consumption	-12%
Sulfuric acid consumption	4%

Table 15 below presents the list of specific data points collected for dissolving pulp mills and MMCF mills by scenario. Life cycle inventory data was used to model product systems for all ten scenarios in the LCA software used (openLCA v1.5). Datasets from the Ecoinvent v3.1 database were used for background processes along with data from RISI Mill Asset database and Chinese market research data.

**Table 15.** Data points collected for each scenario. Refer to the key below the table. Blank cells indicate that data was unavailable.

Parameters	Data Points	Scenarios									
		1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian	10. Belgian Flax Production
<b>Pulpwood Harvest Inputs specific to the Dissolving Pulp Mill</b>											
<b>Wood Sourcing</b>	<ul style="list-style-type: none"> <li>Gathered information on pulpwood/agriculture harvest locations for dissolving pulp production</li> </ul>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	N/A	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>
	<ul style="list-style-type: none"> <li>Collected forest inventory data for different regions to assess forest biome disturbance, based on location of pulpwood harvest</li> </ul>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	N/A	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>	DP <sub>f</sub>
<b>Freshwater Biome</b>	<ul style="list-style-type: none"> <li>Area of watershed/major-hydrobasin for each pulp mill</li> </ul>					N/A					N/A
<b>Chemical Processing Inputs for both Dissolving Pulp Mill and Viscose Fiber Mills</b>											
<b>Production Outputs</b>	<ul style="list-style-type: none"> <li>Annual production of all products, including co- and by-products</li> </ul>	✓	DP <sub>RISI</sub>	DP <sub>RISI</sub>	DP <sub>RISI</sub>	✓	DP <sub>RISI</sub>	DP <sub>RISI</sub>	DP <sub>RISI</sub>	DP <sub>RISI</sub>	✓



Parameters	Data Points	Scenarios									
		1. German Production from Swedish Managed Forest Pulp	2. Asian Production from Canadian Boreal Forest Pulp	3. Chinese Production from Indonesian Rainforest Pulp	4. Chinese Production from Indonesian Plantation Pulp	5. German Production from Recycled Pulp	6. Chinese Production from Chinese Bamboo	7. Chinese Production from Indian Cotton Linter Pulped in China	8. Chinese Production from South African Plantation Pulp	9. Austrian Production from mixed South African Plantation & Austrian	10. Belgian Flax Production
	• Fraction of total sales for each product	✓									
Chemical Inputs	• Amount of chemical inputs by type	✓	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	✓	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>S</sub>	✓
	• Amount of other material inputs by type	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓
Transportation of Materials	Transportation distances to supplier locations										
Energy Inputs	• Amount of fuel consumed, by type	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>S</sub>	✓
	• Amount of electricity consumed	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>S</sub>	✓
	• Amount of steam purchased	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>S</sub>	✓
	• Black liquor generated and consumed	✓	DP <sub>RISI</sub>	DP <sub>RISI</sub>	DP <sub>RISI</sub>	N/A	DP <sub>RISI</sub>	N/A	DP <sub>RISI</sub>	DP <sub>RISI</sub>	N/A
Water Inputs	• Annual water consumption	✓	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	✓	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	DP <sub>S</sub> V <sub>C</sub>	✓
	• Geographic source of consumed water	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓
Direct Emissions	• Annual air emissions, by substance and location of emission (for key unit processes)	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	✓	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	DP <sub>RISI</sub> V <sub>C</sub>	✓
	• Annual water emissions, by substance and location of emission (for key unit processes)	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓
Waste Products	• Amount of hazardous waste, by waste type	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓
	• Amount of non-hazardous waste, by waste type	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	DP <sub>S</sub> V <sub>S</sub>	✓

**KEY**

✓ = Primary data received from dissolving pulp mill and MMCF mills.

N/A= Not applicable

DP<sub>F</sub>= Data for pulpwood from national forest inventory databases.

DP<sub>RISI</sub>= Data for dissolving pulp mill from RISI Mill Asset database

DP<sub>S</sub>= Data from secondary databases and literature

V<sub>C</sub>= Data for MMCF mills from Chinese database

V<sub>S</sub>= Data from secondary databases and literature

An important dataset is related to the assessment of category indicator results for Terrestrial Ecosystem Impacts and forest carbon storage loss. Many data sources were used, with the most important from Swedish National Forest Inventory, Canadian Forest Inventory, Austrian Forest Inventory, the IUCN Red List database and other local species lists, the Eyes on the Forest online database and other literature.

Transportation distances for chemical inputs used at the dissolving pulp mill and MMCF mills are estimated to be in the same region as the location of pulp and fiber mills. Refer to Section 6.10 for more details.

The data quality of the inventory, environmental characterization, and parameter data used was required to be sufficient to differentiate results between the environmental impacts of ten sources of manmade cellulose fibers, given the associated data quality level of results. To ensure the highest possible data quality, the “key” unit processes for each indicator result, which are those unit processes contributing to over 10% of final results across all impact category indicators, were identified. Data collection efforts were focused on the “key” unit processes. A data quality analysis (described in Appendix 1-F) focused on the quality of data used to model these processes, in order to provide an overall data quality rating, by scenario.

## 6.5 LCI Analysis Summary

A life cycle inventory (LCI) analysis was conducted in conformance with ISO 14044 and LEO-S-002. The openLCA software<sup>94</sup> was used to model and analyze the complete set of inputs and outputs associated with all production stages in each product system, by unit process. The LCI of product systems are modeled based on primary data on dissolving pulp mills and staple fiber mills for three of the ten scenarios, and supplemented with site-level data from third part databases such as RISI and Chinese market research firms for other scenarios. Representative data from the Ecoinvent v3.1 database was used to model background processes.<sup>95</sup> The primary energy and resource (chemical, emissions and waste) data used in the LCA model for Scenarios 1, 5 and 10 cannot be disclosed, as this information is confidential. The dissolving pulp mill data is publicly available for purchase on the RISI website, but is not shared in the report due to purchase restrictions. Similar restrictions are applicable to MMCF production data purchased from the Chinese market research company.

Data for category indicators assessed for Terrestrial Ecosystem Impacts is obtained from government forest inventories and threatened species lists, the NatureServe Explorer Database,<sup>96</sup> IUCN Red list species<sup>97</sup> and literature. See Table 16 and Table 17 below for more details on the datasets used for modeling dissolving pulp mill and MMCF mills for all the scenarios. Detailed data sources used for the LCI analysis, by scenario, are provided in Table 18.

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<sup>94</sup> openLCA modeling software, version 1.5.beta1 By GreenDelta.

<sup>95</sup> Ecoinvent v3.1 Swiss Center for Life Cycle Inventories, 2014. The system model used is based on the recycled content cut-off method. <http://www.ecoinvent.org>

<sup>96</sup> NatureServe Explorer: An Online Encyclopedia of Life. <http://explorer.natureserve.org/>

<sup>97</sup> IUCN Red List Species database; <http://www.iucnredlist.org/>

**Table 16.** List of datasets used to model major inputs required for dissolving pulp production for all the scenarios.

Material	Dataset	Data Source	Publication Date
<b>Chemical inputs</b>			
Pulpwood	<ul style="list-style-type: none"> <li>■ hardwood forestry, beech, sustainable forest management</li> <li>■ hardwood forestry, eucalyptus, sustainable forest management</li> <li>■ hardwood forestry, birch, sustainable forest management</li> <li>■ hardwood forestry, for pulp, RoW</li> <li>■ hardwood forestry, for pulp, NORDEL</li> </ul>	Ecoinvent 3.1	2014
Sodium Hydroxide	<ul style="list-style-type: none"> <li>■ Market for sodium hydroxide, without water in 50% solution state</li> <li>■ Market for sodium hydroxide, without water in 50% solution state-CA-QC</li> </ul>	Ecoinvent 3.1	2014
Sulfur dioxide	<ul style="list-style-type: none"> <li>■ Market for sulfur dioxide</li> </ul>	Ecoinvent 3.1	2014
Oxygen	<ul style="list-style-type: none"> <li>■ Market for oxygen liquid</li> </ul>	Ecoinvent 3.1	2014
Lime	<ul style="list-style-type: none"> <li>■ Market for lime</li> <li>■ Lime production, milled, loose-CA-QC</li> </ul>	Ecoinvent 3.1	2014
Hydrogen peroxide	<ul style="list-style-type: none"> <li>■ Market for hydrogen peroxide, without water in 50% solution state</li> </ul>	Ecoinvent 3.1	2014
Sodium Hypochlorite	<ul style="list-style-type: none"> <li>■ Sodium hypochlorite, without water, in 15% solution state- CA-QC</li> </ul>	Ecoinvent 3.1	2014
Sodium chlorate	<ul style="list-style-type: none"> <li>■ Sodium chlorate, powder-CA-QC</li> </ul>	Ecoinvent 3.1	2014
Salts: <ul style="list-style-type: none"> <li>■ Magnesium sulfate</li> <li>■ Sodium sulfate</li> </ul>	<ul style="list-style-type: none"> <li>■ Market for magnesium sulfate</li> <li>■ Market for sodium sulfate</li> </ul>	Ecoinvent 3.1	2014
Other chemicals (salts, polymers, defoamers, organic chemicals, etc.)	<ul style="list-style-type: none"> <li>■ Market for chemicals, organic</li> <li>■ Market for chemicals, inorganic</li> </ul>	Ecoinvent 3.1	2014
<b>Waste Outputs</b>			
Sludge	<ul style="list-style-type: none"> <li>■ Treatment of sludge from pulp and paper production, at sanitary landfill</li> </ul>	Ecoinvent 3.1	2014
Green Liquor	<ul style="list-style-type: none"> <li>■ Treatment of green liquor dregs, residual landfill</li> </ul>	Ecoinvent 3.1	2014
Hazardous waste	<ul style="list-style-type: none"> <li>■ Treatment of hazardous waste, for incineration</li> </ul>	Ecoinvent 3.1	2014
Municipal solid waste	<ul style="list-style-type: none"> <li>■ Process specific burdens, municipal waste incineration</li> </ul>	Ecoinvent 3.1	2014

**Table 17.** List of datasets used to model main chemical inputs used in staple fiber (MMCF) production for all the scenarios.

Material	Dataset	Data Source	Publication Date
<b>Chemical inputs</b>			
Dissolving Pulp	<ul style="list-style-type: none"> <li>■ Dissolving pulp dataset built from inputs listed above in Table 16</li> </ul>	Table 16	2014
Sodium Hydroxide	<ul style="list-style-type: none"> <li>■ Market for sodium hydroxide, without water in 50% solution state</li> </ul>	Ecoinvent 3.1	2014
Sulfuric Acid	<ul style="list-style-type: none"> <li>■ Market for sulfuric acid</li> </ul>	Ecoinvent 3.1	2014
Carbon Disulfide	<ul style="list-style-type: none"> <li>■ Market for carbon disulfide</li> </ul>	Ecoinvent 3.1	2014
Salt: <ul style="list-style-type: none"> <li>■ Zinc monosulfate</li> <li>■ Sodium sulfite</li> </ul>	<ul style="list-style-type: none"> <li>■ Market for zinc monosulfate</li> <li>■ Market for sodium sulfite</li> </ul>	Ecoinvent 3.1	2014  2014
Other Chemical inputs	<ul style="list-style-type: none"> <li>■ Market for chemicals, organic</li> <li>■ Market for chemicals, inorganic</li> </ul>	Ecoinvent 3.1	2014
<b>Waste Outputs</b>			
Sludge	<ul style="list-style-type: none"> <li>■ Treatment of waste textile soiled, municipal incineration</li> </ul>	Ecoinvent 3.1	2014
Hazardous waste	<ul style="list-style-type: none"> <li>■ Treatment of hazardous waste, for incineration</li> </ul>	Ecoinvent 3.1	2014
Municipal solid waste	<ul style="list-style-type: none"> <li>■ Process specific burdens, municipal waste incineration</li> </ul>	Ecoinvent 3.1	2014

**Table 18.** List of the life cycle inventory data sources used, by unit process for each scenario.

Scenario	Data Source	Region Data Represents*	Year of Data
<b>Forest Management and Pulpwood Harvest</b>			
1. German Production from Swedish Managed Forest Pulp	<ul style="list-style-type: none"> <li>Swedish Forest Inventory<sup>98</sup></li> <li>IUCN Red List Species</li> <li>Sweden Species Information Center<sup>99</sup></li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Vasternorrland, Sweden</li> <li>Sweden</li> <li>Vasternorrland, Sweden</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2010-2014</li> <li>Varies</li> <li>2016</li> <li>2014</li> </ul>
2. Asian Production from Canadian Boreal Forest Pulp	<ul style="list-style-type: none"> <li>Canadian Forest Inventory<sup>100</sup></li> <li>IUCN Red List Species</li> <li>COSEWIC<sup>101</sup> and NatureServe<sup>102</sup></li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Ontario, Canada</li> <li>Ontario, Canada</li> <li>Ontario, Canada</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2007-2009</li> <li>Varies</li> <li>Varies</li> <li>2014</li> </ul>
3. Chinese Production from Indonesian Rainforest Pulp	<ul style="list-style-type: none"> <li>Eyes on the Forest Online Database<sup>103</sup></li> <li>IUCN Red List Species</li> <li>CAMP report<sup>104</sup></li> <li>Ecoinvent v3.1</li> <li>Literature<sup>105</sup></li> </ul>	<ul style="list-style-type: none"> <li>Sumatra, Indonesia</li> <li>North Sumatra, Indonesia</li> <li>Sumatra, Indonesia</li> <li>Varies</li> <li>Indonesia</li> </ul>	<ul style="list-style-type: none"> <li>2014</li> <li>Varies</li> <li>Varies</li> <li>Varies</li> <li>Varies</li> </ul>
4. Chinese Production from Indonesian Plantation Pulp	<ul style="list-style-type: none"> <li>Eyes on the Forest Online Database<sup>106</sup></li> <li>IUCN Red List Species</li> <li>CAMP report<sup>107</sup></li> <li>Ecoinvent v3.1</li> <li>Literature<sup>108</sup></li> </ul>	<ul style="list-style-type: none"> <li>Sumatra, Indonesia</li> <li>North Sumatra, Indonesia</li> <li>Sumatra, Indonesia</li> <li>Varies</li> <li>Indonesia</li> </ul>	<ul style="list-style-type: none"> <li>2014</li> <li>Varies</li> <li>Varies</li> <li>Varies</li> <li>Varies</li> </ul>
5. German Production from Recycled Pulp	<ul style="list-style-type: none"> <li>Not Applicable</li> </ul>	<ul style="list-style-type: none"> <li>Not Applicable</li> </ul>	<ul style="list-style-type: none"> <li>Not Applicable</li> </ul>
6. Chinese Production from Chinese Bamboo Pulp	<ul style="list-style-type: none"> <li>Literature<sup>109</sup></li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Sichuan, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2014</li> <li>2014</li> </ul>
7. Chinese Production from Indian Cotton Linter Pulped in China	<ul style="list-style-type: none"> <li>Forest Survey of India<sup>110</sup></li> </ul>	<ul style="list-style-type: none"> <li>Gujarat, India</li> <li>Gujarat, India</li> <li>China</li> </ul>	<ul style="list-style-type: none"> <li>2010</li> <li>2016</li> <li>2014</li> </ul>

<sup>98</sup> Swedish National Forest Inventory, 2015. Forest Statistics. <http://www.slu.se/foreststatistics>

<sup>99</sup> Swedish species information center; <https://artfakta.artdatabanken.se/>

<sup>100</sup> Canada's National Forest Inventory; 2015. <https://nfi.nfis.org/en/>

<sup>101</sup> COSEWIC; <http://www.cosepac.gc.ca/default.asp?lang=En&n=A9DD45B7-1>

<sup>102</sup> NatureServe Explorer: An Online Encyclopedia of Life. <http://explorer.natureserve.org/>

<sup>103</sup> Eyes on the Forest (2012) Sumatra's Forests, their Wildlife, and the Climate Online Database

<sup>104</sup> CBSG. 2003. *Conservation Assessment and Management Plan for Sumatran Threatened Species: Final Report*. IUCN SSC Conservation Breeding Specialist Group, Apple Valley, MN, USA.

<http://www.cbsg.org/sites/cbsg.org/files/documents/SumatranCAMPreport.pdf>

<sup>105</sup> Carbon Stock: <http://www.fao.org/docrep/008/ae537e/ae537e0a.htm>

<sup>106</sup> Eyes on the Forest (2012) Sumatra's Forests, their Wildlife, and the Climate Online Database

<sup>107</sup> CBSG. 2003. *Conservation Assessment and Management Plan for Sumatran Threatened Species: Final Report*. IUCN SSC Conservation Breeding Specialist Group, Apple Valley, MN, USA.

<http://www.cbsg.org/sites/cbsg.org/files/documents/SumatranCAMPreport.pdf>

<sup>108</sup> The potential of oil palm and forest plantations for carbon sequestration on degraded land in Indonesia;

[http://www.zef.de/fileadmin/webfiles/downloads/zefc\\_ecology\\_development/ecol\\_dev\\_28\\_text.pdf](http://www.zef.de/fileadmin/webfiles/downloads/zefc_ecology_development/ecol_dev_28_text.pdf)

<sup>109</sup> Center for International Forestry Research (CIFOR), (Accessed May 2016);

<http://www.worldbank.org/html/cgiar/newsletter/june97/9cifor.html>

<sup>110</sup> Forest survey of India; [http://fsi.nic.in/carbon\\_stock/chapter-4.pdf](http://fsi.nic.in/carbon_stock/chapter-4.pdf)

Scenario	Data Source	Region Data Represents*	Year of Data
	<ul style="list-style-type: none"> <li>Literature<sup>111,112</sup></li> <li>Ecoinvent v3.1</li> </ul>		
8. Chinese Production from South African Plantation Pulp	<ul style="list-style-type: none"> <li>Literature<sup>113</sup></li> <li>IUCN Red List Species</li> <li>Species assessment report<sup>114</sup></li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>South Africa</li> <li>Varies</li> <li>Varies</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2008</li> <li>Varies</li> <li>Varies</li> <li>2014</li> </ul>
9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	<ul style="list-style-type: none"> <li>Austrian Forest Inventory<sup>115</sup></li> <li>IUCN Red List Species</li> <li>Umweltbundesamt<sup>116</sup></li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Gmunden district, Upper Austria</li> <li>Austria</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2007-2009</li> <li>Varies</li> <li>2009</li> <li>2014</li> </ul>
10. Belgian Flax Production	<ul style="list-style-type: none"> <li>Literature<sup>117 118</sup></li> <li>IUCN Red List Species</li> <li>INBO<sup>119</sup></li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Belgium</li> <li>Belgium</li> <li>Flanders, Belgium</li> <li>Europe</li> </ul>	<ul style="list-style-type: none"> <li>2009</li> <li>Varies</li> <li>Varies</li> <li>2014</li> </ul>
<b>Dissolving Pulp Production</b>			
1. German Production from Swedish Managed Forest Pulp	<ul style="list-style-type: none"> <li>Swedish DP mill</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Örnsköldsvik, Sweden</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
2. Asian Production from Canadian Boreal Forest Pulp	<ul style="list-style-type: none"> <li>RISI Asset Mill Database</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Canada</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
3. Chinese Production from Indonesian Rainforest Pulp	<ul style="list-style-type: none"> <li>RISI Asset Mill Database</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>North Sumatra, Indonesia</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
4. Chinese Production from Indonesian Plantation Pulp	<ul style="list-style-type: none"> <li>Same as Scenario 3</li> </ul>	<ul style="list-style-type: none"> <li>Same as Scenario 3</li> </ul>	
5. German Production from Recycled Pulp	<ul style="list-style-type: none"> <li>Recycled DP Mill</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Stockholm, Sweden</li> <li>Europe</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
6. Chinese Production from Chinese Bamboo Pulp	<ul style="list-style-type: none"> <li>RISI Asset Mill Database</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Hebei, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>

<sup>111</sup> Chaudhury, Swati, et al. "Land use and cropping effects on carbon in black soils of semi-arid tropical India." *CURRENT SCIENCE* 110.9 (2016): 1692.

<sup>112</sup> Cotton Incorporated (2011). Life Cycle Assessment of Cotton Fiber and Fabric.

<sup>113</sup> Du Toit, B. (2008). Effects of site management on growth, biomass partitioning and light use efficiency in a young stand of *Eucalyptus grandis* in South Africa. *Forest Ecology and Management*, 255(7), 2324-2336.

<sup>114</sup> Hanekom, M., Zdanow, L., & van Staden, s. (2015). Terrestrial ecological and wetland assessment as part of the environmental authorisation process for the proposed new denmark colliery destoning plant, Mpumalanga province. This report was provided to SCS by a wildlife conservation expert based in South Africa

<sup>115</sup> Austrian Forest Inventory Survey 2007-2009; <http://bfw.ac.at/rz/wi.auswahl>

<sup>116</sup> Umweltbundesamt (2009); Red list species list (based on IUCN criteria) compiled by Austrian government; [http://www.umweltbundesamt.at/umweltsituation/umweltinfo/opendata/oed\\_naturschutz/?cgiproxy\\_url=http%3A%2F%2Fhtpapp5.umweltbundesamt.at%2Fdata%2Fdataset.jsf%3Bjsessionid%3D6F1403E765F4FAB08C4EAE03022C96FA%3Fid%3D44](http://www.umweltbundesamt.at/umweltsituation/umweltinfo/opendata/oed_naturschutz/?cgiproxy_url=http%3A%2F%2Fhtpapp5.umweltbundesamt.at%2Fdata%2Fdataset.jsf%3Bjsessionid%3D6F1403E765F4FAB08C4EAE03022C96FA%3Fid%3D44)

<sup>117</sup> Turunen, L., & van der Werf, H. (2006). Life cycle analysis of hemp textile yarn. *INRA, French National Institute for Agronomy Research, France*.

<sup>118</sup> Schelhaas, M.J., Varis, S., Schuck, A. and Nabuurs, G.J., 2006, EFISCEN Inventory Database, European Forest Institute, Joensuu, Finland, [http://www.efi.int/portal/virtual\\_library/databases/efiscen/](http://www.efi.int/portal/virtual_library/databases/efiscen/)

<sup>119</sup> Instituut Natuur-En Bosonderzoek (INBO); <https://www.inbo.be/en/search/content/red%2520lijst>

Scenario	Data Source	Region Data Represents*	Year of Data
7. Chinese Production from Indian Cotton Linter Pulped in China	<ul style="list-style-type: none"> <li>RISI Asset Mill Database</li> <li>Ecoinvent v3.1</li> <li>Literature<sup>120</sup></li> </ul>	<ul style="list-style-type: none"> <li>Xinjiang, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
8. Chinese Production from South African Plantation Pulp	<ul style="list-style-type: none"> <li>RISI Asset Mill Database</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Mpumalanga, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	<ul style="list-style-type: none"> <li>RISI Asset Mill Database</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Upper Austria, Austria/South Africa</li> <li>Europe</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
10. Belgian Flax Production	<ul style="list-style-type: none"> <li>Not Applicable</li> </ul>	<ul style="list-style-type: none"> <li>Not Applicable</li> </ul>	<ul style="list-style-type: none"> <li>Not Applicable</li> </ul>
<b>Viscose Fiber Production</b>			
1. German Production from Swedish Managed Forest Pulp	<ul style="list-style-type: none"> <li>German MMCF mill</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Obenburg, Germany</li> <li>Europe</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
2. Asian Production from Canadian Boreal Forest Pulp	<ul style="list-style-type: none"> <li>Chinese market research company</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2014</li> </ul>
3. Chinese Production from Indonesian Rainforest Pulp	<ul style="list-style-type: none"> <li>Chinese market research company</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Fujian/Jiangxi, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2010</li> </ul>
4. Chinese Production from Indonesian Plantation Pulp	<ul style="list-style-type: none"> <li>Same as Scenario 3</li> </ul>	<ul style="list-style-type: none"> <li>Same as Scenario 3</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> </ul>
5. German Production from Recycled Pulp	<ul style="list-style-type: none"> <li>German MMCF mill</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Obenburg, Germany</li> <li>Europe</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> </ul>
6. Chinese Production from Chinese Bamboo Pulp	<ul style="list-style-type: none"> <li>Chinese market research company</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Jilin, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2010</li> </ul>
7: Chinese Production from Indian Cotton Linter Pulped in China	<ul style="list-style-type: none"> <li>Chinese market research company</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Xinjiang, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2010</li> </ul>
8. Chinese Production from South African Plantation Pulp	<ul style="list-style-type: none"> <li>Chinese market research company</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Zhejiang, China</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> <li>2010</li> </ul>
9. Austrian Production from mixed South African Plantation & Austrian Managed Forest Pulp	<ul style="list-style-type: none"> <li>Literature</li> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Varies</li> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2010</li> <li>2010</li> </ul>
10. Belgian Flax Production	<ul style="list-style-type: none"> <li>Flax fiber mill data</li> </ul>	<ul style="list-style-type: none"> <li>Belgium</li> </ul>	<ul style="list-style-type: none"> <li>2015</li> </ul>
<b>Electricity Generation, Transmission and Distribution</b>			
All Scenarios	<ul style="list-style-type: none"> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2010</li> </ul>
<b>Other Unit Processes</b>			
All Scenarios	<ul style="list-style-type: none"> <li>Ecoinvent v3.1</li> </ul>	<ul style="list-style-type: none"> <li>Varies</li> </ul>	<ul style="list-style-type: none"> <li>2010</li> </ul>

\*For Ecoinvent v3.1 datasets, region description is according to Ecoinvent dataset.

<sup>120</sup> IPS Engineering (2015); Dissolving pulp from cotton linters; [http://www.ipsengineering.it/Doc/IPS\\_Dissolving\\_pulp.pdf](http://www.ipsengineering.it/Doc/IPS_Dissolving_pulp.pdf)

### 6.5.1 Accounting for Biogenic Carbon Flows

An important component of results related to changes in biogenic carbon are impacts from foregone growth, which affects results for Global Climate Change and Ocean Acidification. The approach used to evaluate results is described conceptually in sections 5.2.2 and 5.2.3, while Appendix 2 contains details.

Another important climatic effect are the emissions and absorption of climate pollutants at the time of harvests, including:

- Net forest regrowth, which is assumed to sequester atmospheric CO<sub>2</sub> in the year that it occurs.
- During logging, decay and/or combustion of aboveground logging residues (i.e., “slash”) and carbon stored in tree roots were assumed to occur immediately, with all of the carbon assumed to be converted into emissions of CO<sub>2</sub> (this is applicable to all scenarios except 5, 7 and 10). It is assumed that slash left on the site is 25% of the harvest volume. Belowground roots are assumed to have a carbon mass same as in slash. These fractions are considered typical of most forestry practices, and have been used in past LCAs.<sup>121</sup> In case of Scenarios 7 and 10, it is assumed that residues left on the field make a negligible contribution to emissions.
- Soil carbon releases, which are not included. This is a limitation that is discussed in Section 4.3.2.

For product biogenic carbon storage, for each scenario, MMCF can be approximated as cellulose (C<sub>6</sub>H<sub>10</sub>O<sub>5</sub>), each kg of MMCF contains 0.44 kg of carbon, corresponding to 1.6 tons of CO<sub>2</sub>e per ton of MMCF. Results for carbon stored in the products are illustrated in Figure 5.

### 6.5.2 Estimating Black Carbon Emissions

In this study, a fraction of the inventory data (38%) for PM<sub>2.5</sub> was considered to be emitted as black carbon. This is a conservative estimate based on natural gas combustion sources published in literature<sup>122</sup>. It is to be noted that the combustion process and the presence of emission controls in boiler units will affect the amount of black carbon in PM<sub>2.5</sub> emissions. Even with the conservatively high factor applied, black carbon is a relatively modest contributor to results for most scenarios. The only exception were the scenarios from Indonesia, where black carbon emissions from lignite coal combustion were a major single contributor to results. The black carbon emission factors here were revised for accuracy. The best data available was for brown coal combustion from stoker facilities, from Bond 2004<sup>123</sup>, indicating a black carbon to PM fraction of 5%. In initial calculations for several scenarios, black carbon emissions accounted for a non-negligible fraction of total warming impacts (i.e., between

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<sup>121</sup> SCS Global Services, October 2015. Life Cycle Assessment of Reincarnation 100 Coated Freesheet Compared to Virgin Paper Products.

<sup>122</sup> U.S. Evtl Prot. Agency (2012) Report to Congress on Black Carbon

<sup>123</sup> Bond, T. C., D. G. Streets, K. F. Yarber, S. M. Nelson, J.-H. Woo, and Z. Klimont (2004), A technology-based global inventory of black and organic carbon emissions from combustion, *J. Geophys. Res.*, 109, D14203, doi: [10.1029/2003JD003697](https://doi.org/10.1029/2003JD003697).



10% and 20%). These scenarios included Scenario 2, 5, and 9. These scenarios have key operations located in Europe and North America, where black carbon emissions are primarily from transportation. The black carbon (BC) to particulate matter (PM) emission ratio used is considered reasonable, as for transport, this fraction is quite high, between 30% and 60%. For other scenarios, the black carbon contribution was relatively small, even with the conservatively high estimate, and further refinements were not necessary as they would not affect the comparison between scenarios.

## **6.6 LCIA Methodology Summary**

The LCA conforms to ISO 14044, the draft LEO-S-002 standard, and the Roundwood PCR. The LCIA methodology in the draft LEO-S-002 standard requires that all impacts relevant to production of MMCF from any source be accounted for, and that the metrics used be environmentally relevant and based in a scientific and technically valid approach. As a sensitivity analysis, LCA results conforming to the draft LEO-S-002 framework are compared with results calculated using the CML Method (see Section 5.3).

Final LCA results are based upon the compilation of category indicator results for all core impact categories (see Section 4.2 for a list of core impact categories, and LCA results, for staple fiber from each source). Category indicators numerically represent the contribution of specific unit processes to midpoints in the environmental mechanism for each core impact category. For example, energy consumption contributes to the depletion of energy resources, which is characterized using the Non-Renewable Energy Resource Depletion indicator.

Each category indicator result is calculated using characterization factors (CF) which are applied to LCI data per flow. For some impact categories, two CF are used: potency potential characterization factors (PP-CFs) and midpoint characterization factors (M-CFs). PP-CFs characterize the relative potency of emissions, resource uses, or land uses, in causing impacts. M-CFs characterize the actual effect on the receiving environment of these emissions, resource uses, or land uses, which can vary on a site-specific basis.

The significance of the impact categories, along with an overview of the calculation approach and notes on interpretation of results, is given in Section 5.2. The in depth data sources, equations, and CFs, used to calculate results, is given in Appendix 2.

## **6.7 Data Quality**

To assess the confidence in the comparison of ten product systems for MMCF production, the data quality of each indicator result was assessed, in order to judge the significance of differences in impact levels between all the sources of MMCF considered. The data quality analysis accounts for the cumulative effects of input uncertainty, data variability and model imprecision. More information on the data quality analysis can be found in Appendix 1-F.

## 6.8 Key unit processes

The key unit processes related to production of fiber in the scenarios considered are:

- Dissolving pulp production.
- Manmade cellulose fiber production.
- Electricity consumption at the pulp and fiber mills.
- Sulfur dioxide production (used at mills).
- Sulfuric acid production (used at mills).
- Sodium hydroxide production (used at mills).

A description of the key unit processes identified across all the ten scenarios are provided in Appendix 1-D. The key data points and assumptions related to calculating LCA results for these processes, such as materials inputs and other parameters, are also provided.

## 6.9 Scope, LCI, LCIA, for key unit processes by Scenario

A discussion of the scope, LCI analysis, and LCIA, for key unit processes for each source of MMCF are provided in the sections below.

### 6.9.1 Scenario 1: German Production from Swedish Managed Forest Pulp: MMCF from pulp originating in Sweden

There are several steps involved in the production of MMCF at German MMCF mill:

- Forest management and timber harvest (see Sections 6.9.1.1, and Appendix 1-D).
- Dissolving pulp production (see Section 6.9.2.1 and Appendix 1-D).
- MMCF production (see Sections 6.9.3.1 and Appendix 1-D).

Dissolving pulp and MMCF production also require energy and chemical inputs. Refer to Sections 6.9.1.2.1, 6.9.1.2.2 below for more details.

#### 6.9.1.1 Forestry in Mill Fiber Basket

The Swedish DP mill, located in Örnsköldsvik municipality in Sweden, sources approximately 50% of its pulpwood from regions in Northern Sweden. The remaining pulpwood is imported from southern Sweden, Latvia, Lithuania, Denmark and Scotland. However, lack of information on specific pulpwood harvest locations in these countries, made it impossible to assess impacts across all the timberlands supplying pulpwood to the mill. The fiber basket defined for this study is a subset of timberlands in Northern Sweden (Södra Norrland), selected carefully to represent impacts from forestry supplying pulpwood to this mill.

The production of pulpwood includes forest management practices and timber harvests in many different forest types, varying by region, even within the same fiber basket. This forestry affects not only

the areas subject to harvest, but also adjacent areas due to effects on the continuity of the overall terrestrial ecoregion. The impacts to local terrestrial ecoregion, freshwater systems, wetlands, and species habitats occur across the entire landscape<sup>124,125</sup>. In the fiber baskets for all pulp mills included in each scenario, the assessment considered a large enough area to accurately represent the degree of these impacts across large regions.

For these impact categories, site-specific data were required in order to assess impacts. To facilitate the assessment for these impact categories, a subset of fiber basket areas called Forest Analysis Units (FAUs) are defined across portions of each fiber basket. The FAU are large enough to represent the degree of impacts occurring across the breadth of each fiber basket, and yet small enough in area to facilitate data collection and analysis. Each FAU includes several counties or provinces, selected based on the fraction of pulpwood supplied to local mills, the availability of forestlands in the region which can represent the undisturbed and fully disturbed reference areas, the number of plots available for the basis of the assessment, and whether the local forests and forest management practices are typical of conditions in the entire fiber basket for this mill.

The Swedish NFI provide forestry inventory data which is averaged across each county in Sweden. Based on the available data and the above considerations, Västernorrland County was defined as the FAU in the fiber basket<sup>126</sup>. This county comprises of Ångermanland and Medelpad provinces, which is in close proximity to the dissolving pulp mill.

Although representing a fraction of total pulpwood supply, conditions in the forests in Västernorrland county are a good indication of conditions in the other forests in the region, which are located nearby (mostly in adjacent counties) in the same ecoregion, and with the same set of threatened species. Forests in this county are representative of the most common logging practices in the fiber basket.

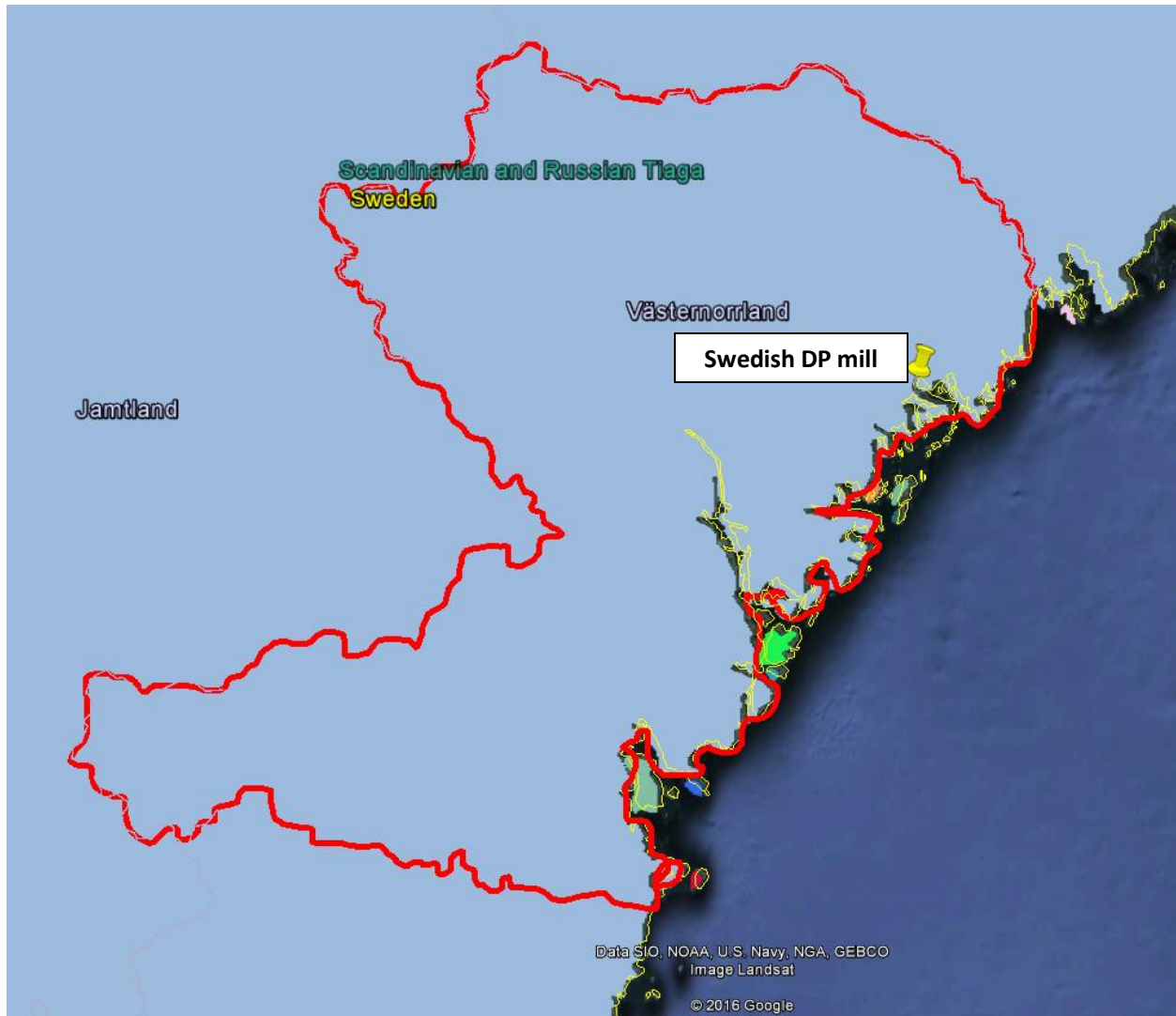
The timberlands included in FAU are only those in private ownership; these timberlands produce more than 89% of the total timber produced in each FAU. The selected FAU is presented in Figure 28.

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<sup>124</sup> Lindenmayer, D.B., J.F. Franklin, and J. Fischer (2006). General management principles and a checklist of strategies to guide forest biodiversity conservation. *Biological Conservation* 131: 433-445.

<sup>125</sup> Calabrese, J.M., and W. F. Fagan (2004). A comparison-shopper's guide to connectivity metrics. *Front Ecol Environ*; 2(10): 529-536.

<sup>126</sup> Note: Specific data on conditions in the forest operators supplying the mill were not provided by the Swedish DP mill, and so this information is strictly based on regional average forest conditions in this region.



**Figure 28.** The Swedish DP mill and ecoregion. The defined FAU, Vasternorrland County is outlined in red. All forests in Vasternorrland County are considered in the study.

The Swedish DP mill fiber basket lies in the *Boreal forest/Taiga* biome, as defined by the WWF<sup>127</sup>. A majority of the pulpwood production occurs within the Scandinavian and Russian Taiga ecoregion in the *Boreal forest/Taiga* biome. Impacts to the Scandinavian and Russian Taiga ecoregion are included in the scope. For more details, refer to Appendix 1-D.

#### 6.9.1.1.1 Terrestrial Disturbance Assessment

To assess terrestrial disturbance, forest conditions are compared in the Forest Analysis Unit (FAU, which is an area of timberland used to represent forest ecosystem impacts resulting from forestry operations),

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<sup>127</sup> WWF Wildfinder Database, 2012; <https://www.worldwildlife.org/science/wildfinder/>

to an Undisturbed Reference Area (URA, a reference area representing “undisturbed” conditions). In this assessment:

- The FAU is forest land used for timber production by private companies in Västernorrland county; 0.68 million hectares are impacted by forestry in the FAU.
- The URA is a mature forest with forest stands which have an average age of over 80 years, and includes forest land owned by private companies in Västernorrland County, where forest stand age is 80 years or more. Conditions in FAU are compared to 0.23 million hectares of URA in Västernorrland county.

Specific data for the following ecological conditions were available and included in the terrestrial disturbance calculations for FAU and URA:

1. Forest compositional structure, including 5 most common tree species by stand age class and area, dominant forest types by stand volume and area.
2. Biomass measurements in the forest, including biomass in live trees, dead trees, live and dead understory.

More detailed data on soil conditions (i.e., soil depth and organic matter content) were not available. Since soil carbon correlates with aboveground biomass, inclusion of biomass measurements reflects trends in soil carbon storage. (See Section 4.3.2 for more discussion of the data availability regarding soil carbon changes and potential implications on results.) Detailed measurements of landscape fragmentation were also not available. Census of the vertebrate species community was unavailable. The average percent reduction in tree species in the FAU was assumed as a proxy for percent reduction in native vertebrate species in FAU compared to undisturbed conditions. These omissions could affect results for terrestrial disturbance.

Figure 8 presents a summary of the terrestrial conditions for all fiber baskets, based on the reporting requirements of the PCR for Roundwood<sup>128</sup>. The terrestrial disturbance was calculated based on the measurements of the ecological conditions shown in Table 2 of Appendix 1-C, which are regional averages obtained from the Swedish Forest Inventory website for year 2012. Result for land use is relative to the production of one thousand cubic meters of timber, based on average site productivity<sup>129</sup> data of 4 m<sup>3</sup>/ha/year in Västernorrland County. The Appendix 1-C provides more detailed information on the terrestrial’s current conditions in this region.

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<sup>128</sup> PCR Module for Roundwood Production:

[https://www.scsglobalservices.com/files/resources/pcr\\_final\\_wood-products\\_101816.pdf](https://www.scsglobalservices.com/files/resources/pcr_final_wood-products_101816.pdf)

<sup>129</sup> Average site productivity is defined at the average cubic meter of timber per hectare per year. The Swedish Forest Inventory defines site productivity as the capacity of a forest site to produce timber.

#### **6.9.1.1.2 Key Species Losses Assessment**

In the fiber basket of Swedish DP mill, seven species were found to be affected by logging activities in Västernorrland County, Sweden, based on IUCN Red List Species database and the Swedish species information center. Table 3 in the Appendix 1-C provides the justification and for the inclusion of each species.

#### **6.9.1.2 Dissolving pulp production**

Over the last decade the Swedish DP mill has developed from a traditional pulp mill into a biorefinery<sup>130</sup>. The main products are specialty cellulose, lignin and bioethanol. The mill has a production capacity of 255,000 tons of dissolving cellulose, 120,000 tons of lignin and 14,000 tons of bio-ethanol. The mill consumes nearly 1.4 million cubic meters of softwood species to process dissolving pulp. A fraction of the dissolving pulp produced by Swedish DP mill is sold to the German MMCF mill, and the remaining is consumed by MMCF production facilities in Asia. The DP mill uses a sodium-based sulfite cooking process, as described in detail in Appendix 1-D. Refer to Appendix 1-D for more details on dissolving pulp production process at the Swedish DP mill.

##### **6.9.1.2.1 Chemical Inputs to the Dissolving Pulp Mill**

Sodium hydroxide, sulfur dioxide and hydrogen peroxide are the major chemicals used in the processing, along with additives and chelating agents. Nearly 2.3 tons of wood chips are required to produce 1 ton of dissolving pulp. Sulfur dioxide is generated on-site. It is assumed that production of all chemicals for dissolving pulp production occurs in Sweden. Datasets used for modeling chemical inputs is listed in Section 6.5.

##### **6.9.1.2.2 Energy Inputs to the Dissolving Pulp Mill**

Although the Swedish DP mill generates process steam from black liquor, mills need more steam than can be provided by the recovery process alone. According to the primary data received, the Swedish DP mill purchases electricity and also generates steam in an industrial boiler fueled by oil for its operations. The mill has also been operating a bio treatment plant since 1985 and produces biogas from the remaining organic matter in wastewater streams at the biorefinery site. The plant is the largest producer of biogas in Sweden with ~80 GWh annually produced and a CH<sub>4</sub> content of 85%. Biogas is used as a fuel at the DP mill for heat and electricity production during months of high heat demand, but flared during the summer and other low heat demand periods<sup>131</sup>.

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<sup>130</sup> The biorefinery concept is to upgrade and refine biomass feedstocks to value-added end-products using different conversion processes and integration of resources.

<sup>131</sup> Åberg, Katarina. (2014) "Syngas production by integrating thermal conversion processes in an existing biorefinery."

The electricity dataset was modeled using Ecoinvent 3.1 *market for electricity, medium voltage-SE* for Sweden. Refer to Appendix 1-D for more details.

### 6.9.1.3 MMCF production

The German MMCF mill is located in Obernburg, Germany and has a production capacity of 7000 tons of viscose filament yarn. German MMCF mill produces filament yarn for range of different fiber specifications (22-330 Dtex). The production of viscose filament is described in Appendix 1-D. It is to be noted that German MMCF mill produces viscose filament yarn and not manmade cellulose fiber. As discussed in Section Appendix 1-D, all chemical inputs and processing steps up to spinning stage are identical. Some additional steps are required for viscose filament yarn formation. A unique spool spun yarn technology was developed by German MMCF Mill for manufacturing high quality super fine denier viscose filament yarn, however the technology is proprietary.

#### 6.9.1.3.1 Chemical Inputs to the MMCF Mill

Sodium hydroxide, carbon disulfide and sulfuric acid are the major reagents used in viscose production. Sodium sulfite, zinc sulfate and some textile auxiliaries are also used in the wet spinning process of viscose. Calcium carbonate is used to neutralize sulfuric acid, generating calcium sulfate, which is disposed as sludge from chemical treatment at the facility. About 65% of the carbon disulfide is recovered and reused for xanthation process. It is assumed that all chemicals required for viscose production are manufactured in Germany. The production of sodium hydroxide and sulfuric acid are key unit processes for viscose fiber production. Description of these processes and the datasets used to model these processes are provided in Section 6.5.

#### 6.9.1.3.2 Energy Inputs to the MMCF Mill

The facility energy use data included the energy consumption for yarn formation. According to literature, highest energy consumption occurs in spinning machines during yarn manufacturing<sup>132</sup>. However, since the scope of this study only includes staple fiber production, the energy use for the German MMCF mill was adjusted based on the average energy consumption data for manmade cellulose fiber. The total adjustment was 20% of facility energy use, and since facility energy use accounts for no more than 19% of any indicator result, results do not strongly depend on this assumption.

German MMCF mill purchases electricity and steam for its operations. Electricity consumption is one of the key unit processes for this scenario. It was modeled using Ecoinvent 3.1 dataset *market for electricity, medium voltage-DE* for Germany. Refer to Appendix 1-D for more details.

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<sup>132</sup> Hasanbeigi, A. (2010). Energy-efficiency improvement opportunities for the textile industry. *Lawrence Berkeley National Laboratory*.

## 6.9.2 Scenario 2: Asian Production from Canadian Boreal Forest Pulp: MMCF from pulp originating in Canadian boreal forests

### 6.9.2.1 Forestry in Mill Fiber Basket

The boreal forest is the largest terrestrial carbon sink and home to some of the world's last intact terrestrial and aquatic ecosystems<sup>133</sup>. On consultation with experts, it is believed that many more pulp and paper mills operating in the boreal region are projected to be converted into dissolving grade pulp mills in the near future. In consideration of this impending conversion and stakeholder concerns about preserving Boreal forests in the region, a hypothetical scenario with a dissolving pulp mill operating in the boreal region is examined in this study.

For the purpose of this study, the dissolving pulp mill is assumed to be operating in the province of Ontario and it is assumed that all the pulpwood is sourced from boreal forests in Ontario. The fiber basket for this hypothetical scenario is defined as the region supplying pulpwood within 150 mile radius of the mill<sup>134</sup>.

The primary source of pulpwood for this scenario considers four Forest Management Units (FMUs)<sup>135</sup>: Kenogami, Lake Nipigon, Big Pic and Pic River Forests. In particular, the Kenogami forest has been the site of industrial forestry since 1937, with massive clearcuts spanning across 10,807 hectares over the last few years and 71% of the forest is fragmented<sup>136</sup>. This forestry affects not only the areas subject to harvest, but also adjacent areas due to effects on the continuity of the overall terrestrial ecoregion. The impacts to local ecosystems and species habitats occur across the entire landscape<sup>137,138</sup>. The assessment considered a large enough area to accurately represent the degree of these impacts across large regions.

To facilitate the assessment for these impact categories, 2 FAUs of similar area were defined across portions of each fiber basket, representing all 4 FMUs which supply pulpwood to the hypothetical dissolving pulp mill. Following is a list of FAUs distributed across 4 FMUs in the fiber basket:

- FAU 1 includes portions of Black Spruce forest and Lake Nipigon Forest

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<sup>133</sup> Carlson, Matt, Jeff Wells, and Dina Roberts. *The carbon the world forgot: conserving the capacity of Canada's Boreal Forest region to mitigate and adapt to climate change*. Boreal Songbird Initiative and Canadian Boreal Initiative, Seattle, WE, USA and Ottawa, Canada, 2009.

<sup>134</sup> List of management units and map in Ontario (2016/2017); <https://www.ontario.ca/page/list-management-units-and-map>

<sup>135</sup> Province of Ontario in Canada designate Forest Management Units as land on which commercial forestry activities takes place. There are 42 FMUs in Ontario and each FMU is managed through the issuance of a Sustainable Forest License to different organizations.

<sup>136</sup> The Kenogami Forest (2009);

[http://www.greenpeace.org/canada/global/canada/report/2009/12/Terrace\\_Bay\\_Pulp\\_Report.pdf](http://www.greenpeace.org/canada/global/canada/report/2009/12/Terrace_Bay_Pulp_Report.pdf)

<sup>137</sup> Lindenmayer, D.B., J.F. Franklin, and J. Fischer (2006). General management principles and a checklist of strategies to guide forest biodiversity conservation. *Biological Conservation* 131: 433-445.

<sup>138</sup> Calabrese, J.M., and W. F. Fagan (2004). A comparison-shopper's guide to connectivity metrics. *Front Ecol Environ*; 2(10): 529-536.

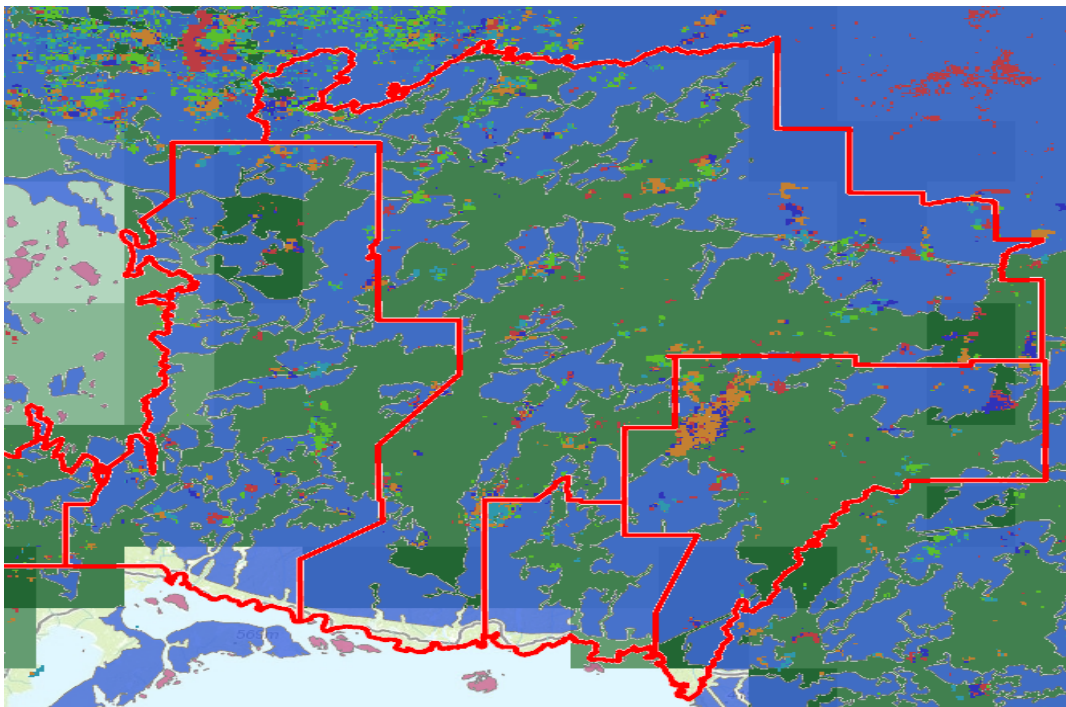


- FAU 2 includes portions of Kenogami forest, Big Pic forest, and Pic River forest

Site-specific forest inventory data was obtained for all 2 FAUs from the Canadian Forest Inventory<sup>139</sup>. The data provided by the Canadian Forest Inventory included detailed information on multiple ground plots in each FAU. Conditions in the defined FAU, represents all the pulpwood supplied directly to the dissolving pulp mill.

A list of parks and protected areas in Ontario were reviewed in order to determine an undisturbed reference area for this scenario. Canadian Forest Inventory data on mature forests in provincial parks and protected areas were used to evaluate the terrestrial ecoregion disturbance impact.

All four FAUs lie in the Central Canadian Shield forests ecoregion. Figure 29 highlights the three FAUs and the ecoregion evaluated in this study.



**Figure 29.** The FAUs boundaries are highlighted in red respectively for the Canadian DP mill fiber basket in Ontario.

The hypothetical dissolving pulp mill fiber basket lies in the Central Canadian Shield forests ecoregion, in the *Boreal forest/Taiga biome*. For more details, refer to Appendix 1-D.

Within the ecoregion considered, there are terrestrial ecosystems, freshwater ecosystems, and wetland ecosystems, which are impacted by forestry.

#### 6.9.2.1.1 Terrestrial Disturbance Assessment

To assess terrestrial disturbance, forest conditions are compared in the Forest Analysis Unit (FAU, which is an area of timberland used to represent forest ecosystem impacts resulting from forestry operations), to an Undisturbed Reference Area (URA, a reference area representing “undisturbed” conditions). In this assessment:

- The FAU is boreal forest land (Crown forest) used for timber production by the hypothetical dissolving pulp mill.
- The URA is a mature forest with forest stands which have an average age of over 80 years, and includes intact blocks of boreal forests, where forest stand age is at least 100 years or more.

Conditions average across 2 FAUs, covering 250, 000 hectares, are compared to conditions in 155,000 hectares of URA.

Following ecological conditions were included in the terrestrial disturbance calculations for FAU and URA:

1. Forest compositional structure, including 5 most common tree species by stand age class and area, dominant forest types by stand volume and area.
2. Biomass measurements in the forest, including biomass in live trees, dead trees, live and dead understory.
3. Stem density and basal area.

More detailed data on soil conditions (i.e., soil depth and organic matter content) were not available. (See Section 4.3.2 for more discussion of the data availability regarding soil carbon changes and potential implications on results.) Detailed measurements of landscape fragmentation were also not available. Census of the vertebrate species community was unavailable. The average percent reduction in tree species in the FAU was assumed as a proxy for percent reduction in native vertebrate species in FAU compared to undisturbed conditions. These omissions could affect results for terrestrial disturbance.

The terrestrial disturbance was calculated based on the site-specific measurements of the ecological conditions shown in Table 4 in the Appendix 1-C. Table 5 presents a summary of the terrestrial conditions for all fiber baskets, based on the reporting requirements of the PCR for Roundwood. Results were averaged across 2 FAUs and 2 URAs. Data provided by the Canadian Forest Inventory was compiled from 2005-2007 in order to calculate results.

#### 6.9.2.1.2 Key Species Losses Assessment

In the fiber basket of the hypothetical dissolving pulp mill, seven species were found to be affected by logging activities in Northwestern Ontario, based on IUCN Red List Species database and other regional

lists noted in Appendix 1<sup>140</sup>. Woodland caribou range across only 33-49 per cent of the forest and wolverines have disappeared from the Kenogami forest. Scientists project that caribou will disappear from 95 per cent of the forest within the next 20 years, due to the logging practices. Table 6 in the Appendix 1-C provides the justification and for the inclusion of each species.

#### **6.9.2.1.3 Wood Resource Depletion Assessment**

This impact category characterizes the reduction in wood resources in the fiber basket of the hypothetical dissolving pulp mill. Results consider the amount of wood harvested to produce 1000 tons of MMCF. Refer to Section 4.2 for results of wood resource depletion for this scenario.

#### **6.9.2.2 Dissolving Pulp Production**

The hypothetical dissolving pulp mill located in Ontario, Canada, is projected to be transformed from a pulp/paper mill to a dissolving grade pulp mill with a production capacity of at least 100,000 tons of dissolving pulp per annum or more in the near future. For the purpose of this study, this hypothetical scenario is examined using composite data on all dissolving pulp mills operating in Canada from the RISI Mill Asset database. The kraft pulping technology is used to represent dissolving pulp operations for this hypothetical scenario. Refer to Appendix 1-D for a description on the kraft pulping process. This scenario assumed that the mill consumes softwood species sourced from the Boreal region as the main source of pulpwood for dissolving pulp production. The dissolving pulp is transported by lake and then by sea from the dissolving pulp mill in Ontario to the MMCF mill in China.

##### **6.9.2.2.1 Chemical Inputs to the Dissolving Pulp Mill**

Sodium hydroxide, sulfur dioxide, sodium chlorate and sodium hypochlorite are the major chemicals used in the processing, along with additives and chelating agents. Nearly 2.4 tons of wood chips are required to produce 1 ton of dissolving pulp. Sodium chlorate and sodium hypochlorite is generated on-site. It is assumed that production of all chemicals for dissolving pulp production occurs in Canada. Datasets used for modeling chemical inputs is listed in Section 6.5.

##### **6.9.2.2.2 Energy Inputs to the Dissolving Pulp Mill**

The mill purchases electricity for its operations and generates steam from the combustion of black liquor, wood/waste solids derived from pulpwood inputs (hog fuel), and other fuels such as fuel oils and sludge waste. The energy consumption relative to the production of 1 ton of pulp at the mill was assessed based on RISI data on annual production of dissolving grade pulp across all dissolving pulp mills operating in Canada.

Electricity was modeled using Ecoinvent 3.1 dataset *market for electricity, medium voltage {CA-ON}* to represent electricity generation in Ontario, Canada.

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<sup>140</sup> IUCN Red List; <http://www.iucnredlist.org/>

### 6.9.2.3 MMCF Production

It is assumed that the hypothetical dissolving pulp mill operating in boreal region will deliver dissolving pulp to an MMCF mill located in China. Considering the concentration of MMCF mills in China, it seems pertinent to explore this scenario. The LCA results for MMCF production in this scenario represents an average of six MMCF mills operating in China. MMCF production method is consistent with the description provided in Appendix 1-D.

### 6.9.2.4 Chemical Inputs to the MMCF Mill

The amount of chemical inputs to the MMCF mill was obtained from a Chinese market research company. Data for CS<sub>2</sub>, H<sub>2</sub>SO<sub>4</sub> and NaOH reagents were provided relative to the production of 1 ton of MMCF and was averaged across 6 MMCF mills. Using this data, approximately 70% of carbon disulfide is assumed to be recovered at the MMCF mill. The MMCF mill requires sodium hydroxide, carbon disulfide and sulfuric acid as the primary chemical input for MMCF production. Ecoinvent 3.1 datasets listed in Section 6.5 were used to model chemical inputs required for this scenario.

### 6.9.2.5 Energy Inputs to the MMCF Mill

Data for six MMCF mills indicated that MMCF mills purchase electricity and steam for its operations. Electricity consumption is one of the key unit processes for this scenario. It was modeled using Ecoinvent 3.1 dataset *market for electricity, medium voltage-CN* for China. Refer to Appendix 1-D for more details.

## 6.9.3 Scenario 3: Chinese Production from Indonesian Rainforest Pulp: MMCF from Indonesian pulp sourced from mixed tropical hardwood

### 6.9.3.1 Forestry in Mill Fiber Basket

The Sumatran DP mill is one of the leading producers of dissolving pulp from eucalyptus plantations in North Sumatra. In this region, native mixed tropical hardwood forests bordering pulpwood concession areas have been harvested and transformed into commercial tree plantations. Based on spatial datasets on pulpwood concession areas that the operating company provides on its webpage, which is consistent with information compiled by the Indonesian Ministry of Forestry<sup>141</sup>, FAUs in these areas were defined across portions of the fiber basket of this mill. In these regions, the analysis considered natural forests in the FAU which were cleared and replaced with eucalyptus plantations. FAUs considered in this study are distributed within 50 miles of the Sumatran DP mill in the following regencies<sup>142</sup> in North Sumatra:

- FAU 1 : 42,000 hectares across West Pakpak Regency and Humbang Hasundutan Regency
- FAU 2: 17,472 hectares in Simalungun Regency

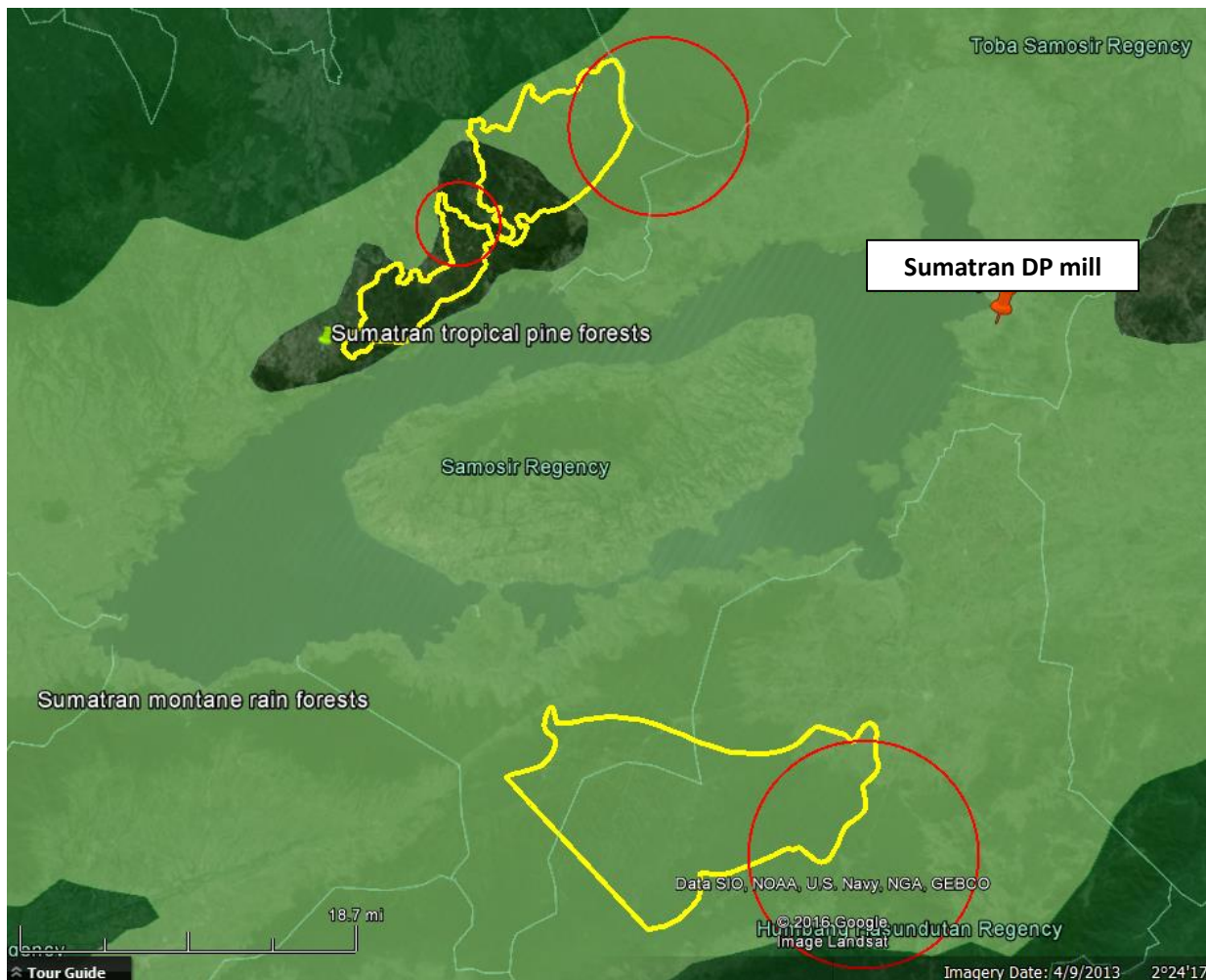
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<sup>141</sup> Eyes on the Forest (2012) Sumatra's Forests, their Wildlife, and the Climate Online Database

<sup>142</sup> Regency is a political subdivision or municipality of a province in Indonesia

- FAU 3: 6,912 hectares in Simalugun Regency

The Sumatran DP Mill fiber basket lies in the Sumatran montane rainforest ecoregion in *tropical and subtropical moist broadleaf forests biome*, as defined by the WWF<sup>143</sup>. A majority of the pulpwood production occurs within this biome FAUs overlap with two ecoregions: Sumatran montane rainforest and Sumatran tropical pine forests. The chosen FAUs and local ecoregions are shown in Figure 30. Refer to Appendix 1-D for more details.



**Figure 30.** The Sumatran DP Mill location and corresponding ecoregions indicated in green and red shade. Harvesting of tropical hardwood occurs on the borders of the pulpwood concession areas. Pulpwood concession areas are indicated in yellow. FAUs are encircled in red.

<sup>143</sup> WWF Wildfinder Database, 2012; <https://www.worldwildlife.org/science/wildfinder/>

### 6.9.3.1.1 Terrestrial Disturbance Assessment

To assess terrestrial disturbance, forest conditions are compared in the Forest Analysis Unit (FAU, which is an area of timberland used to represent forest ecosystem impacts resulting from forestry operations), to an Undisturbed Reference Area (URA, a reference area representing “undisturbed” conditions). In this assessment:

- The FAU includes harvested native mixed tropical hardwood forests, replaced by non-native pulpwood plantations.
- The URA is a primary/natural tropical forest with forest stands containing diverse native tropical hardwood species.

Conditions across three FAUs defined in Figure 30 are compared to native tropical hardwood forests in the URA. Spatial forest structure was determined for FAU and URA based on natural forest cover maps<sup>144</sup> generated specifically for North Sumatra province by the NGO coalition, Eyes on the Forest<sup>145</sup> for the period between 1985 to 2014. Biomass data for natural tropical forest was derived from carbon stock data estimates literature.<sup>146</sup>

Forest inventory data are not disclosed publicly by the Indonesian government. Specific data on forest composition and species abundance was not available. However, the natural forest cover maps generated for Sumatra by Eyes on the Forest in collaboration with WWF and other government agencies, provided high quality information on the fraction of natural forest remaining in the North Sumatra province. The parameters for forest composition and species abundance were assessed based on forest cover loss data for each FAU. More detailed data on soil conditions (i.e., soil depth and organic matter content) were not available. Since soil carbon correlates with aboveground biomass, inclusion of biomass measurements reflects trends in soil carbon storage. (See Section 4.3.2 for more discussion of the data availability regarding soil carbon changes and potential implications on results.) Census of the vertebrate species community was unavailable. These omissions could affect results for terrestrial disturbance.

Figure 2 presents a summary of the terrestrial conditions for all fiber baskets, based on the reporting requirements of the PCR for Roundwood. The terrestrial disturbance was calculated based on the measurements of the ecological conditions shown in Table 8 in Appendix 1-C.

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<sup>144</sup> Maps of primary forest, dominated by trees with a crown cover of more than 10%.

<sup>145</sup> Eyes on the Forest (2012) Sumatra's Forests, their Wildlife, and the Climate Online Database

<sup>146</sup> Natural forest 1985-2008/2009: [WWF Indonesia \(2010\) Sumatra's Forests, their Wildlife and the Climate. Windows in Time: 1985, 1990, 2000 and 2009.](#)

#### 6.9.3.1.2 Key Species Losses

In the fiber basket of the Sumatran DP Mill, fifty five species were found to be affected by logging activities in North Sumatra, based on IUCN Red List Species database<sup>147</sup> and regional species list noted in Appendix 1-C. Figure 4 presents a summary of the key species for all fiber baskets, based on the reporting requirements of the PCR for Roundwood. Table 9 in the Appendix 1-C provides the justification and for the inclusion of each species.

#### 6.9.3.1.3 Wood Resource Depletion

This impact category characterizes the reduction in wood resources in the fiber basket of the Sumatran DP mill. Results consider the amount of wood harvested to produce 1000 tons of MMCF. Refer to Section 4.2 for results of wood resource depletion for this scenario.

### 6.9.3.2 Dissolving Pulp Production

The Sumatran DP mill in North Sumatra, Indonesia has an annual capacity of 230,000 short tons, which comprises of 83% dissolving grade pulp (approximately 190,000 short tons) and 17% bleached hardwood kraft grade pulp. This scenario includes pulpwood from mixed tropical hardwoods are used as the raw material for pulp production. The mill consumes 100% of hardwood pulpwood, and does not purchase any market pulp. The Sumatran DP mill produces dissolving pulp using kraft process as described in Appendix 1-D. This scenario only includes impacts from dissolving pulp produced at the Sumatran DP mill and consumed by Chinese MMCF mills in Fujian and JiuJiang provinces in China. The dissolving pulp is transported by sea from North Sumatra to Fujian and Jiangxi provinces in China.

#### 6.9.3.2.1 Chemical Inputs to the Dissolving Pulp Mill

No specific data were available on the amounts of chemical inputs consumed at the mill. Approximately 2.5 tons of hardwood is used to produce 1 ton of pulp. Since the Sumatran DP mill produces dissolving pulp using kraft process, the composition of cooking liquor differs from the Swedish DP mill process. Thus the Ecoinvent 3.1 dataset on *market for sulfate pulp-GLO*, was used to estimate the amount of chemicals used for one ton of pulp. This data represents the industry average for production of sulfate pulp with totally chlorine free bleaching process.

#### 6.9.3.2.2 Energy Inputs to the Dissolving Pulp Mill

The mill generates 99% of its electricity needs from the combustion of black liquor, wood/waste solids derived from pulpwood inputs, and other fuels such as fuel oils and sludge waste. The energy consumption relative to the production of 1 ton of pulp at the mill was assessed based on annual production data from RISI Mill Asset Database.

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Electricity was modeled using Ecoinvent 3.1 dataset *market for electricity, medium voltage-ID* for Indonesia. Electricity production, especially from lignite is one of the key unit processes for this product system. Emissions associated with transmission and distribution losses are accounted for in this dataset. Ecoinvent datasets for electricity were modified to include black carbon emissions. Refer to Appendix 1-D for more details.

### **6.9.3.3 MMCF Production**

Two Chinese MMCF mills are considered in this scenario: (1) Chinese MMCF mill in Fujian province and (2) Chinese MMCF in Jiangxi province. The Chinese MMCF mill in Fujian is a relatively new fiber mill, with an annual MMCF production capacity of 200,000 tons and has been in operation since December 2013. The Fujian mill produces MMCF as well as other specialty fibers including flame retardant and microdenier fibers. The Chinese MMCF mill in Jiangxi province has an annual production capacity of 110,000 tons. This fiber mill is located on the banks of the Yangtze River, which is one of the transportation hubs in eastern China. This scenario assumes that all the dissolving pulp from the Sumatran DP mill, Indonesia is transported via oceanic tanker to these two MMCF mills.

The Chinese MMCF production method is consistent with the description provided in Appendix 1-D. The LCA results for MMCF production in this scenario represents an average of Fujian and Jiangxi MMCF mills.

#### **6.9.3.3.1 Chemical Inputs to the MMCF Mill**

The amount of chemical inputs to the Chinese MMCF mills were obtained from a Chinese market research company. Primary data for CS<sub>2</sub>, H<sub>2</sub>SO<sub>4</sub> and NaOH reagents were provided relative to the production of 1 ton of MMCF. Approximately 75-77% of carbon disulfide is recovered at the Chinese MMCF mills. It is assumed that all chemicals required for viscose production are manufactured in Fujian and Jiangxi province. The production of sodium hydroxide and sulfuric acid are key unit processes for viscose fiber production. Description of these processes and the Ecoinvent 3.1 datasets used to model these processes are provided in Section 6.5.

#### **6.9.3.3.2 Energy Inputs to the MMCF Mill**

Chinese MMCF mill purchases electricity and steam for its operations. Electricity production from hard coal is one of the key unit processes for this scenario. Ecoinvent 3.2 database provided updated electricity production datasets from hard coal for 32 different provinces in China. Electricity production from hard coal varies by province in China, resulting in differences in environmental impacts from electricity generation. This regional variation was taken into account and the Ecoinvent 3.1 dataset *market for electricity, medium voltage-CN* was modified to include electricity production from hard coal for Fujian and Jiangxi provinces. Emissions associated with transmission and distribution losses are accounted for in this dataset. Refer to Appendix 1-D for more details.



## 6.9.4 Scenario 4: Chinese Production from Indonesian Plantation Pulp: MMCF produced in China, made from Indonesian pulp originating from eucalyptus plantations

### 6.9.4.1 Forestry in Mill Fiber Basket

In the early 1990s, in an effort to boost forest productivity, the Indonesian government began issuing HTI concessions<sup>148</sup> to pulp and paper companies to develop commercial tree plantations. All forestland in Indonesia is owned by the government and leased to companies as HTI concessions for a period of 20-35 years. The Sumatran DP mill produces dissolving pulp in a mill near Toba Lake in North Sumatra, Indonesia. The Sumatran DP mill secured pulpwood plantation concessions of approximately 188,000 hectares in North Sumatra from the Indonesian Ministry of Forestry for conversion of forestland to fast-growing, non-indigenous eucalyptus trees.

Based on availability of spatial data of the HTI concessions that the operating company provides on its webpage, which is consistent with information provided by the Indonesian government<sup>149</sup>, the fiber basket is determined to be within 80 miles of the Sumatran DP mill in North Sumatra province, Indonesia. Eucalyptus plantations harvested in this fiber basket supply all the pulpwood to the Sumatran DP mill. Eucalyptus plantations are harvested in a 6-year cycle by the Sumatran DP mill.

It is estimated that these pulpwood concession areas were originally covered by 68% of native mixed tropical hardwoods, 30% pine forests and approximately 6000 hectares of grassland.<sup>150</sup> FAUs are defined across portions of the fiber basket, on spatial data that the operating company provides on its webpage, consistent with the Eyes on the Forest<sup>151</sup> spatial dataset on pulpwood plantation concessions. Natural forests in FAUs were cleared and replaced with non-native eucalyptus plantations. FAUs considered in this study are distributed within 80 miles of the Sumatran DP mill in the following regencies<sup>152</sup> in North Sumatra:

- FAU 1 : 69,904 hectares across West Pakpak Regency, Humbang Hasundutan Regency and Dairi Regency
- FAU 2: 12,874 hectares in Simalungun Regency
- FAU 3: 6,491 hectares in Samosir and Simalugun Regency

This fiber basket harbors tropical rainforests with forest composition dominated by evergreen and semi-evergreen moist deciduous tree species, identical to Scenario 3. The Sumatran DP fiber basket lies in the *tropical and subtropical moist broadleaf forests biome*, as defined by the WWF<sup>153</sup>. A majority of the

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<sup>148</sup> Refers to forestland allocated by a government or other body for establishment of fast-growing tree plantations for production of timber and wood pulp.

<sup>149</sup> i.b.i.d

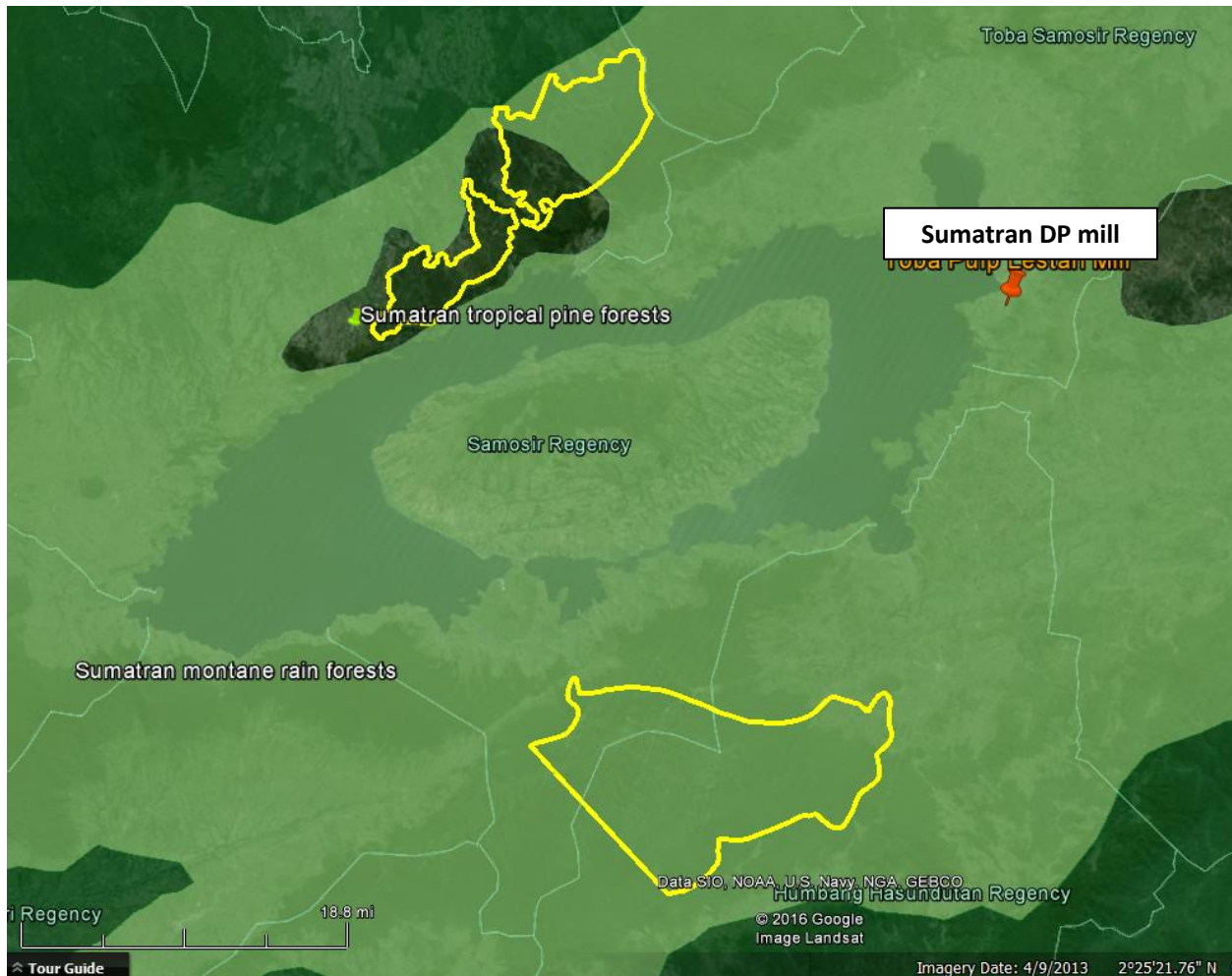
<sup>150</sup> Maturana, Julia. Economic costs and benefits of allocating forest land for industrial tree plantation development in Indonesia. No. CIFOR Working Paper no. 30. 2005.

<sup>151</sup> Eyes on the Forest (2012) Sumatra's Forests, their Wildlife, and the Climate Online Database

<sup>152</sup> Regency is a political subdivision or municipality of a province in Indonesia

<sup>153</sup> WWF Wildfinder Database, 2012; <https://www.worldwildlife.org/science/wildfinder/>

pulpwood production occurs within this biome FAUs overlap with two ecoregions: Sumatran montane rainforest and Sumatran tropical pine forests. Refer to Appendix 1-D for descriptions on these ecoregions. The chosen FAUs and local ecoregions are shown in **Figure 31**. Refer to Appendix 1-D for more details.



**Figure 31.** The Sumatran DP Mill location and corresponding ecoregions indicated in green and red shade. FAUs are outlined in yellow

#### 6.9.4.1.1 Terrestrial Disturbance Assessment

To assess terrestrial disturbance, forest conditions are compared in the Forest Analysis Unit (FAU, which is an area of eucalyptus pulpwood plantations developed by the mill, to an Undisturbed Reference Area (URA, a reference area representing “undisturbed” conditions). In this assessment:

- The FAU is the area consisting of non-native eucalyptus plantations for pulpwood production. These monoculture commercial plantations replace native primary tropical rainforests.
- The URA is a primary tropical rainforest with forest stands containing diverse native tropical hardwood species.

Conditions across three FAUs defined in Figure 31 are compared to native tropical hardwood forests in the URA. Natural forest cover estimates for North Sumatra were retrieved from an online database<sup>154</sup>, based on a decade of research and field investigations performed by WWF and Eyes on the Forest. Spatial forest structure was determined for FAU and URA based on these maps<sup>155</sup> generated specifically for North Sumatra for the period between 1985- 2014, as stated in Scenario 3. Biomass data was derived from carbon stock data estimates published in literature.<sup>156</sup> The same natural forest cover maps referenced in Section 3 were used for calculating terrestrial disturbance results for this scenario. All the data limitations stated in Scenario 3 apply to this scenario as well.

The terrestrial disturbance was calculated in Table 11 of Appendix 1-C based on available measurements of the ecological conditions and data sources listed above. The results presented below were averaged across 3 FAUs.

#### **6.9.4.1.2 Key Species Losses Assessment**

Results presented in Table 9 of Appendix 1-C for Scenario 3 apply here as well.

#### **6.9.4.2 Dissolving Pulp Production**

This scenario considers the same dissolving pulp mill as described in Section 6.9.3.2. However, the only difference lies in the pulpwood input to the Sumatran DP mill in North Sumatra, Indonesia. This scenario considers that the mill consumes 100% of eucalyptus pulpwood. All other conditions remain the same.

##### **6.9.4.2.1 Chemical Inputs to the Dissolving Pulp Mill**

Section 6.9.3.2.1 is applicable here as well.

##### **6.9.4.2.2 Energy Inputs to the Dissolving Pulp Mill**

Section 6.9.3.2.2 is applicable here as well.

#### **6.9.4.3 MMCF Production**

Refer to Section 6.9.3.3 for description on the MMCF mills.

##### **6.9.4.3.1 Chemical Inputs to the MMCF Mill**

Section 6.9.3.3.1 is applicable here as well.

##### **6.9.4.3.2 Energy Inputs to the MMCF Mill**

Section 6.9.3.3.2 is applicable here as well.

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<sup>154</sup> i.b.i.d

<sup>155</sup> Maps of primary forest, dominated by trees with a crown cover of more than 10%.

<sup>156</sup> Carbon stock;

[http://www.zef.de/fileadmin/webfiles/downloads/zefc\\_ecology\\_development/ecol\\_dev\\_28\\_text.pdf](http://www.zef.de/fileadmin/webfiles/downloads/zefc_ecology_development/ecol_dev_28_text.pdf)

## **6.9.5 Scenario 5: German Production from Recycled Pulp: MMCF produced from recycled clothing inputs**

### **6.9.5.1 Textile Recycling**

This scenario starts at the initial collection of clothing (primarily pre-consumer textile clippings) at the textile recycling center, which is then transported to the dissolving pulp unit in Sweden.

### **6.9.5.2 Dissolving Pulp Production**

Recycled DP Mill is a startup company based in Stockholm, Sweden, with a pioneering textile recycling technology which transforms textile clothing into recycled dissolving pulp. This recycled pulp contains high cellulosic content, similar to dissolving pulp and can be used to produce regenerated cellulosic fibers such as viscose, lyocell, cellulose acetate, etc. This company is currently in the process of scaling up its technology with a plant which is located in a facility in Kristinehamn, Sweden. The plant is expected to commence operations in early 2017, with an annual production capacity of 7000 tons of recycled dissolving pulp.

The plant is expected to primarily use pre-consumer textile clippings from a number of European sources for recycled pulp production. However, post-consumer textile clippings are to be incorporated in future.

Based on consultation with Recycled DP Mill, the manufacturing process of recycled dissolving pulp<sup>157</sup> is described below:

- The sorted textiles are shredded and non-textile components are removed with conventional shredding and separation technology.
- A large fraction of the dyes are solubilized in a reductive alkaline step and removed in the subsequent washing step.
- The remaining colored components are bleached.
- The viscosity, or degree of polymerization, is adjusted to suit customer demands by treating the material in a specific environment.
- The non-cellulosic fibers are separated from the material in two separation steps thereby purifying the cellulosic pulp from contaminants.

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<sup>157</sup> Lindström, M., & Henriksson, G. (2014). *U.S. Patent Application No. 14/450,362*.

- The fibers are washed to remove residual process chemicals and the pulp is subsequently dried and ready to be shipped.
- The wastewater discharge consists of COD, BOD and some phosphorus compounds, which is sent to a wastewater treatment plant. Textile dust is the primary waste which is generated in this process.

As the plant has not commenced operations, it was not possible to determine the MMCF mill that would consume this recycled pulp. For the purpose of this study, it is assumed that recycled pulp (from pre-consumer textile clippings) is delivered to MMCF mill in Germany.

#### **6.9.5.2.1 Chemical Inputs to the Dissolving Pulp Mill**

Sodium hydroxide and sulfuric acid are the primary solvent used in this manufacturing process. The main function of sodium hydroxide is to decolorize the textile clippings. Primary data on chemical inputs was provided by Recycled DP Mill relative to the expected annual production of 7000 tons. Ecoinvent 3.1 datasets listed in Section 6.5 were used to model these datasets.

#### **6.9.5.2.2 Energy Inputs to the Dissolving Pulp Mill**

Recycled DP Mill is expected to purchase electricity and steam for its operations. Primary energy data inputs were provided relative to the expected production of 7000 tons of recycled pulp.

The electricity dataset was modeled using Ecoinvent 3.1 *market for electricity, medium voltage-SE* for Sweden.

#### **6.9.5.3 MMCF Production**

Scenario 5: German Production from Recycled Pulp assumes that the German MMCF mill in Obernburg, Germany processes recycled viscose fibers. All the operating conditions for viscose production is identical to Section 6.9.1.3. Refer to Section 6.9.1.3 for more details.

##### **6.9.5.3.1 Chemical Inputs to the MMCF Mill**

Section 6.9.1.3.1 is applicable here as well.

##### **6.9.5.3.2 Energy Inputs to the MMCF Mill**

Section 6.9.1.3.2 is applicable here as well.

## 6.9.6 Scenario 6: Chinese Production from Chinese Bamboo Pulp: MMCF from bamboo pulp originating in China

### 6.9.6.1 Forestry in Mill Fiber Basket

The Hebei DP mill located in Hebei province, produces bamboo pulp production in China. The company which owns the DP mill also owns bamboo plantations in Sichuan, a province in southwest China. Bamboo plantations harvested from this province supply majority of the pulpwood for bamboo pulp production. This company holds the intellectual property rights to its bamboo pulp production. Due to the proprietary nature of data, there was no information available on the mill's supply chain operations. This made it difficult to determine the specific location of Hebei DP mill fiber basket in Sichuan.

Review of publicly available articles and literature suggests that Muchuan County in southern Sichuan, experienced the highest rate of bamboo plantation expansion in early 2000s. Considering the concentration of bamboo plantations and the proximity of pulp/paper mills near Muchuan County in southern Sichuan, it seems reasonable to define Muchuan County as the fiber basket for Hebei DP mill.

Native bamboo forests are interspersed with mixed deciduous forests in higher elevation areas, especially in the Qinglai mountain ranges (known as Qiong bamboo forests) in Sichuan. During the past 15-20 years, these natural bamboo forests have been replaced with monoculture plantations of moso bamboo species<sup>158</sup>.

Approximately 56% of the Muchuan County is covered by forests, of which approximately 38% (29,600 hectares) is occupied by commercial bamboo plantations. 99% of the bamboo plantations in Muchuan County are consumed by the pulp and paper industries.<sup>159</sup> Forestry affects not only the areas subject to harvest, but also adjacent areas due to effects on the continuity of the overall terrestrial ecoregion. The impacts to local ecosystems and species habitats occur across the entire landscape<sup>160 161</sup>. The assessment considered a large enough area to accurately represent the degree of these impacts across large regions.

FAU of 29,600 hectares was defined in Hebei DP mill fiber basket in Sichuan. This FAU lies in the Qionglai-Minshan Conifer Forests. Figure 32 highlights the FAU and the ecoregion.

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<sup>158</sup> <http://pulitzercenter.org/reporting/china%E2%80%99s-appetite-bamboo-damaging-forests>

<sup>159</sup> Mertens, B., Hua, L., Belcher, B., Ruiz-Pérez, M., Maoyi, F., & Xiaosheng, Y. (2008). Spatial patterns and processes of bamboo expansion in Southern China. *Applied Geography*, 28(1), 16-31.

<sup>160</sup> Lindenmayer, D.B., J.F. Franklin, and J. Fischer (2006). General management principles and a checklist of strategies to guide forest biodiversity conservation. *Biological Conservation* 131: 433-445.

<sup>161</sup> Calabrese, J.M., and W. F. Fagan (2004). A comparison-shopper's guide to connectivity metrics. *Front Ecol Environ*; 2(10): 529-536.



**Figure 32.** The defined FAU for Hebei DP mill is outlined in black. The ecoregion is shaded in blue.

The Hebei DP mill fiber basket lies in the Qionglai-Minshan conifer forests ecoregion in *the temperate broadleaf and mixed forest biome*. Refer to Appendix 1-D for more details.

#### 6.9.6.1.1 Terrestrial Disturbance Assessment

To assess terrestrial disturbance, forest conditions are compared in the Forest Analysis Unit (FAU, which is an area of plantation used to represent forest ecosystem impacts resulting from forestry operations), to an Undisturbed Reference Area (URA, a reference area representing “undisturbed” conditions). In this assessment:

- The FAU is the monoculture of bamboo plantations in Sichuan, as a result of clearing natural forests in this region.
- The URA is the area consisting of natural bamboo forests interspersed with mixed deciduous forests.

Conditions in FAU defined in Figure 32 is compared to natural forests in the URA.

Forest inventory data are not disclosed publicly by the Chinese government. Data on forest composition and species abundance was not available. Biomass data for natural forests and bamboo plantations were derived from literature.<sup>162</sup> More detailed data on soil conditions (i.e., soil depth and organic matter content) were not available. Since soil carbon correlates with aboveground biomass, inclusion of

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<sup>162</sup> Bowyer, Jim, et al. (2014) "Bamboo products and their environmental impacts: Revisited."

biomass measurements reflects trends in soil carbon storage. (See Section 4.3.2 for more discussion of the data availability regarding soil carbon changes and potential implications on results.) Detailed measurements of landscape fragmentation were also missing. Census of the vertebrate species community was unavailable. These omissions could affect results for terrestrial disturbance.

Due to lack of site-specific data for the defined FAU and URA in Sichuan, the following default assumptions were made in accordance with the PCR for Roundwood:

- It is assumed that species presence in FAU is reduced by 100% when compared to natural bamboo forests in URA.
- Pulpwood plantations using monoculture of moso bamboo species replace natural forests in FAU. Hence it is assumed that the abundance of most dominant tree species in FAU is reduced by 100% when compared to species diversity in the defined URA.

The terrestrial disturbance was calculated in Table 13 in the Appendix 1-C based on available measurements of the ecological conditions presented in Table 12 in Appendix 1-C and default assumptions listed above.

#### **6.9.6.1.2 Key Species Losses Assessment**

In the fiber basket of Hebei DP Mill, there was insufficient information on the specifics of the regions from which bamboo was sourced to determine a reliable list of species. It was unclear which species were affected negatively by bamboo grown in this region. Results could not be evaluated and are reported as “no data.”

#### **6.9.6.2 Dissolving Pulp Production**

The Hebei DP mill in Hebei, China produces 55,300 short tons of dissolving pulp annually, of which 86% of pulp produced is rayon (viscose) grade, while the remaining is for specialty applications. The mill consumes bamboo as the main source of pulpwood, and does not purchase any market pulp. Although the dissolving pulp is manufactured from bamboo, the chemical processing steps for bamboo pulp are technically the same as processing other species (pine, spruce, beech, etc.) of wood pulp. Hebei DP mill manufactures bamboo pulp using kraft process as described in Appendix 1-D. All dissolving pulp produced from bamboo at Hebei DP mill, is consumed internally by its parent viscose fiber company Jilin MMCF mill located in Jilin, China.

##### **6.9.6.2.1 Chemical Inputs to the Dissolving Pulp Mill**

No specific data were available on the amounts of chemical inputs consumed at the mill. Approximately 2.5 tons of hardwood is used to produce 1 ton of pulp. Since Hebei DP mill produces dissolving pulp using kraft process, the composition of cooking liquor differs from the Swedish DP mill process. Theecoinvent 3.1 dataset on *market for sulfate pulp-GLO*, was used to estimate the amount of chemicals used for one ton of pulp. This data represents the industry average for production of sulfate pulp used in



papermaking with totally chlorine free bleaching process. The RISI Mill Asset Database was used to represent energy inputs (see next section), with good data quality. The Ecoinvent dataset used represents sulfate pulp for papermaking, and so its use to represent chemical inputs has an effect on data quality, which is considered in the data quality analysis.

#### **6.9.6.2.2 Energy Inputs to the Dissolving Pulp Mill**

The mill generates more than 90% of its electricity needs from the combustion of black liquor, wood/waste solids derived from pulpwood inputs, and other fuels such as fuel oils and sludge waste. The energy consumption relative to the production of 1 ton of pulp at the mill was assessed based on annual production data from RISI Mill Asset Database, and is specific to the mill. Electricity generation is one of the key unit processes for this product system. Ecoinvent 3.1 dataset *market for electricity, medium voltage-CN* was modified to include electricity production from hard coal for Hebei province in China. Emissions associated with transmission and distribution losses are accounted for in this dataset. As described in Section 6.9.3.3.2, electricity production dataset in Ecoinvent was modified to include black carbon emissions. Refer to Appendix 1-D for more details.

#### **6.9.6.3 MMCF Production**

The Jilin MMCF mill in Jilin province, China, is one of the leading producers of bamboo viscose fiber in China, with an annual production capacity of 88,000 tons of viscose, of which 55,000 tons comprises of bamboo viscose in both staple fiber and filament yarn forms<sup>163</sup>. The production of MMCF is described in Appendix 1-D. It is to be noted that primary data for the Jilin MMCF mill was obtained for viscose filament yarn production line. As discussed in Appendix 1-D, all chemical inputs and processing steps up to spinning stage are identical. Some additional steps are required for viscose filament yarn formation.

##### **6.9.6.3.1 Chemical Inputs to the MMCF Mill**

The amount of chemical inputs to the Jilin mill was obtained from a Chinese market research company. Data for CS<sub>2</sub>, H<sub>2</sub>SO<sub>4</sub> and NaOH was provided relative to the production of 1 ton of MMCF. Approximately 70% of carbon disulfide is recovered at the Jilin mill. It is assumed that all chemicals required for viscose production are manufactured in Jilin province. The production of sodium hydroxide and sulfuric acid are key unit processes for viscose fiber production. Description of these processes and the Ecoinvent 3.1 datasets used to model these processes are provided in Section 6.5.

##### **6.9.6.3.2 Energy Inputs to the MMCF Mill**

The Jilin mill purchases electricity and steam for its operations. The facility energy use data included the energy consumption for yarn formation. The energy use for Jilin bamboo viscose was adjusted based on the average energy consumption data for manmade cellulose fiber based on the assumption stated for

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<sup>163</sup> <http://www.businesswire.com/news/home/20110309006279/en/Research-Markets-China-Viscose-Fiber-Industry-Report>

German MMCF mill in Section 6.9.1.3.2. Ecoinvent 3.1 dataset *market for electricity, medium voltage-CN* was modified to include electricity production from hard coal for Jilin province. Emissions associated with transmission and distribution losses are accounted for in this dataset. Refer to Appendix 1-D for more details.

## **6.9.7 Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China: MMCF from cotton linter pulp produced in China**

### **6.9.7.1 Cotton Cultivation in Surendranagar district, Gujarat**

A relatively small fraction of dissolving pulp is produced from non-wood pulp, mainly cotton linters. Cotton linters are short fibers obtained from delinting of cotton seeds, which are valuable co-products of cotton ginning process. Xinjiang mill in Xinjiang province, is one of the leading producers of viscose fibers from cotton linter pulp. This company also operates a cotton linter pulp production line in the same region. However, there was no information available on sourcing of cotton linters for the Xinjiang mill. Nor was there data available regarding where cotton is grown in Xinjiang, which would be required to evaluate ecosystem impacts.

A large amount of cotton linter is imported into Xinjiang and Shandong in China, based on import statistics in China for 2015. India is the largest exporter of cotton linters to China; in 2015, India accounting for nearly 43% of the total amount of cotton linters imported by all of China. It is reasonable to assume that a large portion of cotton imported from India into Xinjiang is used in DP mill production; and in India, data were available regarding the areas in which cotton is grown, allowing an evaluation of ecosystem impacts. Hence, Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China considers a hypothetical scenario with Xinjiang mill importing cotton linters from India for cotton linter pulp production. This scenario is geographically limited to consider the impacts from cotton cultivation in the state of Gujarat located in Western India.

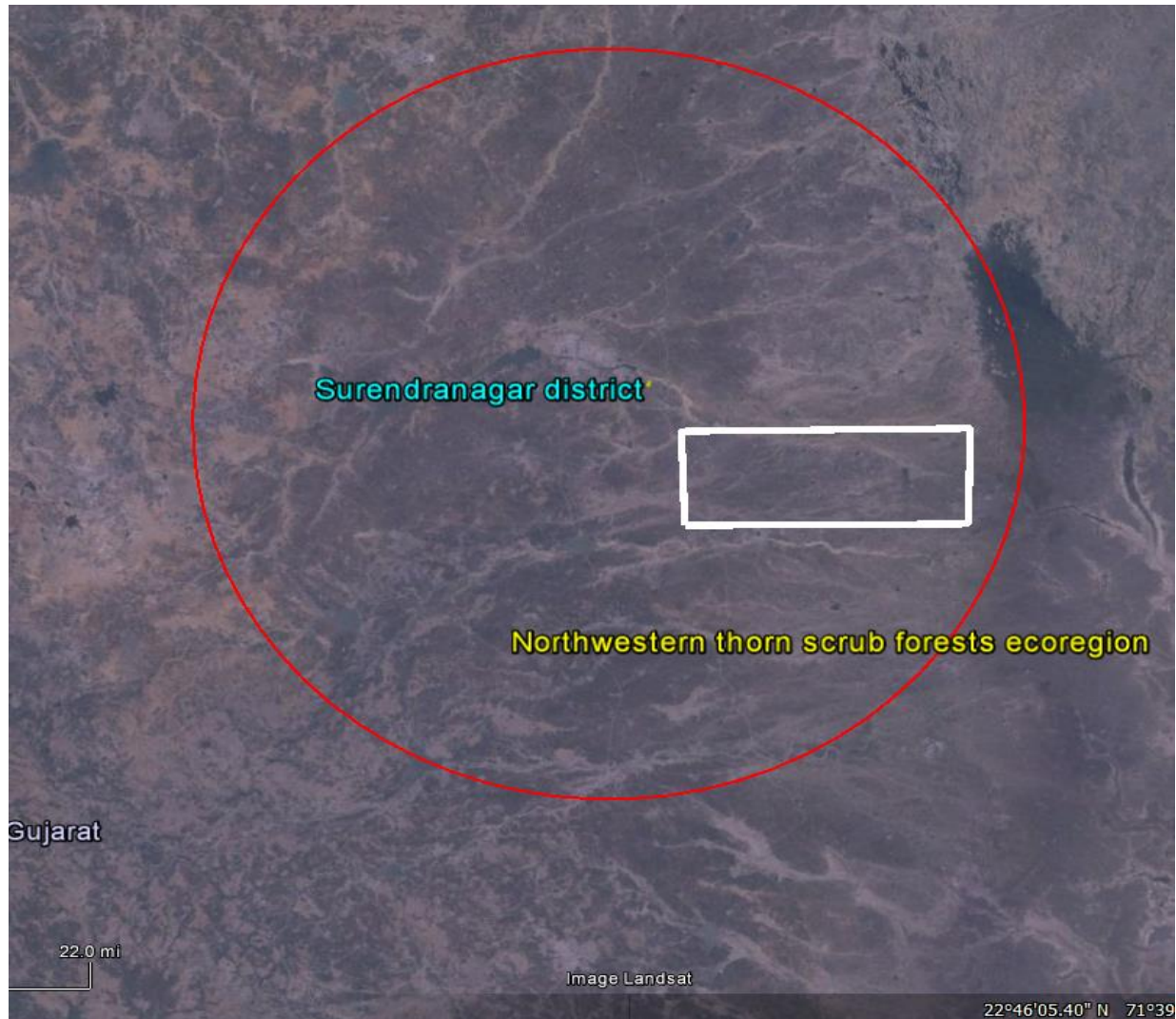
Agricultural maps generated by Gujarat<sup>164</sup> indicate that Surendranagar is the hub of cotton production in the state and nearly 40,700 hectares<sup>165</sup> of this district is covered with cotton crop. Surendranagar district in Gujarat was selected as the fiber basket for the Xinjiang mill.

The FAU was defined across a large portion of cotton growing area in the fiber basket. The fiber basket of the Xinjiang mill lies in the Northwestern thorn scrub forests in the *deserts and xeric shrublands biome*. Impacts to this ecoregion is included in the scope of this assessment. Figure presents the defined FAU and ecoregion for this scenario. See Appendix 1-D for more details.

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<sup>164</sup> Agricultural maps of Gujarat; <http://www.mapsofindia.com/maps/gujarat/gujaratagriculture.htm>

<sup>165</sup> Surendranagar presentation; <http://www.slideshare.net/raval23087/new-surendranagar-presentationppt>



**Figure 33.** The defined FAU for Xinjiang mill is outlined in white. The ecoregion is shaded in green and purple respectively.

#### 6.9.7.1.1 Terrestrial Disturbance Assessment

To assess terrestrial disturbance, conditions are compared in the Forest Analysis Unit (FAU, which is an area cultivated with cotton, to an Undisturbed Reference Area (URA, a reference area representing “undisturbed” conditions). In this assessment:

- The FAU is the area under cotton cultivation. 25,000 hectares of land cultivated with cotton is considered in this assessment.
- The URA is the area of dry thorn scrub forests, native to state of Gujarat in western India.

Conditions in FAU defined in Figure 33 is compared to thorn scrub forests in the URA. Ecological parameters such as forest compositional structure and forest size structure are not applicable in this scenario. The above ground biomass estimates for cotton is assumed to be negligible. Above ground

biomass estimates for thorn scrub forests in URA were derived from literature<sup>166</sup>. This scenario evaluated the difference between estimates for soil organic carbon (SOC)<sup>167</sup> in FAU and URA.

The terrestrial disturbance was calculated in Table 15 of Appendix 1-C based on available measurements of the ecological conditions in Table 14 of Appendix 1-C and default assumptions listed above.

#### **6.9.7.1.2 Key Species Losses Assessment**

For the fiber basket of Xinjiang Mill, there was insufficient information on the specifics of the regions from which cotton was sourced to determine a reliable list of species. It was unclear which species were affected negatively by cotton grown in this region. Results could not be evaluated and are reported as “no data.”

#### **6.9.7.2 Dissolving Pulp Production**

The DP mill in Xinjiang, China has an annual production capacity of 88,000 short tons of dissolving pulp. Cotton, by virtue of having no lignin content, requires less effort in pulping, with fewer raw materials consumed in the pulping process. The Xinjiang mill produces dissolving pulp using kraft process. Refer to Appendix 1-D for detailed description on kraft process. This scenario assumes that all dissolving pulp produced from cotton linters at Xinjiang mill, is consumed internally by its subsidiary viscose fiber mill, located in the same province (Xinjiang) of China.

##### **6.9.7.2.1 Chemical Inputs to the Dissolving Pulp Mill**

No primary data were available on the amounts of chemical inputs consumed at the mill. Approximately 1.2 tons of cotton is required to produce 1 ton of cotton linter pulp. The chemical inputs for Xinjiang mill were modeled based on specific requirements for cotton linter production provided by an engineering firm<sup>168</sup>. Sodium hydroxide and sulfuric acid are the major reagents used for processing cotton linter pulp. The pulp is bleached using hydrogen peroxide solution. Sodium hydroxide production is one of the key unit processes for this scenario.

##### **6.9.7.2.2 Energy Inputs to the Dissolving Pulp Mill**

As cotton fiber contains no lignin and/or hemicellulose, no black liquor is generated from pulping. According to specific data on this mill from the RISI Mill Asset Database, no energy is generated from black liquor. Most energy used at the mill (88%) is produced from fossil fuels, waste wood chips or hog fuel (5%) and purchased electricity (7%). The energy consumption relative to the production of 1 ton of pulp at the mill was assessed based on annual production data from RISI Mill Asset Database.

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<sup>166</sup> Forest survey of India; [http://fsi.nic.in/carbon\\_stock/chapter-4.pdf](http://fsi.nic.in/carbon_stock/chapter-4.pdf)

<sup>167</sup> Chaudhury, Swati, et al. "Land use and cropping effects on carbon in black soils of semi-arid tropical India." *CURRENT SCIENCE* 110.9 (2016): 1692.

<sup>168</sup> Dissolving pulp from cotton linters; IPS Engineering; [http://www.ips-engineering.it/Doc/IPS\\_Dissolving\\_pulp.pdf](http://www.ips-engineering.it/Doc/IPS_Dissolving_pulp.pdf)

Ecoinvent 3.2 database provided updated electricity production datasets from hard coal for 32 different provinces in China. Electricity production from hard coal varies by province in China, resulting in differences in environmental impacts from electricity generation. This regional variation was taken into account and the Ecoinvent 3.1 dataset *market for electricity, medium voltage-CN* was modified to include electricity production from hard coal for Xinjiang province in China. Emissions associated with transmission and distribution losses are accounted for in this dataset.

Electricity generation from hard coal also emits short-lived climate pollutants such as black carbon, nitrogen oxides and primarily sulfur dioxide. As described in Section 6.9.3.3.2, electricity production dataset in Ecoinvent was modified to include black carbon emissions. Refer to Appendix 1-D for more details.

### **6.9.7.3 MMCF Production**

The mill has an annual production capacity of 120,000 tons of MMCF and mainly provides a variety of fiber specifications (mainly 1.2Dx32mm, 1.2Dx38mm 1.5Dx38mm). Although the MMCF mill uses cotton linter pulp, the chemical processing of viscose fiber is identical to the process description in Section Appendix 1-D.

#### **6.9.7.3.1 Chemical Inputs to the MMCF Mill**

The amount of chemical inputs to the Xinjiang mill was obtained from a Chinese market research company. Primary data for CS<sub>2</sub>, H<sub>2</sub>SO<sub>4</sub> and NaOH reagents were provided relative to the production of 1 ton of MMCF. Approximately 70% of carbon disulfide is recovered at the Xinjiang mills. It is assumed that all chemicals required for viscose production are manufactured in Xinjiang province. The production of sodium hydroxide and sulfuric acid are key unit processes for viscose fiber production. Description of these processes and the Ecoinvent 3.1 datasets used to model these processes are provided in Section 6.5.

#### **6.9.7.3.2 Energy Inputs to the MMCF Mill**

The mill purchases electricity and steam for its operations. Since the MMCF mill is located in the same province as the dissolving pulp mill, the same Ecoinvent 3.1 dataset described in Section 6.9.7.2.2 was used to model electricity purchased in the LCA model. All assumptions stated in the above section apply here as well.

### **6.9.8 Scenario 8: Chinese Production from South African Plantation Pulp: MMCF from pulp originating in South Africa**

#### **6.9.8.1 Forestry in Mill Fiber Basket**

The South African DP mill in Mpumalanga province of South Africa is one of the largest dissolving pulp mills in the world. Over 78% of pulpwood supplied to South African DP mill comes from commercial timber plantations of 262,000 hectares in Mpumalanga province. South Africa's native forests and

woodlands are predominated by slow growing tree species, which were inadequate to meet the growing demand for timber. Native grasslands/savannahs and pockets of indigenous forests were transformed to pine plantations for pulpwood in early 1900s.

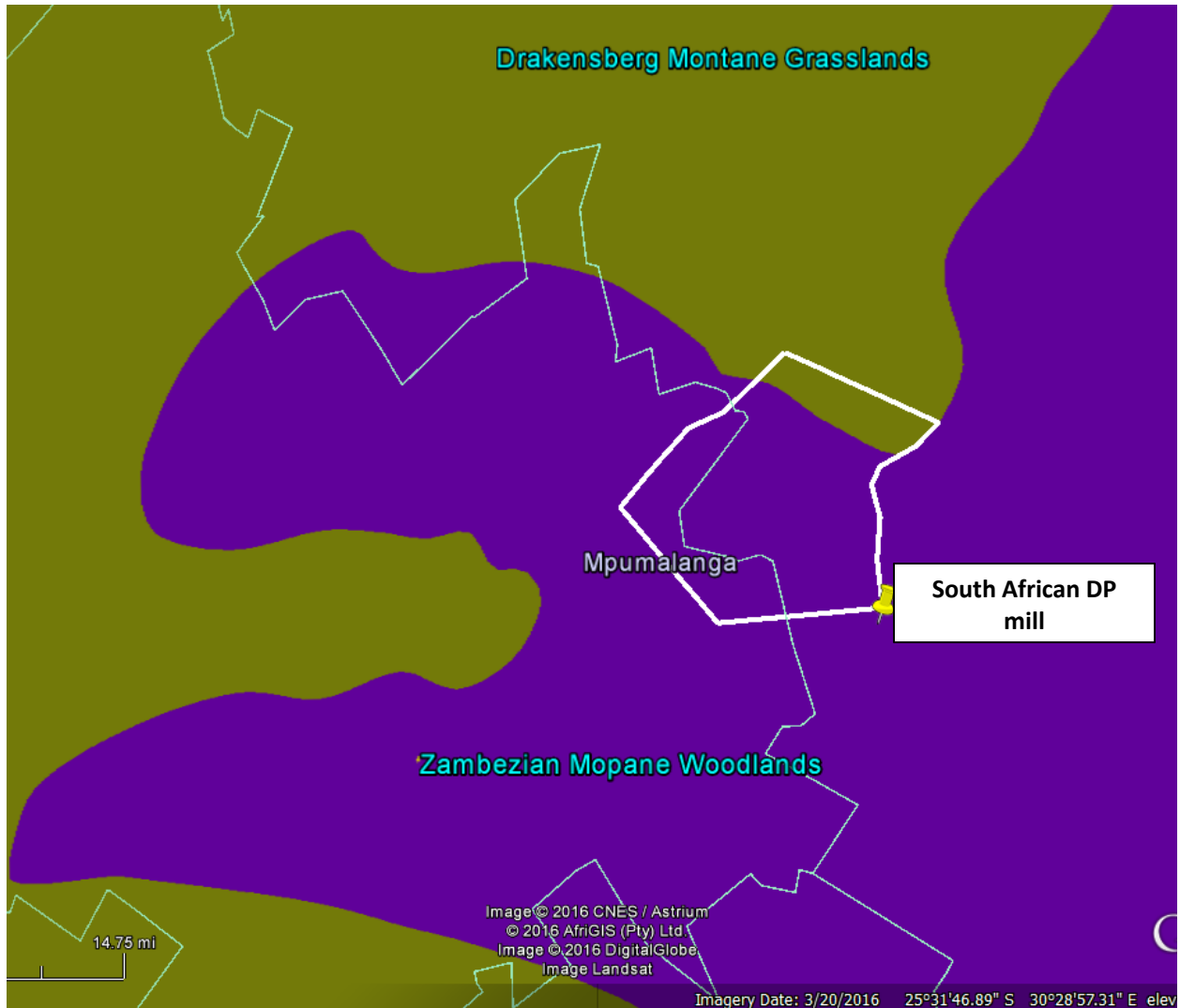
In 1963, farmlands in the Elands River Valley were acquired by South African DP mill for timber plantations. Since 2004, pine forest land was transformed to eucalyptus as a result of conversion of South African DP mill from fiber line to a dissolving pulp mill<sup>169</sup>. In 2010, South African DP Mill purchased Sjonajona plantations, 14,500 hectares of plantations extending between Machadodorp and Barberton in the Mpumalanga province. Based on the information available, fiber basket for South African DP Mill was determined to be within a 75 miles radius of the mill in Mpumalanga province.

The production of pulpwood includes forest management practices and timber harvests in pulpwood plantations within the fiber basket. Impacts associated with this forestry, affects the species habitats across the grassland ecosystem. In the fiber basket, the assessment considered a large enough area to represent the degree of these impacts. Lack of site-specific data on various ecological parameters, made it difficult to assess forest impacts for this scenario. Based on the limited information available, relevant FAU was defined across the portion of the fiber basket in Mpumalanga province. In the fiber basket of the South African DP mill, there are two ecoregions:

(1) Drakensberg montane grassland ecoregion in the *Montane grasslands and shrublands biome*; and (2) Zambeian and mopane woodlands ecoregion in *Tropical and subtropical grasslands, savannas, and shrublands biome*. Impacts to the two ecoregions listed above are included in the scope of this assessment. The FAU and local ecoregions are shown in Figure 34. Refer to Appendix 1-D for more details.

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<sup>169</sup> GeaSphere South Africa, 2012; <http://www.geasphere.org/general-work-of-geasphere/8-2011-12-geasphere-ebook/file>



**Figure 34.** The South African DP mill and ecoregions. The defined FAU is outlined in white. The two ecoregions are shaded in green and purple respectively.

Within each of the two ecoregions considered, there are terrestrial ecosystems, freshwater ecosystems, and wetland ecosystems, which are impacted by forestry.

#### 6.9.8.1.1 Terrestrial Disturbance Assessment

Biologically diverse, native grasslands in the Mpumalanga province were replaced by water-intensive monocultures of eucalyptus plantations. In this assessment:

- The FAU is non-native eucalyptus plantation area developed for pulpwood production by South African mill. 15,000 hectares are impacted by forestry in the FAU.
- The URA is a native montane grassland and shrubland.

Ecological measurements for this scenario were unavailable. Aboveground biomass estimates for URA, which includes dry shrubland is assumed to be 0 tons per hectare. Detailed measurements of landscape fragmentation were also not available. These omissions could affect results for terrestrial disturbance.

There was a limitation in evaluating the terrestrial disturbance for this scenario due to absence of inventory data for the defined FAU and URA. It is believed that species-rich native grasslands are being destroyed at an average rate of 200 square km per annum by commercial afforestation.<sup>170</sup> Based on literature, it was established that 60-80% of South Africa's grasslands have been transformed to commercial timber plantations over many decades and this land transformation is considered to be irreversible.<sup>171</sup> Due to extensive loss of native grasslands and replacement with eucalyptus forest, a profound alteration to the local ecosystem, a terrestrial disturbance factor of 80% ( $\pm$  20%) has been established for this scenario. The terrestrial disturbance was calculated in Table 17 of Appendix 1-C based on the measurements of the ecological conditions shown in Table 16 in Appendix 1-C.

As discussed earlier, because of the conversion from grassland with low carbon storage to a eucalyptus plantation with high carbon storage, there is a net increase in carbon storage in the FAUs. However, the carbon storage impacts should not be considered in isolation, considering the significant ecosystem impacts resulting from the conversion of native grasslands to plantations.

#### **6.9.8.1.2 Key Species Losses Assessment**

In the fiber basket of South African DP mill, fourteen species were found to be affected by logging activities in Mpumalanga, South Africa based on IUCN Red List Species database<sup>172</sup> and regional species list noted in Appendix 1-C. Figure 3 presents a summary of the key species for all fiber baskets, based on the reporting requirements of the PCR for Roundwood. Table 18 in the Appendix 1-C provides the justification and for the inclusion of each species.

#### **6.9.8.2 Dissolving Pulp Production**

The South African DP mill in Mpumalanga, South Africa, has an annual capacity of 639,000 short tons, comprising 27% of dissolving grade rayon pulp (approximately 176,000 short tons), 64% paper pulp and 9% of dissolving grade pulp for specialty applications. The mill predominantly consumes hardwood (eucalyptus pulpwood) species for dissolving pulp production using a kraft process. Refer to Appendix 1-D for detailed description on kraft process. Data from RISI Mill Asset database indicates that this mill manufactures both bleached and unbleached eucalyptus kraft pulp. This scenario assumes that dissolving pulp produced at the South African mill is shipped to Zhejiang MMCF mill in Zhejiang, China.

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<sup>170</sup> <http://www.geosphere.org/layout/grassland/9-2003-11-grassland/file>

<sup>171</sup> MacDonald (1989). Man's role in changing face of South Africa. Biotic diversity in South Africa- concepts and conservation. Oxford University Press. Cape Town. 51-77.

<sup>172</sup>



#### **6.9.8.2.1 Chemical Inputs to the Dissolving Pulp Mill**

No specific data were available on the amounts of chemical inputs consumed at the mill. Approximately 2 tons of hardwood is used to produce 1 ton of pulp. South African DP mill produces dissolving pulp using kraft process, so the composition of cooking liquor differs from the Swedish DP mill process. Thus the Ecoinvent 3.1 dataset on *market for sulfate pulp-GLO*, was used to estimate the amount of chemicals used for one ton of pulp. This data represents the industry average for production of sulfate pulp with totally chlorine free bleaching process. The RISI Mill Asset Database was used to represent energy inputs (see next section), with good data quality. The Ecoinvent dataset used represents sulfate pulp for papermaking, and so its use to represent chemical inputs has an effect on data quality, which is considered in the data quality analysis.

#### **6.9.8.2.2 Energy Inputs to the Dissolving Pulp Mill**

The mill generates 72% of its electricity needs from the combustion of black liquor, wood/waste solids derived from pulpwood inputs, and other fuels such as fuel oils and sludge waste. Additionally, the mill purchases electricity to meet the remainder of its energy requirements. The energy consumption relative to the production of 1 ton of pulp at the mill was assessed based on annual production data from RISI Mill Asset Database.

Electricity was modeled using Ecoinvent 3.1 dataset *market for electricity, medium voltage-ZA* for South Africa. Emissions associated with transmission and distribution losses are accounted for in this dataset. Refer to Appendix 1-D for more details.

#### **6.9.8.3 MMCF Production**

The Zhejiang MMCF Mill located in the Zhejiang province, China, is one of the leading producers of manmade cellulose fibers with an annual production capacity of nearly 280,000 tons of manmade cellulose fibers. This mill produces a variety of differentiated viscose fibers, composed of different sources of pulp (bamboo, cotton and wood pulp). This scenario considers the production of staple fibers from eucalyptus pulp imported from the South African DP mill.

##### **6.9.8.3.1 Chemical Inputs to the MMCF Mill**

The amount of chemical inputs to the Zhejiang mill was obtained from a Chinese market research company. Primary data for  $CS_2$ ,  $H_2SO_4$  and  $NaOH$  reagents were provided relative to the production of 1 ton of MMCF. Approximately 70% of carbon disulfide is recovered at the Zhejiang mill. It is assumed that all chemicals required for viscose production are manufactured in Zhejiang province. The production of sodium hydroxide and sulfuric acid are key unit processes for viscose fiber production. Description of these processes and the Ecoinvent 3.1 datasets used to model these processes are provided in Section 6.5.

### 6.9.8.3.2 Energy Inputs to the MMCF Mill

The Zhejiang MMCF Mill purchases electricity and steam for its operations. Ecoinvent 3.1 dataset *market for electricity, medium voltage-CN* was modified to include electricity production from hard coal for Zhejiang province. Emissions associated with transmission and distribution losses are accounted for in this dataset. Ecoinvent dataset for electricity was modified to include black carbon emissions.

## 6.9.9 Scenario 9: Austrian production from mixed South African Plantation & Austrian Managed Forest Pulp: Lyocell fibers produced from mix of eucalyptus and beechwood pulp

### 6.9.9.1 Forestry in Mill Fiber Basket

Dissolving pulp for lyocell fiber is produced in an Austrian mill from a mix of pulpwood sourced from eucalyptus and beechwood, of which approximately 60% of pulp feed consists of eucalyptus pulp. 50% of beechwood is sourced from Austria, while the remaining pulpwood is sourced from neighboring countries of Germany, Slovakia, Croatia, Czech Republic, Bosnia and Switzerland. The Austrian MMCF mill sources eucalyptus pulp from the South African DP mill. Due to lack of specific information on location of pulpwood harvest from neighboring countries, the fiber basket is determined to be within 200 mile radius of Austrian mill in Upper Austria, and also to include eucalyptus sourced from plantations in South Africa.

The Austrian Forest Inventory provides forestry inventory data on a district level for each province in Austria. Based on the available data, Gmunden district was defined as the FAU in the fiber basket<sup>173</sup>. This district is in close proximity to the Austrian pulp mill in Upper Austria. The FAU is considered to be large enough to represent the degree of impacts occurring across the breadth of the fiber basket. Although representing a fraction of total pulpwood supply, conditions in the forests in Gmunden district are a good indication of forest conditions in neighboring countries, which are located in the same ecoregions, and with the same set of threatened species. Forests in this district are representative of the most common logging practices in the fiber basket.

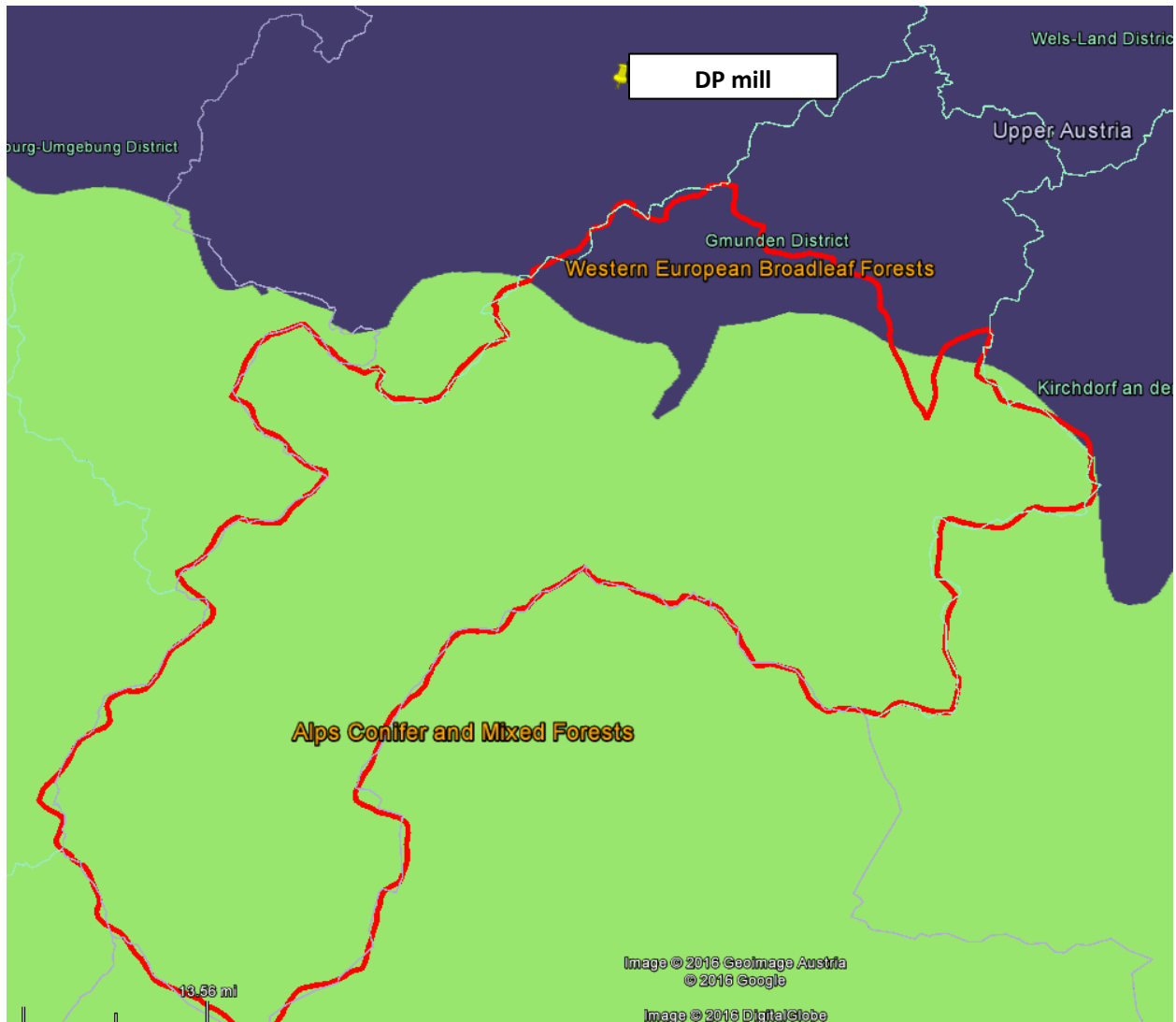
Additionally, an FAU in South Africa was used. The same FAU as used to evaluate terrestrial disturbance for fiber originating in South Africa was used. This results in impacts to the *Zambezian and mopane woodlands* ecoregion (see Section 6.9.8.1.1 for discussion).

The timberlands included in FAU in Austria include forests owned by private companies, government as well as private owners. The Austrian mill fiber basket lies in two ecoregions: (1) the Alps conifer and mixed forests ecoregion in *Temperate coniferous forests biome*; and (2) Western European broadleaf forests ecoregion in *Temperate broadleaf and mixed forests biome*. Majority of the FAU lies in the Alps conifer and mixed forests ecoregion.

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<sup>173</sup> Note: Specific data on conditions in the forest operators supplying the mill were not provided by Swedish DP mill, and so this information is strictly based on regional average forest conditions in this region.

A large fraction of the pulpwood production occurs within the *Temperate coniferous forests biome* and *Temperate broadleaf and mixed forests biome*. Impacts to the two ecoregions listed above are included in the scope of this assessment. The selected FAU in Austria and corresponding ecoregions are presented in Figure 35. For the FAU in South Africa, see Figure 34.



**Figure 35.** The Austrian mill and ecoregions. The defined FAU, Gmunden District is outlined in red. The two ecoregions are shaded in green and purple respectively.

Within the three ecoregions considered in Upper Austria and South Africa, there are terrestrial ecosystems, freshwater ecosystems, and wetland ecosystems, which are impacted by forestry. Refer to Appendix 1-D.

#### 6.9.9.1.1 Terrestrial Disturbance Assessment

The same data on terrestrial disturbance used to calculate results for Scenario 8 was used to calculate terrestrial disturbance for pulpwood originating from South Africa. See Section 6.9.8.1.1 for discussion.

This section describes the approach used to calculate terrestrial disturbance for pulpwood originating in Upper Austria.

For the terrestrial disturbance assessment in Upper Austria:

- The FAU is productive forest land used for timber production by private in Gmunden district in Upper Austria. 42,000 hectares are impacted by forestry in the FAU.
- The URA is a mature forest with forest stands which have an average age of over 80 year or more in Gmunden district.
- Conditions in 42,000 hectares of FAU are compared to 19,000 hectares of URA in Gmunden district.

Following ecological conditions were included in the terrestrial disturbance calculations for FAU and URA:

1. Forest compositional structure, including most prominent tree species by stand age class and area, dominant forest types by stand volume and area.
2. Biomass measurements in the forest were calculated from stand volume estimates, assuming that the carbon content of wood is 50%.

More detailed data on soil conditions (i.e., soil depth and organic matter content) were not available. Since soil carbon correlates with aboveground biomass, inclusion of biomass measurements reflects trends in soil carbon storage. (See Section 4.3.2 more discussion of the data availability regarding soil carbon changes and potential implications on results.) Detailed measurements of landscape fragmentation were also not available. Census of the vertebrate species community was unavailable. The average % reduction in tree species in the FAU was assumed as a proxy for % reduction in native vertebrate species in FAU compared to undisturbed conditions. These omissions could affect results for terrestrial disturbance.

The terrestrial disturbance was calculated in Table 20 of Appendix 1-C based on the measurements of the ecological conditions shown in Table 19 of Appendix 1-C, which are regional averages in Gmunden district, obtained from the Austrian Forest Inventory website for year 2007-2009.

#### **6.9.9.1.2 Key Species Losses Assessment**

In the fiber basket of Austrian mill, twenty five species were found to be affected by logging activities in Upper Austria and South Africa, based on IUCN Red List Species database and regional species list noted in Appendix 1-C. Figure 3 presents a summary of the key species for all fiber baskets, based on the reporting requirements of the PCR for Roundwood. Table 21 in the Appendix 1-C provides the justification and for the inclusion of each species.

### 6.9.9.2 Dissolving Pulp Production

The Austrian pulp mill in Oberosterreich (Upper Austria), Austria, has an annual capacity of approximately 290,000 short tons, comprising 76% of dissolving grade rayon pulp (approximately 220,459 short tons) and 24% of dissolving grade pulp for specialty applications. The mill consumes a mix of hardwood and softwood species and operates as a biorefinery. Austrian pulp process is a magnesium-based sulfite cooking process, as described in Appendix 1-D. The pulp is bleached using totally chlorine free (TCF) bleaching process, where the active bleaching chemical is hydrogen peroxide.

Lyocell fibers are produced from a mix of eucalyptus and beechwood pulp (60% eucalyptus and 40% beechwood). For this scenario, the eucalyptus pulp is assumed to be supplied by the South African DP mill. This scenario assumes that dissolving pulp produced at Austrian pulp mill is consumed internally by Austrian MMCF mill's lyocell fiber production site in Austria.

#### 6.9.9.2.1 Chemical Inputs to the Dissolving Pulp Mill

No specific data were available on the amounts of chemical inputs consumed at the mill. Approximately 2.6 tons of hardwood/softwood is used to produce 1 ton of pulp. The type of chemical inputs for Austrian DP mill are expected to be very similar to the Swedish DP mill. Thus these inputs were modeled using Swedish DP mill data and were supplemented with Ecoinvent 3.1 dataset on *market for sulfate pulp-GLO*. This data represents the industry average for production of sulfate pulp with totally chlorine free bleaching process. It is assumed that all chemicals required for lyocell production are manufactured in Austria. All assumptions for eucalyptus pulp considered in Section 6.8.8.2.1 are applicable here as well.

#### 6.9.9.2.2 Energy Inputs to the Dissolving Pulp Mill

The mill generates more than 90% of its electricity needs from the combustion of black liquor, wood/waste solids derived from pulpwood inputs, and other fuels such as fuel oils and sludge waste. Additionally, the mill also purchases electricity and natural gas to meet the remainder of its energy requirements. The energy consumption relative to the production of 1 ton of pulp at the mill was assessed based on annual production data from RISI Mill Asset Database. Electricity was modeled using Ecoinvent 3.1 dataset *market for electricity, medium voltage-AU* for Austria. Emissions associated with transmission and distribution losses are accounted for in this dataset. All assumptions for eucalyptus pulp considered in Section 6.8.8.2.2 are applicable here as well.

### 6.9.9.3 MMCF Production

The Austrian MMCF mill manufactures lyocell fibers in Austria. The lyocell fiber processing technology was commercialized by the company owning the mill in the early 1990s, with main applications in textile non-woven sectors as well as sportswear/apparel sector. Other producers now use comparable lyocell technologies as well. The Austrian site has an annual production capacity of 60,000 tons of lyocell fiber. A mix of eucalyptus pulp (about 60%) and beechwood pulp (40%) is used as feed for lyocell fiber

processing. The beechwood pulp is consumed from Austrian MMCF mill's internal dissolving pulp mill in Upper Austria. The Austrian MMCF mill is assumed to procure eucalyptus pulp from South African DP mill (refer to description of South African DP mill in Section 6.9.8.2). Refer to Appendix 1-D for detailed description on lyocell fiber processing technology.

#### **6.9.9.3.1 Chemical Inputs to the MMCF Mill**

As explained above, the main chemical input for lyocell fiber is NMMO solvent. There was no information on the amount of chemical inputs used for lyocell fiber production. Also, the background dataset for NMMO solvent was not available in the Ecoinvent database. Thus conservative estimates based on literature (Lenzing LCA study)<sup>174</sup> were adopted for modeling NMMO solvent in this scenario. The study assumed the cradle-to-gate energy consumption of NMMO solvent to be 200GJ/ton. This assumption was built into the LCA model. The amount of NMMO solvent used for fiber dissolution and regeneration was not revealed in the Lenzing LCA study. The amount of NMMO solvent required to make lyocell solvent was adopted from a patent on lyocell fiber production<sup>175</sup>.

#### **6.9.9.3.2 Energy Inputs to the MMCF Mill**

According to a published Lenzing LCA study<sup>176</sup>, the process energy for lyocell production in Austria is supplied by natural gas (70%) and external biomass (30%). However, facility energy use was relative to one ton of lyocell fiber produced was not provided by the producer. Thus, average energy use estimates for viscose fiber production were used to model energy consumption relative to 1 ton of lyocell fiber.

### **6.9.10 Scenario 10: Belgian Flax Production: Flax fibers produced in Belgium from flax co-products grown in Belgium**

#### **6.9.10.1 Flax Cultivation in Belgium**

The flax industry is concentrated in Western Europe, predominantly in the western part of Belgium (West Flanders or Flemish region), northwest of France (Normandie-Manche) and southwest of Netherlands (Zeeus Vlaanderen). Flax is a dual purpose crop, which is cultivated for both fiber and seed. Flax fibers are mainly used in textile applications owing to their superior fiber length and quality; whereas flax seeds yield oil for industrial purposes (e.g. paints, soaps, etc.). This scenario only considers the impacts associated with flax fibers, which are processed using flax co-products in Belgium. Flax fiber mill transforms flax co-products i.e. short fibers from scutching and hackling processes, which are low in quality (typically used in paper or insulation markets), to high quality textile fibers using proprietary processing technology, resulting in a fiber, which is functionally equivalent of MMCF.

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<sup>174</sup> Shen, L., & Patel, M. K. (2010). Life cycle assessment of man-made cellulose fibers. *Lenzinger Berichte*, 88, 1-59.

<sup>175</sup> Based on the patent, Perepelkin, K.E. *Fibre Chem* (2007) 39: 163. doi:10.1007/s10692-007-0032-9, 0.01-0.03 kg of NMMO is required to produce 1 kg of staple fiber. The upper bound estimate of 0.03kg NMMO/ kg staple fiber was used in this study.

<sup>176</sup> i.b.i.d

Flax fiber mill sources flax co-products from Belgian distributors and traders. These Belgian distributors and traders play a major role in the flax market, forming a link between scutchers (fiber and yarn producers) and spinners (hackling process). The scutchers typically have contracts with a numbers of farmers growing flax for them, and may grow their own flax as well. The scutchers harvest and ripple the flax plants, dew ret the plants and subsequently break and scutch the flax to separate fibers from the woody material. Apart from the main product, i.e. the scutched long fiber (used in linen yarns and fabrics), scutching produces 'scutching tow' (i.e. short fibers) and shives as co-products.

Since the Belgian traders work with large number of suppliers, it was difficult to track the precise location of flax farms and subsequent flax co-product processing for Flax fiber mill. FAO reports indicate that Flemish region in Belgium is a major hub of flax production, with 11,600 hectares of land under flax, fiber, and tow cultivation in 2014<sup>177</sup>. The land use impacts from flax cultivation in the Flemish region of Belgium, has been evaluated for this scenario.

The FAU was defined across a large portion of flax growing area in the fiber basket, based on agricultural land cover maps generated by CORINE<sup>178</sup>. The fiber basket of the Flax fiber mill lies in the Western European broadleaf forests ecoregion in *Temperate broadleaf and mixed forests biome*. Impacts to this ecoregion is included in the scope of this assessment. Figure presents the defined FAU and ecoregion for this scenario. See Appendix 1-D for more details.

Review of publicly available articles and literature suggests that over the last two centuries, the forest cover in the Flemish region had gradually decreased to about 50% of the land cover. Although the forest area has remained more or less stable 19<sup>th</sup> and 20<sup>th</sup> century, the spatial distribution of forests has dramatically changed; with deforestation on fertile loam soil (30-50% decrease) and new afforestation on alluvial meadows. A large part of the remaining forest cover in the Flemish region consists of afforested lands, in particular even-aged poplar and coniferous plantation, which have gradually transformed to mixed stands. These plantations are less than 80 years old and only a small fraction of the forest cover (15-20%) was forested at the end of the 18<sup>th</sup> century<sup>179</sup>.

#### 6.9.10.1.1 Terrestrial Disturbance Assessment

It is believed that in the last century (especially after the two world wars), the forest areas in the fertile loam region in Flemish area, Belgium were deforested for agriculture<sup>180</sup>. To assess terrestrial disturbance, conditions are compared in the Forest Analysis Unit (FAU, which is an area cultivated with flax, to an Undisturbed Reference Area (URA, a reference area representing "undisturbed" conditions). In this assessment:

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<sup>177</sup> FAO FAOSTAT database output on Flax, Fibre, and Tow. Accessed on 12/18/16 from

<http://www.fao.org/faostat/en/#data/QC> <http://www.fao.org/ag/agp/agpc/doc/counprof/belgium/belgium.htm#5pasture>

<sup>178</sup> Corine Land Cover Map (2006); <http://www.eea.europa.eu/data-and-maps/explore-interactive-maps/corine-landcover-2006>

<sup>179</sup> Integration of Nature Protection in Belgian Forest Policy;

<http://www.eficent.efi.int/files/attachments/eficent/projects/belgium.pdf>

<sup>180</sup> i.b.i.d

- The FAU is the area under flax cultivation. 4,000 hectares of land cultivated with flax is considered in this assessment.
- The URA is the area of native forest area in the Flemish region.

Conditions in FAU is compared to native forests in the URA. Ecological parameters such as forest compositional structure and forest size structure are not applicable to FAU in this scenario. The above ground biomass estimates for flax is assumed to be negligible. However, soil organic carbon (SOC) estimates were available for fertile soils in the Flemish region and were derived from literature<sup>181</sup>. In case of URA, biomass measurements in the forest were calculated from stand volume estimates, assuming that the carbon content of wood is 50% based on data from the European Forest Institute<sup>182</sup>. Since soil carbon correlates with aboveground biomass, inclusion of biomass measurements reflects trends in soil carbon storage. (See Section 4.3.2 for more discussion of the data availability regarding soil carbon changes and potential implications on results.) Detailed measurements of landscape fragmentation were not available. This scenario evaluated the difference between the total biomass estimates in FAU and URA. See Table 23 in Appendix 1-C for terrestrial disturbance assessment results.

#### 6.9.10.1.2 Key Species Losses Assessment

The fiber basket of the flax fiber mill, six species were found to be affected by transformation of forests to agricultural land for flax cultivation in Belgium, based on IUCN Red List Species database and regional species list noted in Appendix 1-C. Figure 3 presents a summary of the key species for all fiber baskets, based on the reporting requirements of the PCR for Roundwood. Table 24 in the Appendix 1-C provides the justification and for the inclusion of each species.

#### 6.9.10.2 Flax Fiber Production

This scenario considers the production of flax fibers from flax co-products at the Belgium facility. Following provides a brief overview on the preparation of flax co-products, which serve as a raw material for flax fiber production:

##### Flax co-product production

- Flax straws are harvested in the Flemish region and they undergo retting process. Retting is the desirable decomposition of the flax straw that allows the fibers to favorably separate from the non-fiber plant material.
- Retting is followed by a mechanical operation called scutching, which separates the fibers from the bark and the woody core parts of flax plants. Apart from the main product, i.e. the scutched

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<sup>181</sup> SOC estimate; <http://users.ugent.be/~ssleutel/Sleutelpdf/Mestdagh%20et%20al.%202009.pdf>

<sup>182</sup> Schelhaas, M.J., Varis, S., Schuck, A. and Nabuurs, G.J., 2006, EFIScen Inventory Database, European Forest Institute, Joensuu, Finland, [http://www.efi.int/portal/virtual\\_library/databases/efiscen/](http://www.efi.int/portal/virtual_library/databases/efiscen/)



long fiber (used in linen yarns and fabrics), scutching produces 'scutching tow' (i.e. short fibers) and shives as co-products.

- Scutching is followed by hackling, a process which involves bundling of fibers to form sliver, the onset of linen yarn formation. In this hackling process, some fibers invariably break down into short fibers resulting in a co-product known as 'hackling tow'.

#### Flax fiber production

Raw material (flax co-products) are transported by truck from the distributor to the manufacturing facility in Belgium. It is unbaled and batch processed in a typical cotton bleaching equipment. The flax co-products are subjected to a proprietary chemical process to extract, soften and brighten the fibers. Note that the transformation of raw flax co-products to flax fiber does not involve any pulping operation. While the specific sequence and formulations is proprietary, in general, the process can be described as soaking the raw fibers in a series of baths filled with alkaline solutions followed by clean water rinses. The fibers are subsequently dried on a natural gas powered belt dryer. The finished flax fiber resembles cotton in terms of feel and appearance and is generally used in blends of different yarns.

Impacts to these co-products were allocated on a mass basis, using yield data (% of input mass) for scutching and hackling processes obtained from literature (see Table 18).

##### **6.9.10.2.1 Chemical Inputs to the MMCF Mill**

Sodium hydroxide (caustic soda) is the primary chemical to raise pH. The specific ratio of alkali to processed fiber is proprietary. Primary data on chemical inputs was provided by Flax fiber mill relative to the annual production of 1500 tons. Ecoinvent 3.1 datasets listed in Section 6.5 were used to model these datasets.

##### **6.9.10.2.2 Energy Inputs to the MMCF Mill**

Flax fiber mill purchases electricity for its operations. Primary energy data inputs were provided relative to the production of 1500 tons of flax fiber. The electricity dataset was modeled using Ecoinvent 3.1 *market for electricity, medium voltage-BE* for Belgium.

## 6.10 Transportation

Dissolving pulp mills are operated within close proximity to the pulpwood harvest locations. Transportation of pulpwood to the dissolving pulp mills was estimated based on the fiber basket defined for each scenario. The major MMCF mills are concentrated in China and these mills import dissolving pulp from overseas resulting in long transportation distances as reported in Appendix 1-D. The Acid plant database was used to estimate the chemical suppliers of sulfuric acid for Scenario 1 and 5<sup>183</sup>. Data on transport distances for other chemical inputs were not available for mills located in China. To avoid any bias, the same road freight transport of 200 miles was assumed as a default distance for all scenarios.

Following datasets were used to model transportation for all the scenarios:

- *Transport, freight, lorry >32 metric ton, EURO4* from the Ecoinvent v3.1 database was used to model transport by road. This assumes that large heavy-duty diesel trucks transport all materials.
- For ship transport, the Ecoinvent v3.1 dataset *Market for transport, freight, sea, transoceanic ship* was used.

Refer to Table 26 and Table 27 in Appendix 1-D for transportation distances used to model each of the ten scenarios.

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<sup>183</sup> Acid plant database: [http://www.sulphuric-acid.com/sulphuric-acid-on-the-web/acid%20plants/Acid\\_Plant\\_Index.htm](http://www.sulphuric-acid.com/sulphuric-acid-on-the-web/acid%20plants/Acid_Plant_Index.htm)

## **6.11 Checks for Completeness, Sensitivity, and Consistency**

During the course of the study, several iterative steps of scope definition, LCI analysis, and LCIA, were completed. An interpretive phase was also completed. The interpretation conforms to ISO 14044 requirements. This includes the identification of significant issues, evaluation (including completeness, sensitivity, and consistency checks), sensitivity analyses, and a data quality assessment.

### **6.11.1 Completeness Check**

The inventory datasets used included all relevant flows. The other data sources used, especially those related to the assessment of Terrestrial and Freshwater Ecosystem Impacts and forest carbon storage loss (affecting those impacts in the group of Climate Change and Ocean Acidification Impacts), are complete, capturing all relevant impacts. The only exceptions are for Ground Level Ozone Exposure Risks, Freshwater Disturbance, Wetland disturbance and Eutrophication impacts. Data was not available to determine the degree to which freshwater ecosystems were impacted. Data on water emissions discharged to impaired water bodies from the dissolving pulp mills and fiber mills was not available for most scenarios and results were not assessed.

### **6.11.2 Sensitivity Check**

As part of an iterative process, sensitivity checks to the key assumptions, methodological choices, data uncertainties, parameters, inventory data, and characterization data were done whenever possible. The result of the sensitivity checks for the key assumptions is discussed in Section 4.3.1. The unit processes which are major contributors to indicator results are identified.

### **6.11.3 Consistency Check**

Throughout all stages of this LCA, methodological choices and practices were consistent with ISO 14044 and the draft LEO-S-002 standard.

## 7 Conclusions

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This study's purpose is to compare the production of manmade cellulose fiber (comprising of viscose, lyocell and flax fibers) produced in ten different scenarios, accounting for a comprehensive set of environmental impact categories. To satisfy the stated goal, the impact profile of fibers manufactured in ten scenarios are assessed using LCA in conformance with ISO 14044, and the draft LEO-S-002 standard.

This LCA study measures the effects of production of manmade cellulose fibers across these ten scenarios, including all relevant impacts involved in raw material extraction, dissolving pulp production, and staple fiber production. A few scenarios are also covered by policies made under the CanopyStyle campaign, as discussed in Section 3.1.1. Impacts associated with the use and end-of-life of MMCF are excluded. It is to be noted that these impacts during downstream processing (e.g. weaving, knitting, dyeing, finishing, etc.), use and waste management stages may differ depending on the source of MMCF. This study is the first to date which looks at 10 scenarios of MMCF production, with a focus on analyzing impacts associated with fibers from different locations, supply chains, and manufactured using different mill technologies.

It can be concluded that the choice of the MMCF raw material input is a critical one with overarching effects on life cycle analysis of impacts. The research indicates that while there is no source of MMCF which is unambiguously environmentally preferable across all impact categories, Scenario 10: Belgian Flax Production seems favorable across majority of the impact categories, followed by Scenario 5: German Production from Recycled Pulp.

All raw material inputs of MMCF have benefits and disadvantages environmentally. However, some sources of fiber have more benefits, and fewer disadvantages, than others. Specifically:

- Comparison of these LCA results for the ten different scenarios indicate that MMCF from Scenario 5: German Production from Recycled Pulp and Scenario 10: Belgian Flax Production have lowest impacts and Scenario 2: Asian Production from Canadian Boreal Forest Pulp, Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian Plantation Pulp and Scenario 7: Chinese Production from Indian Cotton Linter Pulped in China should be avoided. These findings should be reconciled with existing corporate policies and commitments related to forests as part of making procurement decisions.
- Scenario 3: Chinese Production from Indonesian Rainforest Pulp, Scenario 4: Chinese Production from Indonesian Plantation Pulp are the worst performers in multiple categories, including Global Climate Change, Climate Hotspot, Ocean Acidification (applies to Scenario 3 only), Terrestrial Disturbance (applies to Scenario 3 only), Regional acidification, Non-renewable resource depletion and Human Health impacts. These two scenarios are also the worst performers in terms of number of species affected by habitat loss. This is due to the rapid and large scale conversion of forests in this region, as well as the highly diverse nature of local ecosystems.

- Impacts to Terrestrial and Freshwater Ecosystem are a major driver for many impact categories, with the exception of Scenario 5: German Production from Recycled Pulp. There is wide variation in the level of impacts on forest ecosystems as described below.
  - Wood resource depletion impacts are only relevant for Scenario 2: Asian Production from Canadian Boreal Forest Pulp, and Scenario 3: Chinese Production from Indonesian Rainforest Pulp. These are the only regions where a depletion in valuable wood resources is occurring.
  - Scenario 3: Chinese Production from Indonesian Rainforest Pulp, exhibits the highest terrestrial disturbance (Figure 7), followed by Scenario 2: Asian Production from Canadian Boreal Forest Pulp. Of note, Scenario 2 is the 2<sup>nd</sup> worst performer for Global Climate Change, faring better only than Scenario 3, where carbon loss is very high. These are the worst performing options across all potential sources of MMCF by a wide margin.

## PEER PREVIEW PANEL FINDINGS

This critical review panel reviewed 4 drafts of the Life Cycle Assessment Comparing Ten Sources of Manmade Cellulose Fiber, conducted by SCS Global Services. Based on expertise that covers the range of investigations included in this LCA, the panel paid particular attention to ensuring that the LCA:

- Conforms methodologically to the international LCA standard (ISO-14044) comparative LCA study evaluated the life cycle impact profile of manmade cellulose fibers from ten difference sources, conforming to ISO 14040 and 14044.
- Compares the life cycle footprint of the 10 fiber sources included in the study, using primary data whenever available, public data as specific as possible, and local data when needed.
- Inventory data for DP and MMCF plants was based on a mix of specific data provided by the plant operators, supplemented for several mills using site-level databases that were reasonable and considered to be of appropriate data quality, similar to the data quality of primary data collected from manufacturers.
- Recognizes and acknowledges limitations of the data when necessary, while advocating for further research to further improve future analyses.
- Some indicators used in the impact assessment phase have not been used in an LCA for viscose fiber (eg. climate change indicator incorporating indirect impacts of SO<sub>2</sub> and NO<sub>x</sub> emissions) before. A sensitivity analysis was performed showing that the relative results between scenarios were rather consistent with relative results between scenarios obtained with the CML impact assessment coefficients and indicators (eg for climate change and acidification), which is a positive feature of the study.
- Provides transparency to the greatest extent possible.
- Assures accessibility to the information and process as completely as possible, including to non-technical readers.

The review panel held a series of discussions after the 2nd draft, to explore critical issues. It submitted nearly 700 comments during the first 3 rounds of review, all of which were addressed and incorporated in substantive ways. The panel then provided more than 48 comments focusing on ever finer points on the last draft, all of which were addressed and incorporated.

As a result of this intensive review, we consider that this LCA provides an extensive report on the environmental impacts of manmade cellulose fibers, In addition, the report's transparency and accessibility has been an essential priority to us. We are satisfied that this LCA meets ISO 14040 and ISO 14044 standards.



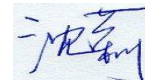
**Neva Murtha (Chair)**  
Senior Campaign Manager  
Canopy



**Olivier Muller**  
PwC Stratégie,  
Développement Durable,  
PricewaterhouseCoopers Advisory



**Dr. Richard Condit**  
Smithsonian Tropical  
Institute



**Dr. Li Shen**  
Assistant Professor,  
Energy & Resources,  
Copernicus Institute of  
Sustainable Development,  
Utrecht University