Universität für Bodenkultur Wien
University of Natural Resources
and Life Sciences, Vienna

Master Thesis

Guideline for creating LCA inventories for wood production in the paper industry

Submitted by

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in the framework of the Master program

Stoffliche und energetische Nutzung nachwachsender Rohstoffe
(NAWARO)

in partial fulfilment of the requirements for the academic degree

Diplom-Ingenieur

Vienna, September 2022

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Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 01.09.2022 David Schwarzinger *(manu propria)*

Acknowledgements

I would first like to thank my thesis advisor Priv.-Doz. DI. Dr.nat.techn Martin Kühmaier of the Institute of Forest Engineering at the University of Natural Resources and Life Sciences (BOKU). Additionally, I would also like to acknowledge DI. Dr.nat.techn Nicole Unger as the external second reader of this thesis, and I am gratefully indebted to her for her very valuable comments and time on this thesis. The virtual door to both my advisor's office was always open, whenever I was contacting them due to some trouble spots or had a question about my research or writing. They consistently allowed this paper to be my own work, but steered me in the right direction whenever they thought I needed it.

I would also like to thank the expert who was involved in the validation survey for this research project: MSc, Denis Popov. Without his passionate participation and input, the validation survey could not have been successfully conducted.

Finally, I must express my very profound gratitude to my parents and to my girlfriend for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

David Schwarzinger

List of Abbreviations

AGB	Aboveground oven-dry live Biomass
BCEF	Biomass Conversion and Expansion Factor
BEF	Biomass Expansion Factors (BEF)
BECCS	Bioenergy with Carbon Capture and Storage
UNFCC	United Nations Climate Change Conference
CF	Characterization Factors
EF	Environmental Footprint Framework
FRA	Global Forest Resource Assessment
FSC	Forest Stewardship Council
GIS	Geo-Information System
GSV	Growing Stock Volumes (GSV)
HWSD	Harmonized World Soil Database
I/O	Input/Output
IPCC	Intergovernmental Panel on Climate Change
LANCA®	Land Use Indicator Value Calculation in Life Cycle Assessment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle impact assessment
PEF	Product Environmental Footprint
PEFC	Program for Endorsement of Forest Certification Schemes
PNV	Potential Natural Vegetation
PPI	Pulp and Paper Industry
R:S	Root-to-Shoot Ratio (R:S)
RM	Running Meter
SFM	Sustainable Forest Management
SQI	Soil Quality Index
UB	Under Bark

Table of Content

Abstract

Wood is a renewable resource, however, the degree of renewability of its production system strongly depends on the number of fossil-based inputs. Moreover, wood is a key ingredient of paper products. In the north-west federal district of Russia around 62% of the total area are utilized for logging activity of which 70% of harvested wood are used by logging enterprises. Due to the current and future environmental challenges, more and more stakeholders face the question to assess their environmental impact during the production of one's product. One possible methodology to analyze climate impacts is the life-cycle assessment framework. Carrying out a life cycle assessment can be complex and requires in depth expertise. The goal of this thesis is to propose a guideline for generating a live cycle inventory for forest products and to further analyze what aspects influence it. The initial step for creating an inventory, was an intensive desk research to gather needed information. Within this step, the data collection process is included leading to the creation of a questionnaire. In the second step the derived questionnaire is tested in a pilot case. The study site is located in the Republic Komi, Russia which is leased and managed by Mondi. This pilot was evaluated and tested against database values. In the third step, LCIA results were briefly analyzed and key impact factors identified. As a last step a guideline for LCA practitioners was created to model a forest production system. Results show that only few inputs are needed to create an inventory of forest products. Additionally, most forest operations are fuel driven, thus, diesel consumption was recognized as a key driver. In particular transportation processes of pulpwood are a key contributor to the diesel consumption. Next to global warming potential, the impact category land use was analyzed in more depth. Furthermore, data gap exists in regards of regionalized forest inventories in the LCA databases, such as Ecoinvent. If you search for “pulpwood” in Ecoinvent version 3.7.1, for example, unit processes are only based on three countries: Germany, Sweden and Switzerland. In order to model regionalized forest inventories these unit processes need to be adopted to the conditions of relevant forest production systems. Considering the advancing climate change and the need of stakeholders to model their environmental emissions, clear and understandable standards for LCI inventories are essential. This master thesis provides a guideline for LCA practitioners to model a forest production system.

Kurzfassung

Holz ist eine erneuerbare Ressource, allerdings hängt der Grad der Nachhaltigkeit seines Produktionssystems stark von der Anzahl der eingesetzten fossilen Rohstoffe ab. Darüber hinaus ist Holz ein wesentlicher Bestandteil von Papierprodukten. Im nordwestlichen Föderationskreis Russlands werden etwa 62 % der Gesamtfläche für die Holzgewinnung genutzt, wobei 70 % des geernteten Holzes von der Holzindustrie verwendet werden. Aufgrund der aktuellen und zukünftigen ökologischen Herausforderungen stehen immer mehr Akteure vor der Frage, wie sie ihre Umweltauswirkungen bei der Herstellung ihrer Produkte bewerten. Eine mögliche Methode zur Analyse der Klimaauswirkungen ist die Lebenszyklusanalyse. Allerdings kann die Durchführung einer Ökobilanz sehr komplex sein und erfordert umfassendes Fachwissen. Ziel dieser Arbeit ist es daher, herauszufinden, wie eine Ökobilanz für Forstprodukte erstellt werden kann und welche Aspekte die Bilanz beeinflussen. Der erste Schritt zur Erstellung eines Inventars war eine intensive Recherche, um die benötigten Informationen zu sammeln. In diesem ersten Schritt wurden auch benötigte Daten erhoben, die zur Erstellung eines Fragebogens führten. Im zweiten Schritt wird der entwickelte Fragebogen in einem Piloten getestet. Der Untersuchungsstandort befindet sich in der Republik Komi, Russland, und wird von Mondi gepachtet und verwaltet. Dieser Pilot wurde ausgewertet und mit Datenbankwerten verglichen. Im dritten Schritt wurden die LCIA-Ergebnisse kurz analysiert und die wichtigsten Einflussfaktoren ermittelt. Als letzten Schritt wurde ein Leitfaden entwickelt um die Modellierung von Forstmanagementsysteme in Zukunft zu erleichtern. Die Ergebnisse zeigen, dass nur wenige Daten erforderlich sind, um ein Waldinventar von Forstprodukten zu erstellen. Darüber hinaus sind die meisten forstwirtschaftlichen Produktionsprozesse kraftstoffbetrieben, so dass der Dieselverbrauch als einer der wichtigsten Einflussfaktoren erkannt wurde. Vor allem der Transport von Holz trägt wesentlich zum Dieselverbrauch bei. Neben dem globalen Treibhausgaspotential wurde auch die Wirkungskategorie Landnutzung eingehender analysiert. Des Weiteren besteht eine Datenlücke in Bezug auf regionalisierte Waldinventare in den LCA-Datenbanken, wie z.B. Ecoinvent. Sucht man z.B. in Ecoinvent Version 3.7.1 nach "Pulpwood", so werden nur drei Länder als Prozesseinheiten angezeigt: Deutschland, Schweden und die Schweiz. Um regionalisierte Waldinventuren modellieren zu können, müssen diese Einheitsprozesse an die Bedingungen der jeweiligen Waldproduktionssysteme angepasst werden. In Anbetracht des fortschreitenden Klimawandels und der Notwendigkeit für Unternehmen, ihre Umweltemissionen zu modellieren, sind klare und verständliche Standards für die Erstellung von LCA-Inventaren unerlässlich. Daher kann diese Diplomarbeit als Leitfaden für LCA-Praktiker zur Modellierung eines Forstmanagementsystems angesehen werden.

1. Introduction

“Climate change is the greatest threat facing humanity and the stakes could not be higher for our planet. The next decade will be make, or break, for cutting global emissions sufficiently to avoid the worst effects of climate change […]” said President-Designate of 2021 United Nations Climate Change Conference (COP 26), (Sharma, 2021).

Statements like the one from Alok Sharma drastically demonstrates the urgency to act against climate change. The industrial sector is one key stakeholder to facilitate the needed transition to achieve the ambitious targets that are required (Ghoneim, n.d.). Next to the increase in frequency and intensity of weather extremes (Masson-Delmotte et al., 2021), also rising expectations of customers and investors underline the importance for companies to implement climate strategies (Weirens et al., 2021).

1.1 Problem Statement

Throughout the twentieth century the pulp and paper industry (PPI) was one of the big polluters, as technologies such as chlorine bleaching etc., were still in use (Söderholm et al., 2019). This changed in the meantime due to several regulations, however the resource- and capital-intensive industry still contributes to several environmental impacts like, ecotoxicity, photochemical oxidations, acidification, nitrification and climate change (Särkkä et al., 2018). The challenge for PPI in Europe is how to realize the transformation to a low-carbon bioeconomy and deliver the necessary new green innovations. According to Toppinen et al. (2017) investments of the PPI in sustainability have great potential for change. Hence the role of sustainability becomes more and more important in reaching on the one hand its emission reduction goals on the other hand towards the future bioeconomy (Pätäri et al., 2016).

This thesis focuses on pulpwood production for the pulp and paper industry. One key aspect to successfully set reduction targets is the evaluation and measurement of environmental impacts such as greenhouse gas emissions. Around 8.6 million solid cubic meters of round wood were harvested alone for the paper industry in Austria in 2020 (Mader et al., 2020). Looking at the north-west federal district of Russia around 62% of the total area are used for logging activity of which 70% of harvested wood are used by logging enterprises (Perekopskaya & Alekseev, 2019).

Biomass is a renewable resource, but the degree of renewability of its production system strongly depends on the number of non-renewable inputs into the product system in question (Klein et al., 2015).

Additionally, Cardellini et al. (2018) states that

> *[t]he alleged carbon neutrality of forests, namely, the assumption that all removed biomass coming from sustainably managed forests will be entirely sequestered in the future, and hence can be neglected in LCA, has been questioned and disproved. - (p.3)*

As, wood is a key ingredient of a final paper product it is important to understand its overall environmental impact (Cepi, 2021).

A commonly used methodology to assess environmental impacts of processes, products or services is the life-cycle assessment (LCA). LCA is defined in ISO 14044:2006 (2006) as “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle!” – (p.2)

Furthermore, the ISO 14044:2006 (2006) states that a LCA can be divided in following four main phases: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation.

While the ISO Standards provide a structured, comprehensive and internationally standardized framework to determine environmental impacts of products or services, this standard, leaves space for interpretation and assumptions. This is e.g., due to choices of the LCA practitioner during the aggregation of emissions to certain side products, or during the system boundary setting, which all might influence the legitimacy of results of this method.

It is crucial that an LCA is based on robust methodological approaches, such as defining system boundaries, allocation decisions and a consistent nomenclature for involved processes. Additionally, during the provision of wood, a multitude of processes, from establishing the forest area to planting the trees and to the provision of raw wood material to plant gate occur. Thus, several environmental impacts must be taken into account, depending on the forest management system, used harvesting method, or transportation assumptions (Klein et al., 2015). Reliable primary data and a robust inventory will improve the quality of an LCA and, hence, provide better decision support to measure the environmental footprint of a product. Currently, data gap exists in regards of regionalized forest inventories in the LCA databases, such as EcoInvent (Wernet et al., 2016). Additionally, large differences between methodical assumptions and their subsequent results of LCAs in the forestry sector were identified (Klein et al., 2015). The high topicality of this topic is further underlined by various studies e.g., Horn et al. (2021) and institutes like the European paper industry association (Cepi), as forests are increasingly seen as a renewable energy source but also as a potential carbon sink. Thus, it crucial to understand what environmental impacts the production of timber might cause.

1.2 Research Question and Goal Definition

The overarching research question of this thesis is:

How to build a robust inventory for wood production and what aspects influence the impact assessment?

This can be broken down into the following steps:

- What inventory data (and potential data sources) are needed to model wood production for usage in the paper industry?
- Piloting the findings by modelling wood production by using primary data.
- What flows determine the impact in different LCIA methods?

The thesis is supervised by the Institute for Forest Engineering at the University of Applied Life Sciences, Vienna (BOKU). Additionally, the Sustainable Development department of MONDI Group AG, based in Vienna will support this thesis and make the link to relevant people in Mondi for primary data collection.

2. Desk Review

In the following desk review the focus was put on four overarching sections which are highly relevant for estimating the environmental impacts of forest management. First general characteristics of the forest sector were depicted. Secondly the methodology of the LCA framework is described. Thirdly forestry specific issues in the LCA are pointed out to highlight the complexity of the topic. Finally relevant impact categories were described to provide a better feeling of the existing methodology of each impact category.

2.1 Characteristics of the Forestry Sector

According to the Food and Agriculture Organization of the United Nations FAO (2018) a forest is defined as follows:

> *Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. – (p.4)*

In 2020, *Global Forest Resources Assessment* (2020) estimated 202.15 million hectares of forests in EU-27. Additionally, 815.31 million hectares are characterized in the Russian Federation, as forests. This represents 20% of the world's forest area, hence the Russian Federation is the number 1 country with the largest forest area (FAO, 2020).

Forests are multifunctional ecosystems able to provide employment and economic development next to various ecosystem services like carbon sequestration, biodiversity conservation, water regulation, erosion control, habitat, recreation space and many more *(Ninan and Innoue, 2013)*. Between 2010 and 2020, the mean sequestration rate per year of carbon in forest biomass reached 155 million tons in the European region inclusive the Russian Federation. This, sequestration equivalents around 10% of GHG-emissions. From 1990 to 2015, the carbon stock in harvested wood products rose from 2.5 to 2.8 tons of carbon per capita, hence reinforced CO_2 emission reductions (Forest Europe, 2020). Thus, forests can be seen as one of the world's most important renewable resources and key to a sustainable green transition. This is also underlined by the EU Biodiversity Strategy for 2030 by agreeing on a roadmap for planting at least 3 billion additional trees in the EU by 2030 (European Commission, 2021).

However, climate change presents a serious risk for forests globally. Changes in climate affect growth rates of forests, their land coverage and the diversity of species that they support (Eurostat, 2020). The main areas of concern are the increasing hazard to forests related to harmful organisms, mass dying of tree species and the unknown potential of tree species to adapt to changing climate conditions (Forest Europe, 2020). In addition, the frequency and intensity of weather extremes like droughts, storms, forest fires etc. increases due to climate change (Masson-Delmotte et al., 2021). Therefore, it is not surprising that 3% of European forests are impaired mainly by wind, insects, ungulate browsing, and forest fires (Forest Europe, 2020). In the first four months of 2019 in Europe alone, more wildfires have been recorded than in the total year of 2018. Even though forest areas in the EU are increasing, on a global scale deforestation stays the second-major cause of climate change after the burning of fossil fuels (EU Technical Expert Group on Sustainable Finance, 2020). In order to reverse these negative trends resilient forest ecosystems and sustainable forest management practices are crucial.

Von Carlowitz (1713) in his Sylvicultura oeconomica first defined the term sustainability, which might also be described as an idea of "lasting-ness", in the forestry sector. Since then, the concept of sustainable development has advanced and in 1993 Forest Europe laid the foundation for sustainable forest management. Forest Europe (1993) defined it as follows:

> *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 fulfil, 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. – (p.1)*

Nevertheless, further definitions and criteria were needed to promote the concept of sustainable forest management (SFM). Thus, Forest Europe defined the Pan- European criteria in 1998 for SFM (Forest Europe, 1993)*:*

- Maintenance and enrichment of forest resources and their contribution to carbon cycles
- Maintenance and reinforcement of productive functions of forests (wood and non-wood)
- Maintenance, development and appropriate conservation of biological diversity in forest ecosystems
- Maintenance of forest ecosystems' health and vitality
- Maintenance, appropriate enhancement and conservation of protective functions in forest management (notably soil and water)
- Maintenance of other socio economic functions and conditions.

With these six criteria, a set of indicators was adopted to monitor asses and report the progress of SFM. Both the indicators and the criteria were regularly updated during the Ministerial Conferences in the past twenty years.

Later other initiatives like the Forest Stewardship Council (FSC) or the Program for Endorsement of Forest Certification Schemes (PEFC) also published lists of criteria and indicators to exemplify sustainable forest management.

LCA is an adequate method to show if forest management is executed in a sustainable way For the European forest and timber industry, the first concrete life cycle assessments appeared in the 1990s with the aim of scientifically analyzing the impact of non-renewable inputs into a system (Klein et al., 2015). After that several studies were published focusing on harvesting process and transport of round wood Karjalainen (1996), as well as on general guidelines for creating a Life-Cycle Inventory of forest products (Richter & Gugerli, 1996). Figure 1 demonstrates an increase in publications with LCA related topics in the forestry of previous years. Search words such as “LCA” and “Forestry” were used for the creation of figure 1. Klein et al. (2015) related this increase to enhanced economic importance of biomass for energetic purposes.

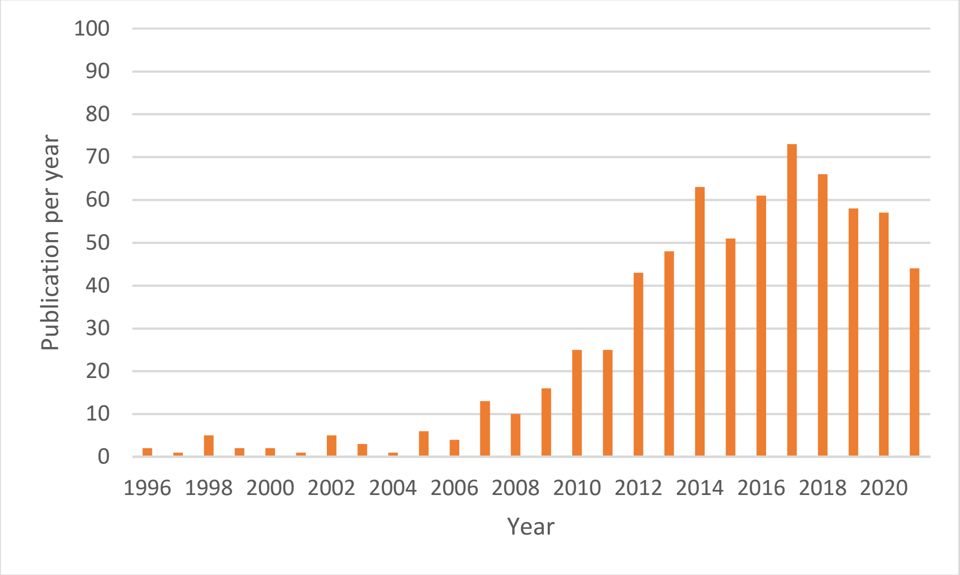


Figure 1: Number of publications related to LCA and forestry (www.scopus.com)

Nevertheless, despite the early implementation of life-cycle thinking in the forestry sector, there is still a lack of information based on scientific research (Heinimann, 2012). The reason for this may be that no forest production is LCA`s main study goal, but rather their resulting products like pellets, wood chips etc. (Klein et al., 2015).

2.2 Role of Forestry in the Bioeconomy Sector

Hetemäki et al. (2017) defines the forest-based bioeconomy as a bioeconomy which encompasses all economic activities that relate to forests and forest ecosystem services. To put this in numbers the European Union bioeconomy sector as a whole contributes to 17% of GDP and provides 9% of overall employment. Looking at the annual turnover of the EU27 bioeconomy in 2009, 13% came from forestry and wood products and 18% came from paper and pulp (European Technology Platforms, 2011). This makes the forestry sector to an important sector in the bioeconomy. As already mentioned in the previous chapter forests provide much more than only biomass. This opens up a lot of opportunities for a holistic forest-based bioeconomy, using the biomass as well as developing innovations connected to the forest ecosystem services (Hetemäki et al., 2017). The forest bioeconomy helps to move away from a fossil-based economy, however, this doesn't mean automatically that the forest-based-bioeconomy is completely sustainable. Additionally, in the fifth assessment report by the Intergovernmental Panel on Climate Change (2015) biomass for bioenergy received special attention as together with carbon capture and storage (BECCS), they were identified to have the highest potential for creating negative emissions. However, the question how to include these kind of set aside forests in a LCA framework is still unclear. This master thesis provides on the one hand a guideline for stakeholders of the forest industry on how to create a life cycle inventory for wood production to enable them to assess their climate impacts. On the other hand, it provides insights of impacts on climate change, land use and carbon stock of the production of one cubic meter wood for proposed study site. Thus, it supports the overall transition towards a sustainable bioeconomy.

2.3 Life Cycle Assessment Framework

LCA is a technique developed to better understand environmental burdens of products, manufactured and consumed. It addresses compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14044:2006, 2006). It can assist in e.g.:

- Recognizing opportunities to enhance the environmental performance of products during their life cycle
- Advising decision-makers in industry, government or non-government organizations (e.g. for the purpose of priority setting, strategic planning, etc.)
- Using it for marketing purposes
- Selection of relevant indicators of environmental performance

An LCA consists of four phases (Figure 2), (a) the goal and scope definition phase, (b) the inventory analysis phase, (c) the impact assessment phase, and (d) the interpretation phase. In the following subsection, these four phases are further described and for each phase, tasks are defined.

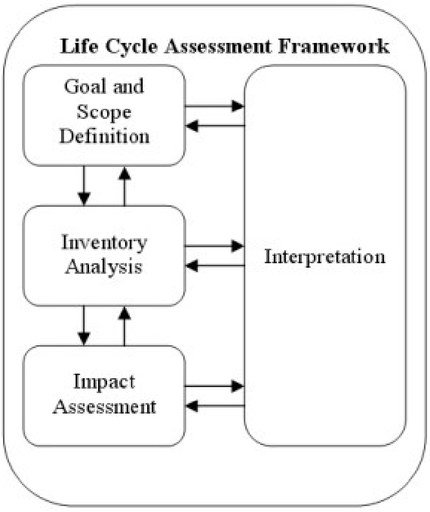


Figure 2: The four phases of an LCA ISO 14044:2006 (2006).

2.3.1 Goal and Scope Definition

The goal and scope definition phase is the beginning of every LCA. It includes the description of system boundary and level of detail of an LCA, which depends on the research object. An LCA might vary significantly in depth and breadth depending on the objective of the LCA.

The goal definition influences all other phases of the LCA as: It guides all detailed aspects of the scope definition, which further provides the framework for the LCI and LCIA work. Quality control of the work is performed with respect to the requirements derived from the objective of the work. If the work extends beyond an LCI study, the results of the LCA will be evaluated, which again is influenced by the objective of the work (European Commission, 2010). Furthermore the ILCD guidance document European Commission (2010) identifies six aspects which shall be included:

- *Intended application(s) of the deliverables / results*
- *Limitations due to the method, assumptions, and impact coverage*
- *Reasons for carrying out the study and decision-context*
- *Target audience of the deliverables / results*
- *Comparative studies to be disclosed to the public*
- *Commissioner of the study and other influential actors*

- (p.29)

During the scope definition phase, the object of the LCI/LCA is defined. It determines the requirements on methodology, quality, reporting, and review in alignment with the goal of the study. Again the ILCD guidance document clearly defines steps that shall be described to derive the scope of an LCI/LCA from the goal (European Commission, 2010):

- *The type(s) of the deliverable(s) of the LCI/LCA study, in line with the intend application(s)*
- *The system or process that is studied and its function(s), functional unit, and reference flow(s)*
- *LCI modelling framework and handling of multifunctional processes and products*
- *System boundaries, completeness requirements, and related cut-off rules*
- *LCIA impact categories to be covered and selection of specific LCIA methods to be applied as well as - if included - normalisation data and weighting set*
- *Other LCI data quality requirements regarding technological, geographical and time-related representativeness and appropriateness*
- *Types, quality and sources of required data and information, and here especially the required precision and maximum permitted uncertainties*
- *Special requirements for comparisons between systems*
- *Identifying critical review needs*
- *Planning reporting of the results*

- (p.51)

A crucial part of the scope definition is the definition of a functional unit. Without a defined function and further a functional unit a comparison or analysis of products or services is not possible. The definition is usually done by using the functional unit of analysed product which states and quantifies the qualitative and quantitative aspects and further answer questions “what”, “how much”, “how well”, and “for how long” . Next to the functional unit which clearly defines the function of the product or service, the reference flow is the flow to which other included input and output flows e.g., elementary flows, waste flows etc. of the product relate. It can relate directly to the functional unit or more product related (European Commission, 2010).

2.3.2 Inventory Analysis

During the inventory analysis phase (LCI), relevant input and output data are collected and further implemented in an inventory to meet the goals of the study (Figure 3). Sources, details about collection processes, time and quality of data indicators shall be referenced (ISO 14044:2006, 2006). Usually the inventory analysis phase is the most time-consuming step of an LCA as data collection, acquisition and modelling need to be conducted. The results of the LCI are the input for the next phase, the LCIA. During the LCI phase data from e.g., environmental, product and waste flows are gathered. Additionally, other information which are relevant for the analyzed system like, statistical data, process and product characteristics etc. are identified. Hence, LCA practitioners focus the data collection process on only selected activities, so called foreground system and base the rest of the study on the background system such as integrated LCI databases. Furthermore, foreground data are understood as the data which reflect the target products accurately (Curran, 2008). Usually, the background system amounts for 99% of unit processes in the modelled system. Thus, quality and availability of unit process data presented by the LCI databases are crucial for an LCA study (Steubing et al., 2016). Although, these forest production unit processes build the very bases for subsequent processes, e.g. wood chips etc., they are often incapable to model and include the conditions of the actual case study (Cardellini et al., 2018).

Depending on the deliverable of the study following steps are required (European Commission, 2010):

- *Identifying the processes that are required for the system*
- *Planning of the collection of the raw data and information, and of data sets from secondary sources*
- *Collecting (typically) for the foreground system unit process inventory data for these processes. An important aspect is the interim quality control and how to deal with missing inventory data*
- *Developing generic LCI data, especially where average or specific data are not available and cannot be developed, typically due to restrictions in data access or budget*
- *Obtaining complementary background data as unit process or LCI result data sets from data providers*
- *Averaging LCI data across process or products, including for developing production, supply and consumption mixes*
- *Modelling the system by connecting and scaling the data sets correctly, so that the system is providing its functional unit.*
- *This modelling includes solving multifunctionality of processes in the system.*

- *Calculating LCI results, i.e. summing up all inputs and outputs of all processes within the system boundaries. If entirely modelled, only the reference flow ("final product") and elementary flows remain in the inventory.*

- (p.154)

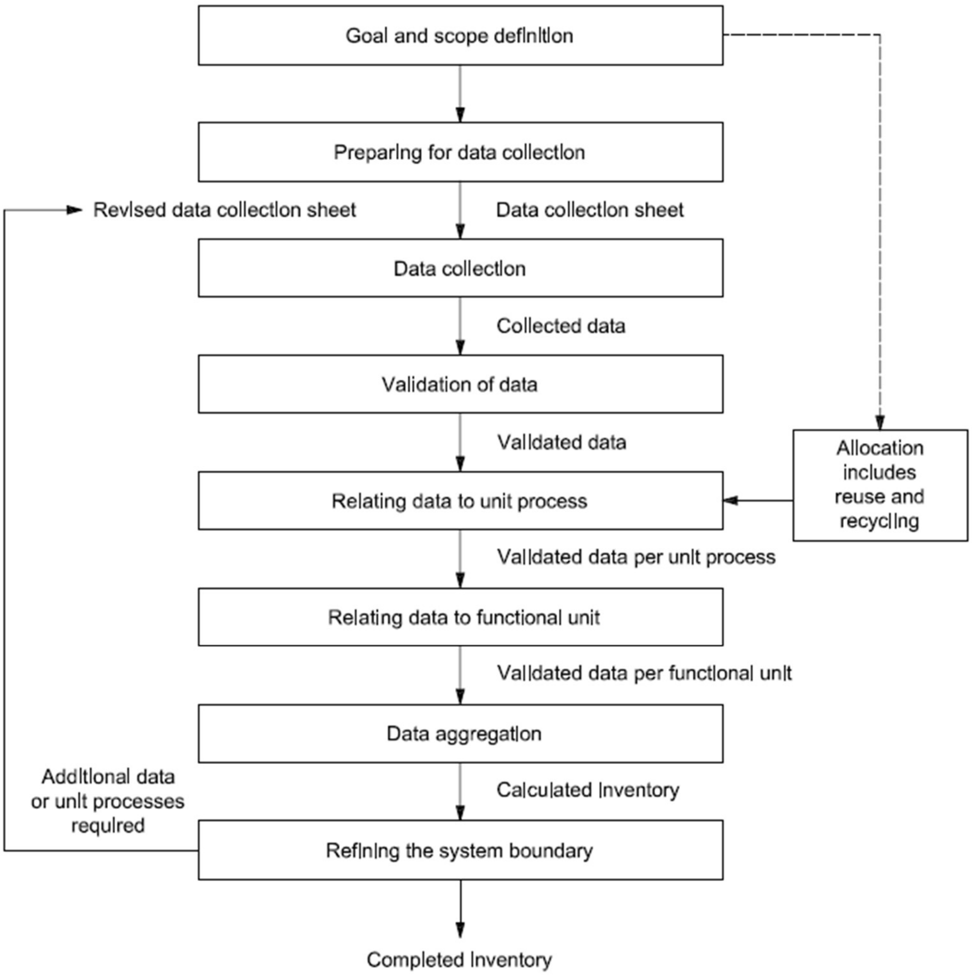


Figure 3: Iterative procedures for inventory analysis by ISO 14044:2006 (2006)

2.3.3 Impact Assessment

The impact assessment phase (LCIA) is the third phase of an LCA. It aims to understand and evaluate the magnitude and significance of the potential environmental impacts of the research subject within the system boundaries. LCIA is the phase in an LCA where the inputs and outputs of elementary flows that have been collected and reported in the inventory are translated into impact indicator results related to human health, natural environment, and resource depletion (European Commission, 2010). The LCIA methods are created by special experts that further provide to the vast majority of LCA practitioners complete sets of these methods. The LCIA results are then received by multiplying the inventory data of the LCI with the characterization factors of the LCIA method.

According to ISO 14044:2006 (2006), the LCIA phase shall include following elements:

- used impact categories, category indicators and characterization models
- connection of LCI results to the chosen impact categories (classification)
- calculation of category indicator results (characterization)

Looking closer at the LCIA method one can distinguish between two main ways of deriving characterization factors (CF): at midpoint or endpoint. According to Goedkoop et al. (2009) the midpoint level placed somewhere along the impact pathway, usually at the point after which the environmental mechanism, like acidification is linking the environmental flows to that category indicator. Midpoint results can look complicated however, they provide a more detailed insight e.g., one can identify trade-offs between impact categories. In comparison, CF at the endpoint level are assigned to three areas of protection, i.e., human health, ecosystem quality and resource scarcity. The endpoint characterization offers more understandable information on the environmental relevance of the flows, though the uncertainty is higher compared to the midpoint CF. Overall LCIA results on midpoint level are more common (Hauschild & Huijbregts, 2015).

Figure 4 exemplifies the concept of category indicators based on environmental mechanism. The impact category “acidification” is utilized as an example. In general, behind every impact category lies its own environmental mechanism (ISO 14044:2006, 2006).

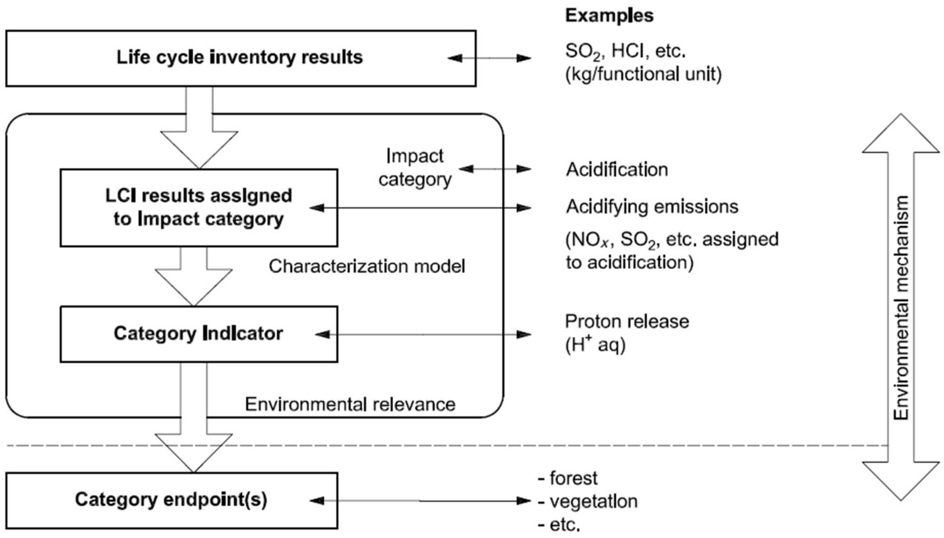


Figure 4: Concept of category indicators by ISO 14044:2006 (2006).

2.3.4 Interpretation

Throughout the iterative process of creating a LCA the life cycle interpretation is the last phase. During which the results of an LCI or an LCIA, or both, are summarized and analyzed as a base for further conclusions, recommendations and decision-making in accordance with the goal and scope definition (ISO 14044:2006, 2006).

Following elements shall be included:

- identification of significant issues during the calculation of the LCI and LCIA results
- assessment of completeness, sensitivity, and consistency checks
- conclusions, limitations and recommendations

Furthermore, the interpretation of the conducted LCA study should be presented in an understandable way. Figure 5 displays the connections between the iterative steps of the LCA and the interpretation phase. It is depicted that first significant issues like, key processes, parameters, assumptions and elementary flows are identified. Afterwards, with the help of quality checks completeness, sensitivity and uncertainty analysis are conducted. Finally, this leads to the formulation of conclusion and recommendations from the LCA study.

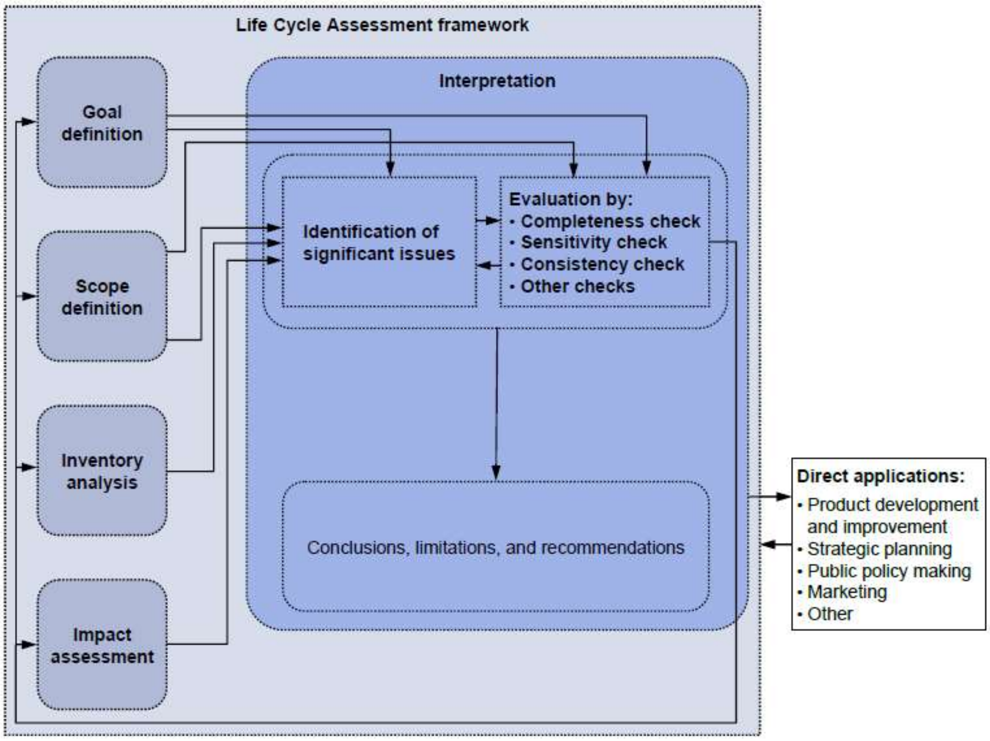


Figure 5: Relations between the interpretation phase and other phases of the LCA ISO 14044:2006 (2006)

2.4 Forestry Specific Issues in the LCA

This section is mainly focusing on specific challenges of the LCA methodology in the forestry sector, as these need to be kept in mind during the calculation of a regionalized forest inventory. First, the limitations of LCI of forest management practices are highlighted followed by an example of a consistent nomenclature and an approach to model forest management systems on a global scale.

2.4.1 Complexity of the Forestry Sector

Cardellini et al. (2018) identified the following challenges to model wood production due to the complexity of the forestry sector:

- Long rotation period of the wood production ranging between 16-120 years depending on the silvicultural system
- Range of products resulting from forest production and silvicultural activities
- Multifunctional nature of forests creating several services and products next to timber (e.g. water, recreation, carbon sequestration, etc.)
- Complicated handling of effects of natural disturbances and climate change on growth estimations of forests.
- Spatial volatility of forest stands and the site-specific growth and management options

In a study of Barbati et al. (2014) 78 types of forest land were classified according to tree species composition, structural differences and functional factors. (Werner & Nebel, 2007) state that tree species and forest management assumptions affect the LCI of wood production. On the one hand tree species vary in density and thus in weight, which lead to higher emissions e.g., during the transportation process. On the other hand the diameter at breast height at point of harvest is also a decisive factor as lower dimensions cause higher GWP due to more fuel consumption and lower productivity (Klein et al., 2015). Additionally forest management options like short rotation forest crops or sustainable managed forests etc., are also influencing the LCI result (Werner & Nebel, 2007). Including the different silvicultural management practices, e.g. shelter wood or clear cut, one gets an even more complicated picture, which underlines the need for consistent guidance for forest LCI inventories.

2.4.2 Specific vs. Proxy Data

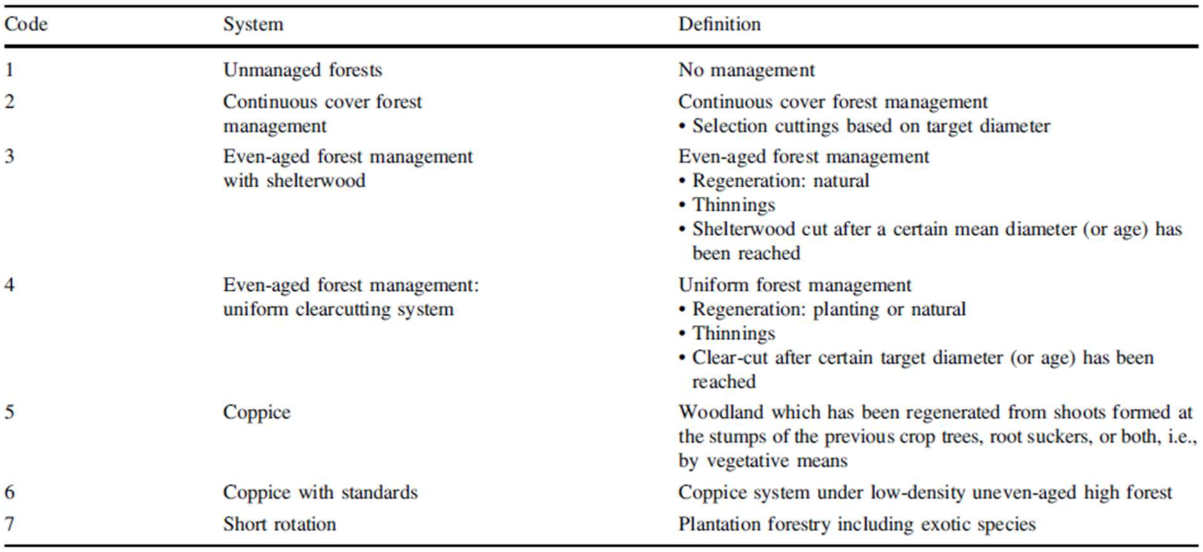
The lack of regionalized data are reflected in the Ecoinvent database version 3. If one looks for the keyword “pulpwood” LCI datasets on only six tree species (beech, birch, oak, pine, spruce and mixed) in three countries (Germany, Sweden, Switzerland) are provided (Wernet et al., 2016). Furthermore, there is no local dataset for the area of the Russian federation, which represents as already stated in section 2.1, the country with the highest share of forests. To overcome the issue of generalized LCI databases and to enable modelling of diverse management practices in various forest management systems it is important to create a consistent framework and nomenclature (Cardellini et al., 2018).

To model regionalized production conditions, following approaches can be identified (Wolf et al., 2016):

- Growth area level: Regionalization is done by mapping specific biomass production conditions.
- Regionalization through the availability of local harvesting systems
- Regionalization through the actual location of the production sites (transport processes reflect actual distances/transport modes)
- Regionalization through specific measurements of Input/Output (I/O) within the forest production sites
- Regionalization based on the actual substitution of alternative, usually fossil energy sources (coal, oil, gas) as well as specific electricity mix

Cardellini et al. (2018) for instance developed a nomenclature that classified seven silvicultural systems connected to European Forestry (Table 1).

Table 1: Silvicultural systems in Europe according to Cardellini et al. (2018).



Code	System	Definition
1	Unmanaged forests	No management
2	Continuous cover forest management	Continuous cover forest management • Selection cuttings based on target diameter
3	Even-aged forest management with shelterwood	Even-aged forest management • Regeneration: natural • Thinnings • Shelterwood cut after a certain mean diameter (or age) has been reached
4	Even-aged forest management: uniform clearcutting system	Uniform forest management • Regeneration: planting or natural • Thinnings • Clear-cut after certain target diameter (or age) has been reached
5	Coppice	Woodland which has been regenerated from shoots formed at the stumps of the previous crop trees, root suckers, or both, i.e., by vegetative means
6	Coppice with standards	Coppice system under low-density uneven-aged high forest
7	Short rotation	Plantation forestry including exotic species

To map silvicultural systems globally, Schulze et al. (2019) further developed two levels of forest management, with three categories each. These categories are mainly based on the national forest data collection of the Global Forest Resource Assessment (FRA) (FAO, 2018). Level 1 encompasses primary, naturally regrown and planted forests. Level 2 differentiates between different forest uses. Based on their model, likelihood maps were calculated and hence provide an estimation of global forest management patterns (Figure 6 and Figure 7). This information about forest management pattern could be helpful to overcome issues of LCA databases described above. For example, for background processes if a company only knows the locations of the specific forest but has no further information about the silvicultural system or forest class.

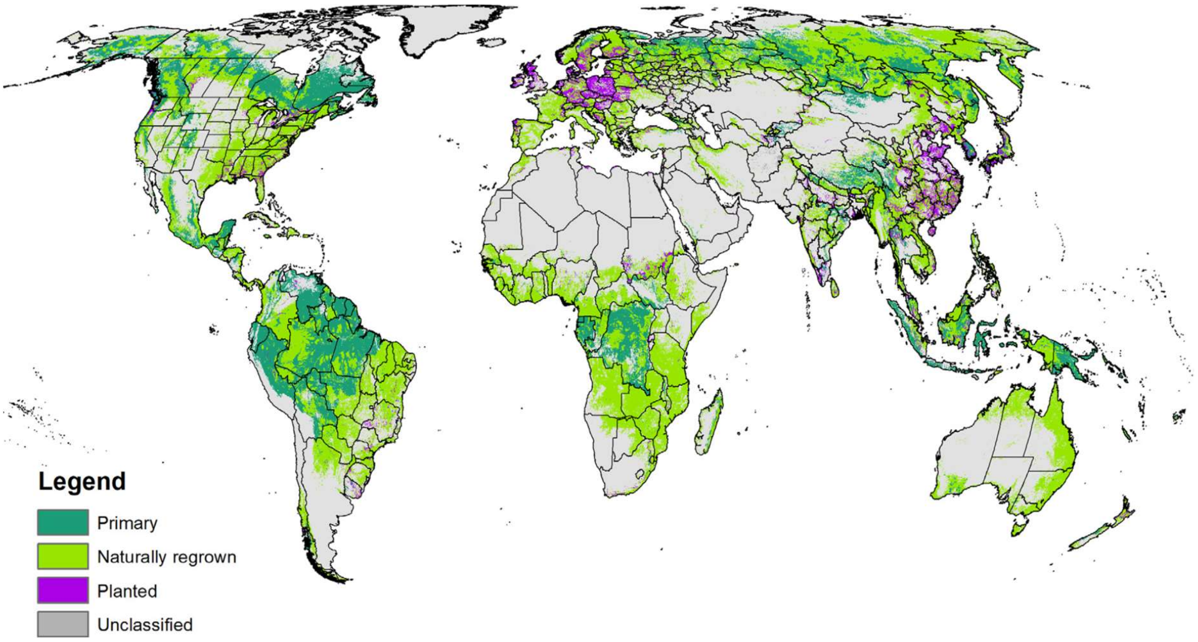


Figure 6: Global pattern of forest classes in 2000, by Schulze et al. (2019).

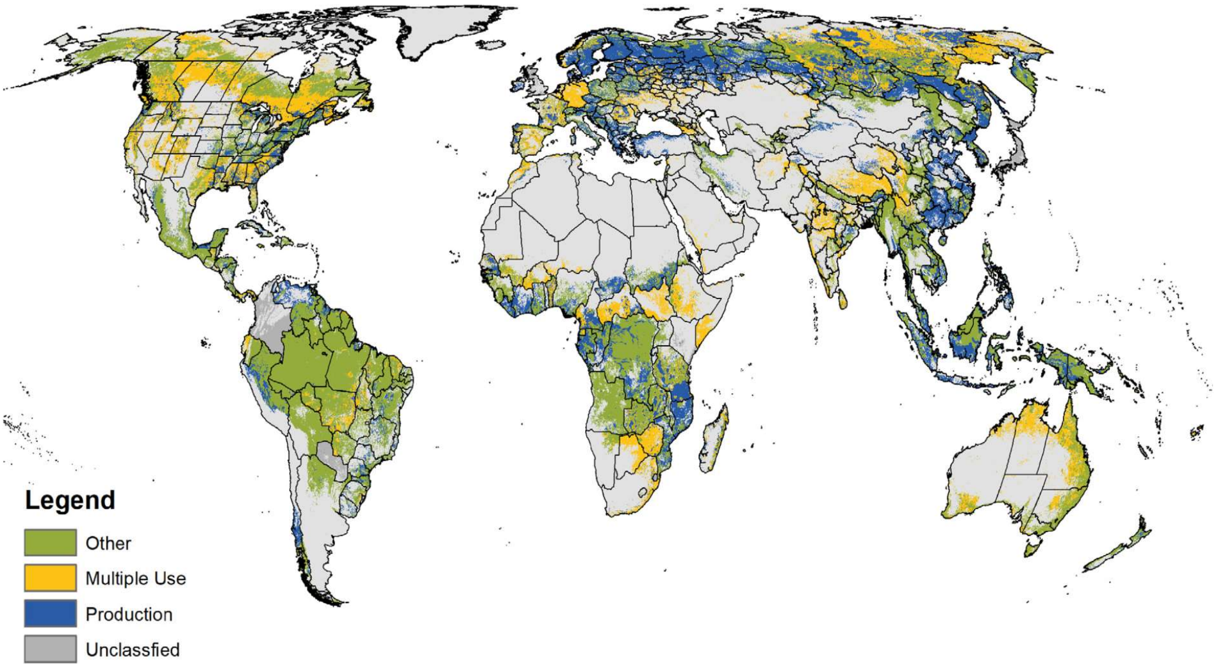


Figure 7: Global patterns of forest uses for the year 2000 by Schulze et al. (2019). The map shows the distribution of forest used for production, multiple purposes or primarily for something else then production (other).

In case site-specific information are available, there are still methodological issues to overcome. In the study from Klein et al. (2015) 22 different peer reviewed LCA studies were analyzed with the goal to support comparability and provide possible solutions. The reviewed studies showed large differences between methodical assumptions and their subsequent results. Especially system boundaries, functional units or allocation assumptions differed. To involve the aspect of sustainable forest management, first a consistent framework for forest production in the LCA needs to be in place, in order to make results comparable within different studies (Klein et al., 2015).

2.4.3 System Boundaries and Included Processes

The system boundary is a key part of the goal and scope definition phase of a LCA (ISO 14044:2006, 2006). It specifies which unit processes are included within the LCA. It is suggested to exemplify the study via a process flow diagram, describing the unit processes and their inter-relationships.

Processes that were left out should be indicated and an explanation should be provided. If data for certain activities are missing or could not be gathered, a best estimation approach should be provided (Klein et al., 2015). As already mentioned above, in forestry, raw wood products need a long time to grow in order to finally provide e.g., one cubic meter of harvested wood in comparison to other industries. Forest management practices, rotation periods, wood qualities and amounts of harvested wood strongly depend on the specific tree species (Cardellini et al., 2018). Thus, next to the process-based system boundaries, temporal system boundaries are essential. There are two options to deal with this topic, such as considering only single moment or a whole rotation period. The “whole rotation approach” includes the whole rotation period, between 16-120 years, depending on the silvicultural system. The “single moment approach” only includes one defined action like e.g., pruning, or final felling. However, this would inhibit the inclusion of all relevant processes (Klein et al., 2015).

As already suggested by Klein et al. (2015), four main processes groups shall be considered with their corresponding processes (Figure 8): secondary processes like off-site processes which are related to the production and provision of raw wood (e.g. planning of forest operations, seed/seedling production and transportation, etc.). Site preparation processes, which include activities to prepare the site (e.g. piling, clearing, soil scarification etc.). Site tending includes measures to improve or to conserve the forest area (e.g. fencing, fertilization, use of pesticides, etc.). Silvicultural and harvesting operations are the actual actions, which are responsible for the tree growth like, stand structuring, extraction of wood, post felling processes and loading on trucks. As an optional processes step chipping and transportation may be included in the system depending on the defined system boundaries (Klein et al., 2015).

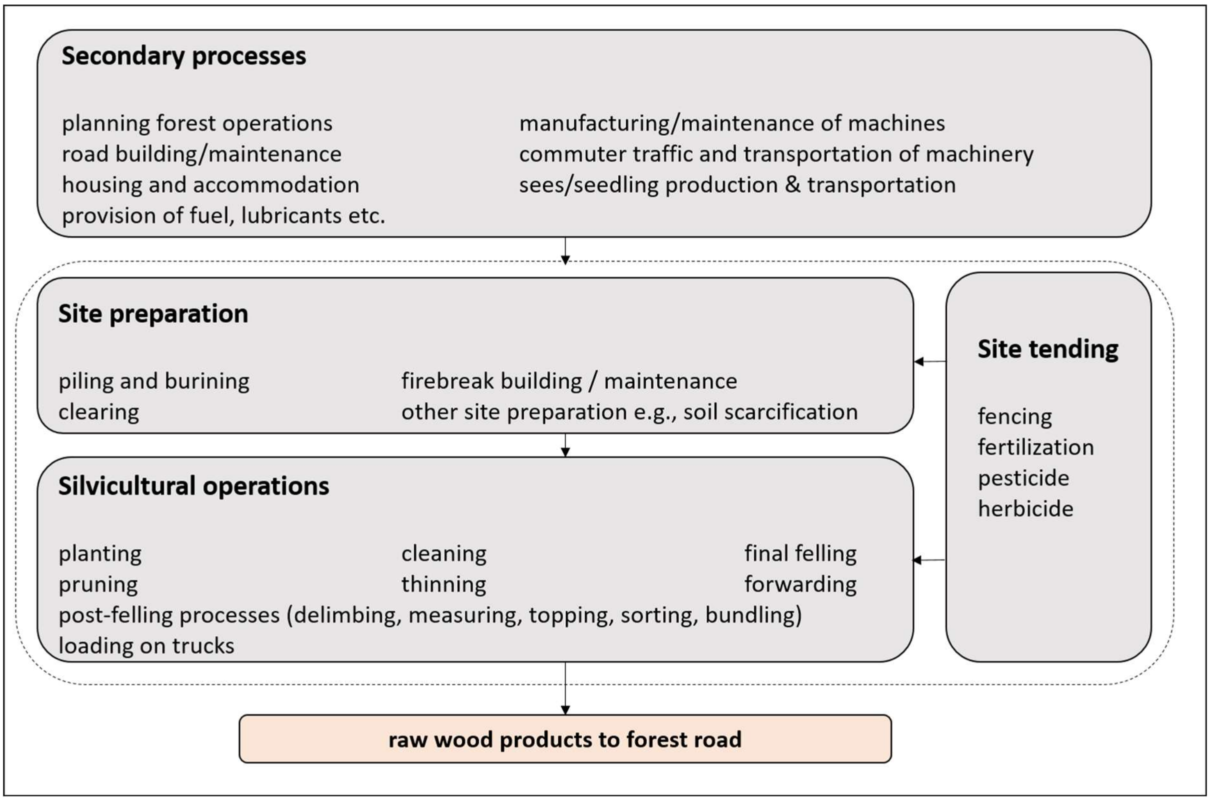


Figure 8: Proposal for a process chain for raw wood as a base for LCA for forest production; adopted but based on Klein et al. (2015)

The activities vary in intensity and execution conditional to different countries and tree species. Additionally, similar process chains are presented by various studies e.g., Kühmaier et al. (2019) including all relevant process steps yet with different process groups. Thus, a clear nomenclature of processes is central to allow comparisons between studies. Forest management processes can be separated into specific and general processes. Specific processes are forest activities (e.g. thinning, final felling, forwarding, etc.), whose environmental impacts are directly related to the reference flow of the LCA. In contrast, general processes are forest activities that cannot be linked directly to environmental impacts. They first must be attributed to the whole amount of raw wood, which is produced within the system boundaries (Klein et al., 2015). On example would be the fencing of the corresponding forest area. Its related emissions correspond to the area of forest production within a certain period. To connect these area-based emissions to the defined functional unit (e.g. cubic meter), one must distribute the emissions over the total amount of wood produced in this area.

2.4.4 Functional Unit

Next to the system boundary the functional unit is also defined in the first phase of a LCA. The definition for the functional unit (FU) as already mentioned in chapter 2.3.1. is described in (ISO 14044:2006, 2006). In the past one cubic meter under bark (ub) was the most frequently used functional unit for forest production activities in forest LCAs (Klein et al., 2015; Kühmaier et al., 2019). Next to the functional unit additional information shall be provided such as, moisture content, wood density, tree species etc. This provides the possibility to calculate other reference flows like, 1 t biomass ub, 1 t of carbon, or 1 MJ (lower heating value) (Klein et al., 2015).

2.4.5 Allocation

There are some overall rules that have to be fulfilled for every LCA when allocation is needed. According to ISO 14044:2006 (2006), the sum of allocated inputs and outputs of the conducted LCA needs to be the same as they were before the allocation process. However, ISO 14044:2006 (2006) states that in general allocation should be avoided if possible by:

> *"[d]ividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3."*
>
> – (p.14)

For forest production subdivision is only suitable if all raw wood products could be calculated separately (e.g., pulpwood, industrial wood and energy wood), otherwise if allocation takes place according to Klein et al. (2015) allocation by mass or volume should be used.

2.5 Relevant Impact Categories for the Forestry Sector

According to ISO 14044:2006 (2006), "[t]he selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system studied, taking the goal and scope into consideration." – (p.17)

Thus, for this master thesis impact categories like global warming potential and land use shall be considered as these were already identified by Klein et al. (2015) to be relevant. The strong attention to the GWP could be due to the rising awareness since 1997, when the Kyoto Protocol was signed (Klein et al., 2015). Additionally, more and more stakeholders are asking for specific carbon footprints of salable products. For the pulp and paper industry land use is an important impact category as wide areas of forest land are used, as well as forest roads have to be built for the production. Although the net change in carbon stock is usually part of GWP it was looked at separately during this master thesis. Next to these three impact categories, Klein et al. (2015) identifies acidification and particulate matter as appropriate categories for modelling wood production processes. However, due to the limited capacity particulate matter and acidification, were left out of scope of this thesis.

2.5.1 Global Warming Potential (GWP)

According to (Masson-Delmotte et al., 2021) co-author of the Intergovernmental Panel on Climate Change (IPCC), the emissions of diverse greenhouse gases will result in an increment of atmospheric gas concentration. This will increase the radiative forcing capacity (W/m^2), and will lead to a rise of global mean temperature. The gases differ e.g., in absorbed energy and residence times. Each gas was provided with a specific global warming potential (GWP). This makes it possible to compare the amount of energy which is absorbed by 1 ton of gas over a given time period, usually 100-years, compared with the emissions of 1 ton of CO_2. As weather extremes are like to get more frequent in future due to climate change, this will directly affect forests worldwide (Masson-Delmotte et al., 2021). Contrary, forests at higher latitudes might profit from enhanced atmospheric carbon dioxide concentrations and rising temperatures, which leads to significant increases in growth and timber production (Nunes et al., 2021). Figure 9 connects the cause and effect chain of increasing greenhouse gas emissions to human health, loss of terrestrial and freshwater ecosystems.

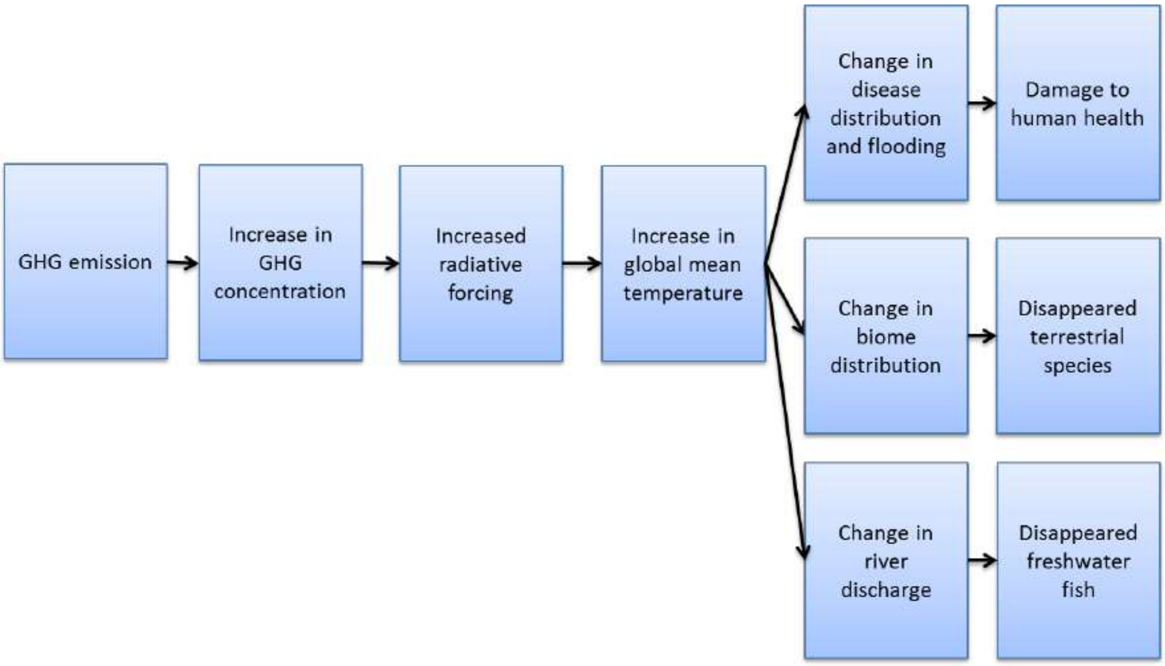
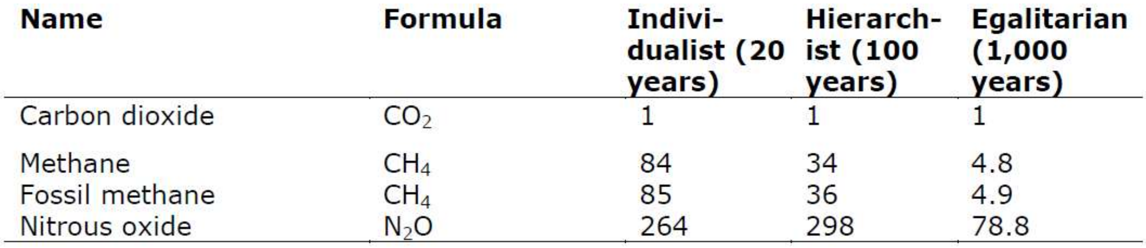


Figure 9: Example of a cause and effect chain from greenhouse gas emissions Huijbregts et al. (2016)

Several LCIA methods (e.g., ReCiPe2016 from Huijbregts et al. (2016), environmental footprint framework (EF), etc.) exist to calculate the impact category climate change. The climate change category is based on the (IPCC) characterization model in 2013, which provides characterization factors for emitted greenhouse gases, referencing them all to CO_2. Therefore, the unit of GWP is CO_2-eq. Looking at the midpoint characterization factors for 100 years of the two above named models one can find slight differences e.g., for methane. These differences arise due to the different approaches of the two methods. The EF 3.0 methodology proposes for methane (fossil) a value of 36.75 CO_2-eq (Fazio et al., 2018). For biogenic carbon modelling of methane, a factor of 34 CO_2-eq shall be used. The decrease can be explained as biogenic carbon modelling includes the sequestration processes of biomass. Looking at the ReCiPe2016 factors for methane, 36 CO_2-eq are listed for fossil methane which is also proposed in the IPCC report 2013 and 34 CO_2-eq for biogenic methane (Table 2). Detailed information regarding characterization factors for the ReCiPe methodology can be found in Huijbregts et al. (2016).

Table 2: GWP for Carbon dioxide, methane, fossil methane and nitrous oxide for the three-time perspectives



Name	**Formula**	**Individualist (20 years)**	**Hierarchist (100 years)**	**Egalitarian (1,000 years)**
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	84	34	4.8
Fossil methane	CH_4	85	36	4.9
Nitrous oxide	N_2O	264	298	78.8

2.5.2 Land Use

The United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative currently provide the current state of practice regarding the land use methodology on which both, EF and ReCiPe base their LCIA methods. Horn et al. (2021) states that,

> “[u]nlike most impact categories, soil quality changes are not following the linear correlative nature of emission-based cause effect chains where more emissions linearly correlate with a higher impact. Furthermore, the impact of land using activities is strongly depending on regional and local conditions such as soil properties and climate.” – (p.8)

Land use is a relevant impact category for forest products as it influences the on-site carbon balance e.g., if forest management systems are changed leading for example to higher soil erosions or forests are transformed into other land uses with different carbon storage etc.

2.5.2.1 Classification of Land Use

Confronted with this challenges, UNEP-SETAC provided a guideline, which describes the theory of transformation and occupation as well as the choice of reference states and regeneration times (Koellner et al., 2013). Figure 10 describes the change of quality of land (ΔQ) that emerge from processes that occur on a land use type and a reference system, e.g., the conversion of soil quality caused by land use activities, such as pasture or forest plantation compared to the reference system of natural vegetation (Horn et al., 2021). Furthermore, three stages during the land use process can be identified, land transformation, land occupation and regeneration. Koellner et al. (2013) defines land occupation as the present type of land use of an area per FU within a certain timeframe [m^2 and year]. Land transformation on the other hand is the already above stated, change of quality between two types of land use. Here one can distinguish between reversible and permanent transformation (relaxation), which is in more detail explained in Koellner et al. (2013).

$$Occupation\ impact = \Delta Q * T_{OCC} * A$$

Equation 1: Occupation impact Koellner et al. (2013)

$$Permanent\ transformation\ impact\ = \Delta Q * A$$

Equation 2: Permanent transformation impact Koellner et al. (2013)

$$Reversible\ transformation\ impact = \Delta Q * T_{reg} * 0{,}5$$

Equation 3: Reversible transformation impact Koellner et al. (2013)

Where: ΔQ is the difference in the ecosystem quality between the reference situation and the current (occupation impacts) or prospective (transformation impacts) land use. A reflects the area occupied. T_{occ} and T_{reg} are the occupied and regeneration time.

Horn et al. (2021) states that differences in the distinction of transformation flows in different LCA software lead to inconsistencies and in to a potential underestimation of the Soil-Quality Index (SQI) in land use modelling. This is due to the fact that no clear differentiation is defined in the nomenclature whether a land use flow is based on reversible or permanent transformation, although various methods use different approaches (Horn et al., 2021).

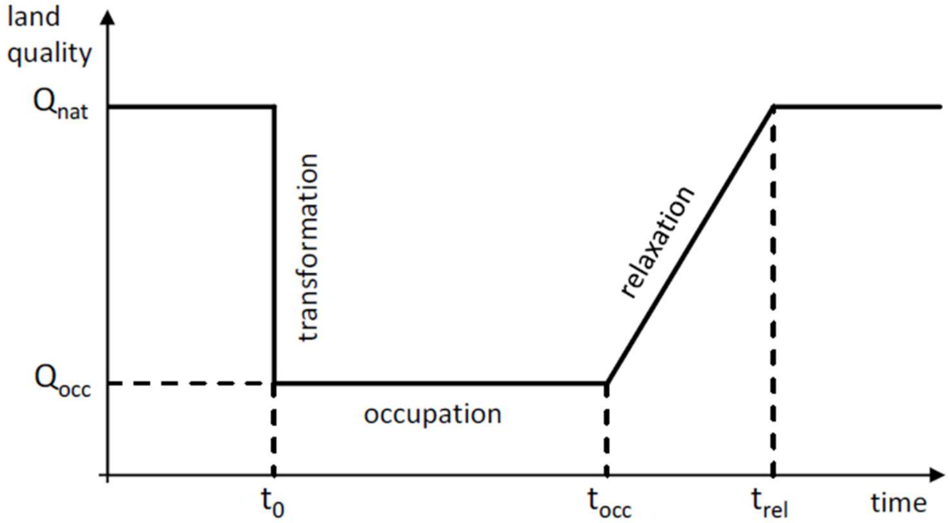


Figure 10: Overview of the three phases of land use. Land transformation and occupation occurs between t_0 and t_{occ}, and relaxation occurs between t_{occ} and t_{rel}. Q_{nat} shows the original, natural land quality and Q_{occ} is the land quality after land transformation Huijbregts et al. (2016).

One main goal of this study is to identify needed information, which are used to further calculate relevant LCIA. To assess land use impacts, information concerning land use types along with details of the land use activities timeframe and site location are needed (Horn et al., 2021). Moreover, a nomenclature of the land use flow classification in LCA has been developed by Koellner et al. (2013).

This classification of the various land use types is also known as environmental footprint framework (EF) flow list, which utilizes the following four-level approach.

- Level 1: Common land use/cover name. It is used to provide information on the common land use or land cover name, like “forest” or “grassland”.
- Level 2: Land status. Here further details on the status of the land are provided, such as “forest, used”
- Level 3: Land management practices. Details on land management (e.g., arable, irrigated) are shared.
- Level 4: Land use intensity. Information on the intensity of a land use practice is provided (e.g., agriculture, arable, extensive).

However, for forestry and grassland the intensity is already provided on the third level (Koellner et al., 2013). The EF flow list has both advantages and downsides. It presents a common nomenclature for land use flows and further lies the basis for implementing land use in the LCA. Nevertheless, as already described, some exception for the forestry sector exists. The two central classification for forests in the UNEP-SETAC framework is between Natural (primary or secondary) and Used (extensive or intensive) forests. Additionally, for forests only seven flows can be chosen, namely: forest (level 1), forest natural (level 2), forest secondary (level 3), forest used (level 2), forest extensive (level 3) and forest intensive (level 3). None of them is on the fourth level, resulting in a differentiation in management practices only between used forests:

1. Extensive, with selective logging, where timber harvesting is followed by regrowth, involving at least three naturally occurring tree species
2. Intensive, with either even-aged stand clear-cut patches, or less than three naturally occurring species at planting/seeding (Koellner et al., 2013).

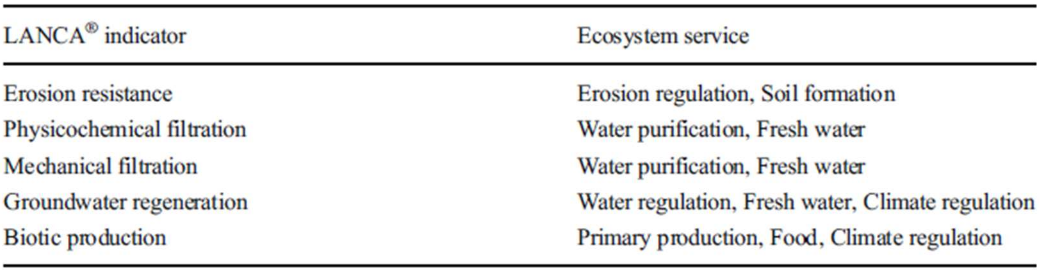
Thus, the flow list is of limited practicability in modelling diverse forest management practices (Horn et al., 2021).

Another crucial part of land use modelling is the so-called reference system. It serves as benchmark against which the quality of land use type is compared with. Three different methodologies exist to model the reference system in LCA, according to Koellner et al., (2013). The one used in ReCiPe, the EF framework and, the Land Use Indicator Value Calculation in Life Cycle Assessment (LANCA®) framework is based on the concept of potential natural vegetation (PNV). The PNV describes the vegetation that could be assumed to exist in areas where no human activities took place. However, there is still no agreement on a common methodology for modelling the reference system across several methods which makes it hard to compare and aggregate results (Horn et al., 2021). The second possible methodology to determine the reference situation is set as the "quasi-natural" vegetation in a particular ecological region, e.g., a biome or an ecoregion. The third possible method uses the current land use situation in a particular region as a reference system (Koellner et al., 2013).

2.5.2.2 LANCA

The LANCA® methodology is directly tailored to the method of the UNEP-SETAC framework and intended for the calculation of the product environmental footprint (PEF) framework (Horn et al., 2021). In the following the focus was put on providing an overview of the LANCA® framework and the parameters that are included within it. In LANCA® framework various indicators are considered like, erosion resistance, mechanical filtering capacity of groundwater, physicochemical filtration capacity of groundwater, groundwater recharge capacity, biotic production potential, which are all finally summarized in the SQI (Table 3).

Table 3: LANCA® indicators for ecosystem services needed for calculating the SQI by Bos et al. (2020).



LANCA® indicator	Ecosystem service
Erosion resistance	Erosion regulation, Soil formation
Physicochemical filtration	Water purification, Fresh water
Mechanical filtration	Water purification, Fresh water
Groundwater regeneration	Water regulation, Fresh water, Climate regulation
Biotic production	Primary production, Food, Climate regulation

The *Product Environmental Footprint Category Rules (PEFCRs)*, (2018) is using an **adopted** version of LANCA® method as its background and states that:

> *Additionally, secondary datasets on forestry currently do not properly capture sustainable forest management practices. As a consequence, results do not accurately reflect different forest management practices in semi-natural forests*. – (p.38)

The adopted version of LANCA® in the EF.3.0 framework utilizes four indicators for calculating the SQI, namely biotic production, erosion resistance, mechanical filtration and groundwater regeneration (European Commission, 2018). The characterization factors of these functions are in line with the UNEP-SETAC framework (Bos et al., 2016; Horn et al., 2021).

In the following subsections, the included indicators of the original LANCA® methodology are briefly described to highlight their impact on the LCI land use result.

The **Soil Quality Index (SQI)** is a mandatory land use impact category from LANCA®, which is based on the model from Bos et al. (2016) and Horn et al. (2016). The indicators for ecosystem services implemented in LANCA® (Table 3) are in the end converted into the SQI. The SQI provides information at a country scale level e.g., Russia, Germany etc. and CFs are utilized to calculate results of land occupation and permanent transformation flows. In order to simplify the interpretation of the multi-indicator LANCA® model a normalization and aggregation process took place to obtain a single score index – the SQI, enabling the quantification of impacts on soil quality (De Laurentiis et al., 2019). According to OECD et al. (2008) it is necessary to first normalize the CF of indicators before they can be further aggregated. Table 4 depicts the CF for "occupation" of the utilized indicators of LANCA®. The CF are area and time independent and thus, also the same for "transformation to". For "transformation from" they are the same but with negative signs (Bos et al., 2016).

Table 4: Characterisation factors of "Occupation" of LANCA®-Indicators for Russian Federation adopted but based on Bos et al. (2016).

Land Use Type	Erosion Potential [kg/m²a]	Infiltration Reduction Potential [m³/m²*a]	Physicochemical Filtration Reduction Potential [mol/m²]	Groundwater Regeneration Reduction Potential [m³/m²*a]	Biotic Production Loss Potential [kg/m²*a]
Forest Primary	-0,000093	0	0	0	0
Forest Secondary	0,000093	0	0	0	0
Forest, Extensive	-0,000093	0	0	0	280000
Forest, Intensive	0,000093	10000	61000	0	520000

De Laurentiis et al. (2019) proposed Equation 4 to re-scale the CFs of LANCA® (Table 4). The results of this equation are dimensionless and defined as points (PT).

$$CF_{i,j} = \frac{CF_{i,j}}{CF_i^{95}} * 100 \left[\frac{PT}{m^2 a}\right]$$

Equation 4: Normalization of LANCA® indicators

Where: $CF_{i,j}$ is the normalized characterisation factor for the indicator i and the elementary flow j. CF_i^{95} is the 95th percentile of the distribution of country-specific CFs for the indicator i.

Finally, the SQI is obtained by aggregating the outcome of the normalized LANCA® indicators. The CFs of each indicator i were summed up, utilizing equal weights (1-1-1-1-1) to in the end receive one single number.

$$\overline{CF_{occ,j}} = \sum_{i=1}^{4} CF_{ij} \quad [PT/m^2\,a]$$

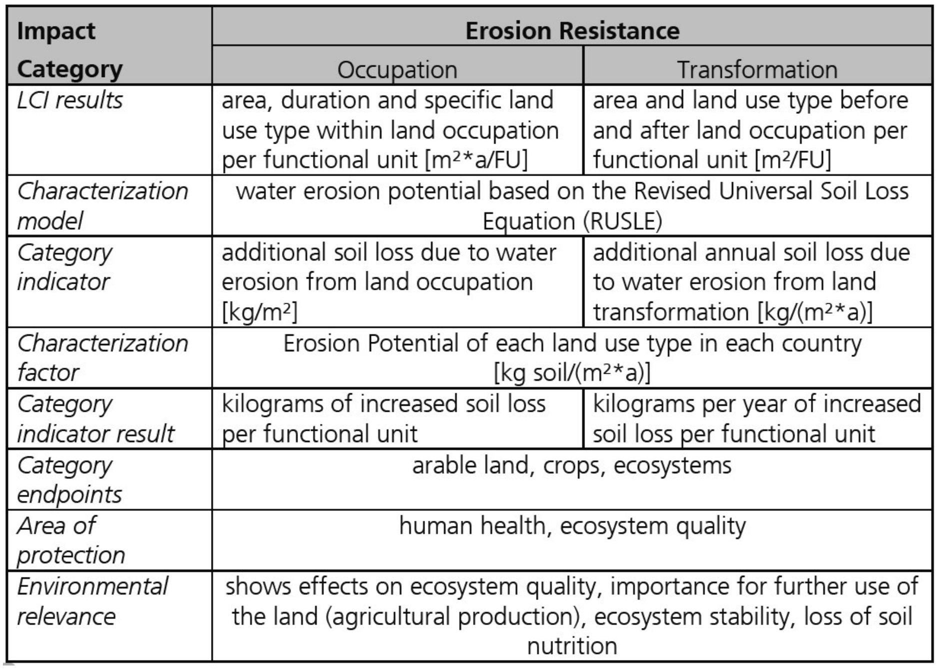
Equation 5: Aggregation of LANCA® indicators to SQI

Where: $CF_{occ,j}$ reflects the aggregated SQI CF for the occupation of land use type j expressed in Pt/m^2a. CF_{ij} is the normalized occupation CF for the indicator i and the elementary flow j (Equation 4).

The outcome is a normalized index factor, expressed in Points/m^2, which supplies each elementary flow in the range of -47 to 318 in the country specific set (Horn et al., 2021). Higher results indicate higher land use impacts, e.g. a high CF value for erosion resistance potential means an increase in soil loss.

A statistical analysis of the correlation among the five indicators of the LANCA® model was conducted in order to select the indicators of highest relevance (De Laurentiis et al., 2019). From this statistical analysis it appeared that the indicators mechanical filtration and the physicochemical filtration show redundant results during the ranking process of land use interventions, when using global characterization factors (De Laurentiis et al., 2019). Therefore as already mentioned the EF 3.0 framework uses an adopted version of LANCA® and uses four indicators for calculating the SQI (European Commission, 2018).

Erosion Resistance is defined as the power to resist erosion and thus, it is an important function of natural ecosystems and included as an indicator of land use in LANCA® (Bos et al., 2016). The basis for calculating the erosion resistance category is the so-called RUSLE model.



Impact Category	**Erosion Resistance**	
	Occupation	Transformation
LCI results	area, duration and specific land use type within land occupation per functional unit [m²*a/FU]	area and land use type before and after land occupation per functional unit [m²/FU]
Characterization model	water erosion potential based on the Revised Universal Soil Loss Equation (RUSLE)	
Category indicator	additional soil loss due to water erosion from land occupation [kg/m²]	additional annual soil loss due to water erosion from land transformation [kg/(m²*a)]
Characterization factor	Erosion Potential of each land use type in each country [kg soil/(m²*a)]	
Category indicator result	kilograms of increased soil loss per functional unit	kilograms per year of increased soil loss per functional unit
Category endpoints	arable land, crops, ecosystems	
Area of protection	human health, ecosystem quality	
Environmental relevance	shows effects on ecosystem quality, importance for further use of the land (agricultural production), ecosystem stability, loss of soil nutrition	

Figure 11: Definition of Erosion Resistance according to ISO 14044:2006 (2006)

Soil losses are determined using Equation 6, where **A** are the calculated soil erosion rates [kg soil/m^2*a], **R** determines the rainfall erosion factor, **K** is the erodibility factor, **LS** represents the slope length factor, **C** is the land cover factor and **P** is based on the support practice factor. Each of these factors include further soil sub-parameters like, soil texture (e.g., clay, silt and sand content), the mean grain size of soil particles, soil permeability and soil structure class, gravel and humus content and a stoniness factor. More information and datasets can be found in (Bos et al., 2016). Data for parameters are gathered from the Harmonized World Soil Database (HWSD) and averaged per country (Horn et al., 2021).

$$\boldsymbol{A = R * K * LS * C * P}$$

Equation 6: Erosion Resistance equation by Reinard et al. (1997)

Next to above stated soil properties and environmental variables, the management of the land also has an impact on the erosion resistance and is implemented in the RUSLE framework with a crop management factor and a conservation practice factor based on (Kuok et al., 2013). However, for forestry regimes there is a lack of data for these two land management parameters. Thus, the conservation practice value is always one for all forest land use flows. For the crop management factor only two differentiations occur: the three land use flows from the EF flow list "forest", "forest, natural" and "forest, extensive" have the same values, as do the land use flows "forest, intensive" and "forest, used". This means that deviations of forest management practices will have no effect on the erosion resistance (Horn et al., 2021).

Mechanical filtration is characterized by the potential of a soil to be mechanically infiltrated by a suspension [m^3 water / (m^2*a)] (Bos et al., 2016). Compared to physical-chemical filtration, which considers the amount of adsorbable cationic pollutants, mechanical filtration models the ability to infiltrate an amount of water into a given soil. Figure 12 depicts the parameters and calculation process for mechanical filtration. Water permeability is generally determined by soil texture, distribution of soil pores, soil type, sediment sequence, groundwater surface, distance to groundwater and type of land use (Bos et al., 2016). To implement a CF for the infiltration-reduction potential in LANCA®, Beck et al. (2010) calculated it with parameters of soil type, depth to the groundwater table and a sealing factor. Yet, the effects of land use on forests have some limitations particularly for the sealing factor. It is based on generic assumptions, which states that intensively used forests have a sealing factor of 5 percent, whereas natural and extensively managed forests have no sealed areas. Unfortunately, additional forest management parameters which could influence soil properties are not implemented, such as soil texture, pH and humus content, which would include e.g. soil compaction through heavy machines, composition of age structure of tree species etc. (Horn et al., 2021).

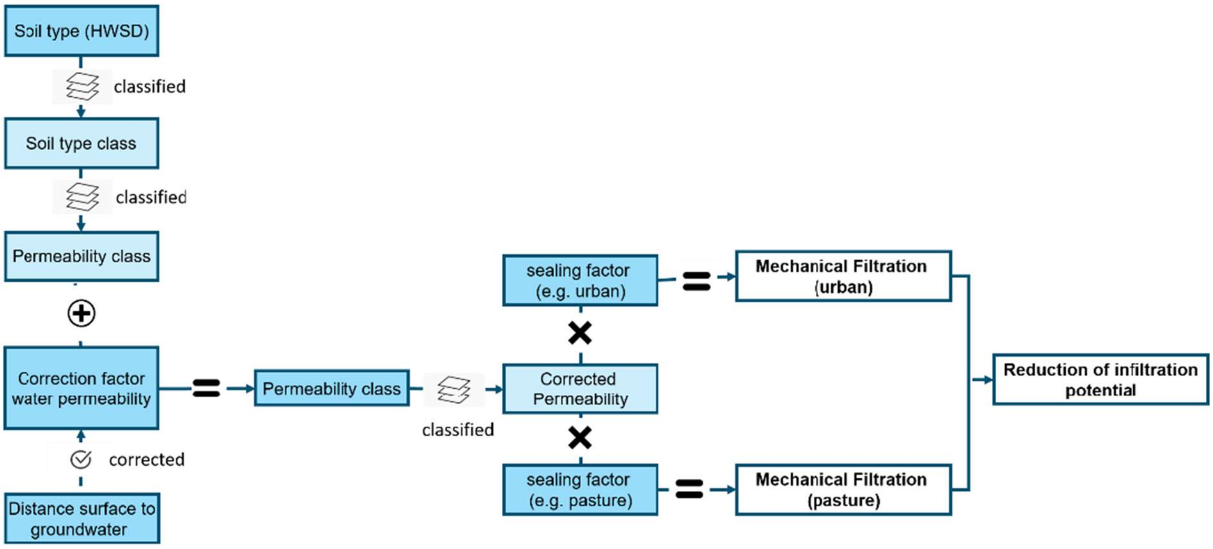


Figure 12: Calculation of mechanical filtration Bos et al. (2020)

As already described earlier **physicochemical filtration** is the function of a soil to fix and exchange cations on clay and humus particles [mol/m²] (Horn et al., 2021). In LANCA® it is calculated by using information on soil properties and surface sealing from several databases and recommendations like the Environmental Atlas Berlin and the Federal Institute for Geosciences and Natural Resources (Bos et al., 2016). For the calculation of physicochemical filtration, in general the pH is an important factor as it influences the effective cation exchange capacity. Accurate calculation steps are depicted in

Figure 13. Limitations are similar to those for the mechanical filtration indicator. They originate from the absence of fertilizer impacts on the pH value and on the assumptions made on sealed areas in different forest management regimes (Horn et al., 2021).

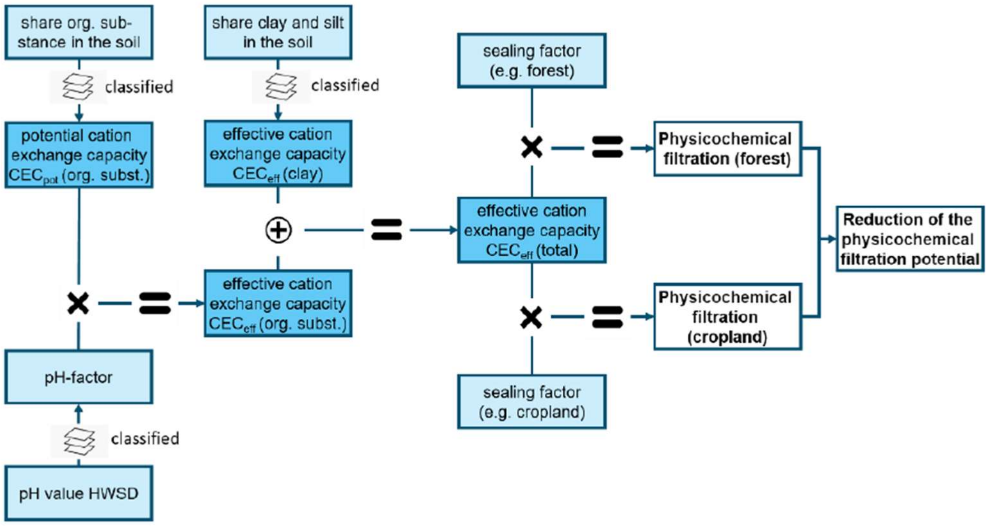


Figure 13: Calculation of physicochemical filtration by Bos et al. (2020)

The **groundwater regeneration** displays the soils function to regenerate groundwater sources and it is further influenced by human land use activities such as sealing or the modification of vegetation. Surface vegetation, the climate zone and the structure of the soil are important factors influencing the groundwater recharge ability (Bos et al., 2016).

In LANCA®, the groundwater regeneration reduction potential [m^3 groundwater regeneration / m^2*a] is calculated and influenced by parameters like soil; slope and type of land use that affect runoff, precipitation, and evapotranspiration (Figure 14).The runoff corrected groundwater regeneration rate, expressed in millimeters per year is used as the characterization model for groundwater regeneration (Bos et al., 2016). Data for mean annual precipitation Hijmans et al. (2015) and the evapotranspiration (Mu et al., 2011) in an area are determined. As there is only one land use type for forest determining the specific surface run off in LANCA®, differently managed forest systems are not represented in the calculation of the groundwater regeneration (Horn et al., 2021).

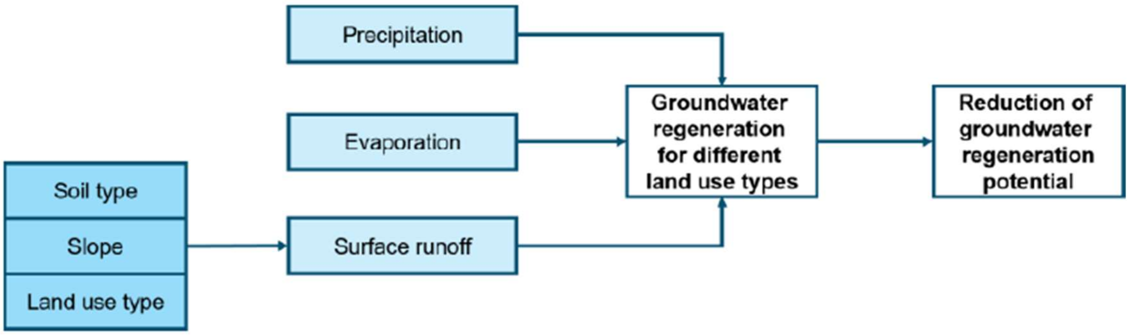


Figure 14: Calculation of groundwater regeneration Bos et al. (2020)

According to Horn et al. (2021), **biotic production** is described as the total mass of biomass produced by organisms above and below ground in a given time, relative to an area. In LANCA® biotic production is expressed as a value per land use type in kg/(m^2*a) (Bos et al., 2016). Thus, for each land use type a certain net primary productivity (NPP) value is assigned. Figure 15 describes the calculation of biotic production. The calculation of the biotic production loss is based on land use types and surface sealing (Bos et al., 2016). Limitations for forest impacts occur, due to assumptions of a standard value for sealing and limited default values for biotic production for different forest management regimes (Horn et al., 2021).

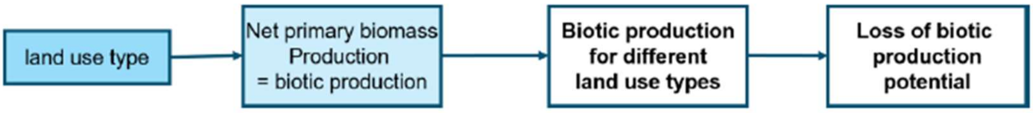


Figure 15: Calculation of biotic production by Bos et al. (2020)

Regionalization: Generally the characterization factors used in the LANCA® framework are presented in Bos et al. (2016) and further developed by Horn et al. (2016). As a new approach Bos et al. (2020) calculated, which is not yet implemented in the EF.3.0, spatially refined CF, using a geo-information system (GIS). Instead of country averages, pixel-based information can be used to gain more reliable results, which is helpful especially in large countries. Nevertheless, for some of the land use flows like, forests, permanent crops, wetlands, arable or grassland still no differences occur in the CF of LANCA® (Horn et al., 2021). This is further underlined by Horn et al. (2021) who states:

> *[h]erein, the modelling always assumes a single land use type covering the whole world (Bos et al. 2020) and is presented in one map displaying the CFs as if the whole world or a region would be covered with e.g. forest.* – (p.19)

Table 5 presents a small section of reference situations per country utilized for the CF calculated in LANCA® (Bos et al., 2016). This issue can be solved in the future by using more precise and refined land use and land cover like forest management intensity maps e.g., the European Forest Information Scenario (EFISCEN Space). EFISCEN Space is created for any kind of forests, handles a broad range of management systems and works with detailed national forest data (Horn et al., 2021). Using data provided e.g., by the EFISCEN Space model makes it possible to aggregate the values of the characterisation factors only in those areas where the type of land use actually occurs per country (Bos et al., 2020).

Table 5: Reference situation for country specific CF, modified but based on Bos et al. (2020)

Russian Federation	Boreal forest or taiga
Rwanda	Savanna
Saba	Rainforest
Saint Barthelemy	Rainforest
Saint Eustatius	Rainforest
Saint Kitts and Nevis	Rainforest
Saint Lucia	Rainforest
Saint Martin	Rainforest
Saint Pierre and Miquelon	Boreal forest or taiga
Saint Vincent and the Grenadines	Rainforest
San Marino	Temperate deciduous forest
Sao Tome and Principe	Rainforest
Saudi Arabia	Desert, semi-desert
Senegal	Savanna
Serbia	Temperate deciduous forest
Sierra Leone	Rainforest
Singapore	Rainforest
Sint Maarten	Rainforest
Slovakia	Temperate deciduous forest
Slovenia	Temperate deciduous forest
Solomon Islands	Rainforest
Somalia	Desert, semi-desert
South Africa	Grassland

2.5.3 Net Change of Carbon Stock

Next to impact categories like GWP or Land-Use, forest biomass stock is an important input to create a forest inventory. The Intergovernmental Panel on Climate Change et al. (2006) state that:

> *[g]reenhouse gas inventory for Forest Land Remaining Forest Land (FF) involves estimation of changes in carbon stock from five carbon pools (i.e., above-ground biomass, below ground biomass, dead wood, litter, and soil organic matter as well as emissions of non-CO2 gases – chapter 4.2.*

In order to model a carbon stock for biomass components based on growing stock volumes (GSV) of a specific forest area, parameters like biomass expansion factors (BEF) and the root-to-shoot ratio (R:S) are needed (IPCC et al., 2006). These parameters significantly vary between different tree species and forests depending on climate and soil conditions, age and levels of productivity (Schepaschenko et al., 2018). In general, the biomass structure of forest ecosystems comprises live biomass, which can be further split into three main divisions: live biomass of trees (stands); the lower layers like the understory, undergrowth and green forest floor; the dead vegetation matter including standing dry trees (snags), fallen wood (logs), stumps, dead roots and dry branches of live trees. Each of the stated divisions contain sequestrated carbon and play a role in the forest carbon cycle (Schepaschenko et al., 2018). According to a forest expert, generally more inputs into forest management could lead to increased or maintained carbon stock over time, which would justify these inputs.

The study of Schepaschenko et al. (2018) is in alignment with the proposed guidelines of the IPPC and provides equations and estimations of forest stand biomass structure and biomass expansion factors for Northern Eurasia, which is why in the following it is described a bit closer. Additionally, the results show lower uncertainties compared to the values of official reporting procedures like the FAO or the IPCC 2006. The spatial distribution of the BEFs, BCEFs and the R:S ratios were created based on regression equations and characteristics of the forest cover (Schepaschenko et al., 2018).

In the following two parameters which are used to model above ground biomass are described.

The BEF is defined in Equation 7 as the ratio of aboveground oven-dry live biomass (AGB) [t/ha] to the stem oven-dry biomass (M_{st}) [t/ha] (IPCC et al., 2006).

$$BEF = \frac{AGB}{M_{st}} = \frac{(BCEF_{st} + BCEF_{br} + BCEF_{fol}}{BCEF_{st}}$$

Equation 7: Calculation of BEF factor by Schepaschenko et al. (2018).

Where $BCEF_{st}$, $BCEF_{br}$ and $BCEF_{fol}$ are the different fractions of the Biomass Conversion and Expansion Factor (BCEF), for stems, branches, and foliage in oven-dry tons per m^3.

The BCEF factor combines the conversion and expansion processes and further transforms the growing stock volume (GSV) [m^3/ha] into AGB:

$$BCEF = BEF \times D = \frac{M_{st} + M_{br} + M_{fol}}{GSV}$$

Equation 8: Calculation of BCEF factor by Intergovernmental Panel on Climate Change et al. (2006)

Where D is basic wood density [tons/m^3] and M_{st}, M_{br}, M_{fol} are the live biomass of stems, branches, and foliage [t/ha].

The BCEF equation can be further divided into a set of BCEF models for stems ($BCEF_{st}$), branches ($BCEF_{br}$) and roots ($BCEF_{ro}$) for planted tree species (Schepaschenko et al., 2018).

$$BCEF = BCEF_{st} + BCEF_{br} + BCEF_{fol} + BCEF_{ro}$$

Equation 9: BCEF calculation by Schepaschenko et al. (2018).

For belowground biomass it is recommended by the Intergovernmental Panel on Climate Change et al. (2006) to use the R:S ratio, which is defined as the ratio between belowground tree live biomass to aboveground tree live biomass:

$$R{:}S = \frac{BCEF_{ro}}{BCEF_{st} + BCEF_{br} + BCEF_{fol}}$$

Equation 10: Calculation of R:S ratio by Schepaschenko et al. (2018)

Where $BCEF_{st}$, $BCEF_{br}$ and $BCEF_{fol}$ are the different fractions of the Biomass Conversion and Expansion Factor (BCEF), for stems, branches, and foliage in oven-dry tons per m^3.

3. Material and Methods

The thesis covers a literature review with the aim to identify necessary data and expertise to create guidelines for an inventory for forest management production processes. The literature review was conducted via various research platforms such as, Google Scholar, Scopus and BokuLit with key words such as, forest management systems, LCA, LCI, Land Use, Russian forest etc. Additionally, relevant webinars of LCA, forestry experts and pulp and paper industry representatives, e.g. Cepi were attended. Next to a webinar of the European paper industry association (Cepi) also a webinar of Frauenhofer Institute influenced the desk review as the cited paper of (Horn et al., 2021) was presented there. A questionnaire was created to gather needed data, which was further tested using primary data (Appendix A). Then, a pilot calculation was carried out to evaluate the outcome of the created inventory comparing it with a dataset in the Ecoinvent database. In the upcoming subsections, these procedures are explained in more detail.

3.1 Questionnaire

Usually data collection is the most time intensive phase of an LCA. Thus, the aim of the questionnaire is to gather needed site-specific data from Russian forest experts, as efficient as possible. As the creation of an inventory of one cubic meter of wood is not straightforward, a large part of the literature review was focusing on finding out what processes shall be included. One has to specially highlight the study from Klein et al. (2015) who reviewed 22 forest related LCAs and provided a first guideline for the creation of forest LCAs. Based on a variety of literature sources (Klein et al., 2015; Kühmaier et al., 2019; Wolf et al., 2016) and several interviews with both LCA and forest experts a questionnaire was further created (Appendix A).

The questionnaire is generally divided into two parts. The first part, the top-down approach, mainly focuses on general questions to get closer information on the study site, e.g. questions regarding the size of the study area, I/O inventories of the forest production etc. In the second part a bottom-up approach was used and questions concentrate on more granular data e.g., productivity rates, amount of used fossil fuels, etc. Figure 16 illustrates the two different approaches in the context of the created inventory.

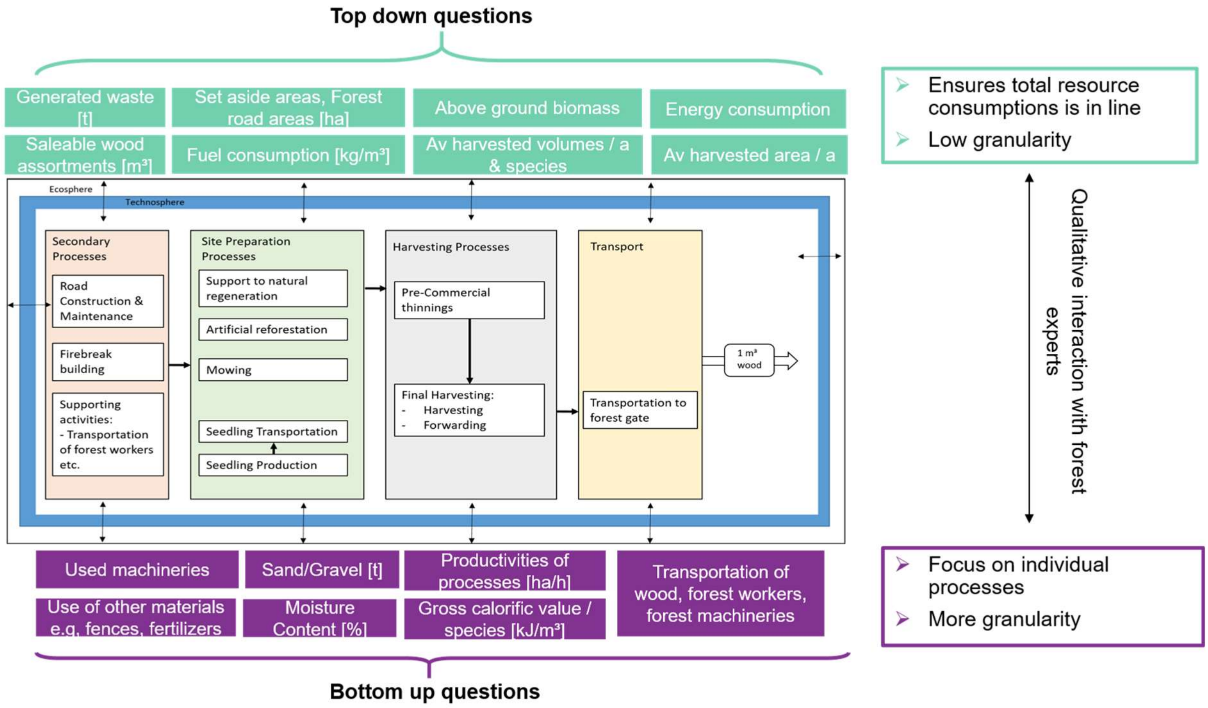


Figure 16: Top Down - Bottom Up Approach of the pilot inventory

An additional distinction in the questionnaire is made between direct and indirect processes. Direct processes include measures in which the input can be directly assigned to the output. For example, if we look at timber harvesting, the environmental impacts that arise can be directly attributed to the quantities harvested. In contrast, there are processes in the system whose inputs and outputs must be assigned to the total amount of timber harvested.

3.2 Pilot of Questionnaire

The questionnaire, which was created based on the desk research was tested in a pilot. This pilot is based at a study site which is located in the republic of Komi, Russia (63° 48′ N, 55° 48′ O) (Figure 17). The annual rainfall is about 700mm and mean temperatures around 1.7° Celsius. It comprises of 2.1 Mio hectares of boreal forest in 2020. Yet, for harvesting processes, only ~75% of the area is used, which is harvested via a clear-cut system. Typically, species like birch, spruce, aspen, pine and minor wood assortments of larch and fir are harvested. 25% of total area of 2.1 Mio hectares are set aside for natural conservation purposes and are not touched. In an own scenario these 25% of set aside land are investigated during the LCIA. Additionally, in 2021 around ~80% of harvested volumes were FSC certified ensuring the fulfillment of natural requirements. Besides natural regeneration, also artificial reforestation takes place. In Figure 17 it can be seen that distances between the harvesting areas are quite long which makes it complicated to create a sufficient road network and transport harvested logs. Looking at the silvicultural and harvesting processes one can find one major difference to established forest management systems in Europe. While in Europe between two and four commercial thinning steps take place, for the study site only one pre-commercial thinning step happens. According to an interviewed forest expert, this is due to the fact, that it is economically not feasible to organize these activities in such a big area that often.

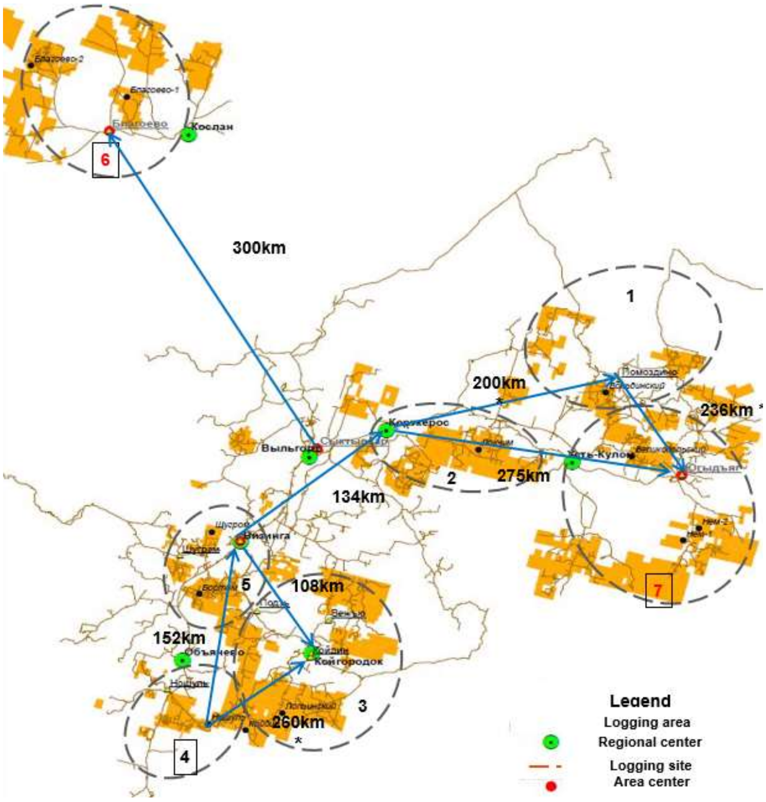


Figure 17: Study site in the Republic of Komi, Russia (Popov, 2012)

3.2.1 System Boundaries and Functional Unit

Forest inventory data gathered by the responsible forest management team in Russia are the main data basis. The study takes data from 2016 until 2020 into account, as only from 2016 onwards data in a sufficient quality were available from the forest site in Syktyvkar. Additionally, no abnormalities, like weather extremes (forest fires, storms) or other calamities appeared during this period. Thus, gathered data during this time period were then transformed into a well-founded “average year” of wood harvesting processes.

Both system boundaries and functional unit are a key part of the goal and scope phase of an LCA. As **functional unit** one cubic meter of green wood under bark, harvested and transported to the forest gate in the republic of Komi, Russia was defined. As the forest site in Komi is distributed over a large area the forest gate was defined as an average transportation process of 200km from the harvesting site. One cubic meter (ub) is the unit most frequently used reference flow in other peer reviewed LCA studies and a common reporting unit in forest systems (Klein et al., 2015). Besides, the volume can easily be transformed with the help of specific densities of the trees to tons, or with specific water contents to an energy content value.

For the system boundaries of this LCI a cradle-to-gate approach was chosen, as this approach better represents the reality, in which forest products, such as pulpwood are only an intermediate product of the total supply chain of e.g., the production of pulp and paper. The cradle-to-gate approach includes all inputs, outputs and potential environmental impacts of a product's life cycle from raw material acquisition across production until the gate of the evaluated forest (ISO 14040, 2006).

The system diagram (Figure 18) is considered for the study. The geographical boundary of the production of one cubic meter wood is delimited to the specific forest area at Komi Republic, Russia. Hence, processes that occur in the forest management system in Russia from the establishment of the stand to the transport of wood logs to the forest gate are included.

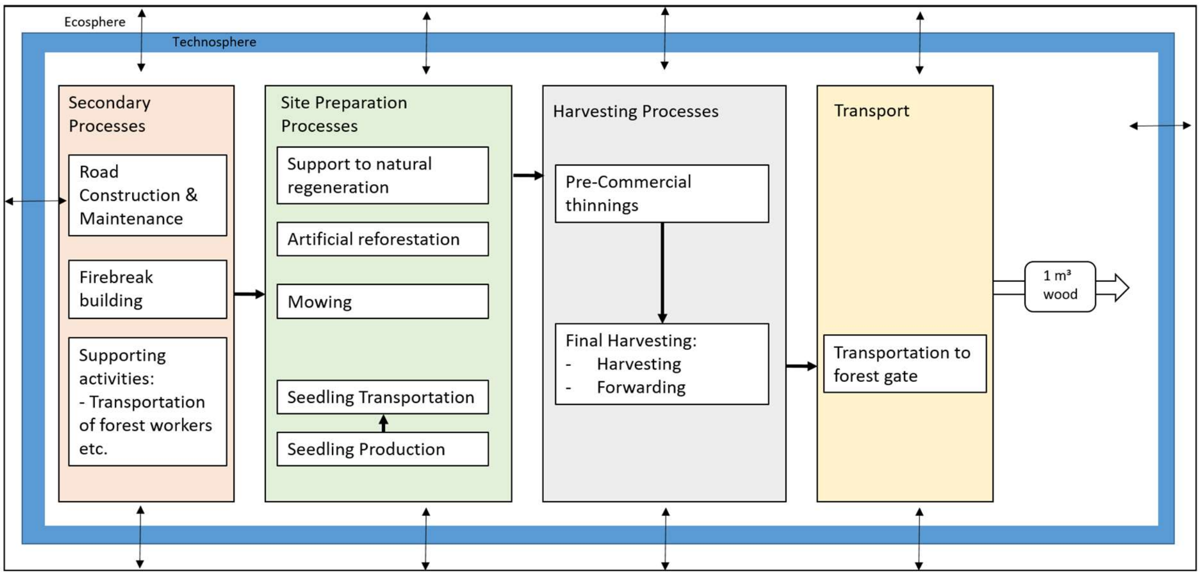


Figure 18: System diagram for the production of one cubic meter under bark at forest gate

As already described in chapter 2.3.1, in contrast to many other land use systems, in which only one year or a few years are considered, the production period of forestry usually extends over several decades, sometimes even centuries. For this study site an average rotation period of 100 years was taken into account. If one considers only a single intervention e.g., a harvesting measure at a certain point in time, processes that may have already occurred decades ago in the course of forest management are neglected. Thus, with regards of defining a temporal system boundary, a whole rotation approach was chosen to include all relevant processes.

The system boundaries of the production system can be divided in foreground and background systems (Figure 19). The foreground system contains information on, firebreak building, road construction, reforestation, harvesting etc. The background system is based on secondary databases such as, Ecoinvent. It provides information on the production of infrastructure, (e.g., greenhouse for seedling production), “Machine operation, load mix” – process, gross calorific value of softwood, density of sand/gravel mix, etc.

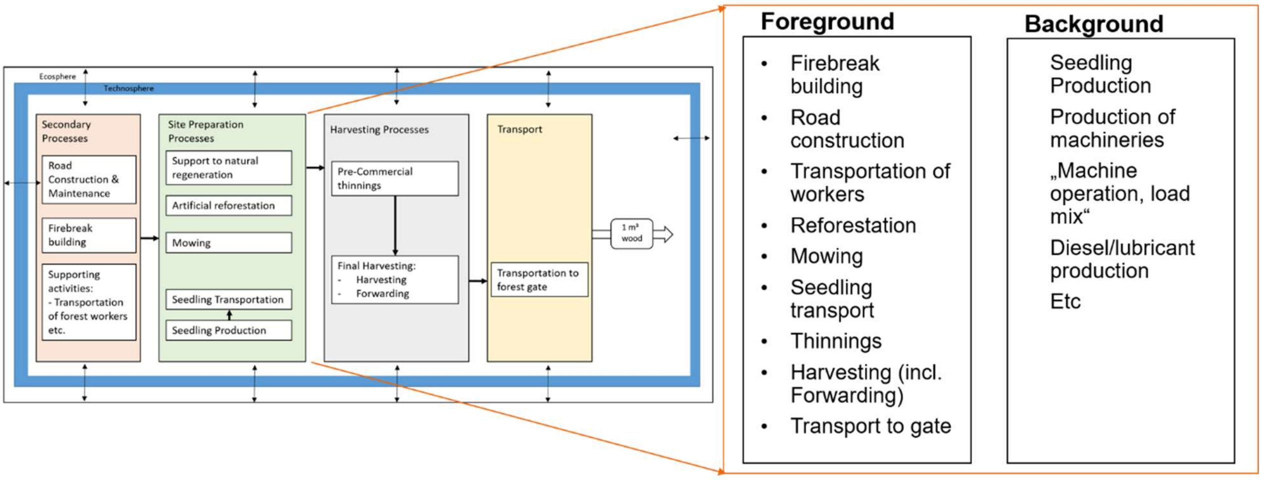


Figure 19: Foreground-Background system of modelled inventory

3.2.2 Data Collection with the Questionnaire

In this chapter, the creation of the life cycle inventory of this work is described in detail. It includes both foreground and background data. Foreground data were generated with the help of a semi-structured questionnaire and provided by responsible forest experts. Background data are composed of a comprehensive literature research and data from Ecoinvent database. The LCI was divided in four production stages: Secondary processes, site preparation processes, harvesting processes and transportation processes of wood logs to forest gate. In general, as also proposed in Figure 3, gathered data were first validated, then related to each unit process and further transformed to proposed functional unit. To ensure the validation and of provided data, input data were analysed and compared with inputs of relevant Ecoinvent unit processes and additionally discussed with forest experts. As a final step after the creation of the inventory it is compared to already existing forest inventories such as, the one modelled by Werner (2010) “softwood forestry, pine, sustainable forest management – Sweden” in order to identify potential limitations and differences.

3.2.2.1 Secondary Processes

This process subgroup comprises the processes of road construction and maintenance as well as firebreak building and supporting activities.

For the subprocess of forest road construction and maintenance, heavy machines, like graders, excavators, trucks, road rollers, bulldozers and grey dozers from the company John Deere are being used. Usually the forest roads in Syktyvkar are 15 to 20 meters wide. Grey dozer, bulldozer and excavators are mainly used to clear the planned road from trees and other obstacles. Afterwards trucks deliver the sand/gravel mixture and machines such as, graders and road rollers are used to straighten the street. Next to the used machineries input data such as diesel consumption and amount of sand/gravel mix were provided for the creation of 1km of forest road. The sand/gravel mixture can be procured within the study site and transportation emissions were already included in the total input of diesel. To calculate to impact of procured sand/gravel per cubic meter wood a density of 1442kg/m^3 is used.

For the modeling of road construction and maintenance a proxy unit process was created for which an average was calculated with following unit process of EcoInvent 3.7.1 “machine operation, diesel, < 18.64 kW, high load factor”, “machine operation, diesel, < 18.64 kW, steady-state” and “machine operation, diesel, < 18.64 kW, low load factor”. This created unit process was named as “machine operation, load mix” [h/kg Diesel] and was further used in several other subprocesses like, firebreak creation, supporting activities and reforestation processes. This is because no unit process for bulldozers, excavators or other heavy machines could be found in Ecoinvent 3.7.1 (Wernet et al., 2016). The unit process was calculated by using following equation:

$$Machine\ operation, load\ mix = \sum_{i=1}^{3} \frac{1}{MO_i} * \frac{1}{3} \qquad [\frac{h}{kgDiesel}]$$

Equation 11: Calculation of unit process "machine operation, load mix"

Where: MO_i represent the three different unit processes of machine operations, <18.64kW, with a high/steady/low load factor.

This calculation step was necessary as received data were on a level of fuel consumption and not typical operating hours per kg diesel were needed to make the data compatible with the background datasets. For the creation of firebreaks, forest workers are using heavy machines, such as bulldozer with large plows or medium excavators produced by John Deere to prepare clear cuts. These firebreaks shall prevent bush fires to spread from one area to another and are usually around four meters wide. Therefore, information of built firebreak distance, utilized machinery and productivity were provided.

Supporting activities were summarized as activities like, workers delivery, delivery of forest machineries, diesel utilization in logging camps, transportation of fuels, lubricants and spare parts. The workers are coming once a week by bus or SUVs to the forest site and stay there until the end of the week in provided logging camps. Forest machineries on the other hand stay at the forest site once delivered via a semitrailer. For the above-mentioned activities the entire amount of utilized diesel was prepared and then further connected with the unit process "machine operation, load mix". The unit process "machine operation, load mix" was used, as the "supporting activities" category couldn't be split by forest experts. Thus, it is described as an approximation for combustion processes for machines < 18.64 kW. The created unit process was found to be suitable for the purpose to model the "supporting activities" process.

3.2.2.2 Site Preparation Processes

"Site Preparation Processes" include following subprocesses: Seedling production, seedling transportation to forest, artificial reforestation, support to natural regeneration and mowing. According to the forest expert in Syktyvkar additional 20-30% of provided diesel inputs for each above-mentioned activity are added due to the transportation of people and equipment to the forest site.

For the seedling production process, the amount of planted seedling was provided. In addition, subsequent unit process of (Werner, 2002) Ecoinvent "tree seedling produced and planted, in heated greenhouse – RER" was used and adopted to the Russian electricity and heating mix. Next to the electricity and heating mix, it was identified that the greenhouse unit process in Ecoinvent also includes packaging material. However, at the Russian forest site no packaging material is used for the transportation of tree seedlings, thus, this leads to uncertainties as no adoption of the unit process was carried out. As a next step these seedlings are then transported with a lorry 16-32 tones to the forest. Forest experts in Russia provided information of transport distance and utilized truck.

For the planting process, two different options were identified: artificial reforestation and support to natural regeneration. At the forest site natural regeneration is supported in a way that the surface is scarified with an excavator so that the upper layer of the soil is removed which makes it easier for the seeds to sprout. For both subprocesses, input data on prepared area and productivity of utilized machines were delivered. The created unit process "machine operation, load mix" was used once again for the implementation in the LCI.

The mowing activity consists of a brushcutter, model "STIHL FS 450-K", for which information of its productivity and fuel consumption were provided. The activity takes place within 10 years after establishing the forest stand. The aim is to remove undesirable growth of plants, which would suppress planted trees. As there is no relevant unit process of a brushcutter in Ecoinvent 3.7.1, the unit process “power sawing, without catalytic converter” is used instead, as this can be seen as a good approximation because of similar size, engine and fuel consumption.

3.2.2.3 Silvicultural and Harvesting Activities

The process subgroup silvicultural and harvesting activities include subprocesses like, pre-commercial thinning and final harvesting which is further divided in harvesting and forwarding.

Similar to the mowing process, also for the pre-commercial thinning process the same model of brushcutter is used. The activity takes place in the forest stand between an age of 10-20 years. The cuttings are not further used and are left in the forest. In managed forests usually, additional thinning process take place, however this is not the case for the examined study site. According to a forest export this is due to the fact that it is economically not feasible, due the remote area to invest in an additional management step.

The harvesting process at the study site occurs after a rotation period between 80-100 years. Clear cuts are the typical harvesting method at the study site. Generally, the maximum allowed clear-cut area is 50ha in the Republic of Komi, nevertheless in average 22 hectares are harvested at the study site. The process begins with establishing the boundaries of the clear-cut area to comply with local regulations, such as the requirement that there have to be 6 years between harvests in adjacent logging areas. According to a forest expert in Russia the reason for that is to make it possible that neighboring forests are able to distribute their seeds at the clear-cut site. As a next step forest teams peg the clear-cut area to make the boundaries visible for subsequent harvester and forwarder. Afterwards the final harvesting takes place. Input data such as, total amount of diesel, lubricant oil per cubic meter of harvested wood for both harvesting and forwarding subprocess were prepared by Russian forest experts. As well as information on productivity of used machines of the model “Ponsse Ergo Harvester” and “Ponsse Buffalo Forwarder”. Additionally, mean forwarding distances were provided.

One year after the final harvest the clear-cut area is controlled by local forest authorities.

To model the harvesting activity, the Ecoinvent unit process “harvesting, forestry harvester” is used. In the description of this unit process modelled by Werner, (2012b), a forestry harvester class two (80-120kW) with a total weight of 14,000kg was used. For the forwarding activity Werner, (2012a) modelled a forwarder class two (10-12to) with an average engine power of 110kW and a total weight of 11,049kg.

3.2.2.4 Transportation

As a last subgroup in the inventory, the transportation processes are included. Therefore, the unit process transport, “freight, lorry >32 metric ton” from Ecoinvent was implemented. The modelled truck in the proposed unit process has a load factor of 29.96t. Input data of specific diesel consumption for the provision of one cubic meter of wood as well as average transportation distances were delivered. Figure 17 provides a general feeling how wide spread the forest camp is, thus an estimation of the average transport distance of about 200km to the forest gate was provided by forest experts. This 200km are divided into the transportation to the intermediate storage ~100km and in the end to the forest gate ~100km. However, it has to be mentioned that deviating moisture contents, higher moisture contents until intermediate storage; lower contents after storage, were not taken into account. In general, a moisture content of about 52% were used for calculating the diesel consumption for transportation of harvested wood. This leads to uncertainties as already Zanuncio et al. (2017) states that differences in moisture content of harvested wood influences the transportation costs and emissions. The utilization rate was estimated to be by around 50% which is also used by the Ecoinvent unit process. As already mentioned above transportation processes of forest workers or transportation of forest machineries is already included in the subprocess “supporting activities”.

4. Findings

This chapter will encompass the results of this master thesis and answers stated research questions. The results first show an overview of utilized processes during the creation of the pilot inventory. As a next step an inventory of an Ecoinvent dataset was compared with the created inventory of a Russian forest site. Ecoinvent was used for this comparison as many LCA practitioners build their calculations on such background datasets. Afterwards, LCIA results of the pilot inventory are illustrated and described and as a final step a guideline for the creation of an LCA inventory was created.

4.1 Overview of relevant processes

Looking at inputs from technosphere, diesel consumption was identified as a key data input and provided by the Russian forestry team for certain subprocesses for which data were available. The structure and identification of relevant processes is partly based on literature sources such as Klein et al. (2015) and the expertise of both an LCA and forest expert at Mondi. In order to make sure that relevant unit processes are suitable for being used in modelled inventory one has to look at e.g., technical data sheets, unit process descriptions of Ecoinvent etc. For example, the unit process of Werner (2012a) in Ecoinvent, models a forwarder with an average engine power of around 110kW. Compared to that the Ponsse Buffalo forwarder, which is used at the study site, has around 210kW. This also applies for the harvesting process, modelled by Werner, (2012b), which uses an average engine power between 80-120kW, yet the Ponsse Buffalo harvester has around 210kW. Thus, a higher diesel usage of the Ponsse Buffalo machines is expected. In the modelled inventory this was partly taken into account via the chosen top down approach, where the total diesel consumption was broken down by forest experts to relevant unit process.

The raw data gathered via the questionnaire are in a next step related to each of the listed subprocesses (Figure 18). It is important to state that during the inventory creation of this study no commercial thinning process took place. Information in Figure 18 need to be highlighted, as they are the main inputs which were essential for the creation of the pilot inventory (Table 6).

Table 6: Overview of relevant processes for modelled forest inventory

Stage	Process		Machine	Source (e.g., Ecoinvent)	Output Unit /m^3
Secondary Processes	Road Construction and Maintenance		Bulldozer, Excavator, Trucks etc.	Machine operation, load mix	m/m^3
	Firebreaks Creation		Bulldozer, Tractor	Machine operation, load mix	m/m^3
	Supporting Activities		workers delivery, logging camps, diesel stations, etc.	Machine operation, load mix	h/m^3
Site Preparation Processes	Seedling Production	Greenhouse	Heated greenhouse	Tree seedling produced and planted, in heated greenhouse - RER	pieces/m^3
		Transport of Seedlings	Lorry (16-32t)	transport, freight, lorry 16-32 metric ton, EURO5 - RER	tkm/m^3
	Soil Preparation	Support to Natural Reforestation	Excavator	Machine operation, load mix	m^2/m^3
		Artificial Reforestation	Excavator	Machine operation, load mix	m^2/m^3
		Mowing	Brushcutter	power sawing, without catalytic converter | Cutoff, U	m^2/m^3
Silvicultural and Harvesting Activities	Pre-commercial thinning's		Brushcutter	power sawing, without catalytic converter | Cutoff, U	m^2/m^3
	Commercial thinning's		Not used at the study site		
	Final harvesting	Harvesting	Harvester	harvesting, forestry harvester | Cutoff, U	h/m^3
		Forwarding	Forwarder	forwarding, forwarder - RER	h/m^3
Transport	Wood Logs Transportation		Lorry >32t	transport, freight, lorry >32 metric ton, EURO5 RER	tkm/m^3
	Forest workers		Included in "supporting activities" for this study		

Inputs from the environment for forest systems are on the one hand the utilized sand and gravel mix for the construction of forest roads, on the other hand the amount of CO_2 which is sequestrated in one cubic meter wood above ground and inputs for calculating the land use impact category. The sequestrated CO_2 was provided by forestry experts following the equations of Schepaschenko et al., (2018), which can be found in chapter 2.5.3. Factors like biomass expansion and conversion factor, wood density the carbon fraction and the root-shoot ratio have to be derived. Impacts of the net change in carbon stock are not influencing the LCIA results of the used EF.3.0 impact method. Nevertheless, in other impact methods such as e.g., "IPCC 2013 GWP 100a (incl. CO_2 uptake)" the value is influencing the results. It was challenging to implement the land use impact category into the LCA software despite the fact that according to Bos et al., 2016 only information on the land use type (forest, grassland, etc.) with additional information of activities timeframe, site location and used area for "occupation" and "transformation" are needed to calculate the impact.

A main difficulty during data acquisition is to stay in line with scope and system boundaries of the LCI. The temptation to gather more and more details for the calculation is strong, yet this often leads to unnecessary delays and efforts, which in the end are often not needed.

4.2 Comparing an Ecoinvent Unit Process with created LCI

Ecoinvent processes are very useful for validating the input data on a unit process level to ensure a creation of a robust inventory. They are able to provide a certain accuracy and thus can be used to evaluate input data for relevant unit processes to look if they are feasible or not. Therefore, input data were cross checked with relevant unit processes of Ecoinvent such as: *"transport, freight, lorry >32 metric ton, EURO5"; "excavation, hydraulic digger – RER"; "power sawing, without catalytic converter"; "harvesting, forestry harvester", "tree seedling production, in heated greenhouse, RER" "forwarding, forwarder – RER" and "softwood forestry, pine, sustainable forest management"* and a study of Kühmaier et al. (2019) who focused on modelling forest management systems in Austria. In particular the unit process of Werner (2010) "softwood forestry, pine, sustainable forest management – Sweden" is further compared with the created LCI of this study, which in the following is referred to as "Russian model".

Table 7: Inputs from technosphere for "softwood forestry, pine, sustainable forest management - SE" unit process, adopted but based on Werner et al. (2010), in Ecoinvent 3.7.1

Inputs from technosphere	**Amount**
Forwarding, forwarder Activity Link: forwarding, forwarder RER	0.0488h
Gravel crushed Activity Link: Marked for gravel crushed	9.34kg
Harvesting, forestry harvester Activity Link: harvesting, forestry harvester RER	0.0979h
Inputs from technosphere	**Amount**
Power sawing without catalytic converter Activity Link: Power sawing without catalytic converter	0.106h
Skidding, skidder Activity Link: skidding skidder, RER	0.00134h
Tree seedling for planting, heated Activity Link: Tree seeding production in heated greenhouse, RER	3.34 unit
Tree seedling for planting, unheated Activity Link: Tree seeding production in unheated greenhouse, RER	7.93 unit

Table 7 provides information of an inventory for 1m^3 of pine under bark in Swedish forests. The general process structure of the Swedish inventory is similar to the LCI of this study, yet some processes are missing. For instance, the creation of firebreaks, the process of artificial reforestation and also transportation of employees were not included in the model of Werner (2010).

Analyzing the inputs of the inventory, one can see that the forwarding process is used for 0.0488 hours/m^3 of harvested wood. This is significantly lower compared to the used value of the inventory in Russia. Additionally, the Swedish model includes a skidding process, though it has only a minor impact. If the skidding is added to the forwarding process, the correlated Russian forwarding process is still higher. Looking at the study from Kühmaier et al. (2019) 0.78 l/ m^3 of forwarded wood is consumed by a forwarder in a deciduous forest. This value is still about 40% lower compared to the value used for the Russian model. Differences could be explained due to the fact that harvesting processes like felling, delimbing, bucking and extracting are strongly depending on utilized productivities and fuel consumption of the used machineries (Klein et al., 2015; Wolf et al., 2016). Therefore, it can be stated that the Russian forwarding process compared to the Swedish and Austrian one is more time intensive due to different structure and diameters of trees and e.g., longer forwarding distances etc., leading to reduced productivities. The harvesting process on the other hand of the Swedish model show a longer utilization period compared to the Russian model. For modelling the Swedish model a harvester type two with average engine power of 80-120kW is used by Werner (2012b). In the Russian model a Ponsse Buffalo harvester with around 210kW is used, which could explain the shorter utilization periods due to higher productivity for the Russian model.

For construction and creation of forest roads in the Swedish model 9.35kg gravel is used per m^3 harvested wood under bark. This represents only about 5% of the amount of sand/gravel mix, which is used for the construction of forest roads in Russia. Additional 15.8MJ/m^3 of diesel were used for the distribution of gravel for forest roads plus for planting activities in the unit process of Werner (2010). Kühmaier et al., (2019) identified for the creation of forest roads in Austria a diesel consumption of about 6.5 liters per running meter (rm) Comparing these inputs from literature sources to the Russian inventory big differences occur. The creation and maintenance of Russian forest roads nearly consume double the amount of diesel utilized in the model of Werner (2010). This might be due to the fact that Russian forest roads are 15-20 meters wide and therefore, the creation and maintenance consume a lot of energy. Moreover, according to a forest expert it has to be mentioned that in comparison to the Russian model, in Sweden transportation takes usually place at public roads. Thus, the Swedish model might not take inputs of e.g., sand/gravel and energy for maintenance of public infrastructure into account.

To model site preparation activities such as pruning, tending etc., the Swedish model is using the same proxy as the Russian inventory. It can be seen that the utilization period of the Swedish model (0.106h/m^3) is significantly longer. However, in the Swedish model the power sawing process is also including the amount of actual power sawing per m^3. This might be one of the reasons of the higher value compared to the Russian model.

In the inventory of Swedish pine forests in total 12 seedlings are planted per m^3. Compared to the Russian forest inventory, this is quite high. The reason for this could be a lower ratio of natural regeneration in the Swedish model (40%) compared to the Russian inventory. Hence, more seedlings need to be produced for reforestation purposes.

Next to all the inputs from technosphere, additional inputs from the environment arise such as uptakes of CO_2 per cubic meter or from e.g. land use.

Impacts of of net change in carbon stock are not influencing the LCIA results of the EF.3.0 impact method as it is excluded from the calculation. However, in other impact methods such as e.g., "IPCC 2013 GWP 100a (incl. CO_2 uptake)" the value is influencing the results. Thus, in order to create a complete inventory, which can be used for several impact methods this value needs to be in place. Therefore, the calculation approach already described in chapter 2.5.3 was chosen to calculate a value for the net change in carbon stock of above ground biomass in Russian forests. The above ground value was chosen as this is the value which is actually then further utilized in our system boundaries. Additional values for e.g., below ground biomass were not included as they are out of scope of this inventory. For the Swedish model, aboveground biomass shows an uptake of 888kg CO_2 from air per m^3, which is compared to the Russian model around 25% lower. However, in the Russian model not only pine is evaluated but also three other tree species, which are all influencing the factor of above ground biomass.

In the course of this master thesis it was not possible to implement a regionalized calculation of each of the LANCA® indicators, as well as a Russian factor. For the land use impact category, the study site area which is used for the production has to be calculated and provided (Table 8).

Table 8: Land Use input data for "softwood forestry, pine, sustainable forest management - SE"-unit process from Werner (2010).

Swedish unit process	Occupation	Transformation from	Transformation to
Forest intensive	1870m^2*a	23.4m^2	23.4m^2
traffic area	7.12m^2*a	0.089m^2	0.089m^2

In general, two scenarios were implemented in the LCI in order to analyse differences in the outcome of land use during the LCIA step. Scenario 1: Utilizes areas that are solemnly used for harvesting timber. Scenario 2 however adds additional 25% to the area in scenario 1 in order to see how the land use impact factor is changing if this additional set aside area is added.

Scenario 1 of the Russian model occupies around three times more area then the Swedish model. Also for the transformation phase, inputs of the Russian study site are around double the area compared to the Swedish site. Looking at inputs of built traffic area, occupied region is nearly the same for both study sites as well as the area for the transformation phase. Looking at inputs of land use, one can additional see a difference in used land use flows. For the Russian model an “extensive forest” flow was chosen. Koellner et al. (2013) defines forest as, “[e]xtensive, with selective logging, where timber extraction is followed by regrowth, including at least three naturally occurring tree species.” – (p.5) and therefore suitable for the forest site in Russia. However, the Swedish model is utilizing an intensive forest land use flow, which might lead to differences in the LCIA results. Additionally, differences of occupied land can be explained due to the historic implementation of extensive forestry in the Russian model with low intensity of silviculture e.g., low percentage of planted area, few pre commercial thinnings, no commercial thinnings, which resulted in much lower productivities of m^3 per ha.

After the implementing the data into the inventory via a LCA software tool, the testing process begins. Thus, an impact method e.g., EF.3.0 in an LCA software like SimaPro, OpenLCA etc., is selected. This was also conducted for the created inventory of this master thesis, as it provides an additional validation step. Outcomes can be compared with already existing LCAs to see if they are feasible. In the following the results of the created LCIA pilot are highlighted.

4.3 LCIA Results

For calculating the LCIA of the study site the impact method EF.3.0 was chosen and in the following analysis the focus was put on the climate change impact category. First results of the conducted LCIA show that forest operations have a significant environmental impact on the GWP (Figure 20).

Following subprocesses show more than 10% of the GWP of the supply chain:

- Felling, processing and forwarding
- Road construction and maintenance
- Transportation processes to forest gate

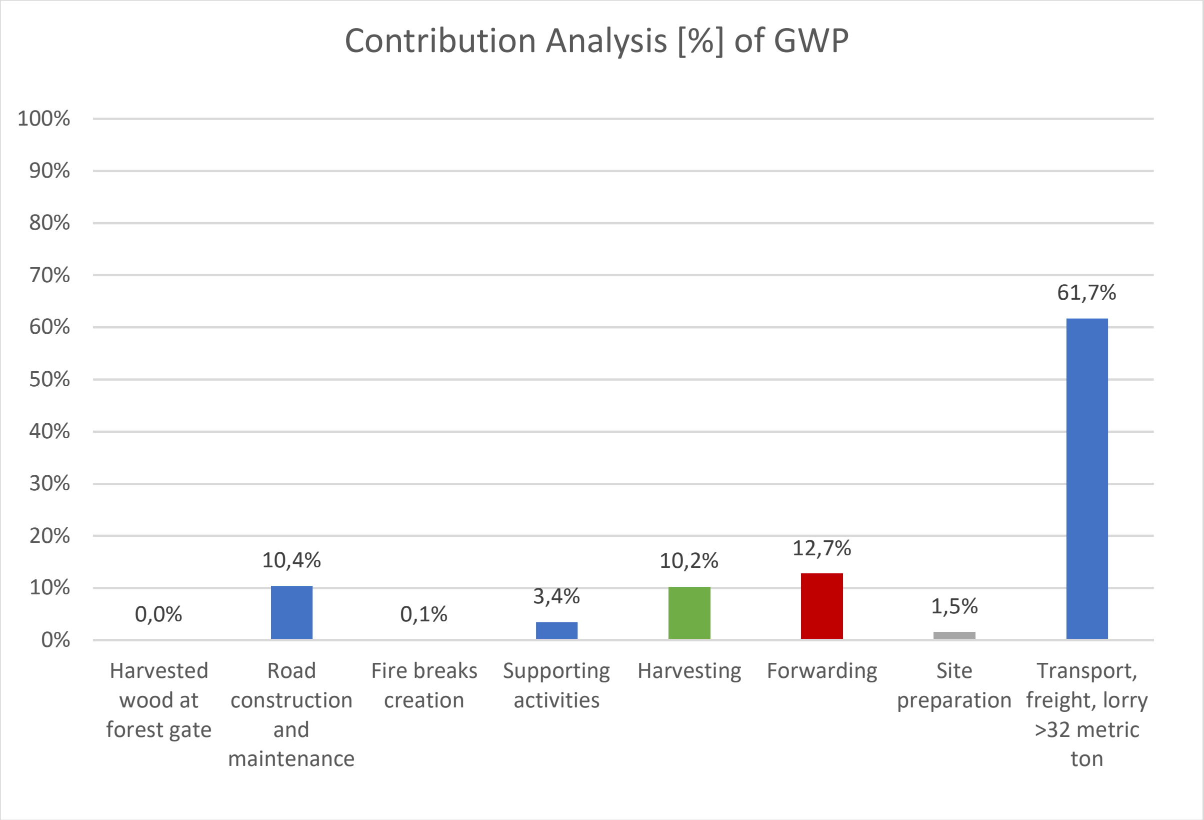


Figure 20: Contribution analysis [%] for the production and distribution of 1m^3 of wood on GWP, presented for each modelled process step.

Secondary processes include supporting activities such as, road construction and maintenance and fire breaks creation. Thus, this process group is accountable for around ~14% of overall GWP. As already described in chapter 3.2.2.1 , "supporting activities" include processes like, workers delivery, delivery of forest machineries, transportation of fuel/lubricants and spare parts and diesel utilization in logging camps. It contributes around 3.4% to the GWP and needs to be highlighted as e.g., the Swedish model is not including processes in this granularity. Road construction and maintenance are the major contributor in this process group and therefore further focus shall be put on this subprocess. A possible reason for this is that during the construction of forest roads, which in Russia are about 15-20m wide, vast amounts of diesel, are needed. Fire breaks creation on the other hand are playing nearly no role in regards of their overall impact to the GWP and can therefore be neglected.

Site preparation: It involves following subprocesses: Seedling production, seedling transportation to forest, artificial reforestation, support to natural regeneration, mowing and pre-commercial thinning's. As one can see in Figure 20, only 1.5% of total GWP are involved in this category. Hence this process group can be seen as a minor contributor to GWP. One of the reason for that might be that the share of natural regenerated trees compared to other forest sites is larger und thus the impact of the production and transportation of the seedlings is also smaller.

Silvicultural and harvesting operations: During harvesting operations, around 23% are emitted, where forwarding has about 13%, felling, and processing about 10% of the impact. Similar values are also shown in the survey of Klein et al. (2015), lying between 1.6 and 6.4 kg CO_2 per cubic meter, however in their study the category "silvicultural operations" includes additional processes like, seedling production, thinning, etc.

Transportation: Transportation processes to forest gate are the major part of CO_2-eq emissions arising during the production of forest logs, emitting ~62%. Therefore, transport is seen as a significant factor for LCA modelling of wood (González-García et al., 2009; Michelsen et al., 2008 and Pieratti et al., 2020). The transportation is of course from site to site different and thus significant deviations may arise during comparisons of one study to another. Additionally, factors like water content, load factor and transportation routes are influencing the uncertainty of the result. Despite the fact that the transportation to forest gate is included in above named studies, it is missing in most Ecoinvent unit process for pulpwood such as "softwood forestry, pine, sustainable forest management - SE" or "softwood forestry, pine, sustainable forest management – DE", created by Werner (2010). This needs to be kept in mind while comparing and using these unit processes.

In the study of Klein et al. (2015), in which 26 forest related LCA were evaluated, the mean GWP emissions from site preparation to forest road (excluding transport to forest gate), were in average 14.3 kg CO_2-eq / m^3, with a standard deviation of 10.7kg CO_2-equivalents per m^3. Comparing the result of this master thesis with the result of Klein et al. (2015), only a minor deviation was identified. Additional LCIA results were included in the comparison e.g., from Werner (2010) who created three ecoinvent datasets:

- *Softwood forestry, pine, sustainable forest management_SE*
- *Softwood forestry, pine, sustainable forest management_DE*
- *Softwood forestry, mixed species, sustainable forest management_CH*.

Results of these dataset are depicted in Table 9:

Table 9: LCIA results [kg CO_2-eq/m³] of compared Ecoinvent processes by Werner (2010)

Ecoinvent 3.7 Sweden	9.9	kg CO_2-eq / m³
Ecoinvent 3.7 Germany	12.4	kg CO_2-eq / m³
Ecoinvent 3.7 Switzerland	13	kg CO_2-eq / m³

Looking at the results of softwood ecoinvent datasets from Sweden, Germany and Switzerland modelled by Werner (2010) only small differences can be depicted between the three countries. Including the results of Klein et al. (2015) and the Russian inventory, values of analysed LCAs vary between 9.9 – 15 kg CO_2-eq / m³, excluding the transportation processes.

Nevertheless, in order to get a clear picture how each of the modelled processes deviate from other studies further research is required.

Next to impacts on climate change, additionally the impact category land use was briefly analysed. As already described in chapter 4.2 two scenarios were defined. First scenario depicts impacts on the actual area which is used for harvesting. Second scenario includes additional 25% set aside area which is solemnly used for conservation purposes. During the analysation of the two scenarios it becomes obvious that the system strongly correlates with the input area. This means if one adds 25% more input area also the land use result is 25% higher.

4.4 Guideline for Creating an LCA Inventory for Wood Production in the Paper Industry

In general the creation of a forest inventory can be broken down into following steps (European Commission, 2010):

- Goal and Scope definition
- Recognizing relevant processes for modelling the system
- Preparing Questionnaire for data collection
- Validating data
- Connecting data to needed unit processes
- Calculating LCI results

In the following the processes are described in more detail.

The first step to create a forest LCI is to **define** its **system boundaries and functional unit**. For the creation of system boundaries the structure of the four sub-processes used in Figure 18 can be used as a first approach. While using a **cradle to gate** approach it is important to include all processes from site establishment to seedling production until the transportation to forest gate. Special attention should be put on the definition of the forest gate and further on the estimation of the transportation distance towards it. Processes that were excluded should be indicated and an explanation should be provided. If data for certain activities are left out, a best estimation approach should be provided or based on generic LCI data. Looking at the temporal system boundaries **a whole rotation approach** is suggested to calculate a well-founded average year. As **reference flow one cubic meter of harvested wood** under bark should be used as this is the unit which is most common in LCAs related to the forest industry and thus makes the study more comparable.

As a next step it is necessary to identify needed processes for modelling the system. For this stage it’s essential to have a clear nomenclature of processes to allow comparisons between studies. Therefore, it is suggested to use proposed structure of (Klein et al., 2015) which is also partly used for the modelled pilot in this study (Figure 8):

- Secondary processes
- Site preparation
- Silvicultural and harvesting operations
- Site tending
- Extracting

Next to processes it is essential to gather needed data for calculating a LCA. To make it as easy as possible for data providers in this case e.g., forest owners the questionnaire for creating an inventory should be split in a top down and a bottom up section. The top down approach is focusing on general information, has a low granularity and ensures that the total resource consumption is in line. Here it is advisable to first focus on fuel driven processes. Table 10 depicts information that need to be gathered via the top-down approach for modelling the production process of one cubic meter of wood during an average production year.

Table 10: Needed information for forest inventory gathered via top-down approach

Top-Down Approach	**Needed Information**	**Unit**
	Harvested volume per year and species	[m³/a]
	Harvested area per year	[ha/a]
	Energy consumption	[MJ/m³]
	Fuel consumption	[kg/m³]
	Saleable wood assortments	[m³]
	Generated waste	[t]
	Used Areas: E.g., set aside, forest road, firebreak, pre-commercial thinning's	[ha]
	Above ground biomass	[m³]

The bottom-up approach concentrates more on details of sub-processes of the suggested system diagram like, stand establishment, site tending, silvicultural and harvesting operations, wood transport to plant gate and infrastructure (Figure 18). This information is harder to obtain and more granular compared to the information gathered via the top-down approach. Table 8 illustrates needed bottom up information for the creation of a forest inventory.

Table 11: Needed information for forest inventory gathered via bottom-up approach

	General information	**Specific information**	**Unit**
Bottom-Up Approach	Used Machines: Excavator, Tractor, Bulldozer, Greydozer, Harvester, Forwarder, Chainsaw, Brushcutter	Productivities	[ha/h]
		Diesel inputs	[kg/h]
		Lubricant inputs	[kg/h]
	Transportation of wood, workers, forest machineries:	Modalities	
		Distances	[km]
		Transported weight	[to]
		Load factor	
		Utilization rate	[%]
	Stand and terrain parameters:	Wood species	
		Gross calorific values	[kJ/m³]
	General information	**Specific information**	**Unit**
	Stand and terrain parameters:	Wood densities	[kg/m³]
		Wood moisture content	[%]
		Carbon content of above ground wood	[C/m³]
	Use of other materials:	Fences	[kg/ha]
		Fertilizers	[kg/ha]
		Pesticides	[kg/ha]
		Sand/Gravel for forest roads	[kg/ha]
		Seedling production	Units/ha

Generally, for identifying needed data one should already have an idea which impact categories shall be modelled during the LCIA. Depending on the impact category different data might be needed e.g., for the "IPCC 2013 GWP 100a (incl. CO_2 uptake)" data for AGB are needed, which are in the EF.3.0 framework neglected. After calculating the GWP and Land Use impact categories of the EF.3.0 framework within the pilot calculation of this study, it is suggested to focus on the calculation of GWP. The impact category land use is not yet reflecting sustainable forest management in a robust and detailed way. Furthermore, during the conducted desk review the calculation of a regional land use factor turns out be very time consuming and complicated. Nevertheless, if one wants to model the land use impact category with the already implemented methodological approach in e.g., the EF 3.0 framework information on the land use type (forest, grassland etc.) with additional details of activities timeframe, site location and used area for "occupation" and "transformation" are needed.

In general, qualitative interactions with forest experts of the study site are highly recommended to avoid misunderstandings and to provide a better understanding for the needs for both sides.

After the collecting and data validation step, the raw data of each subprocess have to be related to the functional unit and further converted into the right data input format. For this step, it is essential to understand the required format in the LCA software for each created unit process in order to calculate it correctly. This process is not straightforward and needs to be thought trough. To make it better understandable, in the following a short example in Table 12 is provided. Data visualized in Table 12 shall only be seen as an example and do not depict the reality.

Table 12: Example for conversion of raw data

Process	**Unit Process**	**Machine**	**Calculation Description**	**Input-Unit Process / m³ wood**	**[unit]**	**Output-Unit Process / wood**	**[unit]**
Site Preparation	Artificial Reforestation	Excavator Komatsu	=(area [ha]/productivity [ha/h])/harvested wood [m³])	0.005	[h]	6.5	m²/m³

The “Input-Unit Process / m^3 wood” column represents the needed input format of the excavator which is used in the unit process “artificial reforestation”. In order to create an inventory this input is then entered into the LCA software tool of the specific unit process. Each unit process, however, also provides an output unit, which could be seen as the reason why it is implemented in the inventory in the first place. In this example, shown in Table 12, the output of the unit process “artificial reforestation” is the cultivated area per cubic meter wood. The calculation description refers to that value. Generally, this process has to be done for each modelled unit process. Thus, the complexity and time consumption need to be taken into account while creating an LCA.

Additionally, inputs from environment like land use need to be implemented separately, as they refer to the overall modelled system and not on specific unit processes. Therefore, parameters such as “occupation”, “transformation from” and “transformation to” need to be defined and calculated correctly.

5. Discussion

The first task of modelling a forest inventory was to conduct an intensive literature research. The aim of the literature study was to identify key elements of the inventory, as well as to formulate the right questions for the upcoming data procurement. Looking at the **creation process** of the questionnaire first a bottom-up approach was chosen and questions on relevant subprocesses were raised. The advantage of this approach is that data for each of the suggested subprocesses are gathered, which can afterwards be modeled with a high granularity. Hence, this makes it more transparent and understandable for future usage of the LCI in a different context. However, it is very time consuming to procure such detailed input data, if they are at all accessible at the referring forest management company. Thus, during the iterative testing process of evaluating and implementing the feedback from relevant forest and LCA experts of Mondi, it was agreed to rather provide data in form of a top-down approach instead. This on the on hand ensures that mass and energy balances are correct as I/O data on the whole forest site are used as a basis. On the other hand, data on e.g., total diesel input for the forest production site are easier available via regular statements of fossil fuel purchases. Combining this with literature and manufacturer's specifications, reliable data can be obtained. Hence, the questionnaire was not used in means of answering each question per se but rather to qualitatively understand what data are needed for the LCI. This is equally important to make sure that experts understand what is needed for the calculation. Besides, the additional interaction and discussion with relevant experts provides valuable insight, which might not have been assessed via a solemn use of the questionnaire. However, external parties often use exactly this method, to send a questionnaire and wait for the outcome, which might lead to significant misunderstandings. This can be avoided via additional qualitative discussion rounds leading to the reduction of feedback loops and time loss.

As previously referred to in chapter 2.5.2, the current **land use framework** of the EF is based but adopted on the LANCA® framework. It is of limited use if one wants to calculate regionalized forest models. In the following, these limitations are again highlighted. In forestry, many different management systems exist, as one must adopt to different tree species, forest site terrain and goal setting. However, in the EF framework, flow nomenclature does not reflect the different available forestry regimes and the different silvicultural systems among countries, only “forestry intensive” and “forestry extensive” can be chosen (Horn et al., 2021). This leads to further uncertainties within LANCA® indicators, like erosion resistance, groundwater regeneration and biotic production. Additional limitations arise within the indicators of mechanical and physicochemical filtration. This is because parameters such as soil texture, pH and humus content, which would include e.g., soil compaction through heavy machines, composition of age structure of tree species etc., are not included. Soil organic carbon and biodiversity are generally missing in the LANCA® framework. Moreover, for a regular LCA practitioner it is difficult to gather and calculate inputs for all LANCA® indicators implemented in the EF.3.0. Table 13 illustrates a complete list of needed LANCA® indicator parameters. However, one has to keep in mind that each of these parameters are calculated via formulas and additional factors, making the calculation even more complicated.

Table 13: Needed parameters for calculating LANCA® indicators in the EF.3.0

LANCA®	Parameter
Erosion Resistance	Soil Erosion Rate
	Erodibility Factor
	Slope Length
	Land Cover Factor
	Support Practice Factor
Mechanical Filtration	Soil texture Classification
	Permeability Determination
	Distance Surface to Groundwater
	Sealing Factor
Groundwater Regeneration	Precipitation
	Surface Runoff
	Evapotranspiration
Biotic Production	Land Occupancy
	Sealing Factor
	Net Primary Biomass Production

Regarding the characterization factors used in background systems in the EF framework one has to keep in mind that significant uncertainties may arise for land use flows like, forests, permanent crops, wetlands, arable or grassland depending on the country of the study site. This is due to the fact that for each country a reference situation is defined, based on the dominant biome with the highest share of this country. However, considering that large countries like Russia or the USA have a high heterogenic landscape using only one biome for the whole country leaves space for improvement. Additionally, despite the fact that Bos et al. (2016) states that environmental flows, with globally and spatially resolved date are available, it was laborious to relate them to the created LCI. Throughout the implementation into the LCA software, information on the utilized area for occupation and transformation processes were asked for. As well as information on the flow nomenclature. This implementation of land use processes into a LCA software was however quite challenging and need to be taken into account.

A present issue within the context of land use and sustainable forest management is the question on how to assess so-called “set aside” areas. These are areas, which are not touched by silvicultural processes and are solemnly used for conservation purposes. As the EF framework for land use forests are only divided in “forestry intensive” and “forestry extensive”, the impact of set aside areas are not adequately accounted for. To underline this issue two scenarios were created during this study to investigate impacts on land use. As expected the result didn’t differentiate between the set aside area and the area which is utilized for harvesting purposes. In general, it can be seen that the bigger the input area is, the higher are the corresponding impacts of land use. Therefore, the remaining question is if minimum intensity in forest production systems with bigger areas of land occupation is reflected properly in the EF framework. This is specially a problem as more and more forest areas are now seen as so-called carbon sinks and are set aside from forest production in order to store the sequestered carbon in trees. Also the Product Environmental Footprint Category Rules (PEFCRs) (2018) that results of the land use impact need to be treated with caution, as they do not accurately reflect different forest management practices.

Looking at the **production of one cubic meter of pulpwood in Ecoinvent**, it is found that data are only based on three different countries: Germany, Sweden and Switzerland. This may lead to uncertainties if one wants to model a wood-based product in a different location. For example, the wood log, as for this study is sourced in Russia, there is no possibility in Ecoinvent to find a dataset for this regionalized case. Thus, the user must rely on datasets extrapolated and generalized like e.g., “softwood forestry, pine, sustainable forest management - RoW “. In this case, the global dataset has been generated as a copy of the Swedish dataset, which covers prevailing management practices in Sweden, and thus is only to a limited extend suitable for the LCA user. Forest management is complex and does not always follow the same pattern. Processes like, fencing are not always necessary if there is sufficient rejuvenation and low game pressure. Similarly, there are planting or various stand maintenance measures, which might differ. For example, one major difference between forest inventories of Europe compared to this study site in Russia is that commercial thinning processes are not utilized in Russia. Wolf et al. (2016) calculates in his study between 0.12 and 0.36 kg CO_2-eq emissions per m^3 wood for thinning processes, which are therefore not included. According to a forest expert in Komi one reason for this is that the thinning processes are seen as economically not feasible for such a big and remote area. Besides the variation of different supply chains, the processes themselves are not always consistent. The harvesting of wood, for example, can be carried out with different degrees of mechanization (motor-manual with chain saw, harvester, skidder, cable yarder tractor, or forwarder). In addition, transport distances for the provision of raw wood can vary. Seeing that around 60% of emissions arise from the transportation sector it is something to be kept in mind during the evaluation of forest related LCAs. For example in the Russian model there is not only direct transportation to the mill, but also transportation to intermediate storages between the forest and the mill, which significantly increases input of fuel. This is especially critical as Ecoinvent unit processes for pulpwood exclude this process step. Consequently, this creates many different variants of how raw wood can be provided. Despite the named uncertainties that arise while using background datasets, the LCIA result of the pilot inventory show that datasets like the ones from Werner (2010) are all in a similar range.

This master thesis has potential limitations that should be mentioned. Firstly, to fully understand the created LCIA results within this study and especially the impact of transportation processes a detailed sensitivity analysis should be conducted. This would make it possible to find potential bottle necks during the transportation process and provides more clarity.

Secondly, it has to be stated that for the pilot calculation the commercial thinning process was not included at the Russian forest site. This was due to the fact that the study site area is so remote that according to forest experts it is economically not feasible to organise an additional management step.

Thirdly, for modelling seedling production in Russia, the used Ecoinvent process includes packaging material which is however not utilized for the study site. Thus, further time would be needed to gain more insights how this is effecting the result and in a next step to adopt the used background unit process.

Lastly, in order to get a clear picture how each of the modelled processes in this master thesis deviate from other studies further research is required.

6. Conclusion

The present work with the title "Guideline for Creating LCA Inventories for Wood Production in the Pulp and Paper industry" has the objective to provide guidance on how to create a life cycle inventory (LCI) for wood production for the pulp and paper industry.

More and more stakeholders face the challenge to assess their environmental impact during the production of one's product. Despite, biomass is a renewable resource, the degree of renewability of its production system strongly depends on the number of non-renewable inputs into the product system in question. Additionally, during the assessment of renewable feedstocks, such as timber, numerous challenges arise, e.g., to identify needed inventory data, implementing them in a life-cycle assessment (LCA) software etc. This is why this master thesis provides insights on how to handle these challenges. The overall aim was to create a guideline. To ensure its practicability the pilot inventory was based and tested on a forest site in the Republic Komi, Russia. The work was conducted with the help of the Sustainable Development department of Mondi Group AG. First, a literature research was conducted to identify needed data sources to create wished inventory. As a next step, a questionnaire was created to provide insights to responsible forest experts at Mondi. After validating the procured data, they were transformed into the needed format of a LCI. During the process, six main contributions to scientific community were identified.

The first insight is that during the creation process of the questionnaire a bottom up approach was chosen. Nevertheless, throughout the iterative process of evaluating and implementing the feedback from relevant forest and LCA experts of Mondi, it was noticed that a top-down approach is more practical to create an LCI. This has the advantage that mass and energy balances are correct as I/O data on the whole forest site are used as a basis. For example, for the Russian forest site 210kW harvester and forwarder are used, however in the utilized Ecoinvent datasets these are modelled with 120kW machines. Using the top-down approach, resulting uncertainties were avoided to some extent as the fossil fuel consumption was calculated with the actual consumption of the machineries. Additionally, it is more time efficient compared to a bottom-up approach, as input data are not needed in such high granularity.

Secondly, after conducting the literature research, diesel consumption was identified as the key raw data input for creating a forest inventory. This is because most forest processes run on diesel, which show in most cases the biggest impact on climate change. The third finding occurred after finishing the questionnaire and providing it to forest experts in Russia. They were using it more like a guidance document with additional discussion rounds to understand what information are needed, rather than answering questions one by one without having any background. Thus, this is key to qualitatively understand, via asking what and why these data are needed, is key to procure high quality data.

Looking at the structure of created forest inventory, four process groups were implemented: Secondary processes, site preparation processes, silvicultural and harvesting activities and transportation processes. In order to provide additional proof that created inventory is robust it was tested, using the EF.3.0 impact method. Thus, the fourth finding is that forest operations have a significant environmental impact. Next to harvesting and forwarding, road construction/maintenance, and transportation processes to forest gate show impacts of more than 10% of overall climate change potential. Especially transportation processes of harvested wood to forest gate need to be highlighted as they contribute 61% to the result.

The fifth finding is related to the land use impact category. During the desk research it was found that limitations of the adopted version of LANCA® in the EF.3.0 method occur while modelling sustainable forest management systems. This is because only two management options are available: forestry extensive and forestry intensive. This distinction is not enough in order to model complex forest systems. Additionally, it was found during the creation of the inventory that if a forest site commits itself to set 25% of its area out of use for conservation purposes, the land use emissions are getting higher. This is because the system, as already highlighted above, is not differentiating between a set aside area and a forest production area. This could lead to the misperception that intensive forest management systems with minimum land occupation is better than extensive systems. The final finding is related to Ecoinvent unit processes for soft- and hardwood production. They are based on solemnly three different countries, Germany, Sweden, Switzerland and hence are limited in their potential to model regionalized forests.

Considering the advancing climate change and the need of stakeholders to model their environmental emissions, clear and understandable standards for LCI inventories are essential. Thus, this master thesis can be seen as a guideline for LCA practitioners to model a forest management system.

The output gained via this thesis provide valuable information that can assist forest-based industries to reach their greenhouse gas reduction goals and to increase sustainability. However, several possibilities for future research can be identified. Firstly, the potential alternatives for the transportation of harvested pulpwood via modalities such as railway, electrical truck or ship. Additionally, it should be investigated if it is feasible to compensate fossil fuels such as diesel for forest machineries with biodiesel, which could save large amounts of greenhouse gases. Secondly, another field of interest could be to further investigate the land use impact methodology in order to evaluate how forest set aside areas could be implemented and evaluated correctly. Especially, to focus on the question how sustainable managed forests can be modelled within the land use methodology. Thirdly, additional efforts need to be taken to model regionalized land use impacts on a forest specific level. Furthermore, soft- and hardwood production processes in Ecoinvent are currently based on only three different regions: Germany, Sweden and Switzerland. This causes uncertainties if one models forest in other parts of the word. Therefore, additional country specific datasets would be needed.

Figures

Tables

Equations

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Appendix A: Questionnaire

Part A – General study site

Please provide data for each year for the last five years. Be aware to only report data, which are directly related to the forest sight, without including processes from the pulp and paper mill

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1. General Questions

1.1. Please provide information on the total area of the study site [ha].

1.1.1. Please describe the type of usage in ha.

Forest area out of use: E.g., *500,000ha;*

Intensive used forest area: *E.g., 1,000,000 ha.*

1.2. Please name the local tree distribution of the forest site [%]

e.g., Birch XY%, Pine XY% etc.

1.3. Please provide numbers on typical densities and moisture content for each harvested tree species

1.4. Please provide an overview of total energy inputs of the forest sight and average energy inputs per 1m^3 wood per year, for the last 5 years

	Diesel (kg)	Lubricant oil (kg)	Electricity (kWh)	Other energy sources
1m^3 wood ob				
Total				

1.5. Please provide a complete overview of total harvested m^3 wood under bark (ub), generated waste (hazardous, biogenic, etc.) and standing biomass (m^3) per year, for the last 5 years.

	Harvested wood (m^3 ob)	Standing biomass (m^3)	Biogenic waste (tonnes)	Hazardous waste (tonnes)
2016				
2017				
2018				
2019				
2020				

1.6 Please provide an inventory of saleable wood assortments for each forest management step and species (birch, aspen, pine, spruce) per year, for the last 5 years.

E.g. Birch 2016	Harvested pulpwood [m^3]	Industrial wood [m^3]	Fuel wood [m^3]	Other saleable assortment
Thickening care				
First thinning				
Second thinning				
Final felling				
Total output				

E.g. Pine 2017	Harvested pulpwood [m^3]	Industrial wood [m^3]	Fuel wood [m^3]	Other saleable assortment
Thickening care				
First thinning				
Second thinning				
Final felling				
Total output				

1.7 Please describe in detail if irrigation takes please, if so provide figures on total water consumption [m^3] for each forest management step

Part B – Individual sub processes

2. Site preparation

2.1. What activities are undertaken during the site preparation step?
e.g., piling, burning, clearing, firebreak building etc.

2.1.1. What machineries were used during this process?
e.g., bulldozer, trucks etc.

2.1.1.1. How much fuel, lubricants [kg] was consumed by used machineries during the process per year?

2.1.1.2. If possible provide information on productivity [h/ha] and kg/h for each machinery

3. Site tending

Please provide data for each year for the last five years. Be aware to only report data, which are directly related to the forest sight, without including processes from the pulp and paper mill

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3.1. Fences

This subsection aims to assess emissions emerging from the production and installation of fences.

3.1.1.How many fences are built per year and linear meter [m/year]?

3.1.2.How long is their durability in years?

3.1.3.What kind of material was used?

3.1.4.Where do they come from (distance + transport modality)?

3.1.5.What machineries were used to put them up?

3.1.5.1. How much fuel, lubricants [kg] was consumed by used machineries during the process per year?

3.1.5.2. If possible provide information on productivity [h/ha] and kg/h for each machinery

3.2. Fertilization

Production of chemicals, fertilizers etc. are emission intensive inputs and thus shall be included

3.2.1.Please provide a technical data sheet of used fertilizers, pesticides, herbicides and utilized average amount per hectare.

3.2.1.1. Please provide the transportation distance and mode of transport from point of sale to forest site for used substances.
e.g., Mode of transport: truck; distance 500km.

4. Silvicultural and harvesting operations

4.1. Planting

4.1.1. How does the regeneration take place (mechanical planting, manual planting, natural regeneration) + used machineries (incl. process steps)?

4.1.2.How much fuel, lubricants [kg] was consumed by used machineries during the process per year?

4.2. Tending of juvenile trees

4.2.1. What activities are undertaken during the tending step? Used machineries (incl. process steps)?

4.2.2. How much fuel, lubricants [kg] was consumed by used machineries during the process per year?

4.2.3. If possible provide information on productivity [h/ha] and kg/h for each machinery

4.2.4. Size of forestry area [ha/a] for each type of activity of the tending process

4.3. Thickening care

4.3.1. What activities are undertaken during the thickening care? Used machineries (incl. Process steps)?

4.3.2. How much fuel, lubricants [kg] was consumed by used machineries during the process per year?

4.3.3. If possible provide information on productivity [h/ha] and kg/h for each machinery

4.4. First thinning

4.4.1. What activities are undertaken during the thinning process? Used machineries (incl. Process steps and share of utilization for each machinery type)?

4.4.2. Size of forestry area [ha/a] for thinning process:

4.4.3. How much fuel, lubricants [kg] was consumed by used machineries during the process per year?

4.4.4. If possible provide information on productivity [h/ha] and kg/h for each machinery

4.5. Second thinning

4.5.1. What activities are undertaken during the second thinning process? Used machineries (incl. Process steps and share of utilization for each machinery type)?

4.5.2. Size of forestry area [ha/a] for second thinning process:

4.5.3. How much fuel, lubricants [kg] was consumed by used machineries during the process per year?

4.5.4. If possible provide information on productivity [h/ha] and kg/h for each machinery

4.6. Final Felling

4.6.1. What activities are undertaken during the harvesting process e.g., harvesting, forwarding, delimbing etc.? Please name used machineries (incl. Process steps and share of utilization for each machinery type)

4.6.1.1. What kind of machineries are being used during the hauling process of trees?

4.6.1.1.1. How far is the average hauling distance per tree [m/tree]?

4.6.2. Please describe the average harvesting area and method used for each process
e.g., area: 1ha; method: clear-cut; product range: 200m^3 *pulpwood, 100m*^{3} *fuel wood etc.; tree species: birch 60%, pine 40%*

4.6.3. Productivity [m^3/h] and used amount of fuel per hour [l/h] for each type of used machinery during the harvesting process

5. Wood transport to plant gate (please provide following information)

5.1. Average distance [km] and mode of transport

5.2. Used machineries + overall share of utilization

5.3. Average load capacity

5.4. Average utilization ratio
(the ratio of the distance travelled to collect the next load after unloading the product, to the distance travelled to transport the product)

5.5. Productivity [m^3/hour] and used amount of fuel per hour [l/h] for each type of used machinery

6. Infrastructure

Forest roads play an important part during the production of forest products, thus their creation and maintenance shall be included.

6.1. Road construction:

6.1.1. How many roads are being built each year [linear meter /year]

6.1.2. Description of the road construction project (used machineries, area, etc.)

6.1.2.1. How much fuel, lubricants [kg] was consumed by used machineries per linear meter?

6.1.3. What materials are being used during the process?

6.1.3.1. Where do they come from (distance [km] + mode of transport)

6.1.4. What was the productivity [h/ linear meter]?

6.2. Road maintenance:

6.2.1. Maintenance (linear meter / year)

6.2.2. Description of the process (used machineries + materials)

        - 6.2.2.1. How much fuel, lubricants [kg] was consumed by used machineries per linear meter?

        - 6.2.2.2. What was the productivity (hour / linear meter) for each process step?

- 6.3. Provision of fuel, lubricants and forest machineries:
    - 6.3.1. Please provide the transportation distance and mode of transport of fuel, lubricants and forest machineries, from point of sail to forest site.

- 6.4. Commuting of forest workers to forest site
    - 6.4.1. Please provide information on the used mode of transport.

    - 6.4.2. How far is the average commuting distance to the forest site per employee [km/employee]?

- 6.5. Transportation/transition of machineries:
    - 6.5.1. How are forest machineries transported to the forest site?
(*Distance + mode of transport)*