IDENTIFYING LOW CARBON SOURCES OF

Man-Made Cellulosic fibres (MMCF)

Fashion for Climate

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Teminology Used in this Report

Term	Definition
Allocation	Partitioning the inputs to or emissions from a shared process or a product system between the product system under study and one or more other product systems
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.
Carbon dioxide equivalent (CO_2e)	Unit for comparing the radiative forcing of a GHG to that of carbon dioxide (ISO 14067: 2018)
Carbon pool	A reservoir where carbon is stored for a period of time.[1] During photosynthesis, plants remove carbon (as CO_2) from the atmosphere and store it in plant tissue. Until this carbon is cycled back into the atmosphere, it resides in one of a number of "carbon pools." These pools include (a) above ground biomass (e.g., vegetation) in forests, farmland, and other terrestrial environments, (b) below ground biomass (e.g., roots), and (c) biomass-based products (e.g., wood products) both while in use and when stored in a landfill. Carbon can remain in some of these pools for long periods of time, sometimes for centuries. An increase in the stock of sequestered carbon stored in these pools represents a net removal of carbon from the atmosphere; a decrease in the stock represents a net addition of carbon to the atmosphere[2]
Carbon sequestration	The uptake of CO_2 and storage of carbon in biological sinks
Category Indicator	Quantifiable representation of an impact category [Ref. ISO-14044] (Also referred to as "Impact Category Indicator," or simply, "Indicator.")
Comparative Assertion	Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function. [Ref: ISO 14044]
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].
Deficit irrigation	Deficit Irrigation is defined as deliberate and systematic under-irrigation of crops
Deforestation	The conversion of forest to other land use or the permanent reduction of the tree canopy cover below a defined minimum canopy cover threshold (FAO 2016)
Deforestation (FAO 2020)	The conversion of forest to other land use independently whether human-induced or not. Explanatory notes 1. Includes permanent reduction of the tree canopy cover below the minimum 10 percent threshold. 2. It includes areas of forest converted to agriculture, pasture, water reservoirs, mining and urban areas. 3. The term specifically excludes areas where the trees have been removed as a result of harvesting or logging, and where the forest is expected to regenerate naturally or with the aid of silvicultural measures. 4. The term also includes areas where, for example, the impact of disturbance, over-utilization or changing environmental conditions affects the forest to an extent that it cannot sustain a canopy cover above the 10 percent threshold. (FAO 2020)
Effect	A change to human health or the environment.
Emission Factor	A factor that converts activity data into GHG emissions data
Forest	Though definitions vary by government, organization, and intended use, generally an area of land of minimum 0.5 hectares with a tree cover density of 10–30 percent, where trees have potential to reach a minimum height of 2–5 meters at maturity in place (FAO 2016)
Forest cover change or forest loss	The removal or clearance of trees or woody biomass from forest areas which may temporarily reduce tree cover density without necessarily leading to permanent deforestation. Activities such as forestry and shifting agriculture may lead to a temporary loss of tree cover density which is then (fully or partially) reversed through regeneration. (FAO)
Forest degradation	Forest degradation is a process leading to a 'temporary or permanent deterioration in the density or structure of vegetation cover or its species composition'. It is a change in forest attributes that leads to a lower productive capacity caused by an increase in disturbances (FAO).
Forest Fragmentation	Forest fragmentation refers to any process those results in the conversion of formerly continuous forest into patches of forest separated by non-forested lands (FAO)
Functional Unit	Quantified performance of a product system for use as a reference unit. [Ref. ISO 14044].
GHG Emission	Release of a GHG into the atmosphere

Term	Definition
GHG Removal	Withdrawal of GHG from the atmosphere
GHG Sink	Any physical unit or process that stores GHGs; usually refers to forests and underground/deep sea reservoirs of CO_2 [GHG Protocol]
GHG Source	Any physical unit or process which releases a greenhouse gas into the atmosphere. [GHG Protocol]
Global Warming Potential (GWP)	Index or characterization factor, based on radiative properties of GHGs, measuring the radiative forcing following a pulse emission of a unit mass of a given GHG in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide (CO_2) (ISO 14067: 2018)
Greenhouse gas (GHG)	Gaseous constituent of the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds (ISO 14067: 2018)
Hotspot	Within an LCA study a hotspot is a relevant environmental aspect and its position in the life cycle.
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.
Indicator	See Category Indicator.
Input	Product, material or energy flow that enters a unit process. [Ref. ISO 14044].
Intact Forest Landscapes	A seamless mosaic of forests and associated natural treeless ecosystems that exhibit no remotely detected signs of human activity or habitat fragmentation and are large enough to maintain all native biological diversity, including viable populations of wide-ranging species.[3]
Key processes	A unit process (or unit operation) contributing over 10-15% to any indicator result.
Life Cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation from providing environment to final disposal.

Term	Definition
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]
Midpoint	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).
Natural forest	Both primary and secondary forests that are naturally regenerated with primarily native species. (FAO)
Net forest loss	The change in forest area from one reporting period to another, calculated by subtracting the area of regenerated or reforested area from the area of gross forest loss over the period. (FAO)
Output	Product, material or energy flow that leaves a unit process. [Ref. ISO 14044].
Post-consumer	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.
Primary Data	Quantitative measurement of activity from a product's life cycle that, when multiplied by the appropriate emission factor, determines the GHG emissions arising from a process
Primary Forest	Naturally regenerated forests of native tree species, where there are not clearly visible indications of human activities and the ecological processes are not significantly disturbed. They are sometimes referred to as old-growth forests. These forests are of irreplaceable value for their biodiversity, carbon storage and other ecosystem services, including cultural and heritage values. Natural, mature forests that have not been cleared and regrown in recent history (i.e. the past 30–50 years). Consisting of native species, these forests are largely free from industrial-scale land uses and infrastructure, and ecological processes have not been significantly disturbed. (FAO)

Term	Definition
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]
Reforestation	Reforestation is the re-establishment of forest formations after a temporary condition with less than 10% canopy cover due to human-induced or natural perturbations (FAO).
Secondary Data	Data obtained from sources other than direct measurement of the emissions from processes included in the life cycle of the product
Secondary forest	Forests that have regenerated largely through natural processes after significant removal or disturbance of original forest vegetation (primary forest) by human or natural causes. (FAO)
Sustainable forest management	The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems. [Ref. Forest Europe, https://foresteurope.org/publications/#1471590853638-cbc85f9c-8e6e]
System	See product system.
Time Horizon	A specified timeframe.
Unit Process	Smallest element considered in the life cycle assessment for which input and output data are quantified [Ref: ISO 14044].

Acronyms

BAT	Best Available Techniques
CH4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DP	Dissolving Pulp
ECF	Elemental Chlorine Free
EIA	U.S. Energy Information Administration
EU	European Union
FAO	Food and Agriculture Organization
FSC	Forest Stewardship Council
GHG	Greenhouse gas
GFW	Global Forest Watch
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
IEA	International Energy Agency
IFL	Intact Forest Landscape
IPCC	Intergovernmental Panel on Climate Change
Kg	kilogram
kWh	kilowatt-hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^3	cubic meter
MJ	Megajoule
MMCF	Manmade Cellulose Fibers
MSI	Materials Sustainability Index
N2O	Nitrous oxide
NaOH	Caustic soda or sodium hydroxide
NMMO	N-methylmorpholine-N-oxide
NOx	Nitrogen oxides
PEF	Product Environment Footprint
PEFC	Programme for the Endorsement of Forest Certification
SAC	Sustainable Apparel Coalition
TCF	Total Chlorine Free
UNEP	United Nations Environmental Programme
UNFCCC	United National Framework Convention on Climate Change
USA	United States of America
VSF	Viscose Staple Fibers

1. Executive Summary

This report summarizes the meta-analysis of 14 existing LCA reports on MMCF and research including modeling parameters used to develop the LCA data, analysis of the main contributors to climate impacts, results of the LCA, and highlighting of key findings, with a goal to identify those key processes which contribute to lower carbon intensive raw materials for the fashion industry.

MMCF production involves extraction of cellulose from different sources of raw material such as wood, waste textiles or other plant-based materials (e.g., cotton linters, bagasse), using different technologies. The report focuses on four key processes driving climate impacts – feedstock sourcing (pulpwood, cotton linters, recycled textiles), dissolving pulp production, MMCF production, and recycling processes (applicable to recycled pulp production).

The key drivers of the climate profile of MMCF production are:

- Land use management, including feedstock harvest Land management choices can influence (reduce, maintain, or increase) the amount of carbon stored in land systems. Carbon dioxide emissions from land use and land use change are a dominant contributor to the greenhouse gas profile of MMCF. However, use of non-wood sources including waste textile scraps and agricultural wastes, eliminates the need to procure virgin wood and can under suitable conditions drive lower impacts to climate. Furthermore, depending on the location and factoring in the avoidance of areas where biogenic carbon is high, use of wood from sustainably managed forests and plantations has some potential to minimize greenhouse gas impacts. Data from existing MMCF LCAs indicate that climate impacts are highly variable, depending on the region and source of MMCF. It is critical to include the greenhouse gas fluxes from land use and land use change activities linked to feedstock harvest.

- Dissolving pulp production

  Dissolving pulp (DP) is the main feedstock used for producing regenerated cellulosic fibers (MMCF). DP mills are energy intensive operations. The environmental performance of a DP mill is influenced by the processing efficiencies in the energy generation plant and the DP production line (chemical and resource optimization), and the selection of pulping and bleaching technologies. Additionally, the type of wood used for pulping may influence the yield, the applied processes and techniques, and the process efficiency.

- Operations at MMCF mills

  Process energy requirements and energy (fuel) mix for pulp dissolution process to prepare MMCF dope solution and impacts associated with caustic soda production are the key factors influencing MMCF production at the MMCF mill. Greenhouse gas emissions are driven by the source of energy used at the mill. Non-integrated mills may either generate steam on-site and/or purchase electricity from the grid. The grid mix of a region can influence the greenhouse gas profile of MMCF mills. Existing LCA studies show that MMCF mills can have higher climate impacts associated with MMCF production due to a coal dominated energy grid mix and heat generation. Integrated pulp and MMCF mills are more energy efficient compared to non-integrated pulp mills. Caustic soda, the main chemical input required for dissolving pulp to regenerate fiber, is one of the main contributors to climate impacts at the MMCF mill and best practice is to produce caustic soda using mercury-free technology such as membrane cell technique to mitigate these emissions. Integrated pulp and fiber production is more energy efficient and has the potential to reduce overall energy use.

The existing LCA research conducted on MMCF production indicates widely variable impacts associated with MMCF sourcing, resulting not only from differences in material feedstocks, but also the region where the fibers originate, the land use and land management practices involved in raw material feedstock extraction, the location of the supply chain operations and the type of mill technology being used, including internal processes at the facilities. These may include recovery of heat chemicals which may reduce environmental impacts.
Most of the current LCA data on MMCF are aggregated

datasets, and the LCAs were not sufficiently transparent to decipher the drivers of MMCF impacts on a process-level. Lack of data on the specific pulp mix/ tree species made it challenging to identify the key contributors to dissolving pulp production. The inconsistencies in climate accounting methodology, data sources, time period of data collection, modeling choices and exclusion of soil carbon fluxes makes it inappropriate to compare LCA results from different LCA studies.

The following provides general guidance for selecting low carbon MMCF.

- The greenhouse gas profile of MMCF is heavily influenced by the type of feedstock and location of feedstock production. The following identifies the top three low carbon sources of MMCF (ranked from lowest to highest source of greenhouse gases). Note that the current list excludes acetate from the comparison due to limited access to LCA data.
    1. Lyocell from low-carbon wood pulp or optimized recycled pulp
    2. Viscose from low-carbon wood pulp or optimized recycled pulp
    3. Modal from low-carbon wood pulp or optimized recycled pulp
- The use of low carbon DP production practices such as operating DP mills as biorefineries, improving pulp yield and optimizing bleach chemical dosage can help in decreasing the greenhouse gas impacts of this stage in the manufacturing process.
- Operating MMCF mills with renewable electricity and heat, integrated pulp fiber mills and deploying closed loop process systems for viscose and modal can influence the greenhouse gas emissions associated with MMCF production.

Based on gate-to-gate MMCF mill energy and chemical input consumption data, it can be concluded that lyocell technology is lower in climate impacts, followed by viscose and modal. Lyocell fiber is a lower carbon MMCF production method and when produced using low-carbon wood pulp or optimized recycled pulp and low carbon energy sources, it has the potential to be the most favorable option for sourcing low carbon MMCF. Recycled pulp feedstock is an emerging development and companies are investing in recycling technologies.

2.

Introduction

The Raw Materials Working Group, convened by the UN Fashion Industry Charter for Climate Action (FICCA), is developing a roadmap for reducing the GHG emissions related to raw material extraction, production and processing, which for some companies can be the most carbon-intensive part of the fashion value chain. The roadmap started by covering the most used materials (cotton and polyester) and will progress to looking at some of the highest impact materials used in the fashion industry to allow signatories to identify the necessary actions to reduce GHG emissions in line with a 1.5°C target pathway.[4] The roadmap will provide guidance on ways to reduce the GHG impact within a single fiber type only, and does not attempt to compare across fiber types and comparisons should not be made between regions for sourcing fibers. For example, using recycled polyester instead of virgin polyester, and climate beneficial farming methods. The focus is on identifying areas to improve over time on a regional basis for different fiber types rather than comparing between regions for sourcing purposes.

The Phase I focus materials are cotton, polyester, and MMCF[5].[6] According to the Textile Exchange's Preferred Fiber & Materials Market Report 2019, cotton, polyester and man-made cellulosic fibers made up over 80% of the global fiber market in 2018. Materials for future consideration will likely include wool, leather, nylon, polyurethane, and silk. The Phase I report is split into two parts: PART I covered cotton and polyester[7] and PART II covers MMCF (this study).

For the purpose of this roadmap, the Working Group has defined the scope of raw material production to start with the cultivation or extraction of a raw material (Tier 4) through to raw material processing and fiber creation (Tier 3). For example, for MMCF this includes feedstock extraction (e.g. pulpwood, agricultural waste, recycled textiles, etc.), dissolving pulp production and fiber production.

All raw materials come with a carbon footprint and we acknowledge that raw materials have significant environmental impacts. Estimates on raw materials range from 15%[8] (as cited in a report released by Quantis in 2018, however this report did not include any animal fibers or leather) to 65%[9] (as reported in Kering's 2019 Environmental Profit and Loss) of a fashion companies' GHG emissions (the percentage will vary based on the types of materials used).

Measuring the footprint of raw materials is complicated. The contributing factors that should be included are all of the processes used to grow or manufacture raw materials as well as the location in which this happens. One of the most used methodologies to measure impacts is a Life Cycle Assessment (LCA). Although these scientific studies have produced credible and industry recognized results, they have their own challenges.

LCAs are either calculated using industry averages that are not applicable to specific regions or factory setting or they are created using geographic or manufacturing-specific data that cannot be used easily for comparison. LCA practitioners must review the following factors before determining the comparability of the environmental profile of multiple products:

- Scope of assessment and function of the products should be the same
- Inclusions and exclusions of the processes should be consistent across all the products
- Time period of data collection should match for the products. When the LCA was produced can also influence the outcome.
- Modeling assumptions should be consistent across all the products
- Consistent databases/data sources, LCA software, and metrics should be used for modeling processes

To manage these challenges, the Raw Materials Working Group has engaged SCS Global Services, experts in the field of LCA development and research as well as collaborated with industry organizations who have pertinent tools and information.

This report summarizes the meta-analysis of 14 existing LCA reports on MMCF and research including modeling parameters used to develop the LCA data, analysis of the main contributors to climate impacts, results of the LCA, and highlighting of key findings, with a goal to identify those key processes which contribute to lower carbon intensive raw materials for the fashion industry. The objective of this report is to:

- Identify low carbon sources of MMCF based on current

knowledge and findings from existing LCA research and analysis
- Provide detailed background information (to the extent available) on MMCF production on a country/regional level and map out regional differences in climate impacts for different types of MMCF
- Outline the key LCA modeling parameters, data gaps and inconsistencies in the existing LCA landscape, and identify areas of improvement to calculate climate impacts on a more consistent basis
- Provide insights into the implications of various feedstock sources used for dissolving pulp production, across diverse geographies (subject to data availability)
- Provide a foundation for stakeholders to define a harmonized approach for climate accounting of MMCF

3.
Scope

3.1
Goal and Scope of Assessment

The primary goal of the study is to identify low carbon sources of manmade cellulosic (MMC) fibers, by geographic region (subject to data availability) based on a literature review of existing LCA studies and research. Table 1 below outlines the scope of assessment for MMCF.

Table 1.

Scope of literature review for MMCF.

Scope	Manmade Cellulose Fibers (MMCF)
Raw material Sub-Type/Sources	• Viscose • Modal • Acetate • Lyocell
Geographic regions under consideration	India, China, Indonesia, Austria, Germany, USA
System boundary/Scope	Cradle-to-fiber gate (staple fibers)
Climate Impact Results reported	Kilogram CO_2e per metric ton of MMCF staple fiber

2.2
System Boundary

The system boundary of the current assessment is illustrated for MMCF.

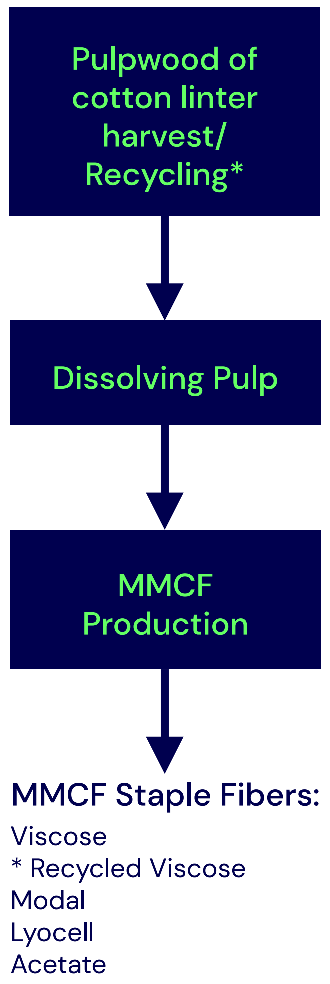


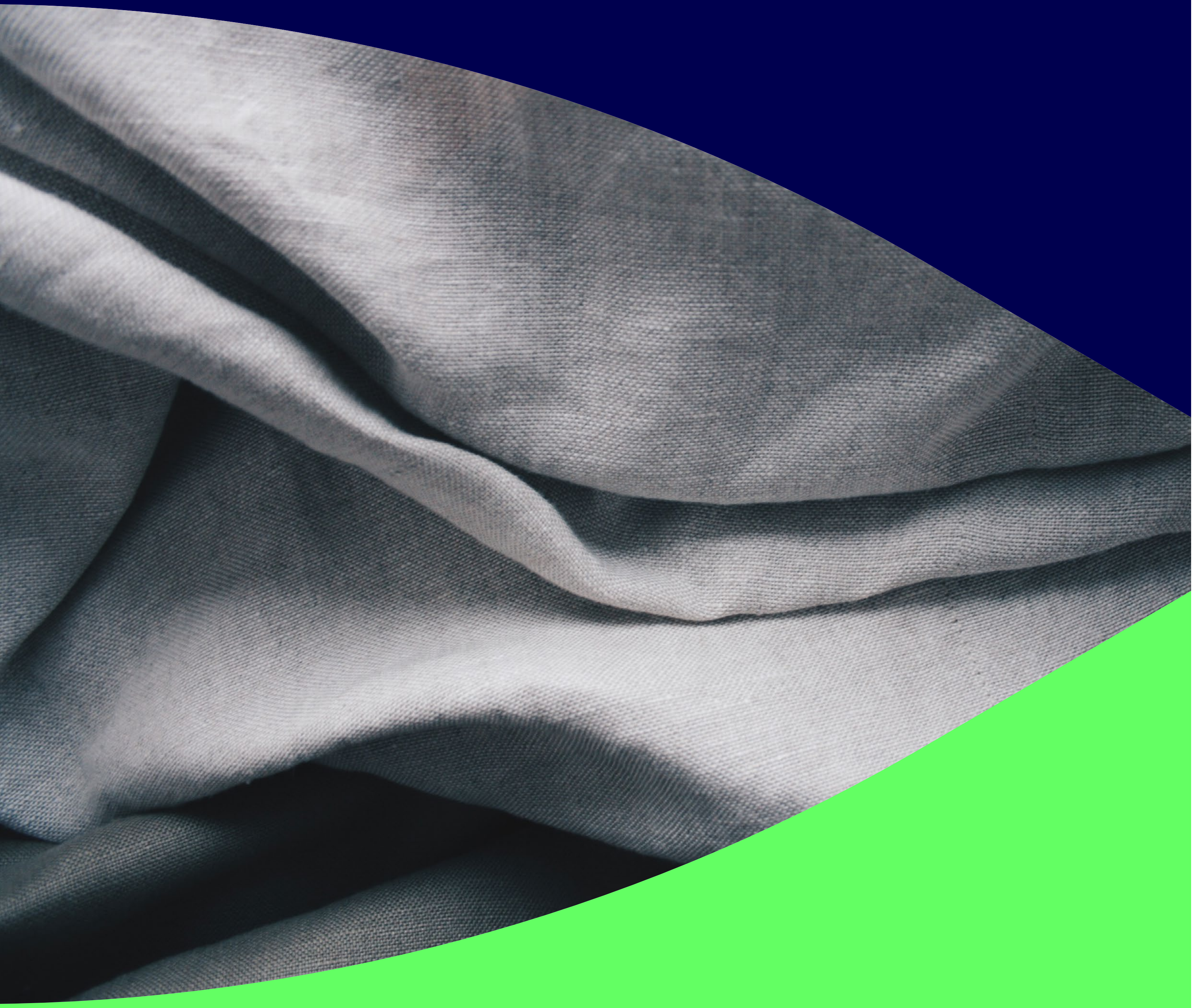
Figure 1.
System boundary of assessment for different types of MMC fibers.

2.3
Review

The UN FICCA Raw Materials Working Group provided access to data and input on the report. In addition, the meta-analysis of the MMCF LCAs was external reviewed by subject matter experts.[10] The reviewers for the MMCF meta-analysis include:

- Amanda Carr, Director of Strategic Initiatives, Canopy
- Neva Murtha, Senior Corporate Campaigner, Canopy

4. Collected Information



4.1 Meta-Analysis of LCA Studies

This section provides an overview of the scope of the literature survey conducted for MMCF. Table 2 below outlines the criteria used to review existing LCA research and reports on manmade cellulosics and retrieve climate data to provide informed conclusions and guidance to the industry on sourcing raw materials.

Table 2.

Scope of literature review for cotton, polyester and MMCF.

Review Criteria	Manmade Cellulose Fibers (MMCF)
Raw material Sub-Type/Sources	• Viscose • Modal • Acetate • Lyocell
Geographic regions under consideration	India, China, Indonesia, Austria, Germany, USA
System boundary/Scope	Cradle-to-fiber gate (staple fibers)
Climate Impact Results reported	Kilogram CO_2e per metric ton of MMCF staple fiber
Key processes driving climate impacts	• Feedstock sourcing (pulpwood, cotton linters, recycled textiles) • Dissolving pulp production • MMCF production • Recycling process (only applicable to recycled pulp production) (Refer to Section 3.4.1)
Factors influencing variability in climate impacts across various geographic regions	• Feedstock for dissolving pulp (e.g., hardwood, softwood, bamboo) • Tree species • Region of pulpwood harvest, land use and land management activities, forest type • Feedstock yield • Pulping technology (sulfite, Kraft, etc.) • Process energy mix • Forest certifications • Bleaching technology (ECF, TCF) • Fiber processing technology (viscose, lyocell, modal) • MMCF spin bath composition • Sulfur recovery technology • Chemical consumption and production • Soil carbon fluxes (Refer to Section 3.4.2 for more details)

Review Criteria	Manmade Cellulose Fibers (MMCF)
Calculation Methodology	IPCC 2007, IPCC 2013 (GWP20), IPCC 2013 (GWP100), CML, Recipe, ILCD, etc.
Primary and Secondary Data	Proportion of primary and secondary data used for modeling and data sources used for filling data gaps
Data collection period	Review data collection period of primary data for each process and fiber type
LCA software	SimaPro, Gabi, openLCA, Milca, RangeLCA, etc.
LCA databases used for modeling	Ecoinvent, GaBi, IDEMAT, USLCI, Plastics Europe, etc.
Key modeling assumptions/data gaps/inconsistencies (Refer to Section 4 for more details)	• Allocation of by-products at pulp and fiber mills • Modeling GHG fluxes from land use and land use change • Credits for biogenic carbon stored in pulp and by-products sold • Modeling soil carbon fluxes
Exclusions	Identify key processes and factors excluded from the model
Limitations	Note limitation of models and data sources applied in the studies (Refer to Section 4)

4.2

Manmade Cellulosic Fibers (MMCF)

Manmade Cellulosic (MMC) fibers accounted for approximately 6.4% of the global fiber market share in 2019, ranking third in terms of volume of global fiber production (after synthetics and cotton)[11] . The market share is expected to grow annually at the rate of ~5% over the next five years and is projected to account for nearly 8.5% of the global fiber market share by 2030[12]. MMCF production involves extraction of cellulose from different sources of raw material such as wood, waste textiles or other plant-based materials (e.g. cotton linters, bagasse), using different technologies. The current scope of the study includes viscose, modal, lyocell and acetate production technologies.

Viscose is the single largest type of MMCF used in the fashion industry, with a market share of 79% of the global MMCF market in 2019, followed by acetate (13% of global MMCF market), lyocell (4.3% of global MMCF market and modal (2.8% of global MMCF market). China is leading the MMCF market, with 66% of global MMCF production, followed by Europe (11.67%) and India (10.42%)[13]. The MMCF market is highly concentrated with ten producers supplying approximately 85.9% of the global MMCF production[14]. Dissolving pulp (DP) is the starting raw material used for producing regenerated cellulosic fibers (MMCF). According to FAO, in 2019, global industrial roundwood removals comprising pulpwood, sawlogs and veneer logs amounted to 2,021 million m3, of which less than 3% is estimated to be used for dissolving pulp production[15].

There are at least 55 active dissolving pulp mills operating worldwide and Figure 2 illustrates the key dissolving pulp producing countries.

Figure 2.

Dissolving wood pulp producing countries in 2019.
(Adapted from FAO)

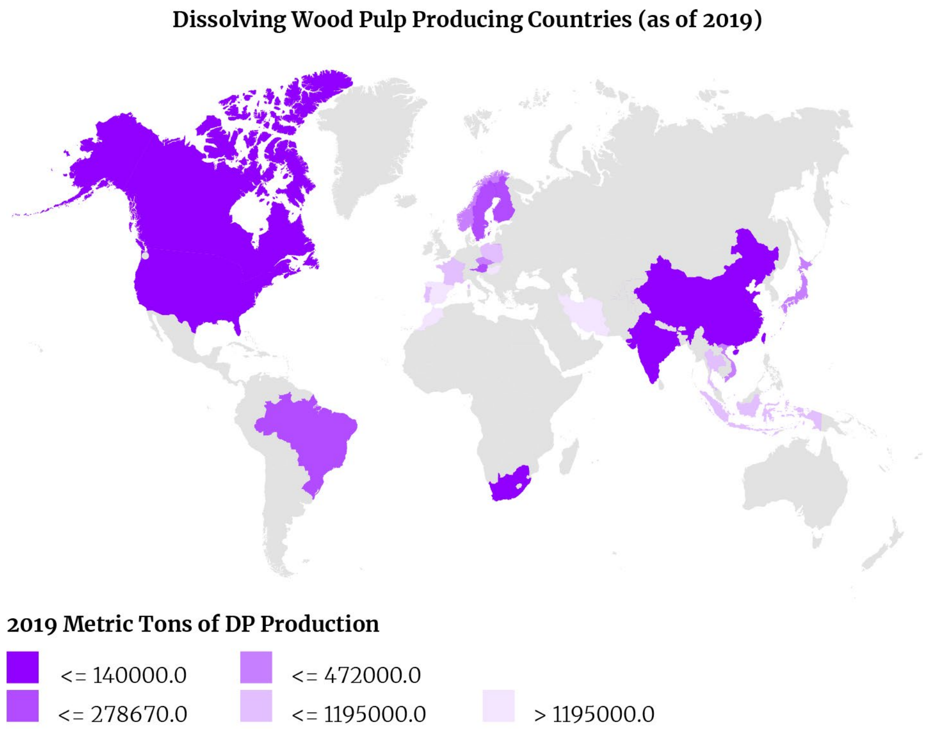


Table 3.

Scope of assessment for MMCF, by type and country (VSF: Viscose Staple Fiber; MMCF: Manmade Cellulose Fiber)

Sources of MMCF	Dissolving Pulp Production Regions	MMCF Production Regions
VSF from managed temperate forests	Europe, Canada, USA	India, China, Indonesia, Austria, Germany, USA
VSF from boreal forests	Canada	China
VSF from plantations converted from intact forest landscapes*	Indonesia	Indonesia, China
VSF from plantations established on degraded lands or other areas**	Indonesia, South Africa, Brazil	India, China, Indonesia
VSF from bamboo plantation	China	China
VSF from cotton linters	China, USA	China, USA
VSF from recycled pulp	Sweden, Netherlands, USA	China, Austria, Germany
Lyocell	Europe	China, Austria, USA
Modal	Europe, Canada, South Africa, USA	India, China, Austria
Acetate	USA, South Africa and Canada	USA

***Plantations converted from intact forest landscapes considers the conversion of primary forests within intact forest landscapes (IFL) defined by http://intactforests.org/ to establish wood fiber plantations. IFL identifies unfragmented forest landscapes with high conservation value critical for stabilizing terrestrial carbon storage, maintaining biodiversity and which does not exhibit any alterations by human activities.**

****Plantations established on land which is degraded or does not cover any primary forest.**

4.2.1 MMCF Results

The existing LCA research conducted on MMCF production indicates widely variable impacts associated with MMCF sourcing, resulting not only from differences in material feedstocks, but also the region where the fibers originate, the land use and land management practices involved in raw material feedstock extraction, the location of the supply chain operations and the type of mill technology being used, including internal processes at the facilities. These may include recovery of heat chemicals which may reduce environmental impacts.

Most of the current LCA data on MMCF are aggregated datasets the LCAs were not sufficiently transparent to decipher the drivers of MMCF impacts on a process-level. Lack of data on the specific pulp mix/tree species made it challenging to identify the key contributors to dissolving pulp production. The inconsistencies in climate accounting methodology, data sources, time period of data collection, modeling choices and exclusion of soil carbon fluxes makes it inappropriate to to compare LCA results from different LCA studies. Based on a meta-analysis of 14 LCA studies (refer to Table 16 in the Annex for a detailed list of studies), an attempt is made to showcase the regional variability of LCA results for MMCF in Figure 3 through Figure 5. Regional variability is not a measure of impact, but demonstrates a factor related to the reliability of modeling different MMCF products across regions, so for example Figure 3 does not indicate Modal produced globally has a higher impact than Modal produced in India. The values in Figure 3 are unitless, and are calculated as the ratio of GHG result to the lowest value for each fiber type assessed (VSF, lyocell, acetate and modal).[16]

Figure 3.

This chart shows the regional variability of four types of MMCF production (VSF, lyocell, acetate and modal) in China, India, Austria, USA and Germany. Note that the X-axis shows the relative magnitude of variation and does not represent the GHG impact values. Regional variability is not a measure of impact, but demonstrates a factor related to the variability of modeling different MMCF products across regions, so for example this figure does not indicate Modal produced globally has a higher impact than Modal produced in India. It excludes product biogenic carbon credits and excludes GHG fluxes from land use and land use change activities linked to forestry operations. Neglecting climate impacts from land use and land use change could potentially have some implications on identifying and prioritizing GHG mitigation measures in the forestry sector.

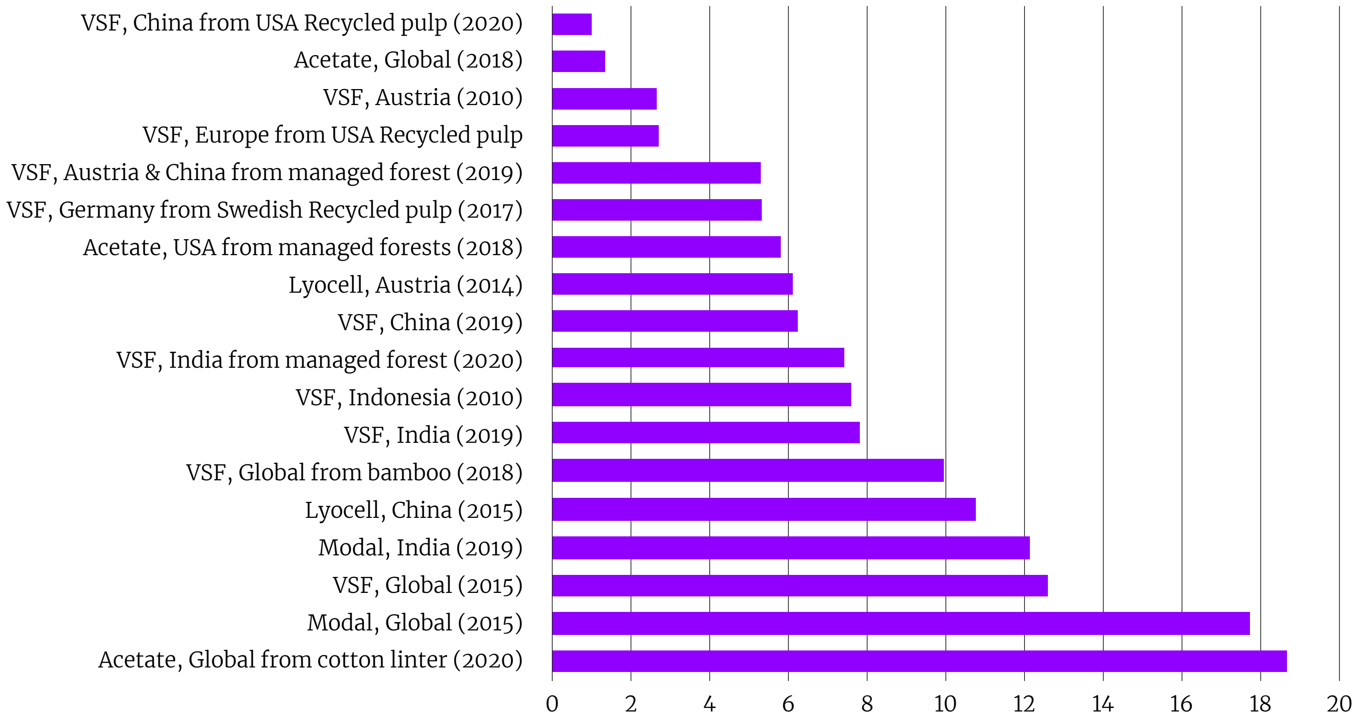


Figure 4.

Higg MSI scores for lyocell, viscose staple fibre, modal and acetate, illustrating the relative greenhouse gas emissions (GHG) associated with the fibre and location of production (where indicated; and excluding product biogenic carbon credits and GHG fluxes from land use and land use change activities linked to forestry operation). Higg Co.v3.0 (August 2020); https://apparelcoalition.org/higg-product-tools/

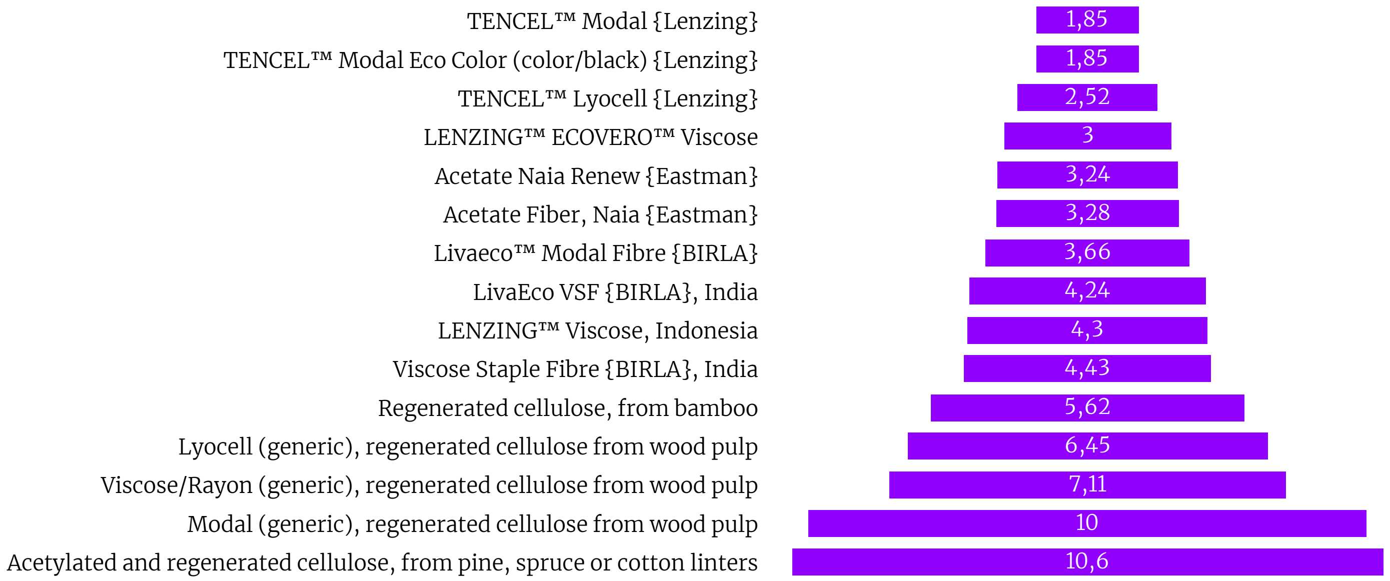
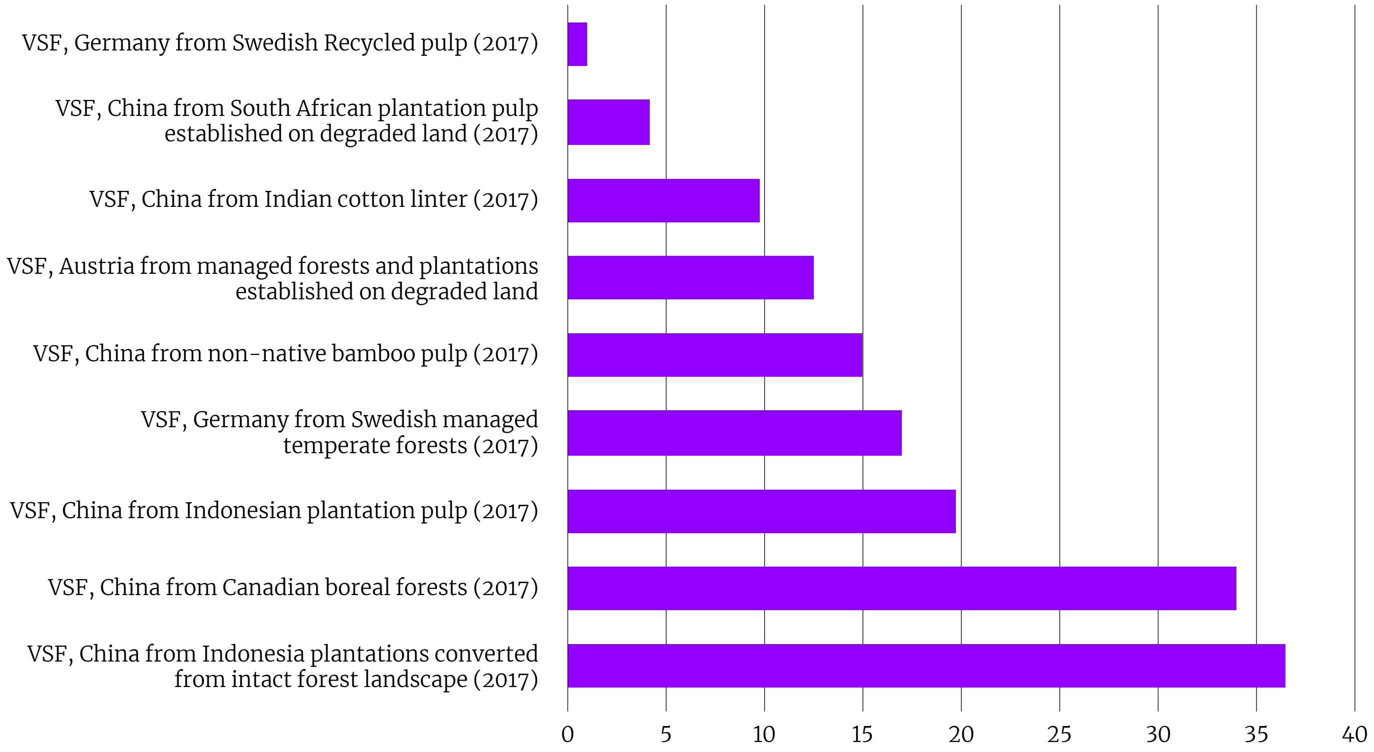


Figure 5.

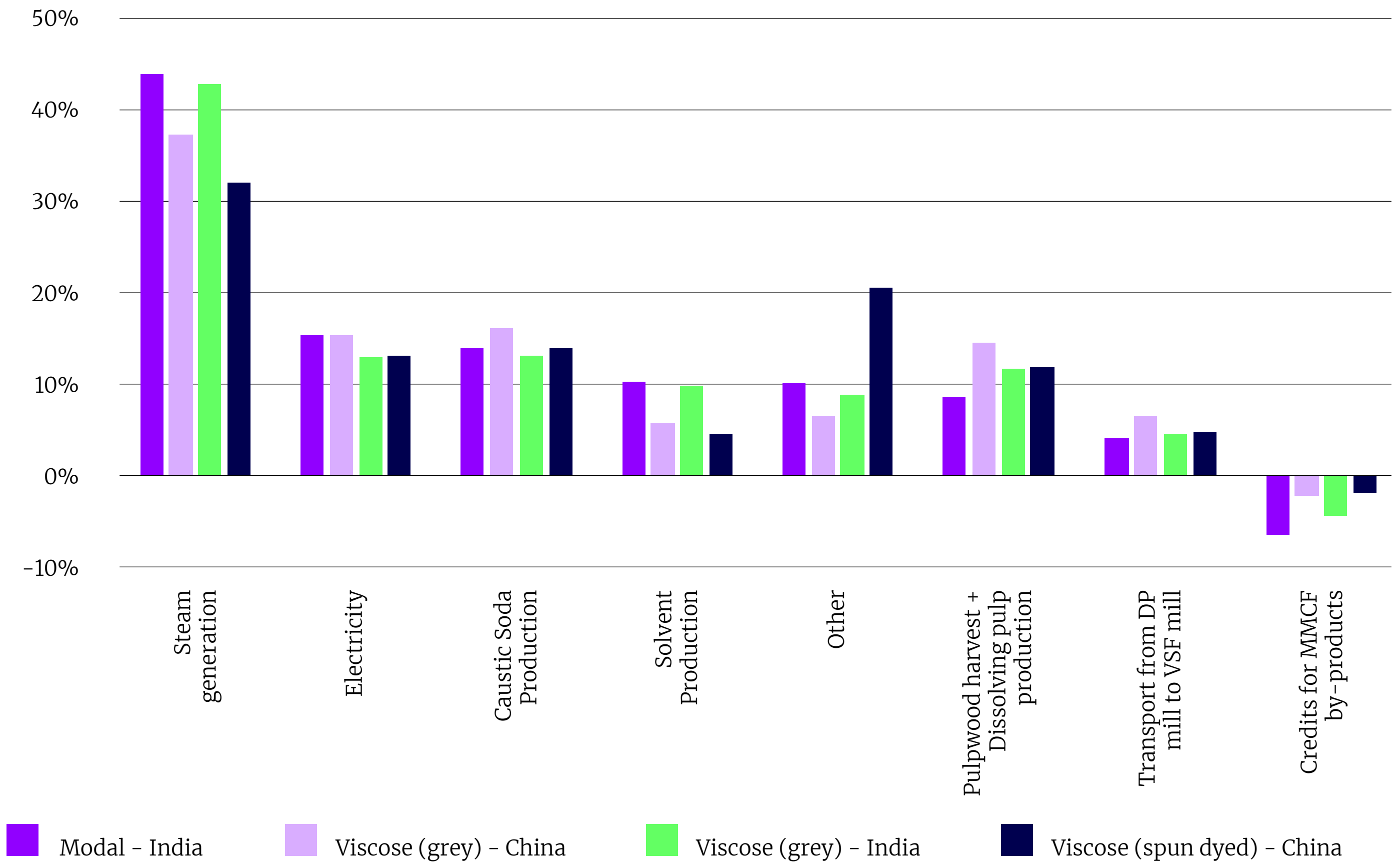
Regional variability of sourcing feedstock from nine regions for viscose staple fibre (VSF) production in China and Europe. The X-axis shows the relative magnitude of variation in emissions and does not represent actual greenhouse gas emissions.



This report builds upon the data retrieved from existing LCAs and aims to provide a foundation for modeling MMCF on a regional level, by MMCF type. Figure 6 illustrates the process-level breakdown of viscose and modal, based on data availability.

Figure 6.

This chart highlights the key process contributors to Viscose and Modal Production based on data shared by MMCF manufacturers (it excludes product biogenic carbon content and foregone forest carbon storage losses). It is evident that modal is more energy intensive compared to viscose production due to higher pulp and chemical input. Steam and electricity used in viscose and modal production are one of the main contributors to GHG emissions. The source of energy has a big influence on the LCA results.



In general, based on review of existing data presented in Figure 3 through Figure 6, the following key hotspots of MMCF production are mapped:

- *Pulpwood harvest*: Land management choices can influence (reduce, maintain, or increase) the amount of carbon stored in land systems. Carbon dioxide emissions from land use and land use change are a dominant contributor to the GHG profile of MMCF. However, use of non-wood sources including waste textile scraps and agricultural wastes, eliminates the need to procure virgin wood and can under suitable conditions drive lower GHG impacts. Furthermore, depending on the location, use of wood from sustainably managed forests and plantations has the potential to minimize GHG impacts. Refer to Section 4.2.1.1 for a detailed matrix comparing the different forest conditions on a country-level.
- *MMCF production*: Process steam and electricity requirements for MMCF dope solution preparation, upstream impacts associated with caustic soda production. Refer to Section 3.2.2.4.

- *Dissolving pulp production*: Process energy requirements for fiberline and pulp drying operations, impacts associated with energy and chemical production bleaching sequence, and upstream impacts associated with caustic soda production.

4.2.1.1 Qualitative Matrix Highlighting Influence of Feedstock Sourcing on the Climate

Choice of the MMCF raw material input is a critical one with overarching effects on life cycle analysis of MMCF. Approximately 85% of the global dissolving pulp is produced from softwood/hardwood pulp so it is vital to investigate further to identify the key regions supplying pulpwood to the MMCF industry, as forestry practices vary by region and can have various implications.

Table 4 examines different feedstock sources of pulp, by region, based on the following publicly available parameters:

- Net forest cover data of country (assessed based on data retrieved from Global Forest Watch)
- Proportion of forest area under independently verified forest management schemes (FSC, PEFC)
- Percent of intact forest cover based on latest available data (assessed based on data retrieved from Global Forest Watch);
- Identify risk of sourcing from Intact Forest Landscapes, old-growth forests of high conservation value and high carbon stocks[17] based on Canopy's ForestMapper tool;
- Identify whether pulpwood harvest is a key driver of forest loss and degradation based on the geospatial analysis of forest maps conducted by WWF; and
- *Net forest GHG flux from land use and land use change*[18]: Global Forest Watch simulated the forest GHG fluxes including gross emissions, gross removals and net GHG flux (difference between emissions and removals) at 30m from 2001-2019. Net forest-related fluxes are shown with two component gross fluxes: gross emissions from land-use change and other forest disturbances and gross removals occurring in undisturbed forests as well as removals from forest regrowth after disturbance.

While assessments should be conducted on a site-specific level to determine the risk of pulpwood sourcing, due to data constraints, a high-level summary of the current global forest resource landscape is presented for relevant countries involved in the MMCF supply chain. Site-specific assessments of carbon stocks from pulpwood harvest sites are generally recommended.

Limitations exist within Global Forest Watch dataset:

On the Intact Forest Cover dataset, Global Forest Watch notes: "Results should be interpreted with caution. The intact forest cover was created through visual interpretation of Landsat images by experts. The map may contain inaccuracies due to limitations in the spatial resolution of the imagery and lack of ancillary information about local land-use practices in some regions".

On the time frame: The GFW data only covers 2001-2020. This time period may exclude degradation occurring prior or post this time including degradation from intact forests.

Two specific regional examples of concerns of applying this global data set are also noted:

For South Africa, Sappi, does not agree with GFW carbon flux map and states that: "1) The GFW data underestimates removals in fast growing plantations. 2) We suggest the alternative use of The South African National Land Cover dataset[19]. 3) With reference to Table 8, the areas (Mha) per province do not align with South African official data sources".

For Europe, one publication noted an error in the Global Forest Watch algorithm resulting in an overestimate of the clearcuts in Europe, as natural disturbances were not properly accounted for.

Table 4.

Qualitative assessment of Climate Impacts from feedstock harvest activities, by MMCF source for key regions. For more details, refer to Section 4.2.2.1.

GENERAL INFORMATION		Data Source: FAO 2020 Global Forest Resource Assessment[20]		Data Source: FAO 2020 Global Forest Resource Assessment [21]			Data Source: Global Forest Watch[22]	Data Source: Canopy ForestMapper	Data Source: WWF Deforestation Front (2021)[23]	Data Source: Global Forest Watch: Forest GHG Fluxes[24]			Net Climate Impact from Land Use and direct Land Use Change
COUNTRY	Primary Feedstock Sources for Dissolving Pulp	Average forest cover change (from 2000-2020)		FSC Certified (%)- as of 2019-2020	PEFC certified (%)- as of 2019-2020	Double Certification (FSC and PEFC)- as of 2019-2020	Intact Forest Cover (as of 2016, % of tree cover)[25]	Canopy ForestMapper: Risk of sourcing from ancient & endangered forests	Is pulpwood forestry a direct driver of deforestation according to WWF?	GHG emissions from land use and other forest disturbances $MtCO_2e$/year (2001-2020)	GHG removals from forest regrowth $MtCO_2e$/year (2001-2020)	Net forest GHG flux= Emissions-Removals $MtCO_2e$/year (2001-2020)	Net climate impact from land use and land use change (LULUC) per hectare per year tCO_2e/ha/year
Austria	Hardwood: beech	0.09%	Increase	586.8 ha[26]	82%	Not available	0%	Some	Not reported, regions in the temperate biome were not included in scope	8.7	-30.0	-21.3	-3.1*
	Recycled textiles	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Brazil	Eucalyptus/Acacia plantations	-0.36%	Decrease	1%	1%	1%	45%	Significant	Cattle ranging and large scale agriculture is the main cause of deforestation in then Brazilian Amazon basin and the Cerrado regions. While large scale logging in the Amazon basin is a cause for forest degradation, the pulpwood plantations have not been identified as a driver of deforestation in this region	184.0	-236.0	-52.0	-20.8
Canada	Hardwood: aspen; Softwood: pine, spruce	-0.01%[27]	Decrease	50,390,040.6 ha	42%	6%	41%	Significant	Not reported, regions in the temperate biome were not included in scope	251.0	-732.0	-481.0	-1.4
China	Bamboo	0.96%	Increase	1,286,996.8 ha	1%	0%	0.77%	Some	Not reported, regions in the temperate biome were not included in scope	222.0	-749.0	-527.0	-5.1
	Cotton Linters			Not applicable	Not applicable	Not applicable		Not applicable	Not reported, regions in the temperate biome were not included in scope	Not applicable	Not applicable	Not applicable	No data
Czech Republic	Hardwood: beech; Softwood: pine, spruce	0.07%	Increase	4%	66%	2%	0%	Some	Not reported, regions in the temperate biome were not included in scope	11.7	-19.9	-8.2	-3.1*

GENERAL INFORMATION		Data Source: FAO 2020 Global Forest Resource Assessment[20]		Data Source: FAO 2020 Global Forest Resource Assessment [21]			Data Source: Global Forest Watch[22]	Data Source: Canopy ForestMapper	Data Source: WWF Deforestation Front (2021)[23]	Data Source: Global Forest Watch: Forest GHG Fluxes[24]			Net Climate Impact from Land Use and direct Land Use Change
COUNTRY	Primary Feedstock Sources for Dissolving Pulp	Average forest cover change (from 2000-2020)		FSC Certified (%)- as of 2019-2020	PEFC certified (%)- as of 2019-2020	Double Certification (FSC and PEFC)- as of 2019-2020	Intact Forest Cover (as of 2016, % of tree cover)[25]	Canopy ForestMapper: Risk of sourcing from ancient & endangered forests	Is pulpwood forestry a direct driver of deforestation according to WWF?	GHG emissions from land use and other forest disturbances MtCO$_2$e/year (2001-2020)	GHG removals from forest regrowth MtCO$_2$e/year (2001-2020)	Net forest GHG flux= Emissions-Removals MtCO$_2$e/year (2001-2020)	Net climate impact from land use and land use change (LULUC) per hectare per year tCO$_2$e/ha/year
Finland	Softwood: spruce, pine	0.01%	Increase	11%	90%	10%	2.60%	Some	Not reported, regions in the temperate biome were not included in scope	40.4	-76.8	-36.4	-3.1*
Germany	Hardwood: beech, oak; Softwood: pine, spruce	0.01%	Increase	13%	67%	10%	0%	None	Not reported, regions in the temperate biome were not included in scope	24.7	-100.0	-75.3	-3.1*
Indonesia	Eucalyptus/Acacia plantations converted from intact forest landscapes	-0.60%	Decrease	Not applicable	4%	Not applicable	19%	Significant	WWF identified deforestation from 2006-2009 in Sumatra and Borneo where a fraction of the primary forests were cleared to establish pulpwood plantations. The deforestation peaked in 2015 but has decreased since 2015 and is on a downward trend.	40.9	-17.3	23.6	98.3
	Eucalyptus/ Acacia plantations on degraded land			3%		0%	No data	Some	Not reported, regions in the temperate biome were not included in scope	164.0	-77.6	86.8	28.2
Latvia	Hardwood: aspen, birch ; Softwood: pine, spruce	0.15%	Increase	33%	51%	25%	0%	None	Not reported, regions in the temperate biome were not included in scope	11.9	-23.7	-11.8	-3.1*
Norway	Softwood: spruce, pine	0.05%	Increase	0%	61%	4%	0.45%	Some	Not reported, regions in the temperate biome were not included in scope	9.6	-52.8	-43.2	-3.1*
Poland	Hardwood: beech, birch, oak; Softwood: pine	0.17%	Increase	74%	76%	71%	0%	None	Not reported, regions in the temperate biome were not included in scope	21.8	-84.5	-62.7	-3.1*

GENERAL INFORMATION		Data Source: FAO 2020 Global Forest Resource Assessment[20]		Data Source: FAO 2020 Global Forest Resource Assessment [21]			Data Source: Global Forest Watch[22]	Data Source: Canopy ForestMapper	Data Source: WWF Deforestation Front (2021)[23]	Data Source: Global Forest Watch: Forest GHG Fluxes[24]			Net Climate Impact from Land Use and direct Land Use Change
COUNTRY	Primary Feedstock Sources for Dissolving Pulp	Average forest cover change (from 2000-2020)		FSC Certified (%)- as of 2019-2020	PEFC certified (%)- as of 2019-2020	Double Certification (FSC and PEFC)- as of 2019-2020	Intact Forest Cover (as of 2016, % of tree cover)[25]	Canopy ForestMapper: Risk of sourcing from ancient & endangered forests	Is pulpwood forestry a direct driver of deforestation according to WWF?	GHG emissions from land use and other forest disturbances $MtCO_2e$/year (2001-2020)	GHG removals from forest regrowth $MtCO_2e$/year (2001-2020)	Net forest GHG flux= Emissions-Removals $MtCO_2e$/year (2001-2020)	Net climate impact from land use and land use change (LULUC) per hectare per year tCO_2e/ha/year
Russia	Hardwood: birch, larch; Softwood: pine	0.01%	Increase	6%	4%	2%	22%	Significant	Not reported, regions in the temperate biome were not included in scope	659.0	-2420.0	-1761.0	-0.7
Slovakia	Hardwood: beech; Softwood: spruce	0.05%	Increase	11%	63%	7%	0%	None	Not reported, regions in the temperate biome were not included in scope	5.5	-21.2	-15.7	-3.1*
Slovenia	Hardwood: beech; Softwood: spruce	-0.10%	Decrease	21%	24%	20%	0%	Some	Not reported, regions in the temperate biome were not included in scope	1.3	-12.9	-11.6	-3.1*
South Africa	Eucalyptus/Acacia plantations	-0.21%	Decrease	80%	0%	0%	0%	None	Not reported	36.8	-28.5	8.3	3.8
Sweden	Softwood: spruce, pine	0.01%	Increase	42%	57%	44%	2.70%	Some	Not reported, regions in the temperate biome were not included in scope	58.4	-137.0	-78.6	-3.1*
	Recycled Textiles	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
USA	Hardwood: aspen, maple, oak; Softwood: pine	0.01%	Increase	0%	9%	3%	12%	Some	Not reported, regions in the temperate biome were not included in scope	814.0	-1530.0	-716.0	-3.1*
	Recycled textiles	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable

*NOTE on Net climate impact from land use and land use change per hectare per year: It was not possible to extract the GHG flux per area for all the countries due to limitations of the Global Forest Watch analysis feature. Currently, Global Forest Watch filters the GHG flux data for pulpwood plantations in Indonesia, Brazil, South Africa and logging concessions in Canada. Average GHG fluxes for countries in Europe were retrieved from values reported for temperate forests in Table 1 of Harris, Nancy L., et al. "Global maps of twenty-first century forest carbon fluxes." Nature Climate Change 11.3 (2021): 234-240.

- The current LCA landscape assumes carbon neutrality for pulpwood forestry operations, thereby ignoring the biogenic emissions/ removals from land use and land use change. With the advent of publicly available satellite data portals such as Global Forest Watch, it is possible to estimate GHG fluxes from land use and land use change consistently for different regions.
- Overall, recycled pulp has the potential to be the lowest carbon MMCF source if manufactured in regions with clean energy mix. Recycled pulp does not contribute to any GHG emissions from land use and land use change during pulpwood forestry operations. For the feedstock harvest life cycle stage, native bamboo plantations, cotton linter pulp, managed forests in USA and Europe are potential sources of lower carbon MMCF. Plantation forests established on degraded lands prove beneficial from not only a productivity standpoint (plantations have higher yields compared to managed natural/semi-natural forests in Europe and USA), but also increasing the carbon stocks over time, thereby resulting in net GHG removals and are potential sources of low carbon MMCF. On the other hand, plantations established by converting intact forest landscapes forgoes the opportunity for carbon storage (i.e., foregone carbon sequestration), as degradation processes or land conversion reduces carbon uptake from the atmosphere and contributes to global warming.
- The Global Forest Watch data reported Table 4 shows that between 2001-2020,[28] forests in nearly all countries result in net GHG removals (ranging from -3.1 to -20 tCO_2e/hectare per year), that is, gross carbon removals from established and regrowing forests exceeded gross emissions from land-use change and other forest disturbances with the exception of Indonesia and South Africa, which are net emitters. Between 2001 and 2020, plantations in wood fiber concessions in Indonesia emitted 164 $MtCO_2e$/year (including peat drainage and burning), and removed -77.6 $MtCO_2e$/year. This represents a net carbon flux of 86.8 $MtCO_2e$/year[29], which translates to nearly 28 tCO_2e/hectare/year and almost thrice the impact (98 tCO_2e/hectare/year) for plantations established by converting intact forest landscape.
- Forest cover in managed forests in Europe and USA have increased and maintained the carbon stocks over a 20-year period. This is due to sustainable forest management practices in these regions. In contrast, countries such as Indonesia, Brazil and Canada, have seen a net decline in forest cover, resulting in decrease of carbon stocks. Brazil, Canada, Russia and Indonesia are countries with significant proportion of intact and primary forest landscapes and the location of these intact forests present a significant sourcing risk, as per Canopy's ForestMapper Tool for the MMCF supply chain. This finding is similar to the latest IPCC report[30] publication which states that boreal forests and tropical forests are particularly at risk of climate change-induced degradation and forest loss.
- According to WWF, logging has generally declined as a primary driver of deforestation and forest degradation and loss but it remains a key driver is some regions, such as Canada. Pulpwood plantation has been one of the major drivers of deforestation in Sumatra (Indonesia) and Borneo region (Malaysia) in Southeast Asia until 2015. Other drivers of deforestation include land conversion for palm oil production. Out of 14.3 million hectares of tropical forest area in Sumatra, 14.4% of forest area (1.4 million hectares) is estimated to be fragmented (between 2000-2018), 25.2% of forest area (2.5 million hectares of forest cover) was lost between 2004-2014 and ~46.4% of forest area (3.6 Million hectares) of core primary forest remains intact in Sumatra, Indonesia[31]. Actions taken by the Indonesian government, private sector and NGOs to protect the remaining intact forests and peatlands by placing a moratorium on conversion of primary forest and peatlands in fiber concessions has contributed to the rate of decline in forest loss in 2017-2019. While there is a downward trend in rate of forest loss in Indonesia, it is necessary to maintain this trend by strengthening existing policies and taking more positive actions towards forest restoration.
- From 2007-2016, it is estimated that intact forests absorbed approximately 28% of the anthropogenic carbon dioxide(CO_2) emissions, of which 50% of CO_2 was absorbed by intact tropical forests. An analysis of global distribution of wood removals by Global Forest Watch (GFW) between 2001 and 2019 indicates that 72% of gross removals were concentrated in older (>20 years) secondary natural and seminatural forests, 12% in tropical primary forests, 10% in plantations, 3.5% in young (<20 years) forest regrowth, 1.3% in mangroves and 0.34% in boreal and temperate intact forest landscapes[32]. The GFW analysis reveals that 27% of the global net forest carbon sink falls within protected areas[33].

A forest loss assessment by WWF between 2001-2015 attributes 27% forest loss to expansion of agricultural commodities, 26% forest to forestry, 24% forest loss to shifting agriculture and 23% to wildfires[34]. The rate of species decline is on the rise and is closely linked to intactness of forest ecosystems. Records from 21 countries, found that the population of native species reduced by a considerable 20% since 1900, while the numbers of invasive species increased to around 70% after 1970[35]. In the latest IPCC report projections indicate that if global temperatures rise to 1.50C, out of 105,000 species studied, 6% of insects, 8% of plants and 4% of vertebrates are likely to lose nearly 50% of their habitat and geographic range. A 20C rise in global temperatures is likely to impact the habitat range of 18% of insects, 16% of plants and 8% of vertebrates[36].

The goals of the Paris Climate Accord with regard to limiting global warming to 1.50C to 20C cannot be met by avoiding deforestation alone. The United Nations emphasizes that forests are the largest terrestrial carbon sinks and removal of 100 to 1000 gigatons of carbon dioxide[37] in the twenty first century by forest restoration and increasing forest cover is not only a cost effect method[38], but also has tremendous potential to limit global warming to 1.50C above pre-industrial levels[39].

Section 4.2.2.1 provides a detailed description of the current status of global forest resources and the importance of including GHG fluxes from land use and land use change activities in the feedstock harvest stage.

Section 4.2.1.2 presents a qualitative matrix to identify low carbon production MMCF production method by reviewing the key production parameters for four types of MMCF including viscose, modal, lyocell and acetate.

4.2.1.2 Qualitative Matrix Highlighting the Influence of MMCF production parameters on the Climate

It is to be noted that due to lack of process-level data on acetate fibers, acetate fiber production is not included in this comparison. Overall, lyocell production method is a low carbon MMCF production method (comparison excludes acetate fibers), followed by viscose and modal production methods. Caustic soda (sodium hydroxide) production is one of the largest drivers to GHG impacts of MMCF mills, so replacing caustic soda and carbon disulfide with NMMO solvent (with a very high recovery rate) lowers the GHG profile of lyocell fiber production. However, it is to be noted that current LCAs lack primary data on NMMO solvent production so data quality on lyocell production needs to be improved. Note that the recovery rate of NMMO solvent is very high so the amount of NMMO required for the process is low and the low data quality is not expected to affect the results. Integrated pulp and fiber mills are more energy efficient and likely to use energy generated from pulping operations, driving lower fossil fuel demand and energy demand from the energy grid. The share of fossil fuel for heat in the pulp mills and MMCF plants and for the fuel and/or electric grid mix of a region can influence the GHG profile of an MMCF mills. Existing LCA studies show that MMCF mills located in Asia (China, India, Indonesia, etc.) can have higher climate impacts associated with MMCF production compared to European MMCF mills due to a coal dominated heat generation and energy grid mix.

Table 5.

Qualitative assessment of Climate Impacts of MMCF production, by type of MMCF. **Table 15** in Section 4.2.2.4 describes the MMCF production parameters in more detail.

LEGEND			
INPUT REQUIREMENTS			
+	++	+++	++++
Low	Low-Medium	Medium	High
Low GHG Impact		Low-Medium GHG Impact	High GHG Impact

MMCF production parameters	Viscose Staple Fiber	Lyocell	Modal	Acetate*
Production Method	Xanthation	Direct Dissolution	Xanthation	Acetylation
MMCF spinbath composition	Sulfuric acid, zinc sulfate	NMMO, water	Sulfuric acid, zinc sulfate	
Spinning Method	Wet spinning	Wet spinning	Wet spinning	Dry spinning
By-products from MMCF Production process	sodium sulfate		sodium sulfate	
Solvent for pulp dissolution	Caustic soda (NaOH), Carbon disulfide (CS2)	N-methylmorpholine-N-oxide (NMMO)	Caustic soda (NaOH), Carbon disulfide (CS2)	Acetic acid, acetone
Solvent consumption	+++	+	++++	Unknown
Solvent recovery	75-90%**	99.9%	75-90%**	97%
Recovery technology	CAP, Condensation: CS2; Sulfuric acid: WSA	Unknown	CAP, Condensation: CS2; Sulfuric acid: WSA	Unknown
Pulp consumption	+++	++	+++	++++
Caustic consumption	+++		++++	
Sulfuric acid consumption	+++		++++	
Energy consumption-Integrated Mill (with pulp production)	++	++	+++	Unknown
Energy consumption-Non-integrated Mill (with pulp production)	+++	+++	++++	Unknown
Scenario 1: Biomass for energy (steam and power)- Integrated Mill (with pulp production)	++	++	+++	Unknown
Scenario 2: Coal for energy (steam and power)- Non-integrated mill	+++	+++	++++	Unknown
Scenario 3: Gas for energy (steam and power)- Non-integrated mill	+++	+++	++++	Unknown

***Limited data availability on cellulose diacetate. **90% recovery achieved with state-of-the art technologies: Carbon Disulfide Plant (CAP) and Wet sulfuric acid plant (WSA)**

It is to be noted that due to lack of process-level data on acetate fibers, acetate fiber production is not included in this comparison. Overall, lyocell production method is a low carbon MMCF production method (comparison excludes acetate fibers), followed by viscose and modal production methods. Caustic soda (sodium hydroxide) production is one of the largest drivers to GHG impacts of MMCF mills, so replacing caustic soda and carbon disulfide with NMMO solvent (with a very high recovery rate) lowers the GHG profile of lyocell fiber production. However, it is to be noted that current LCAs lack primary data on NMMO solvent production so data quality on lyocell production needs to be improved. Note that the recovery rate of NMMO solvent is very high so the amount of NMMO required for the process is low and the low data quality is not expected to affect the results. Integrated pulp and fiber mills are more energy efficient and likely to use energy generated from pulping operations, driving lower fossil fuel demand and energy demand from the energy grid. The share of fossil fuel for heat in the pulp mills and MMCF plants and for the fuel and/or electric grid mix of a region can influence the GHG profile of an MMCF mills. Existing LCA studies show that MMCF mills located in Asia (China, India, Indonesia, etc.) can have higher climate impacts associated with MMCF production compared to European MMCF mills due to a coal dominated heat generation and energy grid mix.

4.2.2 Key factors influencing climate impacts

As highlighted in Section 3.2.1, the key drivers of the climate profile of MMCF are:

- *Land use management, including feedstock harvest*: Over the several decades, while logging has generally declined as a primary driver of deforestation and forest degradation and loss, it remains a significant factor in some regions. Data from existing MMCF LCAs presented in Section 4.2 indicate that climate impacts are highly variable, depending on the region and source of MMCF. It is critical to include the GHG fluxes from land use and land use change activities linked to feedstock harvest. Refer to Section 4.2.2.1 for more details.
- *Dissolving pulp production*: Process energy requirements for fiberline and pulp drying operations, energy and chemical dosage for bleaching sequence, caustic soda consumption are the key factors affecting dissolving pulp production. Refer to Section 4.2.2.2 for more details.
- *Operations at MMCF mills*: Process energy requirements and energy (fuel) mix for pulp dissolution process to prepare MMCF dope solution and impacts associated with caustic soda production are the key factors influencing MMCF production. Refer to 4.2.2.4 for more details.

Sections 4.2.2.1, 4.2.2.2 and 4.2.2.4 provide an overview of the landscape of MMCF production in key regions and highlights the key pivotal factors that influence climate impacts associated with four different types of MMCF.

4.2.2.1 Feedstock Harvest

MMCF is primarily manufactured from pulpwood, with more than 60 million m3 of pulpwood extracted on an annual basis[40]. On an average, about 2.5-3 metric tons of trees are required to produce 1 metric ton of viscose. Growing forests (including their soils) are the largest and most effective terrestrial carbon sinks. Land management choices can influence (reduce, maintain, or increase) the amount of carbon stored in land systems.

In the industrialized countries, primary forests were widely cleared for agriculture and the remaining forests were overexploited for centuries in history. About 300 years ago, the silvicultural principle of sustainability was developed by German foresters to ensure an adequate continued supply of wood. Originally it meant that trees are only harvested at the rate at which they can grow back. A shift from deforestation to reforestation to managed forests occurred in the 19th and 20th century and is ongoing with growing forest areas and carbon stocks in many countries of Europe and North America, and recently also China[41]. As of today, primary and old-growth forests in the Europe are rare, small and fragmented, representing below 3% of the total forest extent of Europe and are mainly concentrated in Sweden, Finland, Bulgaria and Romania[42].

The WWF conducted a fragmentation analysis using forest maps for 2000 and 2018 and found that nearly two-thirds of total deforestation occurred in tropical and sub-tropical biomes, followed by boreal and temperate forests[43]. The amount of forest area (includes primary forest and degraded forest area) replaced by wood fiber plantations each year increased during the early 2000s and peaked in 2012, with a decline beginning in 2013. Global Forest Watch (GFW) analyzed data for ten tropical countries (Argentina, Brazil, Cambodia, China, India, Indonesia, Malaysia, Rwanda, South Africa and Vietnam) and found that between 2000-2015, approximately 1.8 million hectares of forest area (includes primary forest and degraded forest area) was estimated to be replaced by pulpwood plantations.[44]

Table 6 lists the key countries supplying pulpwood for dissolving pulp production, by MMCF source, and outlines the main tree species relevant to MMCF production. Note that while many dissolving pulp mills are located in the vicinity of pulpwood harvest regions, pulpwood can flow beyond the geographic locations of dissolving pulp production. For example, boreal forest chips from Russia can be found in dissolving pulp mills in Europe[45]. of pulpwood is very important and certification schemes can be used as a tool to trace the origin of pulpwood (refer to 4.2.2.1.2 for more details).

Table 6.

Key feedstock sourcing regions for dissolving pulp production, specified by MMCF source.
(KEY: H: Hardwood; S: Softwood; X: applicable and grey cells indicates that it is not applicable)

COUNTRY	Main Feedstock Sources relevant to Dissolving Pulp production (H: Hardwood; S: Softwood)	MMCF SOURCE						
		Managed Temperate Forests	From Boreal Forests	Plantations converted from Intact Forest Landscape	Plantations established on degraded land and other areas	Bamboo	Cotton Linters	Recycled Pulp
Austria	H: fagus Recycled clothing	X						X
Brazil	H: eucalyptus globulus				X			
Canada	H: populus ; S: pinus, picea	X	X					
China	H: bambusoideae Cotton linters					X	X	
Czech Republic	H: fagus ; S: pinus, picea	X						
Finland	S: pinus, picea	X						
Germany	H: fagus, fagaceae; S: pinus, picea	X						
Indonesia	H: E. grandis/E. pellita/E. europhylla, fabaceae			X	X			
Latvia	H: populus, betula ; S: pinus, picea	X						
Norway	S: picea, pinus	X						

COUNTRY	Main Feedstock Sources relevant to Dissolving Pulp production (H: Hardwood; S: Softwood)	MMCF SOURCE						
		Managed Temperate Forests	From Boreal Forests	Plantations converted from Intact Forest Landscape	Plantations established on degraded land and other areas	Bamboo	Cotton Linters	Recycled Pulp
Poland	H: fagus, betula, fagaceae; S: pinus	X						
Russia	H: betula, larch; S: pinus	X	X					
Slovakia	H: fagus; S: picea	X						
Slovenia	H: fagus; S: picea	X						
South Africa	H: E. grandis/E. nintens, fabaceae				X			
Sweden	S: picea, pinus Recycled clothing	X						X
USA	H: populus, sapindaceae, fagaceae; S: pinus Recycled clothing	X						X

In 2018 Canopy mapped a large subset of the world’s forests, referred to as Ancient and Endangered Forests[46], that are priorities for conservation because of their high carbon values and value for species habitat. Canopy identifies the following forest landscapes as Ancient and Endangered Forest and assesses pulpwood sourcing risks in the MMCF supply chain using their ForestMapper[47] tool:

- Canadian and Russian Boreal Forests;
- Coastal Temperate Rainforests;
- Tropical Forests and Peatlands of Indonesia;
- Tropical Forests of the Amazon;
- Tropical Forests of West Africa.

4.2.2.1.1 Current status of global forest resources

There are five major climate zones including boreal, polar, temperate, sub-tropical and tropical. The tropical climate zone is home to 45% of forestlands globally, followed by boreal, temperate and sub-tropical zones. According to the latest 2020 FAO report[48], global forest area constitutes nearly 93% of naturally regenerating forests (3.75 billion ha) and 7 % of planted forests (290 million ha). Approximately one-third (34 percent) of the world’s forests are primary forests[49], of which 61 percent of primary forests are predominantly found in three countries: Brazil, Canada and the Russian Federation (as shown in Table 7). The area of primary forest has decreased by 81 million hectares since 1990, but the rate of loss more than halved in 2010–2020 compared with the previous decade. The area of naturally regenerating forests has decreased since 1990 (at a declining rate of loss), but the area of planted forests increased by 123 million hectares. Plantation forests cover about 131 million ha, which is 3 percent of the global forest area and 45 percent of the total area of planted forests. Other planted forests, which comprise 55 percent of all planted forests, are not intensively managed, and they may resemble natural forests at stand maturity.

Table 7 was created by reviewing the latest available data from Global Forest Watch and FAO’s Global Forest Assessment reports. It exhibits the current distribution of forest types and carbon stocks (above ground, below ground and soil organic carbon stocks) for key countries supplying pulpwood to dissolving pulp mills.

Table 7.

Current distribution of forests and carbon stocks for countries supplying pulpwood to DP mills. Forest cover distribution data is estimated based on the FAO's 2020 Global Forest Assessment Report[50]. Carbon stock distribution is calculated based on the data retreived from Global Forest Watch Dashboard[51]. **Figure 7 illustrates the above ground and below ground carbon stocks for key countries listed below. Figure 7 provides the net forest cover change (%) from 2000-2020.**

COUNTRY	1.a Primary forest (% of total forest area)	1.b Naturally regenerated forest (% of total forest area)	1.c Planted forest (% of total forest area)	2.a Above ground carbon	2.b Below ground carbon	2.c Soil organic carbon
Austria	3%	53%	44%	25%	7%	68%
Brazil	41%	57%	2%	22%	6%	72%
Canada	59%	36%	5%	7%	2%	91%
China	6%	57%	38%	14%	4%	82%
Czech Republic	0%	0%	100%	24%	6%	70%
Finland	1%	68%	31%	9%	2%	88%
Germany	0%	54%	46%	21%	5%	74%
Indonesia	51%	44%	5%	34%	9%	57%
Latvia	0%	81%	18%	13%	3%	84%
Norway	1%	86%	13%	8%	2%	89%
Poland	1%	4%	95%	16%	4%	79%
Russia	34%	64%	2%	8%	2%	90%
Slovakia	1%	49%	49%	27%	7%	65%
Slovenia	4%	93%	3%	29%	8%	63%
South Africa	10%	71%	19%	9%	2%	89%
Sweden	9%	42%	49%	11%	3%	87%
USA	24%	67%	9%	16%	4%	80%

While primary forests are those which have never been industrially logged, naturally regenerated forests are forests that were previously logged and allowed to regenerate. Planted forests are forests that have been logged and replanted for industrial forestry operations. Majority of the forested regions in Europe have forest management plans and supply pulpwood to dissolving pulp mills; in contrast, only 25% of forests in African and less than 20% of forests in South America have established forest management plans. In the context of MMCF, pulpwood plantations (eucalyptus, acacia and bamboo) are managed in South Africa (predominantly in Mpumalanga and KwaZulu Natal regions[52]), Brazil (Santa Catarina, Sao Paulo and Minas Gerais[53]), Indonesia (Sumatra and Kalimanthan[54]) and China (bamboo plantations predominantly in Fujian and Zhejiang) and are used as feedstock in dissolving pulp production as well.

The above table shows that over 60% of the carbon is stored in the soils, and in boreal forest regions of Canada and Russia, over 90% of the carbon is stored in the soil. It is imperative to conserve existing carbon pools in forest ecosystems and soils by controlling the drivers of deforestation and forest degradation[55]. Conservation of these carbon pools will also preserve the biodiversity, and eliminate deforestation-driven changes to water availability and climate variability.

Data in the figure below shows that managed forests in Europe have maintained the carbon stocks over a 20-year period, with some regions increasing forest cover, resulting in an increase in carbon stocks. In contrast, there has been a dip in carbon stocks in Indonesia, Brazil and Canada. Carbon stocks can vary depending on the forest type and climatic conditions. While managed forests in Europe store carbon more than 90 tC/ha (excluding soil organic carbon), in contrast, plantations store around 55 tC/ha (excluding soil organic carbon). Another important way that carbon is stored over time is in harvested wood products, which can substitute non-renewable, carbon intensive materials. Land conversion from a natural or primary forest to plantations releases much of the stored carbon (biogenic carbon) and increases the GHG impacts. Plantations such as eucalyptus and acacia have a short rotation cycle of 5-10 years and while they rapidly absorb carbon up to 5 tC/ha/year, regular harvesting and clearing of plantations releases stored carbon back into the atmosphere, contributing to GHG impacts. By contrast, natural forests continue to sequester carbon for many decades, if left unharvested. The loss of primary forests forgoes the opportunity for carbon storage (i.e., foregone carbon sequestration), as degradation processes or land conversion reduces carbon uptake from the atmosphere and contributes to global warming.

The actual size of carbon sinks in primary forests are subject of a recent debate. Some research suggests that the amount of carbon sequestered globally by primary forests has been overestimated in the past research. Some primary forests can even become carbon sources[56]. This is not to say that primary forests are not important for climate change mitigation. However, their value lies often in the already accumulated carbon stock, and biodiversity levels that should be maintained. Further research into the role of primary forests as carbon sinks, in different climates and regions, is warranted.

On the other hand, plantations established on degraded lands (e.g. Brazil) could prove beneficial from not only a productivity standpoint, but also increasing the carbon stocks over time, thereby resulting in net GHG removals. Plantations yield more wood per hectare compared to natural forests so if managed well, the GHG intensity of pulpwood production can be reduced considerably. Between 2001-2020, plantation forests in Brazil emitted 184MtCO$_2$e/year and removed -236 MtCO$_2$e/year, resulting in a net carbon flux of52MtCO$_2$e/year[57], which translates to nearly -20 t CO$_2$e/hectare/year.

Figure 7.

Average biomass stocks including above ground biomass, below ground biomass and dead wood in tC/ha from 1990-2020, by country. (Data retrieved from FAO 2020 Global Forest Resource Assessment database). Historical data on soil organic carbon was not available so it was not possible to include soil carbon estimates in this chart. It is important to note that as shown in Table 7, over 88%-90% of the carbon stocks in boreal forest regions in Canada, Russia, Norway and Finland are locked in the soil, which is nearly 1.5 to 2 times the soil carbon stored in other countries. Zero values represent data not reported for the time period.

Global Forest Watch (GFW) displays the net exchange of carbon between forests and the atmosphere between 2001-2020[58], calculated as the difference between forest carbon emissions from stand-replacing forest disturbances and carbon removals from forest regrowth. Emissions arise from stand-replacing disturbances while removals occur where forest was maintained or expanded. Emissions include all relevant ecosystem carbon pools (aboveground biomass, belowground biomass, dead wood, litter, soil), while removals are into the aboveground and belowground biomass pools. Table 8 displays the average annual emissions, removals, and net flux on a regional-level[59]. It should be noted that regional level averages were only available for select countries.

Table 8.

Average annual GHG emissions, GHG removals, and net forest GHG flux for regions within Canada, Indonesia, Brazil and South Africa. Refer to the Appendix for a brief overview on the steps applied to retrieve this information from Global Forest Watch.

Region	GHG Emissions MtCO$_2$e/yr	GHG Removals MtCO$_2$e/yr	Net forest GHG flux MtCO$_2$e/yr	Area (Mha)	Net forest GHG flux per hectare per year tCO$_2$e/ha/yr
Canada: Logging concessions					
Quebec	46.3	-146	-99.8	81.4	-1.23
Ontario	36.7	-153	-116	71.9	-1.61
British Columbia	115	-315	-200	67.1	-2.98
Saskatchewan	8.42	-2.11	-11	39.6	-0.28
Alberta	26.9	-19.4	-18.1	36.8	-0.49
Manitoba	3.17	-23.8	-20.6	35.9	-0.57
New Brunswick	11.1	-19.9	-8.76	6.22	-1.41
Indonesia: Plantations					
Riau	67	-23.1	43.9	0.256225	171.33
Sumatera Selatan	37	-20.3	16.7	0.264387	63.16

Region	GHG Emissions MtCO$_2$e/yr	GHG Removals MtCO$_2$e/yr	Net forest GHG flux MtCO$_2$e/yr	Area (Mha)	Net forest GHG flux per hectare per year tCO$_2$e/ha/yr
Jambi	16.6	-7.91	8.72	0.16632	52.43
Sumatera Utara	4.58	-2.11	2.48	0.043366	57.19
Lampung	0.37	-0.315	0.056	0.006037	9.28
Kalimanthan Selatan	4.25	-2.76	1.49	0.062832	23.71
Kalimanthan Timur	21.2	-15	6.19	0.072072	85.89
South Africa: Plantations					
Mpumalanga	14.8	-11.4	3.4	0.22	15.45
KwaZulu-Natal	16.5	-11.7	4.77	0.1716	27.80
Limpopo	1.53	-1.45	0.081	0.033	2.45
Western Cape	1.45	-1.33	0.117	0.0308	3.80
Eastern Cape	2.43	-2.43	0.00514	0.0264	0.19
Brazil: Plantations					
Santa Catarina	16.4	-30.5	-14	0.853507	-16.40
Parana	16.2	-17.4	-1.23	0.352061	-3.49
Espirito Santo	7.36	-8.22	-0.86	0.303496	-2.83
Sao Paulo	24.4	-30.4	-6	0.243691	-24.62
Minas Gerais	52.3	-67.2	-14.8	0.213115	-69.45
Rio Grande do Sul	11.6	-18	-6.43	0.190074	-33.83
Matto Grosso do Sul	14.1	-17.7	-3.67	0.13104	-28.01
Bahia	20.3	-22.3	-2.01	0.060278	-33.35

The importance of incorporating regionality in LCA is evident in the table above as it shows how the climate impacts from forestry activities can vary depending on the sourcing location of pulpwood. For example, within Indonesia, there is a wide variation in GHG emissions depending on the soil type (mineral soils versus peat drainage), with emissions ranging from 9tCO$_2$e/hectare/year to 171tCO$_2$e/hectare/year. Note that the Global Forest Watch data only considers emissions from stand-replacing disturbances and does not factor in the emissions from forest degradation. Accurate ground-based measurements are the key for assessing true impact of land-use and land-use change impacts.

For example, government statistics data from South Africa show a different situation than the GFW data[60].

Province	2020 SA NLC	
	ha	Mha
Eastern Cape	195,450	0.19545
Free State	86,928	0.08693
Gauteng	35,385	0.03539
KwaZulu-Natal	745,063	0.74506
Mpumalanga	775,182	0.77518
North West	42,925	0.04293
Northen Cape	2,049	0.00205
Limpopo	87,892	0.08789
Western Cape	86,077	0.08608

According to Sappi, Net forest GHG flux per ha per year in South Africa values are too high. In this situation, the GFW Model may underestimate removals in fast growing plantations, and overestimates emissions[61].

4.2.2.1.2 Inclusion of biogenic carbon in LCA Modeling

From an LCA perspective, most impact assessment methods for assessing climate impacts exclude biogenic carbon flows, and assume zero impact as it is believed that the biomass stock will regrow to store the same level of carbon. However, as discussed above, on a net basis, the forest cover has been reduced in some regions, and it is critical to include biogenic carbon emissions from biomass-based fuels, direct land use change and changes in land use management, as it can be a key contributor to climate impacts. Both ISO 14067:2018 standard and EU PEF pilot guidance, mandate the users to account for biogenic GHG emissions and removals from direct land use change and land management occurring over a 20-year timeframe. When changes in use or management of land cause changes in carbon stocks (changes in above and belowground) over 20 year timeframe compared to the reference land use, the net changes in soil and biomass carbon stocks should be attributed to the products.

Currently there is no consensus on what reference system to use but a recent tool[62] published by WWF looks at two reference systems:

1. *Net zero reference*: this approach assumes that forest is in steady state with no changes in carbon pools. The accounts for carbon emissions from harvesting, thinning, harvest residue decomposition and uptake from forest regrowth.
2. *Foregone sequestration*: this approach considers the burden of an avoided continuous accumulation of carbon based on the rationale that forests are harvested at mean annual increment and would continue to grow if not harvested[63]. Foregone forest carbon sequestration essentially looks at the "opportunity cost" associated with ongoing harvests. It is the forest growth avoided as a result of harvesting pulpwood before it attains equilibrium (i.e. avoided carbon uptake).

Currently, there is no harmonized methodology to evaluate biogenic carbon but a consensus is expected to be reached by development of a new guidance on carbon removal and land use by the World Resources Institute[64].

The foregone sequestration approach was used in one LCA of MMCF published in 2017[65], which found that depending on the pulpwood sourcing region and forest management practices, the carbon storage levels can vary significantly. A comparison of different feedstocks sourced for MMCF found that over a 20-year time period, forest carbon storage losses/foregone carbon sequestration from pulpwood logging potentially accounts for 32% of climate impacts for Swedish managed forests, 46% of climate impacts from Canadian boreal forests, 31% of climate impacts from Indonesian plantation pulp, 9% of climate impacts from South African plantation pulp and 27% of climate impacts for Chinese (non-native) bamboo plantations.

4.2.2.1.3 Certification schemes

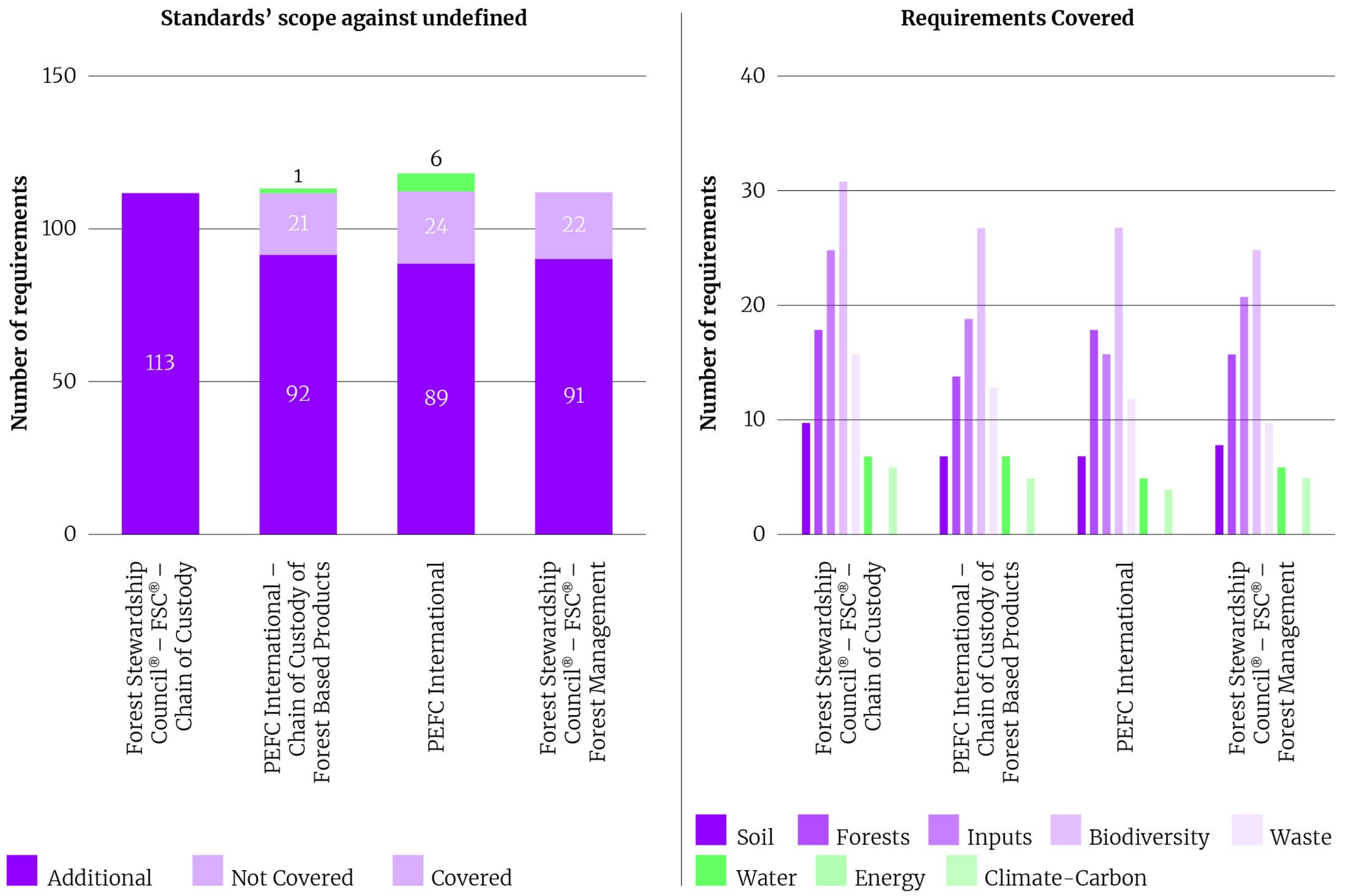
Since their inception, forest certification standards have been designed to operate at the forest management unit. Given today's ecological reality, global and regional rates of deforestation and impacts from conversion – it must be recognized that no forest certification system mandates landscape level conservation planning that prioritizes the protection of remaining Ancient and Endangered Forests including Intact Forest Landscapes (IFLs) and primary/natural forests and their social and ecological values, carbon storage and biodiversity at the scope and scale recommended by global conservation scientists and many of the targets defined by the United Nations. This should change. Forest certification is one tool, that therefore must be coupled with protection requirements within certified management units, and through planning and coordination beyond the boundaries of specific forest management units to look at the needs of ecosystems.

As forest certification standards mature, such as is the case with PEFC in Indonesia, their scope may become more aligned with FSC requirements. However, several standard comparisons[66], highlight how increased 'prescriptiveness' results in more ecological certainty of sustainable forest management in the forest and/or supports Indigenous involvement. This is an indication of the strength of performance-oriented standards rather than process-based standards. Therefore, until all forest certification systems adopt outcome-oriented performance standards, indicators, and thresholds, including for in-the-forest results, and in how the auditors work with the standards, process-oriented standards and indicators should be used to support performance standards, rather than substitute for them.

According to the TE 2020 report[67], 40-50% of forests supplying dissolving pulp for MMCF production are FSC and/or PEFC certified (including Chain of Custody certifications), and <1% of pulp is from recycled sources. It should be noted that this figure includes the volume of fiber certified to Chain of Custody (CoC) certification, which differs from certified forest management and allows fiber from a certified forest management unit (FMU), as well as non FMU certified/uncertified controlled sources and recycled content, to be tracked through the supply chain. It is used by mills that wish to produce products with certified claims, but it does not mean all the fiber is from a certified forest. CoC is a process by which the mill can prove that the ability to track the origin of fiber inputs, and has the ability to segregate certified fiber from non-certified fiber.

Figure 8.

This chart has been adapted from International Trade Centre's Sustainability Standards Map[68]. It is summary of number of requirements for FSC Chain of Custody, FSC-Forest Management, PEFC International-Forest Management and PEFC International-Chain of Custody of Forest Based Products, by category.



Note that PEFC and FSC standards differ by country so the requirements also differ on a country level. As an example, the table below provides a limited subjective comparison of PEFC and FSC certification standards in Indonesia to help stakeholders understand the nuances of certification schemes.

Table 9.

Key differentiators between FSC and PEFC forest management standards in Indonesia.

Parameter	FSC[69]	PEFC[70]
Cut-off date	Forest converted after 1994 cannot be certified	Forest converted after December 2010 cannot be certified
Seeds	GMO seeds prohibited	No such requirement
High Conservation Value Forests	Establishment of conservation zones within the FMU (forest management unit) and that such zones shall be the subject of scientifically valid monitoring of key ecological indicators	Apply appropriate management measures to minimize the pressures of forest management on key protected and endangered fauna species
Species	Shall requirement: documentation of monitoring methods of key species of fauna within the forest management unit to estimate population changes over time	Requires species monitoring but monitoring methods are not required to be documented
Fertilizer/ Pesticide use	Requirement: to reduce and avoid the use of pesticides and fertilizers	Requirement: do not use inorganic fertilizers
Restoration of degraded site	Requirement: where degraded sites are identified, forest management units shall include restoration program	Requires restoration of degraded sites only when restoration can add economic, environmental, social and cultural values.
Conservation zones	Requirement: establishment of conservation zones within the forest management unit and conservation zones are subject to scientifically valid monitoring of key ecological indicators	Requires forest manager to apply appropriate management measures to minimize the pressures of forest management on key protected and endangered fauna species.
	Requires at least 10% of forest management unit to be identified, mapped and managed as conservation zones (no commercial management)	No minimum requirement regarding the proportion of forest management unit to be designated as conservation zone.
Forest Management Plan	Forest management plan should be updated every 5 years	Forest management plan should be updated every 10 years

Over the past decade, the MMCF sector has taken positive strides towards enhancing transparency and traceability of by mapping the supply chain and identifying pulp producers and pulpwood sources. The CanopyStyle Verification Audit evaluates the practices of viscose producers and determines the risk of sourcing from Ancient and Endangered Forests and other controversial sources. As of 2022, 76.3% of global MMCF production has been audited according to Canopy Style guidelines[71].

4.2.2.2 Dissolving Pulp Production

Dissolving pulp (DP) is the main feedstock used for producing regenerated cellulosic fibers (MMCF) and on an average, 1000-1100 kg of DP is required to produce 1 metric ton of viscose[72]. Modal requires more pulp and chemical input compared to viscose. DP is a specialty pulp, which is higher in quality and contains higher alpha cellulose content (above 90% cellulose), lower impurity level and is bleached to higher levels of brightness, compared to pulp used in paper application. DP mills source wood (certified or uncertified) from the vicinity of the mill or from the open market, depending on the tree species requirement (either softwood trees or hardwood trees) and the pulping technology deployed at the mill.

Pulpwood is debarked, chipped and treated with cooking liquor (liquor composition varies depending on the pulping technology) to extract cellulose from wood and remove impurities (i.e., lignin, hemicellulose and other extractives). The residual liquor is evaporated to recover black liquor (containing about 70% organic compounds) and the bark from debarking operation is used as an energy source to fuel the boilers on-site. The raw pulp is washed and screened to remove residual impurities. This is followed by the bleaching process (using either ECF or TCF[73] technology), a critical process for removal of lignin (delignification) and hemicellulose using energy intensive chemicals (e.g., chlorine dioxide, oxygen, hydrogen peroxide, etc.). The pulp is then screened, dried in sheets and baled.

DP mills are highly energy intensive operations

Typically, DP mills generate on-site heat (high-pressure steam) by combusting by-products such as black liquor and waste bark (from debarking operations) in recovery boilers and high-pressure steam is used to generate electrical power in turbo generators. According to EU BAT[74], black liquor and bark waste generates 18 GJ/ metric ton pulp and 4.2 GJ/ metric ton pulp, respectively. Some mills are often self-sufficient in meeting its demand and can even generate surplus energy, which is exported back to the electricity grid. The environmental performance of a DP mill is influenced by the processing efficiencies in the energy generation plant and the DP production line (chemical and resource optimization), and the selection of pulping and bleaching technologies.

Table 10 provides an overview of the pulping technology, bleaching methods and by-products generated at the DP mill, based on the location of the mills supplying pulp for MMCF production. Section 4.2.2.3.2 provides a detailed description the pulping technologies and Section 4.2.2.3.3 describes the differences between ECF and TCF bleaching technologies.

Table 10.

Summary of key dissolving pulp producing regions and parameters distinguishing the pulp production including pulp type, pulping technology, bleaching technology, chemical composition and derivation of by-products. **(PHK: Prehydrolysis Kraft Pulp; AS: Acid Sulfite pulp; ECF: Elemental Chlorine Free bleaching; TCF: Totally Chlorine Free bleaching).**

Approximately, 85% of dissolving pulp is made from softwood (spruce, pine) or hardwood (beech, eucalyptus), while about 10% is made from cotton linter[75]. Sweden and Norway are the main producers of softwood pulp in Europe, while Austria and Czech Republic produce hardwood pulp. Recycled pulp production from waste textiles is an emerging technology in Sweden, Netherlands and USA, and efforts are currently underway to transition from small scale to commercial scale of production. Section 8 provides more detail on the new innovative technologies in the MMCF landscape. Section 4.2.2.3 presents a qualitative matrix to interpret the differences in DP pulping technologies on a country level. Section 4.2.2.3.1 through 4.2.2.3.3 provide a detailed background of the key factors influencing the GHG emission profile of DP production.

Conventional pulp								Recycled pulp		
Dissolving Pulp Production Parameters	**Europe (Austria, Czech Republic, Norway, Sweden)**	**Canada**	**USA**	**Indonesia**	**China**	**South Africa**	**Brazil**	**Sweden**	**Netherlands**	**USA**
Pulp type	Softwood+ Hardwood	Softwood+ Hardwood	Softwood+ Hardwood	Hardwood-eucalyptus/ acacia	Cotton Linter, Bamboo	Hardwood-eucalyptus/ acacia	Hardwood- eucalyptus	Recycled Pulp from waste textiles	Recycled Pulp from waste textiles	Recycled Pulp from waste textiles
Pulping Technology	PHK, AS	PHK, AS	PHK	PHK	PHK	PHK, AS	PHK			
Bleaching Technology	TCF	ECF								
Key Delignification/ Bleaching chemical consumption	Ozone (O_3), Oxygen (O_2), Hydrogen peroxide (H_2O_2), Sodium Hydroxide (NaOH)	Chlorine dioxide (ClO_2), Oxygen (O_2), Hydrogen peroxide (H2O2), Sodium Hydroxide (NaOH)	Chlorine dioxide (ClO_2), Oxygen (O2), Hydrogen peroxide (H_2O_2), Sodium Hydroxide (NaOH)	Chlorine dioxide (ClO_2), Oxygen (O_2), Hydrogen peroxide (H_2O_2), Sodium Hydroxide (NaOH)	Chlorine dioxide (ClO_2), Oxygen (O_2), Hydrogen peroxide (H_2O_2), Sodium Hydroxide (NaOH)	Chlorine dioxide (ClO_2), Oxygen (O_2), Hydrogen peroxide (H2O2), Sodium Hydroxide (NaOH)	Chlorine dioxide (ClO_2), Oxygen (O_2), Hydrogen peroxide (H_2O_2), Sodium Hydroxide (NaOH)	NaOH	NaOH	NaOH
Cooking liquor	AS: Magnesium bisulfite PHK: sodium sulfite, NaOH	AS: Magnesium bisulfite PHK: sodium sulfite, NaOH	PHK: sodium sulfite, NaOH	PHK: sodium sulfite, NaOH	PHK: sodium sulfite, NaOH	AS: Magnesium bisulfite PHK: sodium sulfite, NaOH	PHK: sodium sulfite, NaOH			
Biorefinery (yes/no)	Yes	No	No	No	No	No	No	No	No	No
By-products?	Yes: bioethanol, lignin, acetic acid, black liquor for on-site energy, (AU: furfural, xylose, lignin-sulfonate, soda ash, mother liquor)	Black liquor for on-site energy	Black liquor for on-site energy	Black liquor for on-site energy, methanol from condensing off-gases (SOG)	Black liquor for on-site energy	Black liquor for on-site energy	Black liquor for on-site energy			

Key climate hotspots associated with dissolving pulp production include:

- *Process energy requirements for fiberline and pulp drying operations*: According to EU BAT, the pulp drying operation accounts of about 25% of the steam and 15-20% of electricity and majority of the climate impacts are connected to combustion of fuels (e.g., black liquor, bark, biomass, natural gas, oil, coal, etc.) for energy generation. Recovery boilers, lime kilns and auxiliary boilers release air pollutants including emissions of carbon dioxide, carbon monoxide, particulates, nitrous oxides, total reduced sulfur compounds, etc. and DP mills are equipped with abatement technologies to minimize the release of air pollutants.
    - Integrated pulp and fiber mills (pulp mill with MMCF production line) are more energy efficient compared to non-integrated pulp mills, driving lower GHG emissions. As MMCF production is concentrated in China, DP is shipped across the continent, so in the current landscape of MMCF, very few DP mills are integrated in MMCF production.
    - Biorefineries can be highly efficient as they maximize the potential of wood inputs, by generating multiple valuable products such as dissolving pulp, lignosulfates, bioenergy (from black liquor, bioethanol), acetic acid, etc. Best practice to lower GHG emissions would be to operate DP mills as biorefineries and minimize the energy and resource inputs.
- *Bleaching operation*: process energy requirements and impacts from bleach chemical production are the main sources of climate impacts. Refer to Section 4.2.2.3.3 for more details.
- *Caustic soda production*: this is the main chemical input required for processing wood chips into pulp and is an energy intensive manufacturing process.

Most of the current LCA data on MMCF are aggregated datasets so the LCAs were not sufficiently transparent to decipher the drivers of dissolving pulp production impacts on a process-level and a lack of data on the specific pulp mix/tree species made it challenging to quantify DP impacts on a regional level, by pulp type. Section 4.2.2.3 presents a qualitative matrix which maps out the various dissolving pulp production technologies (i.e., sulfite; kraft) on a country level, by pulp type and interprets the effects of four key factors on the GHG profile of dissolving pulp production:

1. Wood or raw material (cotton linters, waste textiles) consumption for DP production,
2. Recovered energy from black liquor to replace fossil fuels
3. Alkali consumption (e.g. caustic soda) for DP production, and
4. Oxygen delignification and bleach chemical inputs for DP production.

This matrix was created by examining process conditions cited in EU's Best Available Techniques for Pulp and Paper[76], EU BAT Polymers[77] and literature[78]. It should be noted that process conditions are very site specific and can vary depending on the specific mix of tree species, so apply caution before using this matrix to definitively draw comparison between DP production practices. This matrix attempts to highlight the regional differences in DP production practices, but site-specific data would be required to draw conclusions. However, it can be determined that recycled pulp is a low carbon DP that can be used for MMCF production.

Table 11.

Qualitative assessment of Dissolving Pulp Production Technologies, by Pulp Type and Region.

LEGEND

INPUT REQUIREMENTS

+	++ +++	++++	+++++
Low	Low-medium	Medium	High
Low GHG Impact	Low-Medium GHG Impact	Medium GHG Impact	High GHG Impact

Dissolving Pulp Technology	Main Tree species	Dissolving pulp production region	Biorefinery	By-products	Lignin content	Recovered energy from black liquor	Alkali consumption	Oxygen for delignification/ Bleach chemical consumption	Interpretation
						↑ the amount of recovered energy from black liquor, ↓ GHG impacts as energy demand from other sources is reduced	↓ alkali consumption leads ↓ GHG impacts	↓ bleach chemical consumption leads to ↓ GHG impacts	
Sulfite pulping: ECF bleaching	Hardwood: eucalyptus/ acacia	South Africa		Black liquor for on-site energy	~27%-28%	++	++	+++	Higher cellulose content compared to other hardwoods/softwoods so wood consumption is low and easier to bleach compared to other wood species. Black liquor generation is lower compared to softwood. Higher nitrogen content in black liquor compared to softwood so NOx emissions from hardwood black liquor combusted in recovery boiler is higher compared to softwood black liquor recovery boiler.
Sulfite pulping: TCF bleaching	Softwood: spruce, pine	Europe [Sweden (SE), Norway (NO), Czech Republic (CZ)], Canada	Europe	SE&NO: bioethanol, lignin, black liquor for on-site energy |CZ: soda ash, magnesium-lignin-sulfo-nate	~27%	++++	+++	++++	Higher lignin content so requires more oxygen/bleach chemicals for extraction compared to hardwood. Ozone production for bleaching is energy intensive. Higher lignin content, generates more black liquor, resulting in more recovered energy and other by-products of lignin, and lower climate impacts due to reduced primary energy demand. Uses up to 50% less water compared to ECF so energy required to treat effluent discharge is lower compared to ECF technology. Lower climate impacts from processing due to integrated resource efficiency (energy, water, fiber raw material). Sulfite pulping yield for softwood is slightly higher compared to hardwood.
	Hardwood: beech	Europe (Austria)	Europe	AU: Acetic acid, furfural, xylose, lignin-sulfo-nate, soda ash, mother liquor|	~23%-25%	+++	++	+++	TCF bleaching has a lower temperature profile compared to ECF, so steam consumption might be lower. Lower lignin content, so less amount of alkali and bleach chemicals are required in the process. Ozone production for bleaching is energy intensive. Uses up to 50% less water compared to ECF so energy required to treat effluent discharge is lower compared to ECF technology. Lower climate impacts from processing due to integrated resource efficiency (energy, water, fiber raw material). AOX emissions to water are reduced and chlorine-organic compounds are not formed in TCF bleaching. *The climate impacts are estimated to be low because the biorefinery generates multiple products.
	Softwood: spruce, pine	Canada, USA		Black liquor for on-site energy	~27%	++++	+++	++++	Higher lignin content so requires more oxygen/bleach chemicals for extraction compared to hardwood. Higher lignin content, generates more black liquor, resulting in more recovered energy and reduces energy demand from other sources.

Dissolving Pulp Technology	Main Tree species	Dissolving pulp production region	Biorefinery	By-products	Lignin content	Recovered energy from black liquor	Alkali consumption	Oxygen for delignification/ Bleach chemical consumption	Interpretation
						↑ the amount of recovered energy from black liquor, ↓ GHG impacts as energy demand from other sources is reduced	↓ alkali consumption leads ↓ GHG impacts	↓ bleach chemical consumption leads to ↓ GHG impacts	
PHK pulping: ECF bleaching	Hardwood: birch, maple, oak, aspen, etc.	Canada, USA		Black liquor for on-site energy	~23%-25%	+++	++	+++	Bleach chemical and alkali consumption is lower for hardwoods compared to softwood and pulp yields are higher for hardwoods compared to softwood
	Hardwood: eucalyptus/ acacia	South Africa		Black liquor for on-site energy	~27%-28%	++	++	+++	Higher cellulose content compared to other hardwoods/softwoods so it is relatively easier to bleach compared to other wood species. Black liquor generation is lower compared to softwood. Higher nitrogen content in black liquor compared to softwood so NOx emissions from hardwood black liquor combusted in recovery boiler is higher compared to softwood black liquor recovery boiler.
		Indonesia, Brazil		Black liquor for on-site energy		++	++	+++	
	Bamboo	China			~23%	++	++++	+++++	Requires harsher cooking and bleaching conditions to penetrate the structure of bamboo and extract impurities.
	Cotton linters	China			<3%	+	+++++	++	Cellulose content is higher than other sources of MMCF so requires less oxygen for delignification. Black liquor generation is low, so recovered energy is lower. Alkali consumption is higher to due to higher trash content.
Recycled pulping process	Waste textiles	Europe (Sweden, Netherlands), USA			0%		+	+	Recycling process purchases electricity/steam as it does not generate black liquor on-site. Delignification is not required so alkali and bleach consumption lower.

4.2.2.3 Qualitative assessment of Dissolving Pulp Production Technologies, by Pulp Type and Region

The subsequent sections provide more detailed background on the following factors influencing GHG impacts at a DP mill: (i) Feedstock used for DP production; (ii) Pulping technology; (iii) Bleaching technology.

4.2.2.3.1 Feedstock used for dissolving pulp production

Pulpwood is the main feedstock for dissolving pulp production, followed by cotton linters. To a certain extent, the type of wood used for pulping may influence the yield, the applied processes and techniques and the process efficiency. Wood is an organic material comprising of 40-50% cellulose, 25-35% hemicellulose, 15-30% lignin and 2-10% extractives. The chemical composition of wood is the primary factor influencing pulp yields and the concentration of cellulose, hemicellulose, lignin and extractive vary by tree species (hardwood and softwood). Higher cellulose to hemicellulose ratio and lower lignin and extractive content result in higher pulp yields. Other factors include wood anatomy, chip size distribution and pulping chemistry. Hardwood lignin is chemically different from softwood lignin, and the differences in lignin chemistry results in different removal rates, thereby influencing the chemical input rates for pulp production. The lignin chemistry also influences the amount of black liquor that is recovered from the cooking process and available for use as an energy source.

While DP production is very site-specific and is highly variable depending on the specific tree species mix, an attempt is made summarize the influence of tree species used in DP to the climate impacts. From an LCA perspective, key takeaways are summarized below:

- Lower wood input (higher pulp yields) leads to lower climate impact and lower GHG fluxes from land use and land use change.
- Tree species with lower lignin content and faster lignin removal (delignification rates) will result in higher pulp yields and lower GHG emissions.
- Higher lignin content may require more chemicals or high temperature cooking conditions to remove the lignin, thereby increasing the GHG emissions. However, the higher the lignin content, the greater the amount of recovered energy from black liquor, which can lower GHG emissions as energy demand from other sources is reduced and there is a potential to generate surplus energy and export it to the grid.
- Use of waste textiles and agricultural waste, such as bagasse, as feedstock is a low carbon source for dissolving pulp production. These wastes require processing for pulp production. Refer to Section 6.1 for more detail.

4.2.2.3.2 Pulping technology

Wood chemistry and composition is a key factor for selecting the appropriate pulping process. DP is produced worldwide using one of the two main commercial pulping technologies: (a) prehydrolysis kraft (PHK) and acid sulfite (AS). As of 2014, PHK and AS technologies constitute 56% and 42% of global DP production respectively[79]. In Canada, 64% of the DP is produced using AS technology, while in China, PHK comprises 78% of DP production[80].

The key difference between the two technologies in the cooking conditions and the cooking liquor composition. The sulfite process produces pulp with alpha cellulose content of 90-92%, whereas the PHK process typically produces pulp with 94-96% alpha cellulose content[81]. There are mills that use either only softwood or only hardwood; others use softwood and hardwood alternately in the same production line. of PHK pulp is made from hardwood species and while softwoods are also suited to PHK pulping technology, the higher lignin content in softwoods can be sensitive to PHK conditions, so care should be taken in selecting the appropriate tree species.

Acid sulfite (AS) pulping technology is more sensitive to the wood properties and species such as Douglas fir, pine or larch with high residual lignin content can react with the cooking liquor[82], impeding the delignification process (i.e., removal of lignin), resulting in low pulp yields (corresponding to higher GHG emissions). Softwoods (spruce) can have higher pulp yields using sulfite (AS) pulping technology compared to kraft (PHK) process. As shown in the table below, the total fiber yield ranges from 45 to 55% (with delignification of about 90%), depending on the wood source and the pulping technology applied.

Table 12.

Typical pulp characteristics for AS and PHK processes, by pulp type. Softwood[83]

	Sulfite (AS) Process		**Kraft (PHK) Process**	
Pulp Type	Softwood	Hardwood	Softwood	Hardwood
Lignin content	25-30%	Eucalyptus 27-30%; Others: 20-25%	25-30%	Eucalyptus 27-30%; Others: 20-25%
Lignin extraction	93.75%	95.04%	94.12%	94.63%
Pulp yield	53%	Eucalyptus: 51-54%; Other:48%	49%	Eucalyptus: 51-54%; Other:50%

According to EU BAT[84], on an average, sulfite (AS) pulping technology requires 50 kg caustic soda (NaOH) per metric ton of DP (91% alpha cellulose content) and the caustic load can increase to 80-100 kg NaOH per metric ton of DP to produce higher purity DP with 92.5% alpha cellulose content. DP of higher purity (i.e., higher alpha cellulose content) correlates to higher dosage of caustic soda, which is an energy intensive chemical, thereby increasing the GHG emissions.

There are three (3) pathways to produce caustic soda (sodium hydroxide): (a) diaphragm cell technique; (b) mercury cell technique and (c) membrane cell technique. It is an electrolysis process in which a salt solution is decomposed electrolytically by direct electric current. All three pathways release chlorine emissions to air via leakage. The mercury cell technology also releases mercury air emissions which is a detrimental hazardous air pollutant. According to EU BAT, membrane cell technology has lower energy demand compared to mercury cell and diaphragm cell techniques, and therefore membrane cell technology is likely to be a low carbon production technology for caustic soda.

The key takeaways from this section are summarized below:

- Pulping technology must be designed according to the wood chemistry and composition, as it will determine the pulp yields. Higher pulp yields will reduce energy and wood input requirements, thereby mitigating GHG emissions.
- Complete feedstock utilization by biorefinery design for co-products extraction improves resource efficiency.
- Energy from black liquor lowers or eliminate the need for fossil fuels.
- Best practice is to optimize the cooking liquor consumption and reduce the dosage of caustic soda, which will also lower the GHG emissions.
- Caustic soda produced using membrane cell technology is lower in carbon compared to mercury cell and diaphragm methods.

Bleaching technology

Bleaching is necessary to remove residual impurities (e.g., lignin) and yield dissolving pulp with high level of brightness for MMCF including viscose, modal and lyocell. There are two main bleaching technologies: Elemental Chlorine Free (ECF) and Totally Chlorine Free (TCF) which primarily differ in the bleach chemical composition and concentration of bleach inputs in the bleaching sequences.

- Elemental Chlorine Free (ECF) bleaching is a bleaching sequence which does not use chlorine gas (Cl_2) and rather uses chlorine dioxide (ClO_2).
- Totally chlorine free (TCF) bleaching process eliminates the use of chlorine containing chemicals and mostly requires oxygen-based chemicals such as ozone (O_3) and hydrogen peroxide (H_2O_2).

In the current landscape, the majority of dissolving wood pulp producers use elemental chlorine free (ECF) pulp bleaching processes. This section investigates the differences between ECF and TCF bleaching technologies and strives to determine whether the bleaching technology influences the GHG impacts associated with dissolving pulp production. Typically, bleach chemicals are produced on-site due to rapid decomposition of chemicals during transit/storage. Both ozone (TCF) and chlorine dioxide (ECF) are GHG intensive chemicals, requiring similar amount of energy per metric ton (as shown in Table 13), so the amount of bleach chemical input required per metric ton of DP will determine the low carbon bleaching technology.

The bleach chemical dosage is formulated based on the lignin chemistry and will vary by tree species. Table 13 summarize the bleach chemical dosage from literature for sulfite pulp (TCF bleaching), bamboo pulp (ECF bleaching), eucalyptus pulp (ECF bleaching) and cotton linter pulp.

Table 13.

Summary of bleach chemical dosage, by chemical type, by pulp type and type of bleaching technologies, based on available data. (TCF: Totally Chlorine Free technology and ECF: Elemental Chlorine Free technology). The GHG emission profile of the bleaching sequence was estimated using ecoinvent v3.6 database.

Bleach Chemical	Energy inputs (kWh/kg)[85]	Sulfite Pulping[86] (Europe)	Bamboo (Brazil)[87]	Eucalyptus[88]	Cotton Linter[89]
		TCF (kg/t)	ECF (kg/t)	ECF (kg/t)	kg/t
Chlorine dioxide	10	0	40	28	0
Sodium hydroxide	1.6	55	122	32	115
Ozone	10	5	0	0	0
Oxygen	0.4	15	20	18	85
Hydrogen Peroxide	3.5	40	3	3	18
TOTAL Climate Impact (kg CO_2e/t)		**202**	**537**	**310**	**268**

The data presented in Table 13 indicates that bamboo pulp requires significantly higher bleach chemical input compared to eucalyptus, cotton linter and wood pulp. This is because bamboo has a higher content of extractives (16.2%), which makes it challenging to efficiently process the material. Cotton linters have high trash content, so it may require more caustic soda for removing impurities compared to eucalyptus and other tree species.

A paper published by de Assis, et. Al conducted laboratory experiments comparing ECF and TCF bleaching technologies for eucalyptus kraft pulp. Data published by de Assis, et. al shows that there is no significant difference in energy consumption when comparing ECF and TCF bleaching sequence for a eucalyptus kraft pulping process.[90] However, TCF bleaching sequences requires less water, so less energy is required to treat the effluents from TCF process. TCF bleaching operation had a lower temperature profile, so the steam consumption was found to be slightly lower compared to ECF bleaching. An article on industrial ozone bleaching practices found that early installation of ozone bleaching sequence lowered the energy cost by 25% and significantly reduced the effluent discharge load compared to conventional ECF[91]. The data is summarized based on site-specific runs for a particular bleach sequence, or experimental data analyzed in a laboratory setting, so it is not appropriate to extrapolate this data for other scenarios. This makes it challenging to draw definitive conclusions to determine the low carbon bleaching technology.

From an LCA perspective, lower bleach chemical consumption correlates to lower GHG emissions in the value chain of bleach chemical production.

Similarly, lower process energy requirements drive lower GHG impacts. Based on review of EU BAT[92] for the pulp sector and other literature, the key takeaways are:

- The bleach chemical dosage, bleaching sequence and temperature profile for ECF and TCF needs to be tailored to not only according to the type of raw material (pulpwood or cotton linters), but also the purity requirements of DP (i.e., alpha cellulose content) and brightness levels. Higher alpha cellulose content and brightness may require a higher dosage of bleach chemical inputs, which can contribute to an increase in the GHG impacts. Lower bleaching temperature profile will reduce the energy demand, thereby decreasing the GHG impacts.
- Bamboo contains higher ratio of extractives (i.e., impurities other than lignin and hemicellulose) and thus requires higher concentration of bleach chemical inputs compared to eucalyptus and other tree species. Bamboo DP production is more GHG intensive than eucalyptus pulp and likely other types of pulp.
- The impact to produce ozone (for TCF) is similar to chlorine dioxide production (for ECF) so it depends on the amount of ozone and ClO_2 bleaching input for these technologies. Ozone is a stronger bleaching agent compared to ClO_2 and chemical consumption of ozone is lower.
- Best practice is to enable a closed-loop bleaching process using ultrafiltration, flotation and separation processes to optimize the bleach chemical inputs and mitigate GHG impacts.

4.2.2.4 MMCF Production

Dissolving pulp (DP) is dissolved in a chemical solution (exact solution varies by MMCF type) and regenerated into MMCF from the solution into a shape suitable in diameter and length for use in textile and nonwoven applications. Table 14 lists the current geographic scope of the study and outlines the main MMCF producing countries, by source of MMCF and the corresponding dissolving pulp producing regions. With the exception of two integrated MMCF mills (located in Austria and Indonesia) with vertically integrated pulp and fiber operations, in the current landscape, most of the MMCF mills are non-integrated and DP is transported via ocean freight across continents to MMCF mills. For example, in 2015, China only produced 3.5% of the global DP production but imported nearly 51% of the global DP production to manufacture MMCF[93]. Note that pulp can flow beyond the geographic locations listed in the table below as MMCF mills often use a mix of dissolving pulp produced across multiple locations.

Table 14.

Geographic scope of MMCF production, by pulp source for the current assessment.

Sources of MMCF	Dissolving Pulp Production Regions	MMCF Production Regions
VSF from managed temperate forests	Europe, Canada, USA	India, China, Indonesia, Austria, Germany, USA
VSF from boreal forests	Canada	China
VSF from plantations converted from intact forest landscapes*	Indonesia	Indonesia, China
VSF from plantations established on degraded lands or other areas**	Indonesia, South Africa, Brazil	India, China, Indonesia
VSF from bamboo plantation	China	China
VSF from cotton linters	China, USA	China, USA
VSF from recycled pulp	Sweden, Netherlands, USA	China, Austria, Germany
Lyocell	Europe	China, Austria, USA
Modal	Europe, Canada, South Africa, USA	India, China, Austria
Acetate	USA, South Africa and Canada	USA

*Plantations converted from intact forest landscapes considers the conversion of primary forests within intact forest landscapes (IFL) defined by http://intactforests.org/ to establish wood fiber plantations. IFL identifies unfragmented forest landscapes with high conservation value critical for stabilizing terrestrial carbon storage, maintaining biodiversity and which does not exhibit any alterations by human activities[94].

**Plantations established on land which is degraded or does not cover any primary forest.

Viscose and modal are produced using xanthation, a derivatized process in which dissolving pulp is immersed in caustic soda (sodium hydroxide) prior to chemical reacted with carbon disulfide (CS_2) solvent (cellulose xanthate) prior to being dissolved in caustic soda to form dope solution. This is followed by a sequence of key processes including (i) ripening, (ii) spin bath preparation (using sulfuric acid, zinc sulfate and sodium sulfate), (iii) wet spinning (viscose solution is extruded through a spinneret into an acidic bath) and (iv) after treatment (drying, desulfurization, bleaching, washing, etc.). Modal is a second-generation technology, essentially a modified viscose process which requires additional pulp and chemical inputs compared to viscose.

In contrast to the viscose process, lyocell is produced by direct dissolution of dissolving pulp in N-methylmorpholine-N-oxide (NMMO) solvent and eliminates carbon disulfide and sodium hydroxide inputs. Acetate fibers are manufactured by (i) combining dissolving pulp with acetic acid to make cellulose acetate, (ii) dissolving cellulose acetate in acetone solvent and (iii) dry spinning of fibers.

Table 15 outlines the key production parameters required for viscose, lyocell, modal and acetate production and highlights the fundamental processing differences between the four types of MMCF.

Table 15.

Typical production parameters, by MMCF type.

MMCF production parameters	Viscose Staple Fiber (VSF)[95]	Lyocell Staple Fiber	Modal Staple Fiber	Acetate[96] (Filament Yarn)
Production Method	Xanthation	Direct dissolution	Xanthation	Acetylation
Pulp consumption (kg/metric ton)	1035-1100	No data	1150-1200	No data
Solvent for pulp dissolution	Caustic soda ($NaOH$), Carbon disulfide (CS_2)	N-methylmorpholine-N-oxide (NMMO)	Caustic soda ($NaOH$), Carbon disulfide (CS_2)	Acetic acid, Acetic anhydride, sulfuric acid, acetone
Caustic consumption (kg/metric ton)	500-700 $NaOH$	No data	900-1700 $NaOH$	No data
Solvent consumption (kg/metric ton)	80-100 CS_2	10-30 NMMO	130-160 CS_2	No data
MMCF spinbath composition	Sulfuric acid, zinc sulfate	Not applicable	Sulfuric acid, zinc sulfate	No data

MMCF production parameters	Viscose Staple Fiber (VSF)[95]	Lyocell Staple Fiber	Modal Staple Fiber	Acetate[96] (Filament Yarn)
Sulfuric acid consumption (kg/ metric ton)	600-1030	Not applicable	950-1650	No data
Chemical Recovery technology	CAP, Condensation: CS2; Sulfuric acid: WSA	No data	CAP, Condensation: CS2; Sulfuric acid: WSA	No data
Facility Energy consumption (GJ/ metric ton)	26-33	No data	32-48	No data
Solvent recovery	75-90%*	99.9%	75-90%*	97%
Spinning Method	Wet spinning	Wet spinning	Wet spinning	Dry spinning
By-products from MMCF Production process	Sodium sulfate	Not applicable	Sodium sulfate	Not applicable

***90% recovery achieved with Carbon Disulfide Plant (CAP) and Wet sulfuric acid plant (WSA)**

Viscose and modal technologies generate sodium sulfate as a co-product from the spin bath process (chemical reaction of sulfuric acid and sodium hydroxide) and is sold to other industries. During the process of regenerating dissolving pulp as viscose and modal fibers in an acid spin bath, carbon disulfide (CS2) and hydrogen sulfide are released as exhaust gases of which 75-90% of CS2 solvent can be recovered depending on the recovery technology deployed on-site. Lyocell and acetate processes are closed loop production processes with 99.5% of NMMO and 97% of acetone solvent recovery respectively.

From an LCA perspective, key climate hotspots associated with MMCF mills include:

- *Process energy requirements for pulp dissolution process to prepare MMCF dope solution*: GHG emissions are driven by the source of energy used at the mill. Non-integrated mills may either generate steam on-site and/or purchase electricity from the grid. The grid mix of a region can influence the GHG profile of MMCF mills. Existing LCA studies show that MMCF mills located in Asia (China, India, Indonesia, etc.) can have higher climate impacts associated with MMCF production compared to European MMCF mills due to a coal dominated energy grid mix and heat generation. Integrated pulp and MMCF mills are more energy efficient compared to non-integrated pulp mills, driving lower GHG emissions because pulping operations use renewable energy[97] (by-products such as black liquor, bark waste, etc.) for on-site energy production and generate excess energy which is sufficient to meet the energy demand of fiber operations.
- *Caustic soda production for viscose and modal*: this is the main chemical input required for dissolving pulp to regenerate fiber. As discussed earlier in Section 4.2.2.2, caustic soda is one of the main contributors to GHG impacts at the MMCF mill because it is an energy intensive chemical. Best practice is to produce caustic soda using mercury-free technology such as membrane cell technique to mitigate GHG impacts.
- *Closed loop manufacturing process for viscose and modal*: Best practice is to enable a closed-loop process by deploying state-of-the- art carbon disulfide (CS2) and sulfur recovery technologies to recover up to 90% of CS2 and recycle sulfuric acid using CAP and WSA technologies respectively.
- *Modal production technology is relatively GHG intensive*: Although viscose and modal are produced using the same method, modal requires more pulp and chemical input compared to viscose so it is more GHG intensive.
- *Low carbon MMCF*: Based on current knowledge, the following provides a brief list of guidance for selecting low carbon MMCF. Refer to Section 6.1 for detailed guidance on low carbon MMCF.
  - *Low carbon dissolving pulp source*: Pulpwood from forests and plantation sites with net GHG removals from land use and land use change activities are a low-carbon feedstock for MMCF production. Note that while this study provides country-level estimates of potential net forest GHG fluxes, site specific assessment is required to determine whether forestry activities have a positive effect on the ecosystem. Furthermore, recycled dissolving pulp produced from waste textiles and dissolving pulp produced from agricultural waste such as bagasse, rice straws, etc. have the potential to become low carbon feedstocks for MMCF production, when production technologies are optimized, large scale is achieved and supply logistics are favourable.
  - *Lyocell production*: Lyocell production technology is lower in carbon compared to viscose and modal due to (i) reduced caustic consumption; (ii) elimination of carbon disulfide and sulfuric chemicals; (iii) 99.9% NMMO solvent recovery.
  - *Integrated MMCF production*: Integrated pulp and fiber production is more energy efficient and has the potential to reduce overall energy use.

5.
Key Gaps

5.1
Inconsistencies/ Factors influencing LCA modeling

In addition to the key gaps documented in Phase 1 of the report[98], this section highlights the gaps specific to MMCF. The mapping of current LCA landscape for MMCF revealed key data gaps, inconsistent modeling approaches and lack of standardized methodology, which makes it inappropriate to compare the environmental performance of one fiber over the other. Overall, datasets lack geographic variability and transparency with respect to climate impacts from land use and land use change activities. In general, existing LCAs on MMCF are not comparable due to the following overarching issues:

5.1.1 Inconsistent time period of data collection

Existing LCAs are modeled with foreground data which is predominantly over 10 years old. LCAs only present a snapshot in time of a specific location and forestry site as progress in process technology would not be captured in the data, so it may not be appropriate to extrapolate results calculated over a decade ago to inform current policies.

5.1.2 Credits applied for biogenic carbon stored in the product

Most MMCF LCAs assign a product biogenic carbon credit based on the biogenic carbon content of MMCF (around 0.39-0.44 kgC/kg fiber). The Product Environmental Footprint (PEF) guidance[99] and ISO 14067[100] standard states that biogenic carbon content of an intermediate product at factory gate shall be reported separately and cannot be included in the net GHG emissions. Furthermore, PEF guidance specifies that for final products, credits can only be accounted when the carbon is stored beyond 100 years in a product.

5.1.3 LCA modeling of climate impacts from land use and land use change

The climate impacts of land use, emissions as well as removals / sequestration, are a topic of debate in the scientific community and concerns all bio-based fibers, cotton, MMCF, and biobased polyester. For example, the time frame in which emissions from biological systems should be accounted for is an important element of the scope of studies on forest products, as well as the spatial frame, whether a single forest stand or a whole landscape is considered. The Greenhouse Gas Protocol is currently "developing new standards/ guidance on how companies and organizations should account for greenhouse gas emissions and carbon removals from land use, land use change, bioenergy, and related topics in their greenhouse gas inventories, building on the Corporate Standard and Scope 3 Standard[101]."

5.1.4 Implication of choice of LCA software and use of different LCA databases

The background LCA databases and selection of LCA software can influence the overall LCA results. It is important to review the LCA software and background data sources and databases used to model LCAs when interpreting data. It is evident that choice of LCA databases to model the background processes and LCA software induces a significant degree of variability in LCA results. LCA results can also vary when different versions of the same LCA database are used. For example, the electricity datasets in ecoinvent LCA database (version 2) were updated to version 3.0, with the update having a significant influence on the LCIA results of almost all products.

5.1.5 Use of different LCA methodology

LCAs apply different climate impact assessment methods including IPCC 2007 GWP 100, IPCC 2013 GWP 100, GWP-20, CML, Recipe, and ILCD, which may make them incomparable due to differences in the characterization factors. For example, the current Global Warming Potential (GWP) of nitrous oxide (N2O) is 265 (based on the latest IPCC 2013 GWP-100 method) but majority of the existing LCA studies used values of either 310 (IPCC 2007) or 298 (older CML method). Nitrous oxide emissions is the single biggest contributor to GHG impacts from field emissions from cotton farming, so using different LCA methods can have a relevant influence on the climate impacts of cotton. Similarly, the GWP of methane has increased from 21 $kgCO_2e$ (IPCC 1995), to 25 (IPCC 2007) and 28-34 (IPCC 2013).

5.2 Data gaps and limitations

- **MMCF:** *Studies exclude soil carbon balances*: Rate of soil carbon accumulation is influenced by changes in land management[102] activities or land use change activities and can play a significant role in the environmental profile of MMCF.
- **MMCF:** *Poor data quality for NMMO solvent production*: Existing LCAs on lyocell production use secondary data for estimating impacts from NMMO solvent production.
- **MMCF:** *Poor data quality for assessing pulpwood harvest impacts*: It is critical to improve data quality of pulpwood harvest process by using site-specific carbon stock assessments to reflect the differences in forest practices and capture benefits of managed forests/plantations and certified forests.
- *MMCF datasets are aggregated so lack of transparency*: Majority of LCA data made available for MMCF production are aggregated and do not provide a breakdown of impacts by key processes (wood harvest/ non-wood source processing, dissolving pulp production and MMCF production). As of the MMCF mills are non-integrated, it makes it challenging to identify the hotspots in the supply chain and understand the influence of differences in feedstocks and sourcing locations.
- MMCF data on recycling: existing LCA studies have data from pilot operations, which need to be extrapolated to full scale operations which are orders of magnitude larger. There is a degree of uncertainty embedded in extrapolation of results based on current data.

It is important to be aware that some of the above-mentioned challenges and gaps may be relevant for LCA studies of other product systems such as cotton, polyester, not only for MMCF fibers. Thus, Industry need to make concerted efforts to create harmonized approaches through existing multi-stakeholder initiatives such as EU PEF development of apparel and Higg products methodology.

6.

Recommendations Based on Current Knowledge

The diversity and variability in conditions to produce MMCF makes it difficult to provide a uniform, fixed set of universal recommendations to source low carbon fibers. There is no one-size fits all approach and the purpose of this report is to serve as an important starting point for harmonizing LCA data collection and improve climate modeling to better inform low carbon sourcing decisions. Due to inconsistencies in LCA modelling and comparability issues associated with existing LCA studies on MMCF, based on consultation with experts, it was determined that it would be inappropriate to provide quantitative GHG emission data for each fiber type on a regional level. The recommendations provided in this report are only based on current knowledge of the LCA landscape of MMCF fibers and is intended to serve as a foundational piece of work for the textile and apparel sector stakeholders to work towards harmonizing climate accounting and policy through improved data collection, consistent methodology, and reporting metrics. Section 6.1 discusses the low carbon MMCF sources and actions that could be undertaken to reduce GHG emissions.

6.1

Man-Made Cellulosic Fibers (MMCF)

The GHG profile of MMCF is heavily influenced by the type of feedstock and location of feedstock production. The qualitative matrices in Table 4 and Table 5 provides a better understanding of the relevant parameters that influence the GHG emission profile of MMCF. The following identifies the top three low carbon sources of MMCF (ranked from lowest to highest source of GHG). *Note that the current list excludes acetate from the comparison due to limited access to LCA data.*

1. **Lyocell from low-carbon wood pulp or optimized recycled pulp**
2. **Viscose from low-carbon wood pulp or optimized recycled pulp**
3. **Modal from low-carbon wood pulp or optimized recycled pulp**

Based on gate-to-gate MMCF mill energy and chemical input consumption data, it can be concluded that lyocell technology is lower in carbon, followed by viscose and modal. **Lyocell** fiber is a low carbon MMCF production method and when produced *using low-carbon wood pulp or optimized recycled pulp and low carbon energy sources*, it has the potential to be the most favorable option for sourcing low carbon MMCF. However, recycled pulp is an emerging development and companies are investing in recycling technologies.

Based on current knowledge of findings presented in Section 4.2, the following recommendations are summarized below in decreasing order of importance. *It should be noted that process conditions are very site specific and can vary depending on the feedstock, technology and energy sources so apply caution before using this study to definitively draw comparison between MMCF fibers.*

6.1.1 Replace high impact pulp sources with low impact pulp sources

Replacing high impact pulp sources with the following feedstocks has the potential to produce low carbon MMCF:

- Pulpwood from managed forests in Europe, USA and plantations grown on degraded agricultural lands that are not prioritized for forest restoration or pulpwood plantation established on land with low carbon stocks
- Replacing wood pulp with low carbon non-wood feedstocks such as waste textiles and agricultural wastes has the potential to reduce GHG emissions of MMCF if technology is scaled, the operations are optimized and if a clean energy mix is used for MMCF production. On an annual basis, US generates 16.9 million tons of discarded clothing[103], EU discards around 5.8 million metric tons of textile[104] and China disposes nearly 26 million tons of clothing105. The recycling rate in US is estimated to be 13.6% and less than 1% in China. Initial studies suggest that approximately 1.1-1.2 metric tons of waste textile scraps are required to produce 1 metric ton of recycled pulp. Currently, there are small scale recycled pulp facilities in Sweden and startups in USA and Netherlands are scaling up their technology to enhance the capacity of recycled pulp production. Based on the current landscape, **recycled dissolving pulp** is a promising low carbon source/feedstock for producing MMCF (viscose, lyocell and modal) but the technology is still emerging and requires significant investment to scale and optimize.

6.1.2 Low carbon DP production practices

- *Biorefinery technology is more energy efficient*: Best practice to lower GHG emissions would be to operate DP mills as biorefineries and minimize the energy and resource inputs and maximize the potential of wood inputs, by generating multiple valuable products such as lignosulfates, bioenergy106 (from black liquor, bioethanol), acetic acid, etc. in addition to dissolving pulp.
- *Improve pulp yield*: Pulping technology must be designed according to the wood chemistry and composition, as it will determine the pulp yields. Higher pulp yields will reduce energy and wood input requirements, thereby mitigating GHG emissions.
- *Optimize bleach chemical dosage and formulation in DP production*: The bleach chemical dosage, bleaching sequence and temperature profile for ECF and TCF needs to be tailored to not only according to the type of raw material (e.g., pulpwood or cotton linters), but also the purity requirements of DP (i.e., alpha cellulose content) and brightness levels. Higher alpha cellulose content and brightness may require a higher dosage of bleach chemical inputs, which can contribute to an increase in the GHG impacts. Lower bleaching temperature profile will reduce the energy demand, thereby decreasing the GHG impacts. Best practice is to enable a closed-loop bleaching process using ultrafiltration, flotation and separation processes to optimize the bleach chemical inputs and mitigate GHG impacts.

6.1.3 Low carbon MMCF production practices

The following provides an overview of the recommendation to produce low-carbon MMCF:

- *Operate MMCF mills with renewable electricity and heat*: GHG emissions are driven by the source of energy used at the mill. Non-integrated mills may either generate steam on-site and purchase electricity from the grid. The grid mix of a region and the fuel mix used for steam generation can influence the GHG profile of an MMCF mills. Existing LCA studies show that MMCF mills located in Asia (China, India, Indonesia, etc.) can have higher climate impacts associated with MMCF production compared to European MMCF mills due to a coal dominated energy grid mix. Process energy requirements for pulp dissolution process to prepare MMCF dope solution is one of the primary GHG hotspot. On-site installation of solar panels or procurement of renewable energy through contractual instruments (PPAs, RECs, GECs) has the potential to offset GHG emissions.
- *Integrated pulp fiber* mills (pulp mill with MMCF production line) are more energy efficient compared to non-integrated MMCF mills, driving lower GHG emissions, because pulping operations use renewable energy (by-products such as black liquor107, bark waste, etc.) for on-site energy production.
- *Closed loop systems for viscose and modal*: Best practice is to enable a closed-loop process by deploying state-of-the-art carbon disulfide (CS2) and sulfur recovery technologies to recover up to 90% of CS2 and recycle sulfuric acid using CAP and WSA technologies, respectively.

6.1.4 Invest in low-impact pulping technology for non-wood sources

Canopy estimates that recycling 25% of global pre-consumer/post-consumer cotton textile waste (5 million metric tons out of 20 million metric tons) and 25% of viscose textile waste (approximately 1.6 million metric ton out of 6 million metric tons) has the potential to replace all the pulpwood currently consumed for manufacturing dissolving pulp108. Diverting textiles from the landfill for textile-to-fiber recycling requires development of infrastructure for post-consumer textile collection, appropriate sorting technologies, by fiber type, especially for blended materials. It is essential for reducing GHGs from MMCF to invest in pulping technology for non-wood source and create a robust circular MMCF supply chain. Recent technology innovations have made it possible to create dissolving pulp from alternative sources such as agricultural wastes (rice straw, bagasse, hemp/flax plant waste) and can be a low carbon source of MMCF. According to Canopy, nineteen producers have made investments in innovative pulping technologies109.

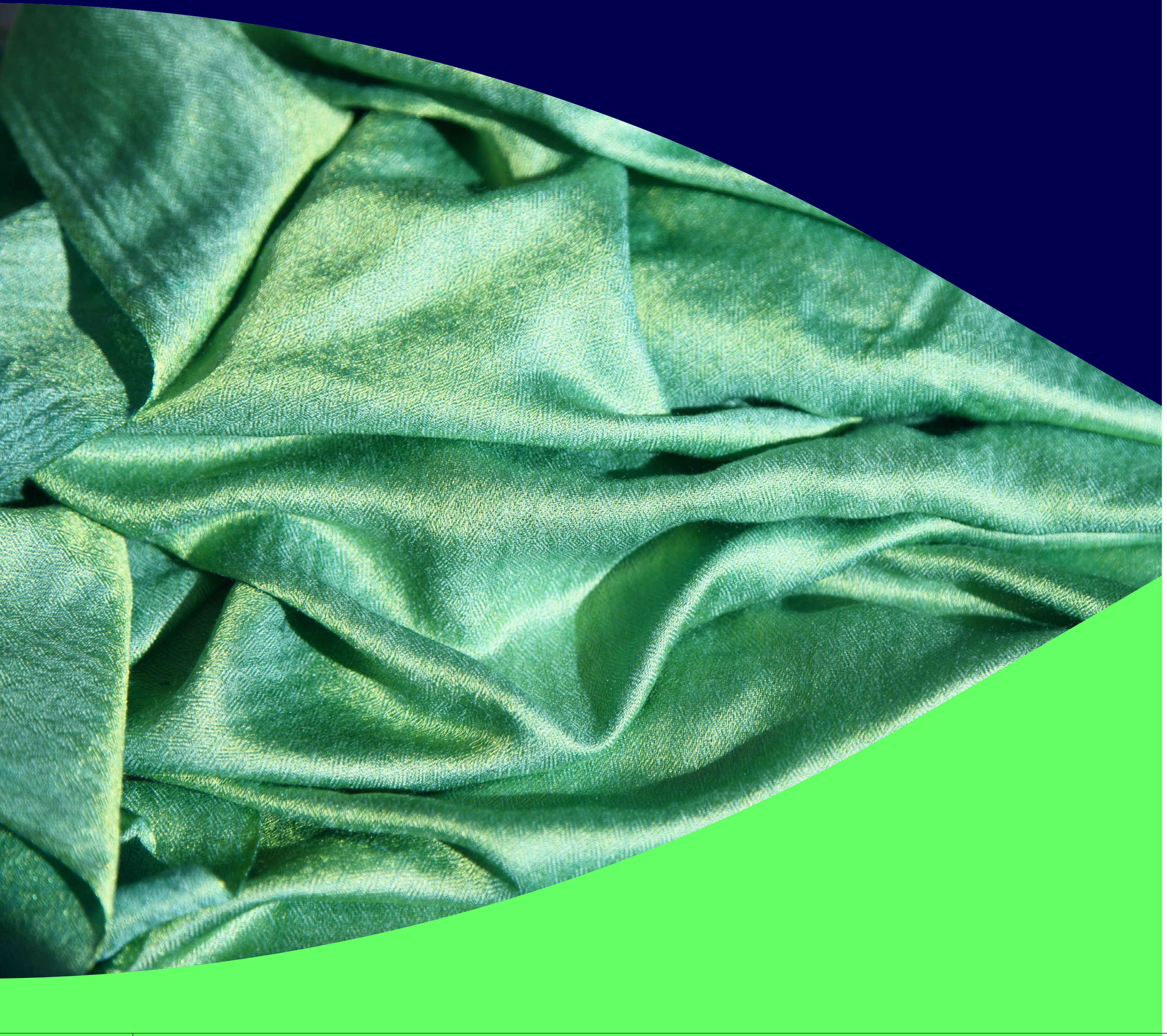
6.1.5 Increase uptake of forest management certification

Best practice is to increase the uptake of performance-oriented forest management certifications coupled with protection requirements within certified management units, and through planning and coordination beyond the boundaries of specific forest management units to look at the needs of ecosystems, to ensure responsible forest and plantation management. , Figure shows that countries with a higher percentage of certified forest areas (predominantly Europe) exhibit stable or a net increase in forest area. In contrast, countries with lower percentage of certified forest area correlates with a decrease in net forest cover area. Current MMCF supply-chain interventions in the form of responsible forest management and sourcing commitments, forest management certification schemes such as FSC, CanopyStyle audits, have made good progress over the past few years, but more work needs to be done. It is necessary to be aware of the nuances of forest management and Chain of Custody (CoC) certification schemes. While CoC is a process by which the mill can prove that the ability to track the origin of fiber inputs, and has the ability to segregate certified fiber from non-certified fiber, it does not mean that all the fiber is sourced from a certified forest. It differs from a forest management standard, which certifies the forest management area (i.e., pulpwood sourcing area). While forest certification has been effective in improving forest management, it is not a foolproof system to halt deforestation, forest degradation and illegal logging.

6.1.6 Low carbon technology for caustic soda production

Caustic soda (sodium hydroxide) is the main chemical input used for dissolving pulp and MMCF production. Best practice is to procure or produce caustic soda using membrane cell technology compared to mercury cell and diaphragm cell technologies.

7. Next Steps with Existing Materials



7.1

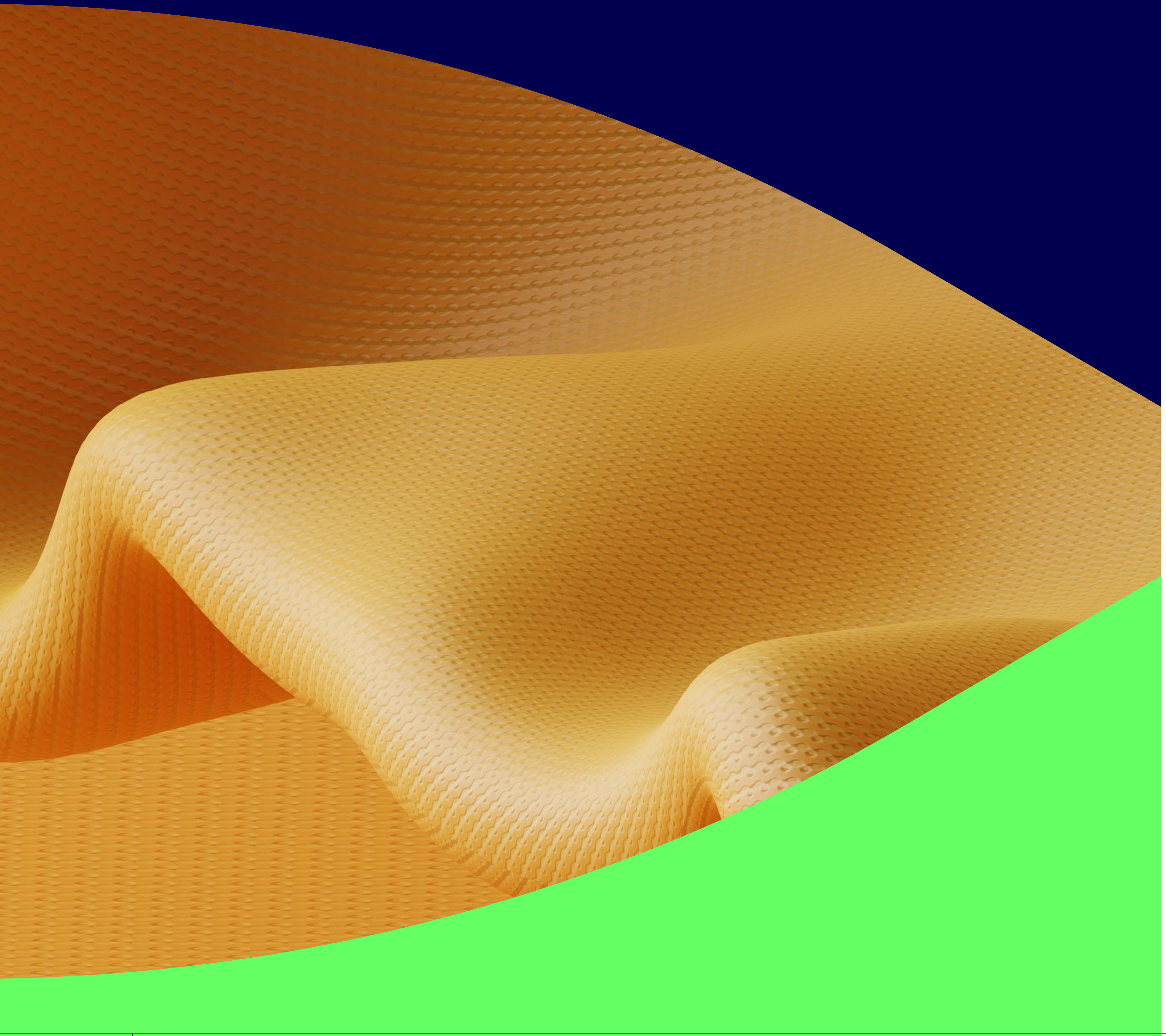
Increase the uptake of certifications

In MMCF, it is valuable to increase the uptake of forest certifications.. On the big picture, a higher share of performance-oriented certified fibers helps the overall climate impact of the global MMCF portfolio. A quantitative assessment to say how much better a certified fiber is compared to a non-certified is at this stage not possible or has to remain very crude. There is no translation of forest certification into LCA currently. A Carbon Monitoring Tool by FSC has been recently published .

The reality of forest product certification in fashion is still that the chain of custody ends mostly at the fiber product. It does not usually go all the way to an apparel product in the store. Recent individual product lines from designers or small brands are a remarkable exception.

8.

Potential for New Fibers



Textile recycling technologies provide an encouraging solution to close the loop on MMCF production, relieving the burden on virgin resources and reducing textile waste. Two key forms of textile recycling exist; mechanical and chemical.

Mechanical recycling is more established but requires high purity feedstock and results in shorter fibers during the recycling process. It can also reduce the performance at yarn and fiber stage so is not fully circular.

Chemical recycling technologies are best placed to tackle the bulk of textile waste, producing fibers of identical (or in some instances superior) quality. That said, key barriers still exist to scaling this technology, particularly around offtake and financing.

Technologies in this space can be broken into two key areas:

- those that recycle cotton from pure waste cotton garments
- those that extract cotton from blended fibers

Technologies dealing with blended waste streams are generally less mature than other recycling technologies. This is in part due to the challenge in separating the fibers from blended garments – leading to long R&D times as well as significant investment required. However, given its been estimated 40% of the textile waste stream is comprised of blended garments, they are tackling an immense problem with a huge opportunity to bring high-value recycled fibers to market at scale

Alongside those that use recycled cotton or cotton blends as feedstock there are also a number of innovators who are using agricultural waste by-products as a feedstock in the production of MMCF fiber. In doing so, they are reducing the reliance on virgin raw material extraction and thus contributing to greater circularity in the industry.

A.
Appendices

A.1
Literature Review Criteria

Questionnaires were shared with MMCF manufacturers for data collection and Table 16 includes the list of parameters included for the literature review criteria for MMCF LCA studies.

Table 16.

Literature review criteria for MMCF LCA studies.

Review Criteria for MMCF	
STUDY REFERENCE/DATA SOURCE	1. Study Name
	2. Date of source
	3. Authors
	4. Who commissioned the study (who paid for it)
	5. Type of study (LCA report (R), peer-reviewed journal paper (J), conference paper (C), master's thesis (T), book chapter (B), or other type of report (OR))
	6. Cross referenced data sources
SCOPE	7. Goal of the study
	8. Scope
	9. Functional Unit (FU)
	10. Geographic Scope of MMCF mill

Review Criteria for MMCF	
GHG Emissions per Metric Ton of MMCF Fiber for KEY PROCESSES	11. Pulpwood Harvest
	12. Credit for Biogenic Carbon Stored in pulp
	13. Dissolving Pulp Production
	14. Credits for by-products at Dissolving Pulp Mill
	15. MMCF Production
	16. Waste Collection
	17. Recycling Process
	18. Credits for by-products at MMCF mill
	19. Climate Change results with credit (kg CO_2e/FU)
	20. Any credits assigned (e.g. biobased carbon content)? If yes, specify in kgCO_2e/FU
	21. GHG emissions from Land Use Change (LUC): (kg CO_2e/FU)
	22. Pulpwood Harvest (Baseline)- kg CO_2e/t MMCF fiber
	23. Dissolving Pulp Production (Baseline) kg CO_2e/t MMCF fiber
	24. MMCF Production (Baseline) kg CO_2e/t MMCF fiber
	25. TOTAL Pulpwood Harvest+Dissolving pulp+MMCF production kg CO_2e/t MMCF fiber
	26. Any credits assigned (e.g. biobased carbon content)? If yes, specify in kgCO_2e/FU

Review Criteria for MMCF	
GHG Emissions per Metric Ton of MMCF Fiber for SUB-PROCESSES	27. Is data available for sub-processes? (Y/N)
	28. 1. TOTAL Chemical production (solvents+salts+acids+alkali bath,etc,)
	29. 1.a Caustic soda/Sodium hydroxide (NaOH) production
	30. 1.b Solvent production for regenerating MMCF (e.g. Carbon disulfide, CS2, acetic acid, etc.)
	31. 2. Dissolving pulp production
	32. 3. Total Energy production (Steam, electricity, gas, etc.)
	33. 3.a Electricity production
	34. 3.b Steam generation
	35. 4. Transport from DP mill to MMCF mill
METHOD	36. LCA Methodology
SOIL	37. Are Soil C fluxes (i.e. soil C sequestration., soil C losses,etc.) included?

Review Criteria for MMCF	
STUDY REFERENCE/DATA SOURCE	38. Feedstock for dissolving pulp (softwood, hardwood, eucalyptus, bamboo, cotton linters)
	39. Specify the tree species (e.g. pine, acacia,spruce, eucalyptus, etc.)
	40. Region of pulpwood harvest
	41. Wood Sourcing: Certified/Managed forest? (e.g. FSC, PEFC, SFI certified?)
	42. Pulping technology for dissolving pulp (sulfite v/s kraft)
	43. Bleaching technology for dissolving pulp (ECF or TCF?)
	44. Dissolving pulp mill location
	45. Wood input per metric ton of pulp (kg /metric ton MMCF)
	46. By-products at DP mill? If yes, then specify
	47. Specify energy source used for dissolving pulp (e.g. wood chips, gas, diesel, purchased electricity, purchased steam, etc.)

Review Criteria for MMCF	
MMCF production parameters	48. Pulp consumption: Enter the amount of pulp input per metric ton of MMCF(kg/metric ton)
	49. Caustic soda (NaOH) consumption (kg/metric ton MMCF)
	50. Sulfuric acid (H2SO4) consumption (kg/metric ton MMCF)
	51. Carbon disulfide(CS2) consumption (kg/metric ton MMCF)
	52. Specify energy source used for fiber production (e.g. wood chips, gas, diesel, purchased electricity, purchased steam)
	53. Specify the SOLVENT used in MMCF production
	54. SULFUR RECOVERY: Is there a technology in place to recover sulfur from Carbon disulfide (CS2) emissions? Specify the type of recovery technology
	55. Enter the % carbon disulfide (CS2) recovered from the process
	56. MMCF spin bath composition
	57. SULFATE RECOVERY: Do you have a technology in place to recover sulfates (e.g. sodium sulfate salt)? Specify the type of recovery technology
	58. Grade of fiber/yarn produced?
	59. BY-PRODUCTS: Do you generate any by-products in the MMCF production process? If yes, specify the by-products
	60. Do you sell the by-products
	61. After treatment of fiber

Review Criteria for MMCF	
NOTES ON DATA COLLECTION, ASSUMPTIONS & PROCESSING FROM REVIEWED STUDIES	62. Primary data
	63. Primary data collection period
	64. Secondary data
	65. Database used for modeling
	66. LCA software?
	67. Notable Assumptions
	68. Notable Limitations
	69. Key Conclusions/Findings from the Study
	70. Comments
	71. Included in the Study
	72. Excluded in the Study
SCORES	73. Higg MSI Score
	74. Canopy Hot Button Ranking (Total Buttons)

A.2

Data Sources and References

Table 17.

Data sources reviewed for MMCF

#	MMCF Type	Study Name	Publication Date	Authors	Commissioner of Study	Geographic Scope/ Country of MMCF mill	Cross-referenced data sources
1	Acetate	Anonymous	2018	Anonymous	Anonymous	USA	
2	VSF	Anonymous	2019	Anonymous	Anonymous	India, China	
3	Modal	Anonymous	2019	Anonymous	Anonymous	India, China	
4	VSF	Life Cycle Assessment Comparing Ten Different Sources of MMCF	2017	Schultz & Suresh et. al		China, Germany	
5	VSF, Modal, Lyocell	Life Cycle Assessment of man-made cellulose fibre	2010	Li Shen. et.al	Lenzing	Austria, Asia	Higg MSI
6	Recycled pulp	Anonymous	2020	Anonymous	Anonymous	USA	
7	Recycled pulp	The life cycle assessment of cellulose pulp from waste cotton via the SaXcell™ process	2017	Oelerich et.a;		Netherlands	
8	Dissolving pulp	Environmental life cycle assessment of a Swedish dissolving pulp mill integrated biorefinery	2011	González-García et.al		Sweden	

#	MMCF Type	Study Name	Publication Date	Authors	Commissioner of Study	Geographic Scope/ Country of MMCF mill	Cross-referenced data sources
9	Dissolving pulp	NEPD-135-298-EN Cellulose (korr des2019)	2016	Ellen Soldal and Ingunn Saur Modahl	Borregard AS	Norway	
10	VFY	EcoCosy Climate Leadership White Paper	2020	CNTAC	CNTAC	China	
11	VSF	GaBi database	2020	Sphera		Global	Higg MSI
12	VSF	ecinventv3.6 database	2019	ecoinvent		Europe	
13	VSF	iber-Bibel-Part-2	2019	Roos et.al	Mistra Future Fashion	Global	#4,5
14	VSF, lyocell, modal	EPL database	2019	pwc	Kering		
15	Pulpwood	Canopy Hot Button Ranking	2019	Canopy		Multiple	
16	VSF	EU BAT Best Available Techniques-Polymers	2007	Joint Research Center		Europe	

A.3

Global Forest Watch Data Retrieval

The following describes the steps applied to retrieve forest GHG emissions, forest carbon removals and net GHG fluxes.

Example: Indonesia

- Go to Global Forest Watch Dashboard: https://gfw.global/3hF6xhj
- To access forest GHG flux data, navigate to the “Climate” tab. Click on the “Filter and Customize” button on the “Forest-Related Greenhouse Gas Fluxes in Indonesia” chart--> Filter by “Plantations” under forest type and “Wood fiber concessions” under Land Category.

FOREST-RELATED GREENHOUSE GAS FLUXES IN INDONESIA

Between **2001** and **2020**, forests in **Indo** … and
removed **-644MtCO₂e/year**. This represe…
304MtCO₂e/year.

FOREST TYPE: All tree cover

LAND CATEGORY: All categories

CANOPY DENSITY: > 30%

>30% tree canopy and tree cover gain

FOREST-RELATED GREENHOUSE GAS FLUXES IN INDONESIA

Between **2001** and **2020**, forests within **p**
concessions, **Indonesia** emitted **164MtC**
-77.6MtCO₂e/year. This represents a net

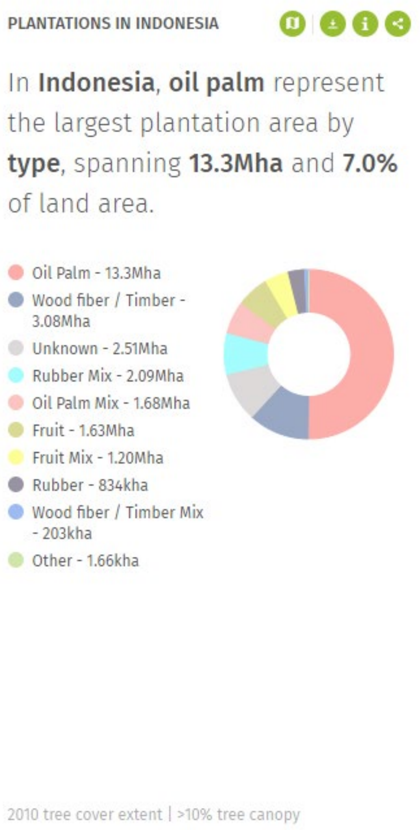
FOREST TYPE: Plantations

LAND CATEGORY: Wood fiber concessions

CANOPY DENSITY: > 30%

>30% tree canopy and tree cover gain

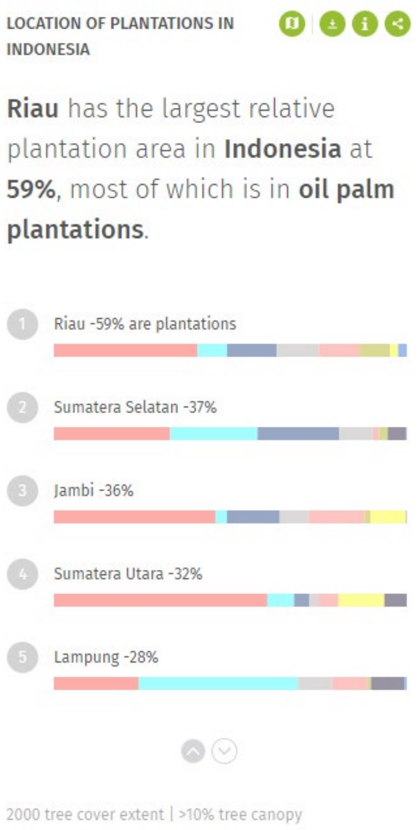
- To identify regions with wood fiber plantations, go to the "Land Cover" tab and list the regions with wood fiber plantations (indicated in blue shade in the screenshot below). And repeat the above step to retrieve forest GHG flux data, by region.
- To identify regions with wood fiber plantations, go to the "Land Cover" tab and list the regions with wood fiber plantations (indicated in blue shade in the screenshot below). And repeat the above step to retrieve forest GHG flux data, by region.
- Repeat the above procedure for other countries and regions.



PLANTATIONS IN INDONESIA

In **Indonesia**, **oil palm** represent the largest plantation area by **type**, spanning **13.3Mha** and **7.0%** of land area.

2010 tree cover extent | >10% tree canopy



LOCATION OF PLANTATIONS IN INDONESIA

Riau has the largest relative plantation area in **Indonesia** at **59%**, most of which is in **oil palm plantations**.

2000 tree cover extent | >10% tree canopy

Endnotes

1 GHG Protocol Carbon Removals Standard, Draft Terms and Definitions (2020)

2 GHG Protocol, A Corporate Accounting and Reporting Standard. Revised edition, March 2004. p. 90. https://ghgprotocol.org/corporate-standard. Accessed 16. October, 2020

3 The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. Potapov, et al. Science Advances. Vol 3. No. 1. Jan 2017.

4

5

6

7 Fashion Industry Charter for Climate Action (2021); Phase 1 (Part 1): Identifying low carbon sources of Cotton and Polyester Fibers; United Nations Climate Change

8

9

10

11 Textile Exchange Preferred Fiber & Materials Market Report 2020.

12 Global Fashion Agenda & The Boston Consulting Group (2017) *Pulse of the fashion industry*. www.copenhagenfashionsummit.com/wp-content/uploads/2017/05/Pulse-of-the-Fashion-Industry_2017.pdf.

13 Based on 2018 production statistics from Changing Markets (November 2019); Dirty Fashion Disrupted; Leaders and laggards revealed.

14 Canopy (2017) *CanopyStyle: Taking the runway by storm: Two years of collaboration*. www.canopystyle.org/assets/CanopyStye-2nd-AnniversaryEdited.pdf.

15 NOTE: 3% is a conservative estimate based on data retrieved from the FAOSTATE database .

The following assumptions were used for estimation.

Global industrial roundwood production: 2021 million m3.

Total DP: 1047 million tonnes, of which ~90% is estimated to be produced from wood sources and remaining from non-wood sources. The % wood use for DP products was estimated assuming 3-6m3 pulpwood/tonnes DP

16 Maxwell, Sean L., Tom Evans, James EM Watson, Alexandra Morel, Hedley Grantham, Adam Duncan, Nancy Harris et al. "Degradation and forgone removals increase the carbon impact of intact forest loss by 626%." Science advances 5, no. 10(2019)

17 Assessed based on data provided by the Canopy team. https://canopyplanet.org/campaigns/protecting-forests/ https://canopyplanet.org/campaigns/protecting-forests/endangered-forests-of-the-world/

18

19 https://egis.environment.gov.za/gis_data_downloads

20 FAO. 2020. Database: https://fra-platform.herokuapp.com/WO/

21 FAO. 2020. Global Forest Resources Assessment 2020: Main report. Rome. https://doi.org/10.4060/ca9825en Database: https://fra-platform.herokuapp.com/WO/

22 Greenpeace, University of Maryland, World Resources Institute and Transparent World. "Intact Forest Landscapes. 2000/2013/2016" Accessed through Global Forest Watch on 06/07/2021. www.globalforestwatch.org

23 Pacheco, P., Mo, K., Dudley, N., Shapiro, A., Aguilar-Amuchastegui, N., Ling, P.Y., Anderson, C. and Marx, A. 2021. Deforestation fronts: Drivers and responses in a changing world. WWF, Gland, Switzerland

24 Adapted from Global Forest Watch maps which display the average annual emissions from, removals (sequestration) by, and net flux of greenhouse gases between forests and the atmosphere between 2001 and 2020. The methods used to calculate these are described in Harris et al. 2021, which introduces a geospatial monitoring framework for estimating global forest carbon fluxes. The methods follow IPCC Guidelines for national greenhouse gas inventories.

Harris et al. (2021). Global maps of 21st century forest carbon fluxes. Accessed on 29/06/2021 from Global Forest Watch.

25 Note from Global Forest Watch on this dataset: Results should be interpreted with caution. The intact forest cover was created through visual interpretation of Landsat images by experts. The map may contain inaccuracies due to limitations in the spatial resolution of the imagery and lack of ancillary information about local land-use practices in some regions.

26 https://maps.fsc.org/portal/apps/webappviewer/index.html?id=fde60ed27f4a4c1b8828290376bc7108&mobileBreakPoint=300

27 Due to FAO forest definitions this does not accurately represent forest degradation

28 An important limitation of the GFW data is that only covers 2001-2020. This time period may exclude degradation occurring prior to this time including degradation from intact forests.

29 Harris et al. (2021). Global maps of 21st century forest carbon fluxes. Accessed on 29/06/2021 from Global Forest Watch.

30 Allen, M., Antwi-Agyei, P., Aragon-Durand, F., Babiker, M., Bertoldi, P., Bind, M., ... & Cramer, W. (2019). Technical Summary: Global warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

31 Pacheco, P., Mo, K., Dudley, N., Shapiro, A., Aguilar-Amuchastegui, N., Ling, P.Y., Anderson, C. and Marx, A. 2021. Deforestation fronts: Drivers and responses in a changing world. WWF, Gland, Switzerland

32 Harris, Nancy L., et al. "Global maps of twenty-first century forest carbon fluxes." *Nature Climate Change* 11.3 (2021): 234-240.

33 https://www.globalforestwatch.org/blog/climate/forests-carbon-emissions-sink-flux/

34 Pacheco, P., Mo, K., Dudley, N., Shapiro, A., Aguilar-Amuchastegui, N., Ling, P.Y., Anderson, C. and Marx, A. 2021. Deforestation fronts: Drivers and responses in a changing world. WWF, Gland, Switzerland

35 IPBES (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages. https://doi.org/10.5281/zenodo.3553579

36 Allen, M., Antwi-Agyei, P., Aragon-Durand, F., Babiker, M., Bertoldi, P., Bind, M., ... & Cramer, W. (2019). Technical Summary: Global warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

37 NYDF Assessment Partners. (2019). Protecting and Restoring Forests: A Story of Large Commitments yet Limited Progress. New York Declaration on Forests Five-Year Assessment Report.

38 UN News:https://news.un.org/en/story/2019/05/1038291

39 Allen, M., Antwi-Agyei, P., Aragon-Durand, F., Babiker, M., Bertoldi, P., Bind, M., ... & Cramer, W. (2019). Technical Summary: Global warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

40 NOTE: 3% is a conservative estimate based on data retrieved from the FAOSTAT database http://www.fao.org/faostat/en/#data/FO.

The following assumptions were used for estimation.
Global industrial roundwood production: 2021 million m3.
Total DP: 1047 million tonnes, of which ~90% is estimated to be produced from wood sources and remaining from non-wood sources.

41 FAO. 2020. Global Forest Resources Assessment 2020: Main report. Rome. https://doi.org/10.4060/ca9825en

42 Barredo Cano, J.I., Brailescu, C., Teller, A., Sabatini, F.M., Mauri, A. and Janouskova, K., Mapping and assessment of primary and old-growth forests in Europe, EUR 30661 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-34229-8, doi:10.2760/13239, JRC124671.

43 Pacheco, P., Mo, K., Dudley, N., Shapiro, A., Aguilar-Amuchastegui, N., Ling, P.Y., Anderson, C. and Marx, A. 2021. Deforestation fronts: Drivers and responses in a changing world. WWF, Gland, Switzerland

44 https://www.globalforestwatch.org/blog/commodities/global-deforestation-agricultural-commodities/ Limitations of this dataset as noted by WRI: The forest extent analysis is limited by various data and attribution issues and methodological assumptions, including the following: • Commodity data sets have limited coverage and quality. • The data cannot capture complex land-use change transitions. • The data measure tree cover loss rather than deforestation directly. • The data may miss some forms of tree cover loss.

45 https://canopyplanet.org/resources/canopystyleaudit/

46 Defined in A Quick Guide to Ancient and Endangered Forests (https://canopyplanet.org/wp-content/ uploads/2018/11/CanopyQuickGuideAncientEndangeredForests.pdf).

47 https://canopyplanet.org/tools/forestmapper/

48 FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

49 FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

50 FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

51 Global Forest Watch (accessed July 2020); https://gfw.global/31Bsiqy

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