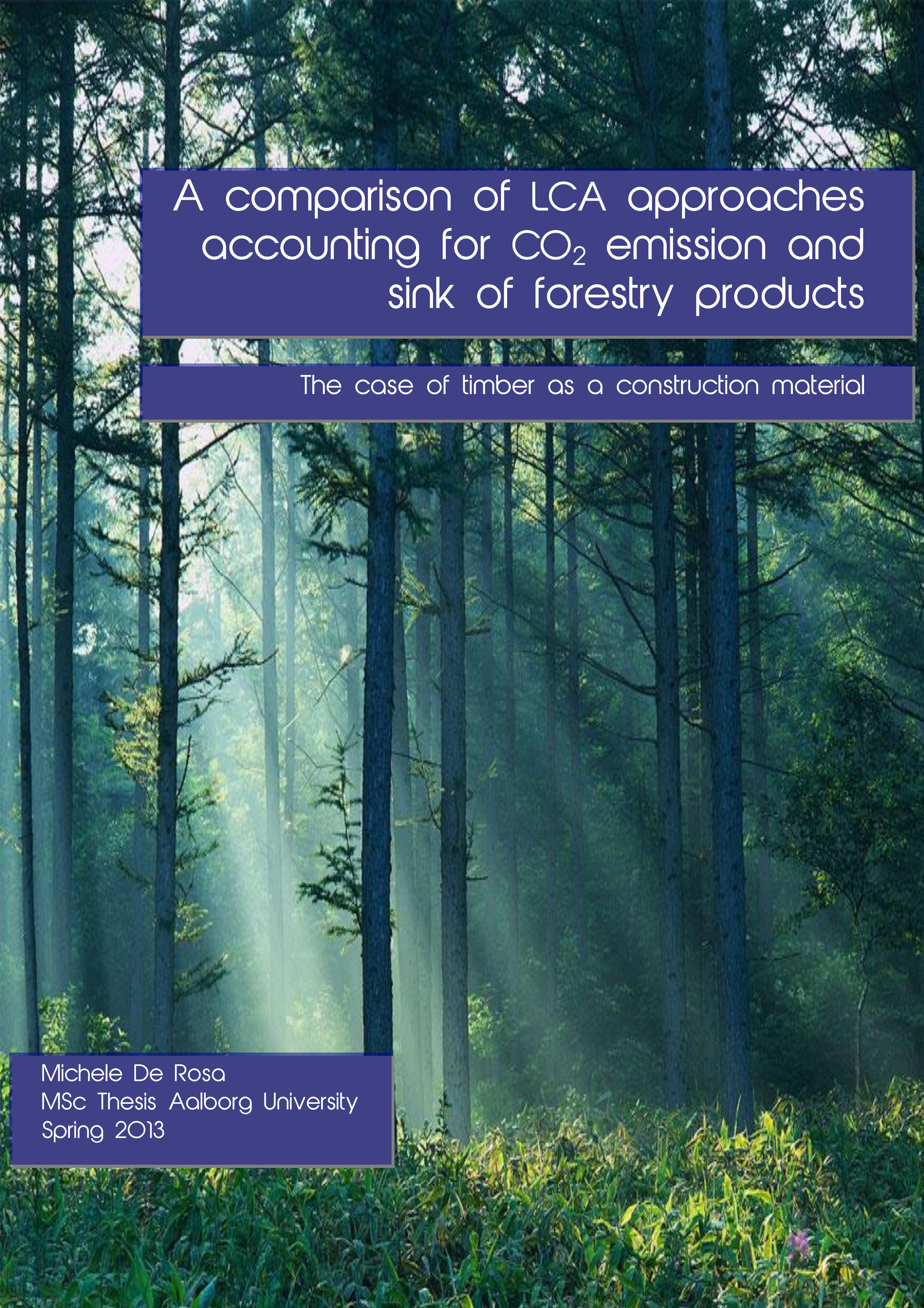

A comparison of LCA approaches accounting for CO_2 emission and sink of forestry products

The case of timber as a construction material

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To Natalie
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Abstract

Life Cycle Assessment (LCA) is a technique used for decision-making support to assess the environmental impact of product systems through its life cycle (ISO 14040 2006) in a diverse range of fields (Curran 2012). Nevertheless, the effective use of LCA is challenged by the suitability of the methods used and the exactness of the modelling assumptions. Due to the increasing attention towards mitigation and adaptation to climate change impact, LCA is extensively used for assessing the environmental impact of forestry products (Brandão, Milà i Canals, and Clift 2011; Rex and Baumann 2007; Werner and Richter 2007; Wessman, Hohenthal, and Kaila 2003). However the inclusion of forest carbon (C) cycle in LCA is not straightforward (Helin et al. 2012; Kløverpris and Mueller 2012). This study explores the suitability of different existing LCA methodological approaches accounting for direct and indirect impacts related to forestry and forest carbon cycles. The research evaluates the indirect Land Use Change (iLUC) impact on forestry and the time accounting of CO_2 emission/uptake of forest biomass.

Forests play a key dual role, both sequestering C from the atmosphere (IPCC 2007) and emitting C due to forest degradation for some years after harvesting or thinning (Mäkipää et al. 1999, 1490-1501) and to products by hastening land-use changes and deforestation. In LCA, biomass from sustainably grown forests tends to be considered C neutral as the C released during combustion, is assumed to be re-sequestered in the growing biomass (Cherubini et al. 2011). Nevertheless C neutrality does not mean that the process implies climate neutrality: if during the time in between C release and sequestration, the C stays in the atmosphere, a warming effect is achieved and the impact can be remarkable. However, whether and how much C is released in the atmosphere, depends on the use of the biomass and its source: if used for long-lived products, if used for substitution of other materials (fossil fuels, construction material) or if a change in the forest C stock occurs (harvesting of stems, branches, roots, litter, soil), and the time considered for the biomass re-growth. The study compares ten LCA methodological approaches to model the following aspects: land use change effects, time horizon, climate indicator for impact assessment and forest C stock. This is done applying different approaches to the same case study to ensure comparability. The selected functional unit was the production of $1m^3$ of spruce as a construction material in Götaland, Sweden, due to the relevance timber is re-gaining as a sustainable construction material (Smith and Snow 2008).

The obtained results are confronted in order to assess strengths and weaknesses of the considered methodologies. The outcome underlines a substantial difference in results and modelling uncertainties, rising further methods issue and standardization requirements for accounting C cycle in LCA.

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List of abbreviations

AG	Above Ground
BG	Below Ground
BIO	Microbial Biomass
BR	Brazil
C	Carbon
°C	Celsius degree
CO_2	Carbon dioxide
CNF	Carbon Neutrality Factor
COP	Conference Of Parties
CRF	Cumulative Radiative Forcing
DPM	Decomposable Plant Material
FU	Functional Unit
GHG	Greenhouse Gasses
GWP	Global Warming Potential
HUM	Humified Organic Matter
IPPC	Intergovernmental Panel for Climate Change
IRF	Impulse Response Function
iLUC	indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
MDG	Millennium Development Goals
NPP_0	Net Primary Production
RPM	Resistant Plant Material
RW	Round Wood
SE	Sweden
SW	Sawn Wood
TH	Time Horizon
UN	United Nations

Preface

This report was written during the spring semester 2013,as the final Master Thesis of the Joint European Master in Environmental Science (JEMES) program at Aalborg University. It is primary addressed to the public, the scientific community, LCA practitioners and of course the examiners. It presents the outcome of an academic research completed during a four-month internship at the Danish Center for Environmental assessment (DCEA) in the department of Development and Planning of Aalborg University (AAU).

The focus of the research was comparing methodological assumption accounting for the impact caused by the use of forestry product in LCA, with regard to both the Life Cycle Inventory and the Life Cycle Impact Assessment phase. To achieve this end, a method to account for the forest carbon cycle was developed based on the existing literature.

The emphasis of the study was on the precision of the model rather than on the precision of the data collected. The objective was the comparison of LCA methodologies, while the case study selected only served the purpose of ensuring the comparability of the results. The main source of data was the literature reviewed and the Ecoinvent database.

The length of the report was defined by the guidelines provided by the study board.

A CD containing the following documents:

- The MS Excel file modeling the system's carbon balance;
- The electronic version of this document;

has been submitted together with this report.

A special recognition goes to Jannick Schmidt and Massimo Pizzol for providing relevant, constructive feedback and support beyond the supervisor role. Their recommendations and questioning contributed to my professional development and to the accomplishment of this work.

1. Introduction

The purpose of this study is to compare a group of methodological approaches and modeling assumptions for accounting the environmental impact of forestry products in Life Cycle Assessment (LCA). The compared methods aim to account for the CO_2 emissions and sink in a forest and for the indirect Land Use Change (iLUC) effects caused by an increase in demand of forestry products. The focus is on wood used for production of long-lived forestry products, rather than biomass for combustion purposes. In particular the case study of spruce production for construction material is considered. Based on previous models, in this study a method for accounting the forest carbon balance is proposed. The biogenic carbon balance is necessary for testing a set of selected LCA methodologies and assesses the relative impact of using of wood product.

Developed mainly in the 1960' and early 1970' during the rising environmental awareness, the LCA technique is today an established decision making tool for assessing both environmental and social impact of system products and processes. Broadening the scope of LCA to account for a diverse range of impacts and sectors is a current challenge. This study focuses on LCA of a forestry product for two main reasons: due to the increasing interest in using wood product for substitution of conventional construction material and due to the challenges of modeling forest carbon cycle in LCA. The goal is to model the forest carbon cycle, investigate to what extend the result of an LCA may change by adopting different methodological choices and how to compromise between a precise model and an acceptable degree of complexity. A case study is chosen to ensure the comparability of the results, obtained performing LCA applying different modeling choices. Those test different LCA modeling practices, selected after a review of the state-of-the-art literature in the field. The LCA are fulfilled using the software SimaPro, a widely used LCA software.

This chapter presents a short introduction on the LCA technique and on the role played by forests and forestry products in climate change.

1.1 The LCA technique

The development of the life cycle concept has its roots in the fifties and sixties in the United States. It was developed from engineering practices and was first mentioned in a RAND Corporation report, referring to the life cycle analysis of costs (Novick 1959). But the commonly accepted cradle of LCA as it is known today is a Coca Cola study dated 1969. Yet, that study had a more restricted focus on resource use and waste management rather than focus on generic environmental aspects (Curran 2012). Since then, the concept has steadily developed, facing issues concerning methods development and standardization. When the environmental issue became of public concern in the early seventies, the cradle to grave analysis concept was already developed.

Environmental Life Cycle Assessment (LCA) gained momentum when the cost of the earlier end-of-pipe approach to solve environmental problem in modern industrial society became more and more expensive. The need for a more comprehensive analysis of the environmental impact of systems from resource use to waste management was rising (Curran 2012). The work of the International Organization for Standardization (ISO) on a series of standards relating to LCA (the 14040 series) began in 1994. In 2006 the environmental management ISO standards 14040 and 14044 replacing the previous versions ISO 14041 to ISO 14043, defined the LCA procedure.

In ISO 14040 the LCA is defined as "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system through its life cycle" (ISO 14040 2006) ISO 14040 also defines four phases of an LCA as follows:

1. Definition of goal and scope;
2. Inventory analysis (known also as Life Cycle Inventory – LCI);
3. Impact assessment (known also as Life Cycle Impact Assessment – LCIA);
4. Interpretation of results.

LCA considers all "aspects of natural environment, human health and resources" (ISO 14040 2006). Because of its completeness and comprehensiveness, LCA is presently an effective technique to assess the environmental impact of products and processes. However, the attempt to broaden the scope of the LCA technique to encompass more and more economic sectors and production processes requires consensus on the methodologies to be applied, if consistent results have to be obtained. In this context, this research investigates the challenges of modeling a forest carbon cycle in LCI and LCIA.

1.2 Forests and climate change

Forests represent the major terrestrial carbon (C) pool and cover more than 30% of global land surface (World Bank 2012). They play a key dual role, acting mainly as carbon sink but also as a C source: C is up-taken through photosynthesis and autonomously released through respiration and biomass decomposition. In addition, biomass-related releases of C are caused by anthropogenic activities, for instance due to the degradation of the residual biomass produces by forest management practices (Mäkipää et al. 1999). This is described in detail in section3.3.

Yet, C from biomass or soil might be released directly, due to direct Land Use Change, or indirectly, due to indirect Land Use Changes (iLUC). Direct Land Use Change (dLUC) takes place when a land use is replaced by a different land use retaining less carbon, for instance directly transforming a forest in arable land. Thus, dLUC is a change in land use within the considered production boundaries. With iLUC is instead meant the change in land use, or land use intensification, caused as a consequence of a direct change in land use on another land (due to a change in demand for land), outside the considered production boundaries.

Because of their net effect as a C sink(Janzen 2004), forests have been considered as a main C sequestration strategy in order to reach the global greenhouse gas emissions abating goal. In a study by Janssen et al. (2003) it was found that Europe's terrestrial biosphere absorbs from 7 to 12% of the total anthropogenic emission accounted in 1995. It is estimated that forests could potentially sequester around 2,000 million tons per year or more globally (Richards and Stokes 2004). Since the Unite Nation (UN) Framework Convention on Climate Change in 1992, the attention towards climate change mitigation action has increased and C capture solutions have been investigated has a possible mitigation strategy. The Kyoto Protocol (UNFCCC 1997) states that C sequestration in terrestrial biomass can be considered as C removed from the atmosphere and included in the national C balance. The emission target adopted at the 15th session of the Conference of the Parties (COP 15) in Copenhagen in December 2009 called for a limit in average temperature increase below 2°C compared to pre-industrial level. The Intergovernmental Panel on Climate Change (IPCC) estimates that to reach this goal CO_2 emission should peak not later than 2015, in order to be reduced from

50 to 85%by 2050 (IPCC 2007). UN Millennium Development Goals (MDG) also recommends a severe decrease of Greenhouse gas (GHG) emission and a reduction of global deforestation of at least 75 % or more by 2020.

Efficient forest management seems an opportunity for increasing C storage in biomass. At the same time, sustainably grown wood could substitute conventional manufactured material, usually resulting in a higher environmental impact and C footprint than wood (Petersen and Solberg 2005; Gustavsson, Pingoud, and Sathre 2006). To compare the environmental impacts resulting from wood product with the impact resulting from conventional manufactured material, the C balance of forestry products and forestry C cycle must be carefully modeled and the result of the modeling correctly analyzed, for instance by using environmental impact assessment techniques as LCA. However, modeling forests in LCA by accounting for the forest C cycle, the iLUC effect, and the several variables of forest processes presents some challenges. Emissions related to iLUC for example, are estimated to be around 9% of global CO_2 emissions (Le Quéré et al. 2012); despite that, they are not always addressed in LCA and there is no agreement on how to account for them (Le Quéré et al. 2012). There is missing consensus also on several aspects concerning how to account for forest C cycle. The next sub-section introduces some of the most debated among them.

1.3 LCA of forestry products

There are currently several approaches for inclusion of forest carbon cycle in LCA techniques. Helin et al. (2012) reviewed several LCA studies dealing in different ways and to a different extent with the problem of forest cycle in LCA: the environmental impact and C foot printing of wood product resulting from studies adopting different LCA approaches may be very different. Wood products made by using wood from sustainable grown forest are often considered to be C neutral since the wood used is considered to re-grow. However, C neutrality does not mean that the process implies climate neutrality (Cherubini et al. 2011). Indeed, during the time in between C release and sequestration the C stays in the atmosphere, as CO_2 or CH_4, entailing a warming effect and the impact can be remarkable. Assessing the potential impact of forestry on climate depends on several factors and modeling assumptions. In their review of LCA of forest products for instance, Helin et al. (2012) considered the following aspects: the initial forest reference situation, the time in between C release and sequestration, the GHG effect indicator adopted, the specific forest model considered (what kind of forest wood harvesting is accounted in the study, e.g. stems, branches, roots, litter, soil) and the final use of the biomass stock (e.g. if used for long-lived products, if used for substitution of other materials as fossil fuels or construction material. Holtsmark (2012) not only investigated the effect of the baseline accounting for C emission and sink but also tested other assumptions made by previous studies, in particular: if they considered a single or repeated harvests, in which phase of their growth the stands were harvested and if a carbon-cycle model was applied. Despite in the literature can be found reviews of different LCA methodological approaches, systematic comparisons of them are rare. This study means to model the forest C cycle and compare the actual modeling approaches by applying them to fulfill an LCA on the same case study to ensure the comparability of the outcomes. After an extensive literature review (see chapter 2), a group of approaches was selected among the most debated modeling options, including the most recent contributions to the scientific debate.

1.4 The research questions and the case study selection: wood as a sustainable building material

Wood has vastly been used as a construction material until the advent of modern densely populated urban areas, where timber was set aside because of its poor fire performances (Smith and Snow 2008). In order to meet the climate change mitigation goals, several wood products are now being considered to replace conventional materials and timber is re-emerging also as a major structural and construction material (Smith and Snow 2008). In the building sector there is an increasing interest in sustainable grown wood as a substitute material (Kam-Biron and Podesto 2011), since it has been found that wood building materials have a lower C footprint than concrete (Gustavsson, Pingoud, and Sathre 2006). Petersen and Solberg (2005) for example, reviewed a series of comparative LCA studies of wood products and competing materials, obtaining similar results. Falk (2009) found that wood products as a construction material have a lower embodied energy than traditional materials. Therefore the focus of this study is on wood used as a construction material.

This research aims to compare different modeling assumptions adopted when including forest C cycle in LCA. Therefore the main research question (RQ) is formulated as follow:

How to include forest carbon cycle in Life Cycle Assessment of forestry products?

In general the precision of life cycle models enhances the accuracy of the LCA results. However a precise model is often difficult to design and requires data that might not be available. This is the reason for introducing assumptions in the model that describe the analyzed system as close as possible to the reality. Thus the following sub-research questions rises:

What would be a good compromise between a accurate LCA model and an acceptable degree of complexity?

There is a growing body of literature questioning the carbon neutrality of forest biomass combustion because the re-sequestration of the combusted C takes place in many decades, due to the slow growth rate of trees (Agostini, Giuntoli, and Boulamanti 2013). The use of biomass as a sustainable fuel is being criticized despite the share of energy produced by biomass will increase. A different use of sustainable grown wood might be the production of long-lived wood products. Due to the increasing interest in using sustainable grown wood as a substitute material, the case study selected for comparing the modeling assumptions is spruce production for construction material. A second and last sub-research question is formulated below:

Does the carbon stored in long-lived products (e.g. timber for construction materials) modify the environmental impact of falling a tree?

Forests are a substantial C stock, both as biomass and as soil organic carbon (IPPC 2001). A considerable percentage of sustainable grown forest providing merchantable wood is located in Scandinavia and Canada, in a boreal or oceanic climate. Therefore it was chosen to model a spruce forest in Götaland, in south Sweden, an oceanic climate area. The large availability of data provided by Statistic Sweden (2013) for Swedish forests also affected the choice of the location. The functional unit is the production of 1 m^3 of spruce used as a construction material. Further details concerning modeling assumptions are presented in chapter 3.

1.5 How to read the report

The report is conceived to be read from cover to cover, thus with a certain flow in mind. However, the abstract and the conclusion were thought to be able to stand alone, being as much comprehensive as possible within the lines limitation.

The paper is structured in seven chapters, each containing subsections: first, the introduction presents the problem area and the research background. The second section is dedicated to summarize the reviewed literature and the state-of-the-art scientific contribution, upon which the research is built. The third chapter introduces the methodology used in the study and finalizes the research question and goal and scope of the study. Section four presents the results of the study and their analysis. Section five is dedicated to the results discussion. Finally the last chapter resumes the research and draws some conclusion from it.

2. Applying LCA technique to forestry product life cycle: the state-of-the-art in the scientific debate

In the scientific literature, several authors present the challenges of assessing the environmental impact of wood products in LCA (e.g. Andrade de Sá, Palmer, and di Falco 2013; Helin et al. 2012; Jonker, Junginger, and Faaij 2013). They review different LCA approaches for modeling forests in LCA. However, systematic comparisons of modeling approaches and their consequent results are rare (Jonker, Junginger, and Faaij 2013) and only deal with some methodological choices. The next section introduces some of the challenges of modeling forests in LCA through an overview of previous studies. The subsections select and further debate the specific assumptions tested in this study.

2.1 The challenges of modeling forests in LCA

An LCA is a complex process, requiring several data, modeling assumption and methodological choices. A preliminary distinction between LCA practices might concerns the two approaches that have developed so far for Life Cycle Inventory (LCI). There are currently two main modeling assumptions in LCI:

- Attributional LCA (ALCA): '*describe the environmentally relevant physical flow of past, present or potential future product* system' (Curran, Mann, and Norris 2005, 853-862);
- Consequential LCA (CLCA): '*studies the environmental consequences of possible (future) changes between alternative product systems' (Weidema 2003);*

This thesis does not attempt to explain in detail the differences between the two modes; the topic is extensively debated in the literature, for example in Finnveden (2009), Rehl et al. (2012), Schmidt (2008), Thomassen et al. (2008) and Weidema (2003). However a difference between ALCA and CLCA relevant for this study is how to deal with the co-product of a process. ALCA handles co-products by economic allocation, which means the impact of co-product is allocated proportionally to the economic value of the product and co-products. Alternatively, it would be also possible to handle co-product by mass allocation. ALCA disregard any market mechanism and identifies the production avoided due to co-product through average date. On the other hand, CLCA deals with co-product allocation through system expansion: the studied product system is expanded to the processes displaced by the co-product. The identification of the displaced product is based on market mechanism and market data. Once the displaced product and its production process are identified, these are assumed substituted by the co-product. The identification of the substituted product in CLCA follows market mechanism instead of average date (Weidema 2003). That means an emerging niche product might substitute a conventionally used one when operating system expansion. This study utilizes a CLCA approach to deal with co-product allocation. Further details on methodology used to deal with the co-products are presented in section 3.4.

Other than the difference in dealing with co-product, the highlight is that different assumptions and LCI data are required weather a consequential or attributional approach is adopted. Thus, the choice of ALCA/CLCA modeling affects the entire design of the LCA study.

The case of LCA of forestry products adds further complexity to the LCI phase. Currently, methods for accounting the forest related GHG emissions and sink and forest carbon cycle modeling are not well developed (Newell and Vos 2012, 23-36) . In their comparative study Newell and Vos (2012) confront three international carbon footprint protocols for accounting forest C pool dynamics. They highlight that wood LCI and C cycle models need further development to include all the forest C pools and the spatial and temporal effect of LUC. With the eloquent title "*The outcome is the assumption*", Holstmark (2012) analyses the influence on the final result of applying a given C cycle model, but also emphasizes how strongly other assumptions affect the assessment of C footprint of forest harvesting. In particular the focuses on the consequences of different harvesting practices and accounting for multiple or single harvest. He concludes that increasing forest harvesting cause a permanent increase of atmospheric CO_2 concentration. Kløverpris and Mueller (2012) instead, focus in particular on the issue of the baseline time accounting for estimation of the iLUC related climate impact. They propose a new method that considers the global land use dynamics consistently with the global warming potential (GWP), independent from the biomass production period. As they state in their paper though, the method is based on the approach of a CLCA, since they consider the market trends at the specific time the study is fulfilled to estimate the consequent market sector and system product involved in the new production and its consequent climate impact. This is an example of how the use of a methodology is linked to the use of other assumption or methodological choices.

Concerning LCIA, a debated aspect is the climate indicator adopted to assess the environmental impact of the emissions associated with forestry products. Kløverpris and Mueller for instance use the indicator Global Warming Potential (GWP) seen over 100 years, also called GWP100, where the accounting period (100 years for GWP100) is here defined as Time Horizon (TH); GWP is a climate impact indicator expressing how much equivalent CO_2 would have caused the same cumulative radiative forcing (CRF) as the CRF caused by the process analyzed, during an accounting period of 100 years. Despite GWP100 is commonly used and 100 years is considered a fair accounting period (Fuglestvedt et al. 2003), different climate indicators and THs are also used. Searchinger et al. for instance (2008) TH of 30 years. Choosing a TH of 20, 500, or any other value, would consequently modify the accounting period of the GWP indicator as well. Jonker et al. (2013) adopt the C payback time (or carbon debt) as a climate indicator for the impact assessment and test the sensitivity of this indicator to other methodological assumptions, such as the forest yield, the reference scenario of the forest, the system boundaries and the C replacement factor.

Helin et al. (2012) carried out an extensive literature review of different approaches used in LCA to account for the forest C cycle. They point out five critical aspects concerning both LCI and LCIA to estimate the C flow of forest biomass:

1. The forest reference scenario, against which to compare the impact of the investigated process;
2. How to account for the timing of emission and sink;
3. The choice of the climate indicator for impact assessment;
4. What forest C stock has to be included in the study;
5. Climate implications of forest product use, accounting for the time in which the C stored in the product is released.

Some of these factors, different approaches towards them present in the literature and their bonds and conflicts, have already been introduced. The fifth criterion instead, looks at the final use of the product (e.g. long-lived wood product or wood as a fossil fuel substitute) to evaluate the related climate implications. Obviously, weather the wood is used in long-lived product or as a biomass for substitute fuel, the resulting GHG emissions and, consequently, the climate impact are remarkably different. The ISO standards do not mention any method for accounting the C storage in wood products (ISO 14040 2006) even though it is relevant which purpose the biomass will serve to determine for how long the C will be stored in the biomass and the consequent climate impact. Cherubini et al. (2011) and Pingoud et al. (2012) developed a method that also considers for how long the C is kept sequestered in the biomass and what are the consequences of this and eventually of a delayed C release at the end of the product life cycle. Although in this study is considered relevant to keep into account the product use and its climate implications, such information are here consider in the choice of the TH and affect the climate indicator. Therefore, the last criterion is not explicitly used, but implicitly considered and embedded in the second and third modeling assumptions. Below is presented a deeper and systematic analysis of the choices made in previous studies with respect to the first four criteria listed above.

2.1.1 Reference situation

As stated in chapter 7.4.4.1 of the ILCD handbook (JRC-IES 2010) it is important to make sure that only the net impact caused by human land management for the analyzed product is considered and not also what would take place anyway. A reference situation is therefore defined as one in which the environmental impact is assumed to be null. When one wants to assess the impact of a specific use on a determined piece of land, it is required to assume a reference scenario, against which the additional effect caused by that specific use can be determined. The reference situation can be static, if based on historical data about the land state, or dynamic, if considers the dynamics of land evolution, referred to the 'non-use' of the area (Milà I Canals et al. 2007). In their paper Milá I Canals et al. suggest to use a dynamic reference situation. They also point out that in ALCA it should be one in which the studied activity does not take place, while in CLCA the reference situation should then be the most likely land use previously to the change in land use due to the studied activity, weather this state was another human land use (with the relative impact) or the natural evolution of the site.

Some of the reviewed studies applied the natural relaxation of the land as a reference situation (Müller-Wenk and Brandäo 2010; Perez-Garcia et al. 2005; Pingoud, Ekholm, and Savolainen 2012b) while others consider alternative land use as a reference scenario (Holtsmark 2011; McKechnie et al. 2011). In particular, to assess the net release of CO_2, Holtsmark (2011) considers a 30% increase of harvesting from Norwegian boreal forests as an alternative land use reference scenario; McKechnie et al. only includes forest biomass not used for other conventional wood products to avoid indirect emission from diversion of wood from current use, due to limited wood resources. In other cases (Cherubini et al. 2011) no reference scenario is considered at all.

2.1.2 Climate indicator

There are two main approaches concerning the use of climate indicators: the first is the adoption of a static approach, which does not take into account the timing of emission and sink of C. A static approach would consider the annual average C stock in the forest Eriksson et al. (2010). This method has the advantage of being simple, because assumes that the emissions occur all in the same time, but doing so it ignores the timing problem, that means when the emission and sink take actually place. The second is a dynamic approach (Levasseur et al. 2010), gaining momentum in the LCA community, where the emissions are weighted for a time-dependent factor accounting for the real climate impact of the emissions. This approach takes in to account the dynamic temporal profile of emission and sink through a dynamic LCI and LCIA. A dynamic approach seems to conform better to the reality, a more precise model of CO_2 emission and sink in forests.

The adoption of different approaches does not lead to equivalent conclusions. The climate change impact is often measured with CO_2 equivalent by means of the GWP100 indicator (IPCC 2007) introduced in section 2.1. In the LCA community it is common practice to use this indicator with a 100 years time frame, despite it is only based on a political convention. Standard for measuring the product C footprints and guidance documents also apply this indicator (Helin et al. 2012). The GWP coefficients used by the IPCC though, are based on a static approach and have a fixed time frame, which leads to a loss of temporal dimension of the emissions. This loss is particularly relevant in the case of biogenic C emissions because in sustainable land management they are assumed re-sequestered in the re-growing biomass (Helin et al. 2012). The decay of anthropogenic CO_2 emissions, (combustion of fossil fuels, deforestation and goods productions) instead, is often modeled following the Bern Carbon Cycle model (IPCC 2007; Joos et al. 1996; 2001), where CO_2 emissions are only considered absorbed by the terrestrial C stock and the top layers of the sea (IPCC 2007). Consequently, the permanence of CO_2emitted from biomass is actually shorter than the fossil CO_2since the latter cannot be considered as offset by the biomass re-growth.

To address this problem, other authors define and apply a climate indicator based on a dynamic approach. Cherubini et al. (2011) for instance, introduced a modified GWP indicator, named GWP_{BIO} that also takes into account the origin of the CO_2: assuming a sustainable land management, the GWP_{BIO} indicator models decay of biogenic CO_2 emissions from biomass combustion as accelerated by the re-growth of the combusted biomass. However this indicator is only applicable for wood used as a biofuel. Pingoud et al. (2012a) further broaden the concept of GWP_{BIO} introducing GWP_{BIOUSE}, an indicator that also considers the use of the biomass, and accounts for the relative cooling impact of biomass used for substituting emission-intensive conventional materials (thus displacing fossil fuel). This indicator offers the opportunity to measure the difference in emission in a comparative study. Schmidt and Brandão (2013) propose a modified definition of the GWP accounting also for the timing of emission and sink. They calculate the GWP indicator as a function of the time interval between a fixed reference time and the real time of emission/sink (see section 3.3.4 for further details).

Holstmark (2011) shows an example of another climate impact indicator, the Carbon Debt: here it is evaluated the time necessary for the biomass stock to re-grow until the point where the C sequestered is equivalent to the C emission caused by the product system under investigation. At this point in time the C debt is then considered repaid.

In the current study the climate indicator based on a dynamic approach is modeled by the modified GWP proposed by Schmidt and Brandão (2013). Further details on the method are presented in section 3.3.4.

2.1.3 Time horizon

Since forest biomass C emission and sink take place in different time, the time horizon considered has a strong impact on the emission and sink accounted from a production process. Biomass from sustainably grown forests tends to be considered C neutral as the C released during combustion, is considered as re-sequestered in the growth phase. However, C neutrality does not mean that the process implies climate neutrality biomass (Cherubini et al. 2011): if during the time in between C release and sequestration, the C remains in the atmosphere as CO_2 or CH_4, a warming effect is achieved and the impact can be remarkable.

A wide range of different TH is applied in the literature: Searchinger et al. for instance (2008) considered a time horizon of 30 years; McKechnie et al. (2011), Pingoud et al. (2012a) and Perez-Garcia et al. of 100 years; Müller and Brandão apply a TH of 500 years and Cherubini et al. show the results obtained for a TH of 20, 100 and 500 years (2011). The choice of TH is irrespective of the approach applied to model the climate impact (section 2.1.2). Static and dynamic climate indicators can be applied with different TH. On the other hand the TH deeply affects the outcome of the impact assessed. The ISO standard do not address the timing issue (Helin et al. 2012). The choice of TH is completely arbitrary even though, as mentioned above, the use of 100 years time frame is common in LCA community.

2.1.4 Modeling of forest carbon stocks

Carbon in forests is present in soil, wood residues, stems and branches. The C stock can also be differentiated in the amount contained in the above ground (AG) biomass and below ground (BG) biomass. It is important here to note that the C contained in the BG biomass does not include the soil C. The forest C stock modeled might account for different C pools: for all the C stocks, only some of them, or for a sub-group of them, such as C in stem. Some authors modeled only the AG forest carbon (Eriksson et al. 2010; Perez-Garcia et al. 2005) while others suggest the inclusion of AG C stock (Helin et al. 2012) and others include all C stocks (Müller-Wenk and Brandäo 2010; Holtsmark 2012; McKechnie et al. 2011).

In general the inclusion of all C stock seems the most accurate modeling practice. However, the calculation of soil organic C is complex (Holtsmark 2011) and might require several data to be calculated. In case the soil C stock is negligible compared to the rest of the C content, for instance for tropical rain forest, it may be ignored for simplicity. Nevertheless in the case of boreal forest the C contained in soil is not negligible: Kjønaas et al. (2000) estimated it counts for more than 80% of the C stored in Norwegian forests and Liski et al. (2006) considered the C contained in soil as litter in boreal forests to be above of 50% of the total. Typically, when old natural forests are converted in forest farms, a net loss of soil C can occur, and the loss it is higher the more frequents are the tree harvesting. Because of that, Zanchi et al. (2010) account for all the C stocks included the soil carbon. On the other hand, in their case study on pine plantations Jonjer et al. (2013) assume that the residues left in the forest balance the soil C loss due to forest harvesting and thus exclude the soil C. In this study the C in soil is not calculated, due to the complexity and lack of sufficient data found for this purpose, but the trees' BG C pool is taken into account. Moreover, this study also considers the emission caused by decomposition of non-harvested residues.

2.2 Forests and iLUC

Accounting for direct and indirect land use change related GHG emission is complex and, if the impact of d/iLUC are not carefully assessed, the results can be misleading. Searchinger et al. (2008) demonstrate that if the iLUC related GHG emissions are accounted, the corn-based ethanol production from croplands in the US increases the total amount of GHG emissions, instead of reducing it as wished. Several other studies looked at the challenges of modeling iLUC. Andrade de Sá et al. (2013) investigated the complexity of relationships between change in demand for land and deforestation or intensification in a different region and the complexity of tracking this indirect relationships. Broch et al. (2013) reviewed some modeling approaches of iLUC common in the USA. Van Stappenet al. (2011) reviewed four methodologies proposed within the EU. However, all the approaches reviewed adopt a time allocation of emission: the emissions due to deforestation are attributed over time by defining an arbitrary amortization period. Allocation is necessary to attribute timing to the iLUC related emissions, which can also take place in long term. The problem with allocation is that it results in an arbitrary choice of the time to which the emissions are attributed. For this reason this study adopts a different methodology, aimed at avoiding time allocation of emission. The methodology is described in Schmidt et al. (2013) and further debated in section 3.4.4.

2.3 Focus of the study

This research presents a method to include the forest C cycle in LCA. The model is then used to compare the effect of applying different values/choices, here referred as options (for variables and/or assumptions). The comparison involves only some of the options introduced in this chapter. These options belong to four groups of methodological choices, both in the LCI and LCIA phase that can influence the final result. Those groups are:

- The land use change model;
- The climate indicator applied for the impact assessment;
- The time horizon selected;
- The forest carbon pool considered.

The reviewed literature underlines that several studies have already been carried out about these topic. The contribution of this study is to systematically assess how the different options compared affect the final result.

The model is consistently designed but it should be said that, due to time and resource constraints, the accuracy of the model has been privileged rather than the precision of the input data. Section 2.1 introduced some of the key factors and most debated methodological assumptions characterizing the attempts of including forest C cycle in LCA. Chapter 3 presents the tested assumption and the values assumed by each parameter. It also presents the methods applied for the testing and for the calculation of the forest carbon balance.

3. Materials and methods

3.1 The functional unit and the system boundaries

In LCA studies, the definition of a functional unit (FU) is a crucial aspect. The FU provide a '*reference to which the input and output data are normalized'* (ISO 14044 2005). Here the FU is the production of 1 m^3 of spruce used for construction material, grown in a boreal forest in Götaland, in south Sweden, an oceanic climate area. All the input and output are normalized to the FU. Statistic Sweden (2013) provides extensive data concerning biomass production, soil composition and climatic information for Swedish forests. This location was chosen as it facilitates the data collection process, but any other forest location could have been considered. Thus the methodology and models proposed in this research can be applied also for other case studies.

This study only identifies as a reference scenario the natural relaxation of the land, even though not of the specific forest plot. The iLUC model (section 3.5) makes possible that the reference is located somewhere else in the world: when demanding the wood an iLUC effect is triggered as natural forest is tuned in productive forest.

Full compliance with ISO 14044 is not a requisite of this study. In fact the focus is only on GHG emissions and climate change impact and furthermore, a sensitivity analysis of the data has not been led, since the purpose of the study is to estimate the effects of the different possible methodological choices rather than testing the accuracy of the data.

The process flow diagram in Figure 1 shows the processes theoretically taking place during the life cycle of the product. Additional details on the system boundaries are provided in section 3.2.4. The diagram represents mass flow with arrows and LCA processes within the system with boxes. The red dashed box wraps the four processes taking place in the forest that defines the biological production of wood. Soil preparation includes plowing and soil fertilization. Fertilizer is in fact used in soil preparation and cultivation. Thinning identifies the practice of falling trees with characteristics less suitable to the purpose of the production, during the growth process. Both the thinning and the harvesting process require diesel for falling trees and produces wood residues. The round wood obtained is then transported to the sawmill from where it is assumed to go out as a final product.

The use stage does not produce any environmental impact, while the disposal scenario assumed here is that the timber is incinerated at the end of its life cycle, after 100 years.

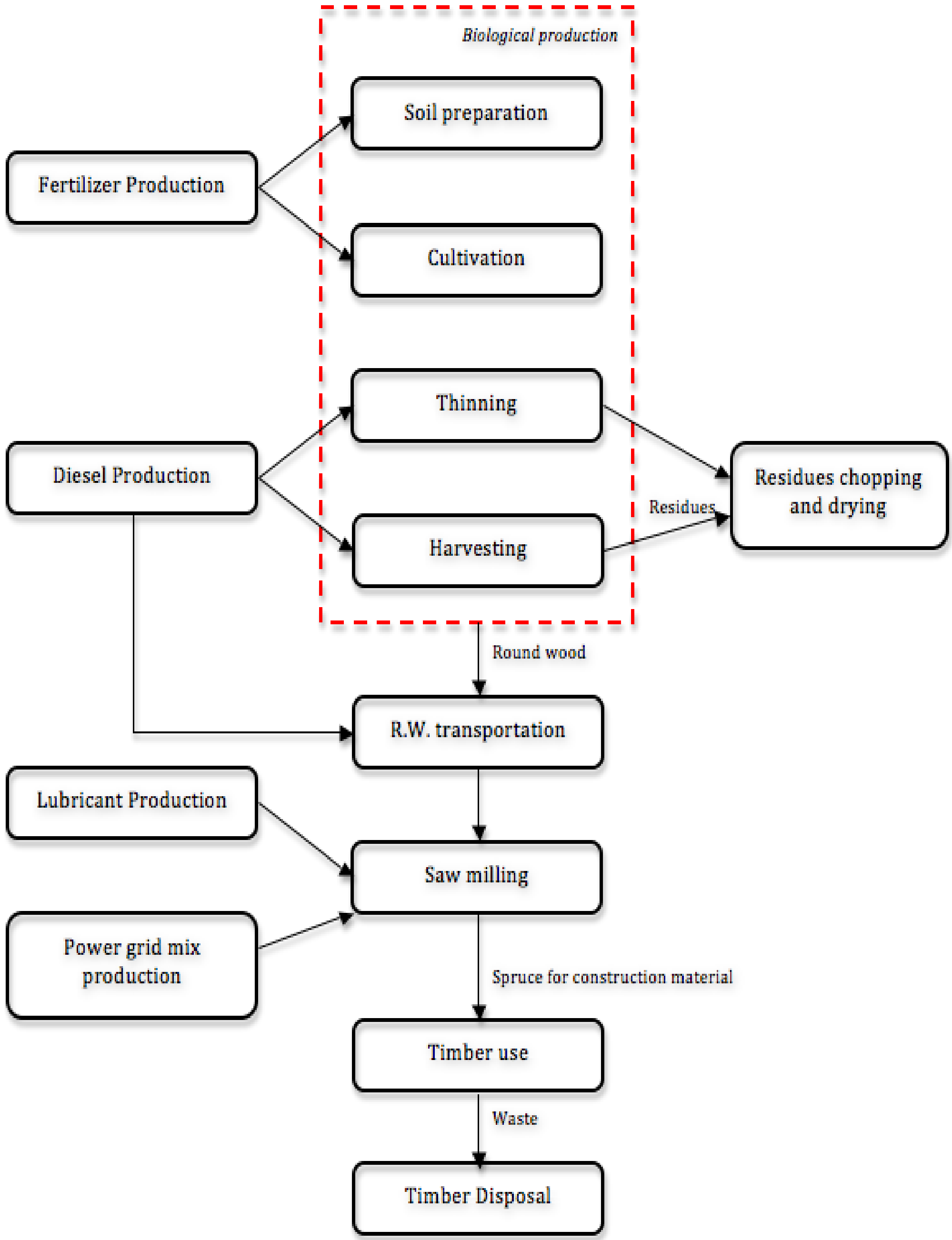

Figure 1 - Process flow diagram. The arrows represent LCA flows, the boxes LCA processes. The dashed red line surrounds the forest biological production.

3.2 Modeling assumptions

3.2.1 Rotation time and fertilizer application

The climatic conditions of a boreal forest slow down the growth of biomass, and a consistent amount of time is necessary before a tree can be considered mature. After a certain time, the tree is assumed as unable to sequester further C, since the amount of C sequestered is offset by its residues decomposition. This time can vary between 70 and 120 years (Storaunet and Rolstad 2002). However, due to economic reasons, in forest management the rotation time of spruce trees can be reduced applying fertilizers and be as short as 35-45 years (Moore 2011). Nevertheless, in the current study a rotation time of 70 years is assumed, because the fertilizer used is considered limited: researches show that usually nutrients other than nitrogen (N), for instance phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), do not increase tree growth rate (Jacobson and Pettersson 2001; Nilsen and Abrahamsen 2003; Nohrstedt 2001). In particular, in a more recent study, Jacobson and Pettersson (2010) found that, considering a standard N dose (150 kg N ha^{-1}), in mature stands increasing the frequency of N fertilization was negatively correlated to the tree growth. They conclude that, in order to keep the cost of marginal wood low and optimize the fertilizer applied, in mature stands an application of 150 kg N ha^{-1}every 8 years is more effective than a fertilization every 4 or 2 years. Grounded on these considerations, in this study is assumed an application of 200 kg N ha^{-1}at forest plantation and 2 applications of 150 kg N ha^{-1}in a mature stand phase as suggested in Jacobson and Pettersson (2010), accounting in total for 500 kg N ha^{-1}.

3.2.2 Thinning

A common practice in forest management is falling part of the trees some years after plantation and during the stands growth, a procedure known as thinning. Thinning modifies the original planting spacing, the growing space available to each tree, by reserving more growing space to the left trees. It usually involves trees with poor growth or stem shape, forks or damaged trees (DPI 2009).

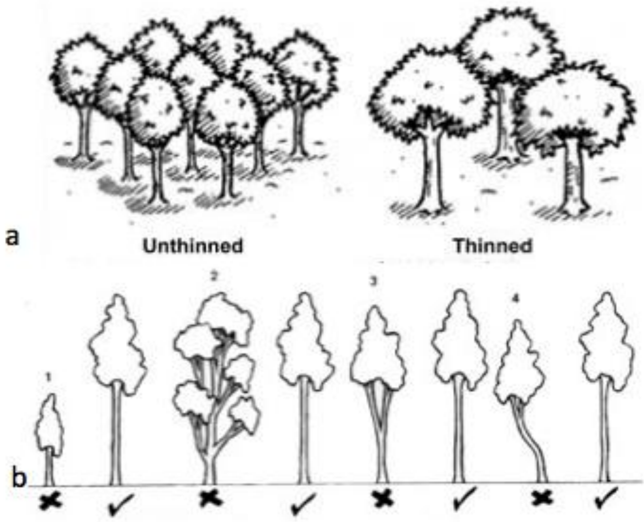

Figure 2 - a) State of the forest before and after thinning procedure; b) Trees removed with thinning are marked with an 'x': trees with a poor growth (1), with large branches (2) or forks (3) and irregular stem's shape (4). Drawings from DPI (2009).

Thinning has diverse effects depending on the tree species to which it is applied. It has been observed that thinning in Norwegian spruce may increase the gross wood production (Nilsson et al. 2010). To optimize individual-tree growth in Norwegian spruce forests, Valsta (1992) suggests a late first thinning and a total number of thinning of 2 or 3. This study assumes that thinning will take place three times during the rotation time (70 years), at 25, 35 and 45 years respectively. This modeling accounts for the fact that the spruce trees' growth rate is higher in the mature phase, i.e. between 25 and 50 years from plantation (see also Figure 10).

3.2.3 Reference flow

The area considered for the forest C balance is 1 hectare of land, with a time frame unit of 1 year. The Net Primary Production (NPP_0) is the reference flow, the measured in t of carbon. NPP_0 has the advantage of accounting for the actual potential production of the land, as this depends not only on the land dimension but also on the climate and location characteristics.

3.2.4 Cut off criteria

In this study, the life cycle stages from wood cultivation to product disposal are included. The wood treatment, i.e. the processing of raw sawn wood into ready-to-use spruce for construction purposes, is excluded from the system boundaries for two reasons:

- Firstly, because the wood treatment depends on the specific purpose the wood serves in the construction (if left raw, partially treated with chemical product or heavily treated). Since this is not a comparative study of different treatments or applications of wood used for construction material, this process is omitted. In fact it neither affects the methodologies (or assumptions) investigated in the current study, nor the final resulting impacts. The raw sawn wood, used as a construction material, is the final product.
- Second, the focus of the study is on GHG emission and the impact on climate change. Other potential impact categories, such as impact of chemical products applied to the timber before the final use, are omitted, despite the fact they might have also environmental relevance.

The cut-off criteria are set according to the environmental significance of the LCA processes (ISO 14044 2005): processes of land management during the rotation time are included (thinning, harvesting, fertilizing), while occasional activities for soil preparation (such as plowing), are excluded. In general, the environmental impact of administrative processes and services (overhead, business travelling etc.) are not accounted, since they are assumed to be not environmentally significant.

3.3 Biogenic carbon cycle in the forest

Modeling the biogenic production and degradation of biomass in the forest is a crucial aspect of this study, since it focuses on the forest C cycle. I n general, plants have a net uptake of C during their growth. Spruce and trees though, have a slower growth rate compared to crops, and continue to store C over a long period of time. The C sequestration process is slow and not linear, as will be shown below. In case of long-lived wood products, most of the C stored in the wood is kept in the final product. However the ordinary merchantable stock of wood is not the whole wood of the tree: wood residues are produced both during the growth of the tree and the harvesting process. To obtain a full forest C balance, it is important to track not only the life cycle of the main product, but also of the contingent by-product and wood residues, both harvested and left in the forest. Here it is assumed that 80% of the total AG residues are harvested. The rest of the AG residues and all of the BG residues are assumed as left in the forest. The non-harvested residues are left in the forest and will gradually decay.

The next sub-sections will explain the models adopted for describing the biomass C uptake and residues degradation (the forest biogenic C balance) and the emission-related effects of using the by-product. Calculation for the LCI of forest biogenic C sink and emission, forest C balance and relative values obtained, for each modeling assumption examined, have been performed in MS Excel. For further details see the attached electronic material.

3.3.1 Methodology to account for the biomass production

The forest biomass production is measured in Net Primary Production, NPP_0, introduced in section3.2.3. The annual production rate per year *t* is calculated according to the Equation 1, i.e. the CARBINE model (Broadmeadow and Matthews 2003).

$$NPP(t) = \frac{NPP_T}{1+10^{\frac{T/2-t}{T/20}}} \qquad (1)$$

Where:

- NPP_T is the total yield at the end of the rotation time;
- T is the rotation time expressed in years.

Figure 3 depicts the biomass NPP, assuming a rotation time of 70 years, an annual increment of spruce biomass of 6,5 m^3 per hectare per year (Statistic Sweden 2013). The AG and BG biomass are calculated considering a BG/AG ratio of 0,3 (IPCC 2006). There are three main stages during the tree growth: a first one, approximately from 0 to 20 years, in which the biomass growth is rather slow; a second stage lasting until 60 years when the biomass production is consistent, and a last stage from 60 years on, where the NPP slows down. Broadmeadow and Matthews (2003) define these three stages as establishment phase, full-vigor phase and mature phase.

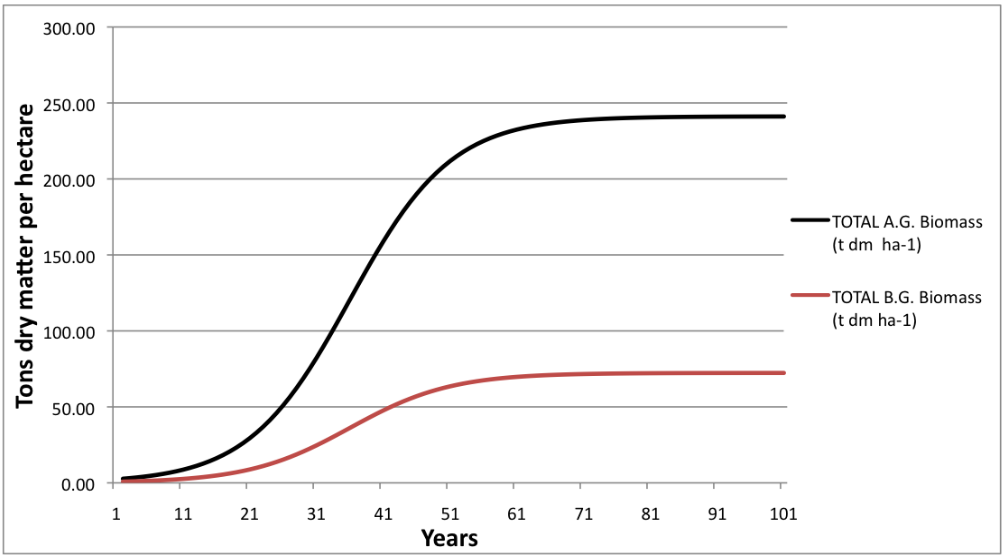

Figure 3 –NPP of above and below ground spruce biomass measured in tons of dry matter per hectare.

The C accumulation in biomass is directly related to the biomass production. If a C content in biomass of 0,51% is assumed (IPCC 2006), the C stored in the growing biomass can be depicted inFigure 4. The C accumulation during the first phase is relatively low, compared to the full-vigor phase where the C uptake rapidly increases. In the last stage a long-term equilibrium is reached, since the mortality and disturbance cause a loss of C that offset the C sequestered.

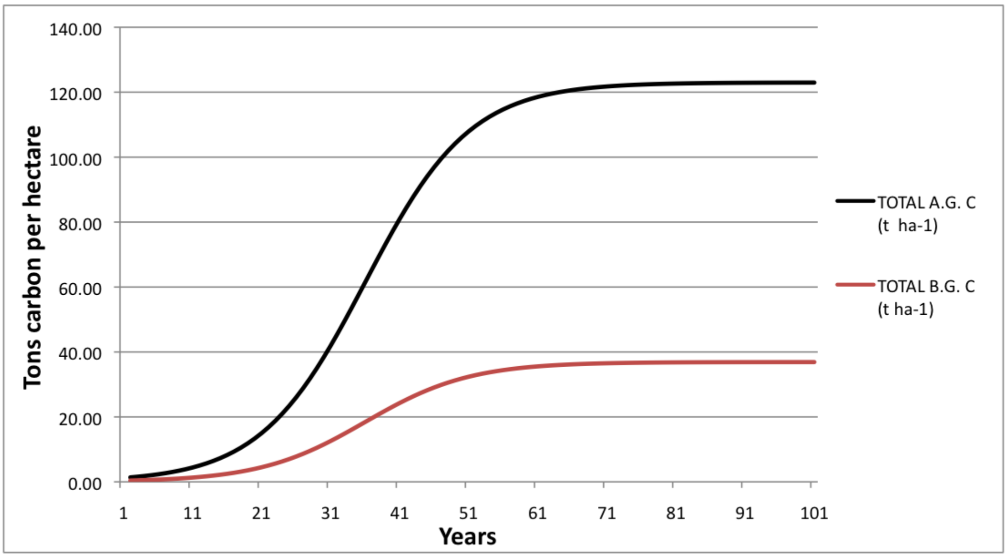

Figure 4 - Spruce C accumulation in AG and BG biomass measured in tons of carbon per hectare.

The biomass production and C sequestration were calculated for the AG and BG pools. The AG biomass was further subdivided in ordinary merchantable growing stock, harvested residues and non-harvested residues. The BG biomass was divided in harvested residues and non-harvested residues. Further details concerning the calculations can be found on the attached electronic material.

3.3.2 Forest biomass degradation

The biomass degradation is modeled according to the ROTHC-26 model (Coleman and Jenkinson 2008). The model divides all the soil organic C between Decomposable Plant Material (DPM) and Resistant Plant Material. Each of them further decomposes in Microbial Biomass (BIO), Humified Organic Matter (HOM) and part of the C is released and, combined with oxygen, forms CO_2 emissions as shown in Figure 5.

According to the model, the decomposing plant material goes through the DPM and RPM phases only once. The ROTHC-26 model defines this ratio for agricultural crops and improved grasslands. Other values of the DPM/RPM ratio are defined for unimproved grassland and scrub, and deciduous or tropical woodland. In this study the DPM/RPM ratio of 1.44 for agricultural crops and improved grasslands is adopted, since it appears the closest approximation to woodland. That means 59% of the plant material decomposes as a DPM and 41% as a RPM. The decomposition rate constant *k* for DPM is 10 while for RPM is 0.3. The material further decompose in BIO with a value of *k* equal to 0.66 and in HUM, k= 0.02.

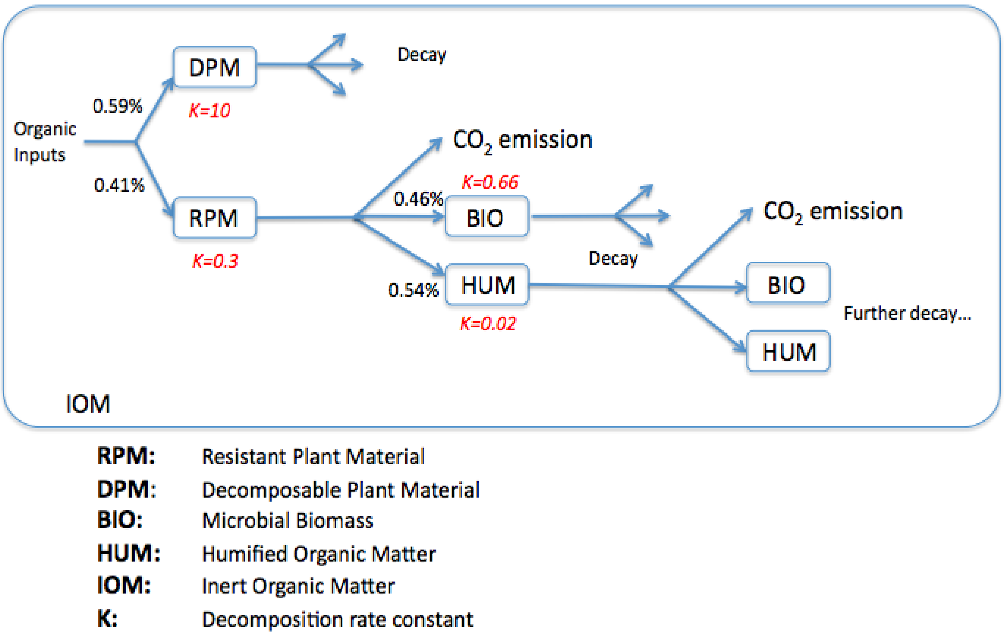

Figure 5 - Structure of the ROTHC-26 model. Own elaboration from Coleman and Jankinson(2008)

The decomposition of material in the forest is modeled as in Equation 2:

[illegible] *(2)*

Where:

- Y is the remaining material in year *t*
- k is the decomposition rate constant
- t is the time after wood removal expressed in years
- a is the rate modifying factor for temperature
- b is the rate modifying factor for moisture
- c is the soil cover rate modifying factor

Further details about the calculation of the rate modifying factors can be found in Coleman and Jenkinson (2008) and in the annexes electronic material.

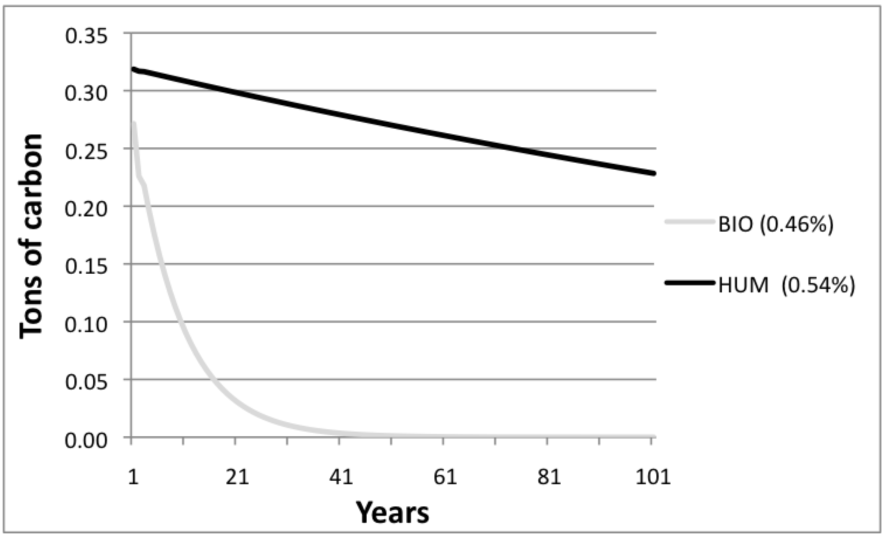

Figure 6 - 100 years decomposition of DPM (0.59% of the total material) in BIO and HUM of 1 ton of biomass.

Figure 6shows the decomposition of the DPM percentage of 1t of C in BIO and HUM for a timeframe of 100 years. The 0.46% of the material decomposes as a BIO with a *k*=0.66, while the 0.54% decomposes as a HUM with a *k*=0.02. The decomposition of BIO is much more rapid than the decomposition of HUM.

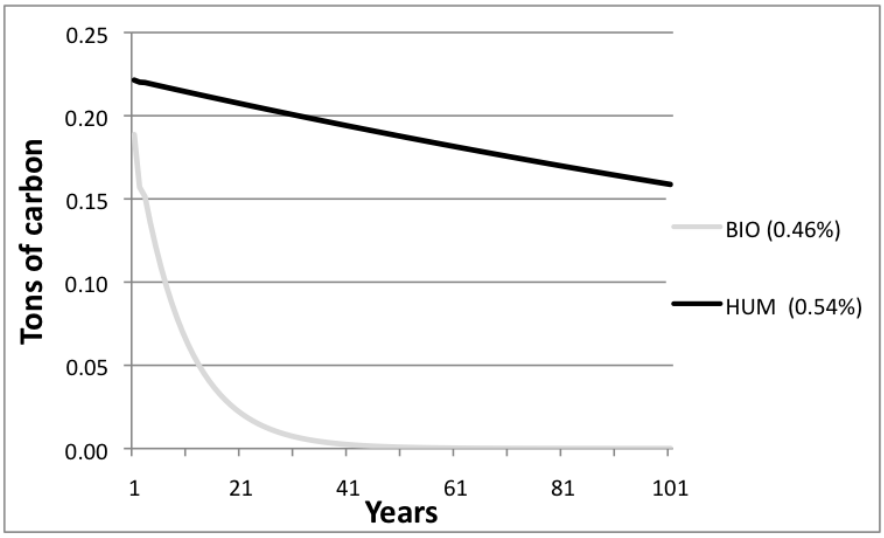

Figure 7 - 100 years decomposition of RPM (0.41% of the total material) in BIO and HUM of 1 ton of biomass.

Similarly, Figure 7 shows the decomposition of the RPM percentage of 1t of C in BIO and HUM for a timeframe of 100 years. The same considerations done for figure 6 can be replied for Figure 7.

3.3.3 Forest biogenic carbon balance

Once modeled the biological C uptake and release in the forest, it is possible to calculate the forest C balance per year. Figure 8shows the categorization of biomass made in this study.

A first distinction is made between above ground (AG) and below ground (BG) biomass, since they have a different growth rate. The ratio B.G./A.G. for spruce equals 0.3 (IPCC 2006). The share of harvested residues is here assumed to be 80% of the AG residues, while the BG residues are modeled as non-harvested. A further distinction is made between biomass stored in stem, harvest residues and non-harvest residues. The latter are further split in A.G. and B.G. residues. Based on these categories, the input and output of forest C considered in the balance are shown in Figure 9. Inputs are divided in four categories: C up-taken in stems, in harvest residues, C stored in AG non-harvested residues and BG non-harvested residues. Similarly, four output categories mirroring the inputs are defined. The difference between these categories is relevant because the wood use (and/or degradation) changes according to them and consequently, the C released need to be modeled in different ways according to the output category to which it belongs. When calculating the balance for the C stored in the growing biomass (the trees), the thinning activities, described in section 3.2, needs to be taken into account. When trees are chopped down during the thinning, the C stored in their stems and in the harvested residues has to be subtracted to the total amount of C stored in the forest.

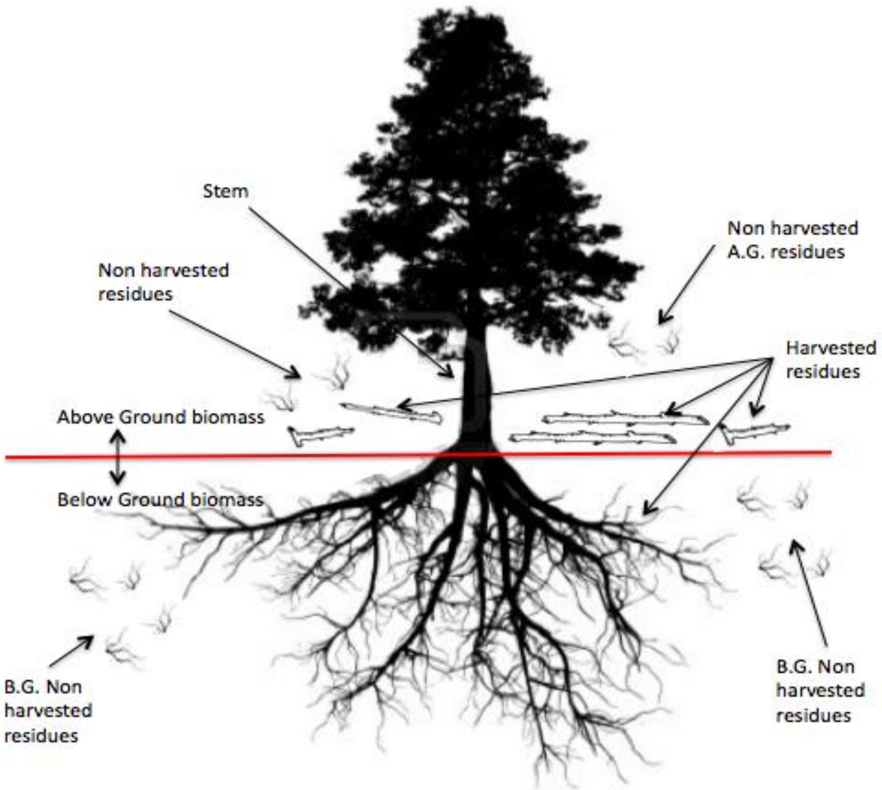

Figure 8 - Distinction between biomass categories modeled in the present study. A first distinction is made between above ground and below ground biomass. The above ground biomass is further divided in harvested stem, harvested residues and above ground non-harvested residues. The below ground biomass is further divided in harvested residues and non-harvested residues. Tree from Dreamstime (2013).

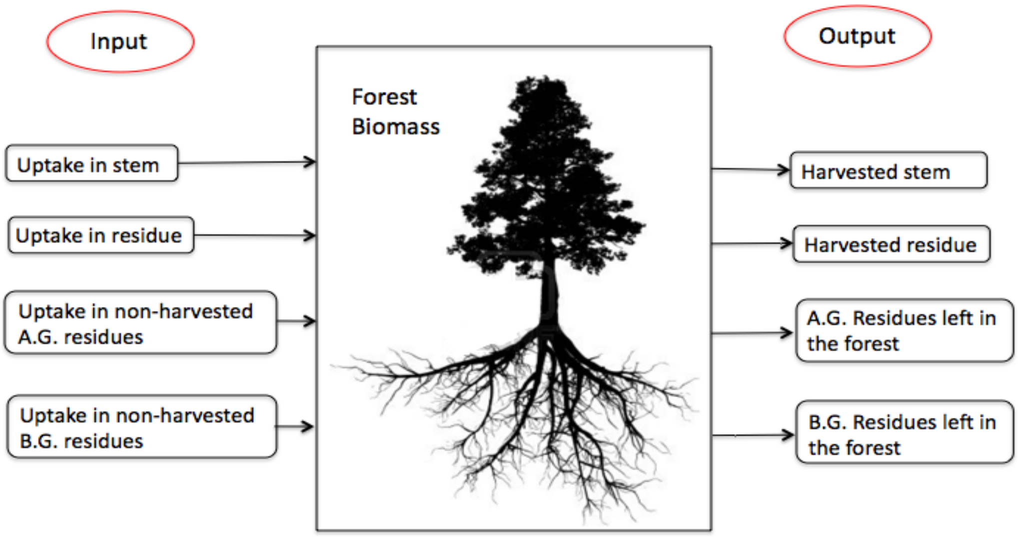

Figure 9 - Forest carbon input and output contributing to the forest carbon balance. The biomass categories defined in figure 8 provide the inputs and outputs depicted in this figure. Trees from Dreamstime (2013).

Figure 10shows how the thinning procedure modifies the trend of the C stored in the forest, specifically in the total amount of harvested stem wood and harvested wood residues in the forest. As described in section 3.2.2, three thinning activities take place after 25, 35 and 45 years. In Figure 10, these years coincide with a drop of the C stored in the forest in stem and residues, as the thinned stems and residues are assumed harvested.

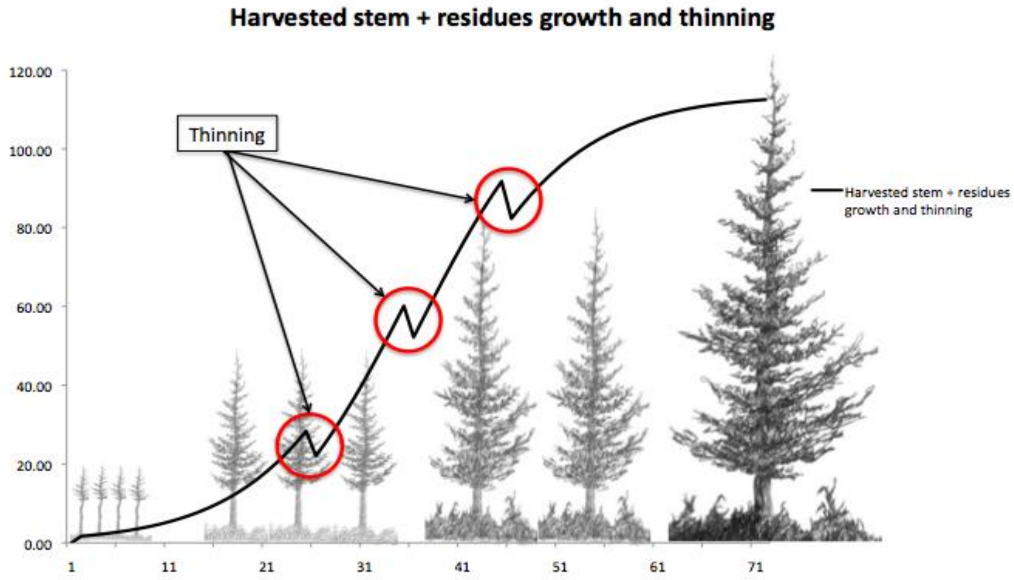

Figure 10 - Carbon stored in stems and residues and the effect of thinning and harvesting residues. Trees from Dreamstime (2013)

In this study it is assumed that the wood already present in the market immediately satisfies the demand of wood; the wood harvested today obviously grew in the previously 70 years (assuming a time horizon of 70 years). With regard to figure 11 below, t_1 is the time the wood is harvested and t_0 the time the harvested wood was planted.

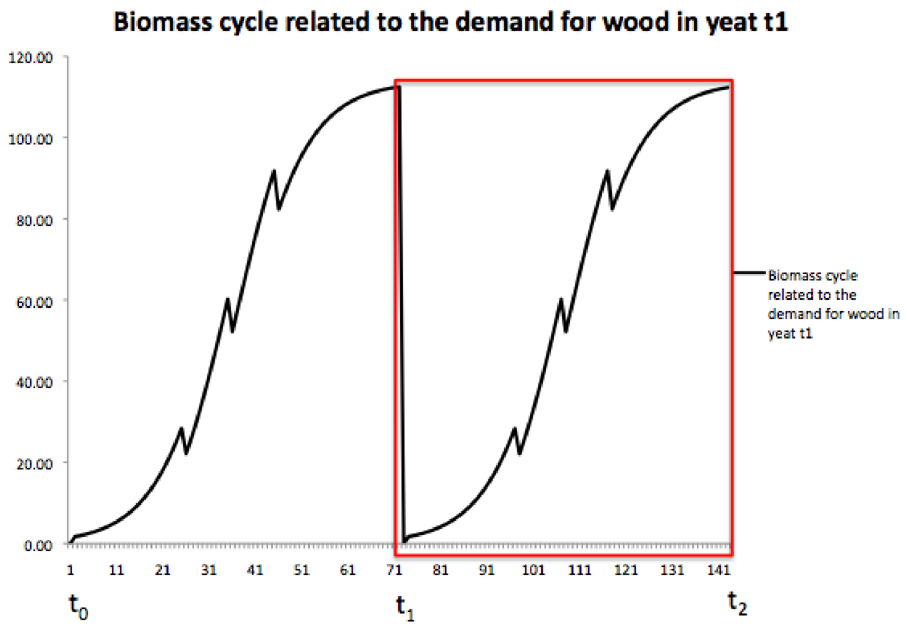

Figure 11 – Cycle of the living biomass related to the demand of wood in year t_1. The biomass harvested in year t_1 was planted in year t_0, where $t_0 = t_1 - TH$; similarly, the biomass planted at year t_1 to replace the harvested one, will be harvested in t_2, where $t_2 = t_1 + TH$. This study considers the time window outlined by the red line, from $t_1$tot$_2$.

At $t_1$new trees are supposed to be replanted to replace the harvested wood, that will be harvested after 70 years, in t_2. In this study it is assumed that the environmental impact of harvesting wood in t_1 is related to the replanted biomass in year t_1 and harvested in t_2, rather than to the biomass planted in t_0 and harvested in t_1. The red line in Figure 11 outlines the time window considered in this study. In light of these assumptions, the C balance is calculated as shown in Table 1.

According to the results of the model (see Table 1 and annexes electronic material), at time t_1 the trees are harvested together with residues, accounting for 90% of the total biomass harvested during the rotation time. Each subsequent year the biomass annual increment is added as an input. As shown in Figure 11, in $t_1$the outputs of harvested residues and stems are not zero since at the beginning of$t_1$the previously planted tree are chopped down and the residues left in the forest from the last thinning on are harvested. Thus the output 'Harvested stem' is only present when the tree is fell, while there is an output 'Harvested residues' each time a thinning procedure takes place. The balance of growing biomass is shown in Table 3for the first ten years, for the years in which the thinning activities take place and the last three years before harvesting, as an example.

Table 1 – Calculation of the C stored in the growing biomass. The table accounts for C inputs and outputs. Inputs and outputs are further characterized in four subcategories. The values are expressed only as an example for the first 10 years, the years in which the thinning takes place and the last 3 years

		Inputs				Outputs			
% of harvest biomass	Year	Uptake: Harvested stems	Uptake: harvested residues	Uptake: Non-harvested AG residues	Uptake: Non-harvested BG residues	Harvested stems	Harvested residues	AG Residues left in forest	BG Residues left in forest
90%	1	1.178	0.167	0.042	0.416	103.39	2.99	3.312	32.908
0%	2	0.163	0.023	0.006	0.058			0.000	0.000
0%	3	0.186	0.026	0.007	0.066			0.000	0.000
0%	4	0.211	0.030	0.008	0.075			0.000	0.000
0%	5	0.240	0.034	0.009	0.085			0.000	0.000
0%	6	0.272	0.039	0.010	0.096			0.000	0.000
0%	7	0.309	0.044	0.011	0.109			0.000	0.000
0%	8	0.350	0.050	0.012	0.124			0.000	0.000
0%	9	0.396	0.056	0.014	0.140			0.000	0.000
0%	10	0.448	0.064	0.016	0.158			0.000	0.000
...	...	...	...	...	...	...	...	...	...
3%	25	2.205	0.314	0.078	0.779		3.14	0.098	0.972
...	...	...	...	...	...	...	...	...	...
4%	35	3.430	0.488	0.122	1.212		4.28	0.133	1.325
...	...	...	...	...	...	...	...	...	...
4%	45	2.378	0.338	0.085	0.840		4.28	0.133	1.325
...	...	...	...	...	...	...	...	...	...
0%	68	0.186	0.079	0.007	0.013			0.000	0.000
0%	69	0.163	0.069	0.006	0.012			0.000	0.000
0%	70	0.144	0.061	0.005	0.010			0.000	0.000
		HARVESTING							

All the input and output in Table 1are balanced. Note that in order to obtained the full carbon balance, this has to be calculated with respect to the assumed rotation time.

Accounting for the C decomposition process of biomass residues in this case it is not simply the sum of the annual decomposed materiel: each year the decomposition process follows a different dynamic. More exactly, it follows the curve described in equation 2 in section 3.3.2. That means, to account the annual biomass decomposition, the decomposition of residues fell each year should be considered independently from each other, because the decomposition function is not linear, and the decomposition rate changes according to the age of the residues. The final CO_2 output is hence calculated according to the equation:

$$Y(t) = c\sum_{t=1}^{T} E_t k \qquad (3)$$

where:

- $Y(t)$ is the total amount of CO_2 emitted in year t;
- E is the total input of residues in year t;
- k is the value of the decomposition function in year i;
- c is the atomic weight ratio between CO_2 and C (44/12);
- T is the rotation time

In Table 2, $Y(t)$is reported in the column 'CO_2emission', E in 'C (in CO_2) emission', k in 'Decomposition function'.

Table 2–Calculation of the biomass decomposition. All the inputs and outputs are in balance. The values are expressed only as an example for the first 10 years, at 70, 100, 500 and 1000 years

	Inputs		Outputs		Inputs	Outputs	
Year	AG Residues left in forest	BG Residues left in forest	C (in CO2) emission	Addition to C stock	CO2 uptake	CO2 emissions	Decom-position function
1	3.312	32.908	2.896	33.324	6.611	10.618	8.00%
2	0.000	0.000	0.520	-0.520	0.918	1.908	1.44%
3	0.000	0.000	1.456	-1.456	1.043	5.339	4.02%
4	0.000	0.000	1.311	-1.311	1.185	4.807	3.62%
5	0.000	0.000	1.181	-1.181	1.346	4.331	3.26%
6	0.000	0.000	1.065	-1.065	1.528	3.904	2.94%
7	0.000	0.000	0.960	-0.960	1.733	3.521	2.65%
8	0.000	0.000	0.867	-0.867	1.964	3.179	2.39%
9	0.000	0.000	0.783	-0.783	2.224	2.871	2.16%
10	0.000	0.000	0.708	-0.708	2.515	2.596	1.95%
...	...	...	...	...	...	...	...
70	0.000	0.000	0.065	-0.065	0.807	0.239	0.15%
...	...	...	...	...	...	...	...
100	0.000	0.000	0.015	-0.015	0.000	0.054	0.13%
...	...	...	...	...	...	...	...
500	0.000	0.000	0.004	0.000	0.000	0.014	0.03%
...	...	...	...	...	...	...	...
1000	0.000	0.000	0.001	0.000	0.000	0.003	0.01%

These values of emissions obtained are then multiplied for the dynamic GWP calculated by equation 5 (see next section). Note that the values of the dynamic GWP are dependent on the TH adopted. More details are available consulting the MS Excel file (sheet 'GWP time') in the annexes electronic materials.

3.3.4 Impact assessment of emissions

Section 2.1 and **¡Error! No se encuentra el origen de la referencia.** introduced the Global Warming Potential among other climate indicators used for the impact assessment of emission. IPCC (2007) suggests the use of the GWP with a TH of 100 years, expressing the equivalent CO_2 that would have caused the same cumulative radiative forcing (CRF) as the emissions analyzed, in a TH of 100 years. In practice, the GWP is often used to express the greenhouse effect of different emissions in relation to CO_2 and its decay rate. Section 2.1.2 explained how this indicator could be applied both with static or a dynamic approach; this study applies the GWP indicator to test both the cases.

With regard to the dynamic approach, the current study applies the GWP indicator proposed by Schmidt and Brandão (2013). As explained in section 2.1.4, when considering a static approach the Bern C cycle is used to describe the decay of the fraction of CO_2 pulse emission in air over time (IPCC 2007). The CRF of CO_2 and the compared substance in this case is calculated by means of an integral and the GWP is the ratio of these integrals, as shown in the flowing equation:

$$GWP_i = \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_{CO_2}(t)\,dt} \qquad (4)$$

where:

- GWP_i is the global warming potential for the substance *i*
- TH is the applied time horizon
- RF_i is the radiative forcing for substance *i*
- RF_{CO2} is the radiative forcing relative to CO_2

In order to account for the different timing of emissions (dynamic approach), in this study equation 1 is modified as follow (Schmidt and Brandão 2013):

$$GWP_{i,\Delta t} = \frac{\int_0^{TH} RF_{i,\Delta t}(t-\Delta t)\,dt}{\int_0^{TH} RF_{CO_2,t=0}(t)\,dt} \qquad (5)$$

where:

- $GWP_{i,\Delta t}$ is the global warming potential for the substance *i*emitted at time Δt relative to t=0
- TH is the applied time horizon
- RF_i is the radiative forcing for substance *i*, emitted at time t Δt relative to t=0
- $RF_{CO2,t=o}$ is the radiative forcing relative to CO_2emitted at t=0

The GWP calculated in equation 5 decreases with time. Multiplying the value of the carbon dioxide emission/sink for the GWP factor calculated in equation 5 attenuates the consequent impact because the emission/uptake is delayed of a Δt amount of time (Schmidt and Brandão 2013). The GWP indicator calculated in equation 5 therefore, accounts for the timing of the emission/sink of C and it is a dynamic climate indicator.

3.4 By-products and system expansion

Section 3.3 explained how the forest C cycle has been modeled. In this paragraph the C balance is extended to the whole life cycle, looking also at the sawmilling process and the use of by-product of both forest and sawmill. Figure 12 depicts the C inputs and outputs of all the LCA processes considered. For each process, the mass flow is in balance. The balance is shown in tons of C and tons of CO_2.

There are in total two source of by-product: the harvested residues, by-product of the forest plantation and the chips and slabs, by-product of the sawmilling process. The consulted literature identifies the market of unspecified wood (wood pellet, wood pulp and paper industry) as the most likely to employ the by-product ‘wood residues’ (Reinhard, Weidema, and Schmidt 2010; Cocchi 2012). Thus here it is assumed that the harvested residues are used in the market of unspecified wood (wood pellet, wood pulp and paper industry. According to a consequential LCA modeling (see section 2.1), a eucalyptus tree farm in Brazil has been assumed to be the one directly affected by the production of the by-product wood residues. This plantation and location is considered the most likely supplier for the unspecified wood market (Reinhard, Weidema, and Schmidt 2010; Cocchi 2012). The by-product hence displaces an equal amount of wood produced in Brazil, used in the pulp and paper industries (Figure 12). Operating a system expansion allows to encompass the impact of the avoided production of eucalyptus.

In order to assess the impact of the by-product from the wood system in Sweden, a similar model described in this chapter for the spruce plantation in Sweden has been developed for the carbon balance in one hectare of eucalyptus plantation in Brazil.

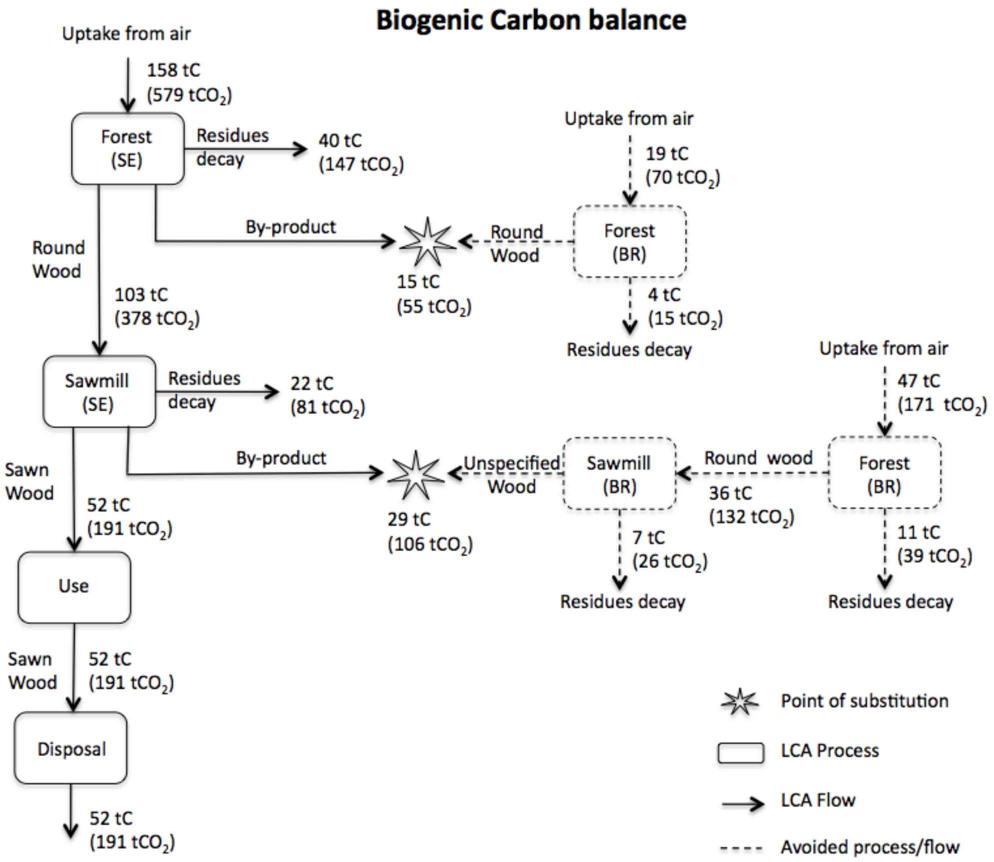

Figure 12 - Total biogenic carbon balance. The figure depicts the whole biogenic carbon balance, from the uptake of carbon from air in wood, through the processing of wood, until the use and disposal phase. Here it is assumed that the by-product will merge the unspecified wood market (wood fuel, pulp and paper industry), to be used as pulp and paper wood. It will displace an equal amount of Eucalyptus from a Brazilian forest farm, identified as the most likely supplier of wood for the unspecified wood market. The boxes represent LCA processes, the arrows LCA flows. The dashed lines represent avoided flows and processes, related to the displaced production in Brazil. The stars indicate the point of substitution. The carbon is in balance for each LCA process, which means for each box the sum of the inputs it is equal to the sum of the output. Inputs and outputs are shown both as tons of carbon and tons of carbon dioxide.

Note that despite the methodology used is the same, the variables have been adjusted by using values related to a eucalyptus forest in a tropical area. Details concerning the modeling of the Brazilian plantation are available in the annexes electronic materials. The output of the eucalyptus forest plantation has been normalized to the amount of by-product substituted by the spruce plantation's residues. In Figure 12 the point of substitution is marked with a star.

The sawmilling process has as a main output the final product, sawn wood (SW), sawn chips and slabs as a by-product, and wood particles (dust, shavings, bark) as a waste wood output. The waste wood decomposes according to the wood decomposition function and will gradually release C in the air as carbon dioxide. More details about the model of the sawmill are available in the MS Excel file in the annexes electronic materials.

The by-product of the 'Sawmill (SE)' displaces an equal amount of wood from a eucalyptus plantation in Brazil. The by-product of 'Sawmill (SE)' is not RW but SW (Figure 12). Thus, the substituted material has to be SW too. For this purpose, a Brazilian sawmill process, 'Sawmill (BR)', is modeled and the output normalized to the output of by-product from the process 'Sawmill (SE)'. 'Sawmill (BR)' has no by-product since both sawn wood, chips and slabs are used for pulp and paper production. The product of the Brazilian sawmill accounts for the 76% of the RW in input.

The sawmilling process in Sweden has as a main output the final product sawn wood (SW), accounting for 44% of the RW, sawn chips and slabs as a by-product, 29% of the RW in input, and wood particles (dust, shavings, bark) as a waste wood output, 23% of the RW. The waste wood decomposes according to the wood decomposition function and will gradually release C in the air as carbon dioxide. For more detail concerning the modeling of the sawmilling processes see the annexes electronic material. Data concerning the percentages of output products from RW in different regions are based on UNECE-FAO (2010).

Finally, the use and disposal processes have as an output simply the total amount of C present in the product: there are no additional emissions in the use and disposal stage of the product life cycle.

3.5 Indirect Land Use Change (iLUC)

This research adopts the approach proposed by Schmidt et al. (2013) to account for the iLUC effect. This iLUC can be used both in ALCA and CLCA to model land use of crops, forestland or other land use types in all regions in the world. Assuming that a change in land use is caused by a change in market demand, Schmidt et al. (2013) pinpoint four different markets for lands and land use classes:

- Arable land;
- Forest land;
- Range land;
- Other land (not suitable for production);

Here the interest is in the market for forestland; the iLUC model identifies four different inputs (or variables) capable to produce a change in the market for land:

- Forestland already in use;
- Transformation in forestland;
- Forest intensification;
- Forest displacement;

The forestland already in use does not have any effect in the market since it is assumed to be already full utilized and unable to increase the productivity. It is only listed in the inventory to make the model flexible to ALCA and CLCA approaches. In fact while the CLCA modeling would only consider the annual change in land's productivity (thus only accounting for land transformation and intensification) as able to affect the output, the ALCA modeling considers the average of all suppliers to the market to determine the final output. The iLUC model also assumes that forest displacement activities are not affected by the change in demand for land in the long term and for small-scale changes. The final emissions for the considered market of land are calculated as the sum of the emissions associated to the inputs of that market.

Usually emissions related to land's occupation are allocated over a period of time, called amortization period. That means emissions caused by a change in land use today can be allocated over several years, but the number of years to account for the allocation are arbitrary. Schmidt et al. (2013) avoid the emission allocation over a period of time by modeling the effect of deforestation differently: they consider only system expansion instead of allocation. That means the emissions take place the first year the land is occupied, and are avoided the next year, since the land is already in use (the system is already "expanded"): for instance if an hectare of forest land is occupied in year 1, the total arable land is "expanded" of one hectare and the emission caused by deforestation occur in year 1. In year 2, the total arable land already includes the hectare occupied in year 1. Therefore, assuming the hectare is still in use in year 2, it will be used without deforestation (avoided emissions), since the land was deforested in year 1. This produces a net emission from land use change equal to zero, but an accelerated climate effect. In fact the emission took place earlier then the future land use change.

3.6 Tested methodological assumptions

Based on an extensive literature review (see chapter 2), four main methodological choices are examined in this study. Their effects on the final results are assessed and compared against each other. The purpose of this section is to introduce the values (if quantitative) or assumptions (if qualitative) relative to these options.

Table 3 shows the modeling assumptions and methodological choices tested in this study. The first scenario ('1' in Table 3) listed for each factor ('A', 'B', 'C', 'D') in Table 3) is the *default* assumption, i.e. it is the scenario considered when the other factors are tested. Two different land use modeling are firstly considered: a scenario in which the iLUC effect is modeled, and one in which the iLUC effect is not modeled. The first (A1 in Table 3) suggests the adoption of a consequential modeling to model an increase in demand of land use due to the request of the product specified in the FU. The second scenario (A2 in Table 3), does not model the land and does not account for the iLUC effect.

Table 3– LCA modeling choices and methodological assumptions compared in this study

A) LAND USE MODEL
1. Indirect land use change modeling (ILUC)
2. No-iLUC modeling
B) CLIMATE INDICATOR
1. Dynamic approach: CO_2 based on GWP
2. Static approach: GWP set to a constant, 1 per year<=TH; GWP = 0 per year>TH
C) TIME HORIZON
1. 100 years
2. 20 years
3. 500 years
4. 1000 years
D) FORES C STOCK MODELLING
1. All terrestrial carbon stock
2. Only C stock in Stem wood
3. Above Ground Carbon

The second factor considered (B in Table 3) is the climate indicator. It is common in LCA to calculate the C footprints regardless of the timing of C emission and sink by using a static climate indicator (see section 2.1.2). The static approach (B1 in Table 3) does not detect the climate implication of the timing of emissions, as underlined in several publications (Levasseur et al. 2010; Pingoud, Ekholm, and Savolainen 2012a). However it is often used as a climate indicator and, therefore, tested in this study. The climate indicator applied for the static approach is a constant GWP, set to 1 for the time equivalent to the TH and 0 otherwise. The second option tested adopts a dynamic approach (B2 in Table 3). A dynamic approach for climate impact assessment means that the emissions are weighted for a time-dependent characterization factor. The Characterization factor depends on the TH adopted: its values decreases from 1 to 0, so that the emissions are multiplied for a factor 1 in year 1 and for a factor 0 at year equal to the TH. The GWP indicator introduced in section 2.1 and defined in 3.3.4 is the climate indicator adopted in this study to model the dynamic approach.

Other indicators introduced in section**¡Error! No se encuentra el origen de la referencia.** are not applicable to this study. In fact, GWP_{BIO} refers to wood used as fuel, and adapt the GWP used for fossil fuel to the case of biomass fuel; GWP_{BIOUSE} is applicable to a comparative study, since accounts also for the avoided impact of the displaced product, for example in the case of this study, the concrete replaced by the wood.

The third aspect tested is the TH. Four scenarios have been considered, applying different time horizons (C in Table 3): a TH of 100, 20, 500 and 1000 years. A TH of 100 is the most common assumption and the one adopted by the Kyoto Protocol (UNFCCC 1997). Twenty years TH is relevant for assessing the short-term environmental effects of the system. This is a rather relevant indication for policy makers to keep the temperature increase below 2°C, the target adopted at the COP 15 to limit the effects of climate change. A TH of 500 years is considered to assess the long-term effect of using long-lived wood products and the time to re-pay the C debt accumulated by the production process. The last TH=1000 is tested only for the static approach. When using the static approach, the GWP is set equal to 1 for years minor or equal to the TH, 0 otherwise. If a dynamic approach is adopted, the GWP factor is already close to 0 after 500 years, thus it is of little interest to test a TH of 1000 years with a dynamic approach.

The last factor concerns which C pool is considered in the forest (D in Table 3). Three options are considered in this case accounting for all the carbon stocks, AG and BG (D1 in Table 3), only the C stored in the tree’s stem (D2 in Table 3) and the AG carbon pool (B1 in Table 3).

The climate implication of forest product use illustrated in section 2.1.5, is not explicitly considered here as a parameter. This can be accounted by including the product disposal process in the process flow, and measured choosing the TH (that affects the value of the climate indicator). For example, in this study, the product is used as construction material, the climate impacts are considered in the product disposal stage by choosing a TH of 100, 20 or 500 years. If a TH of 100 or 500 years is considered, it is reasonable to assume that the construction material will be disposed within this timeframe. In that moment the C stored in it will be released, assuming the wood is incinerated at the end of the life cycle. The product use phase results in a climate change mitigation effect, since C is stored in the product while the product is in use. If the assumption of a TH equal to 20 years is made, the C stored in timber is considered as not released at all, again without consequences on climate but with a mitigation effect. On the contrary, if a different product use is considered, for example wood-based biofuel, the emissions resulting from combustion are anyway considered, independently on the TH.

3.6.1 Modeling assumptions testing plan

A testing plan was developed to compare the methodological choices investigated in this study. Table 4 shows the schema of the testing plan. It foresees the comparison of ten different modeling approaches. The colors in Table 4 group the compared approaches; the blue colored variables are kept constant (frozen variables) to ensure the comparability of the results.

Table 4 - Schema of modeling assumption testing plan. The letters and numbers refer to Table 3.

LCAs n.	LAND USE MODEL	CLIMATE INDICATOR	TIME HORIZON	FORES C STOCK MODELING
1	**A1**	**B1**	**C1**	**D1**
2	**A2**	"	"	"
3	A1	**B1** (with GWP-20)	**C2**	"
4	"	**B1** (with GWP-500)	**C3**	"
5	"	**B2**	**C1**	"
6	"	**B1** (with GWP-20)	**C2**	"
7	"	**B1** (with GWP-500)	**C3**	"
8	"	**B2**	**C4**	"
9	"	B1	C1	**D2**
10	"	"	"	**D3**

Legend: **X#** - A tested variable
X# - B, C tested variable
X# - D tested variable
X# - frozen variable

It is important to remember that the FU (1 m^3 of spruce used as a construction material) is the same for each scenario tested in this study as summarized in Table 4. Note also that, as explained above and reported in Table 4, the static approach is tested with TH=1000, while the dynamic approach is only tested with regards to the first three value of TH.

4. Results and analysis

Before presenting the results this section demonstrates that the developed model is fully balanced. Table 2 shows that the input and output for all the LCA processes are in balance. It is important to check the reliability of the model because from that derives the strength of the results. Figure 13 is a SimaPro screenshot of the C balance check result. The C balance check is an impact category developed to verify that the entire C up-taken from the analyzed system is at some point also emitted.

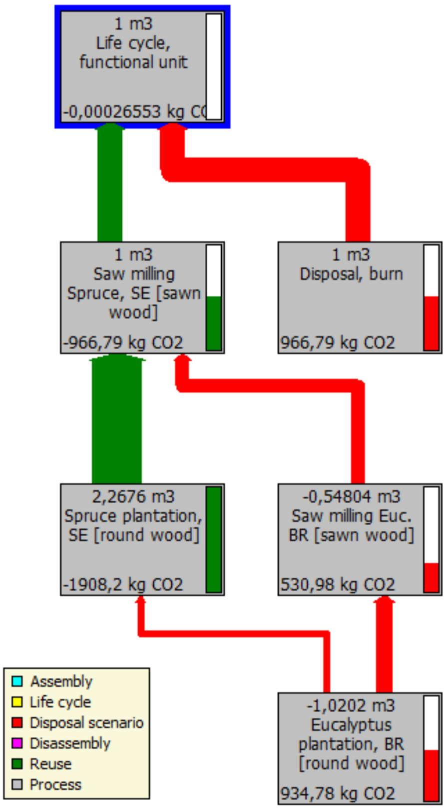

Figure 13 - Results of the carbon balance check

The figure was obtained as a result of the first scenario modeled, but very similar or equal results can be obtained for the other cases. It demonstrates that the system modeled is in balance, approximated to a negligible order of magnitude. In fact the C flow for 1 m^3 is in average 1 ton, while the error shown in the Life cycle functional unit is 0,2g. In Figure 13 the figures at the bottom of the boxes report the GHG emissions measured as GWP in terms of CO_2 equivalent. The numbers are obtained by using the option cumulative indicator in SimaPro.

Figure 14 and Figure 15 show the results obtained for the first scenario modeled, respectively reporting the emission with a cumulative indicator and for the single processes. For practical reasons, the results of the ten scenarios are not presented with the SimaPro network graphic. This is done only in Figure 14 and Figure 15 as an example. The figures illustrating the network obtained for the other scenarios are shown in the Appendices. An overview of the results is instead presented in Table 5.

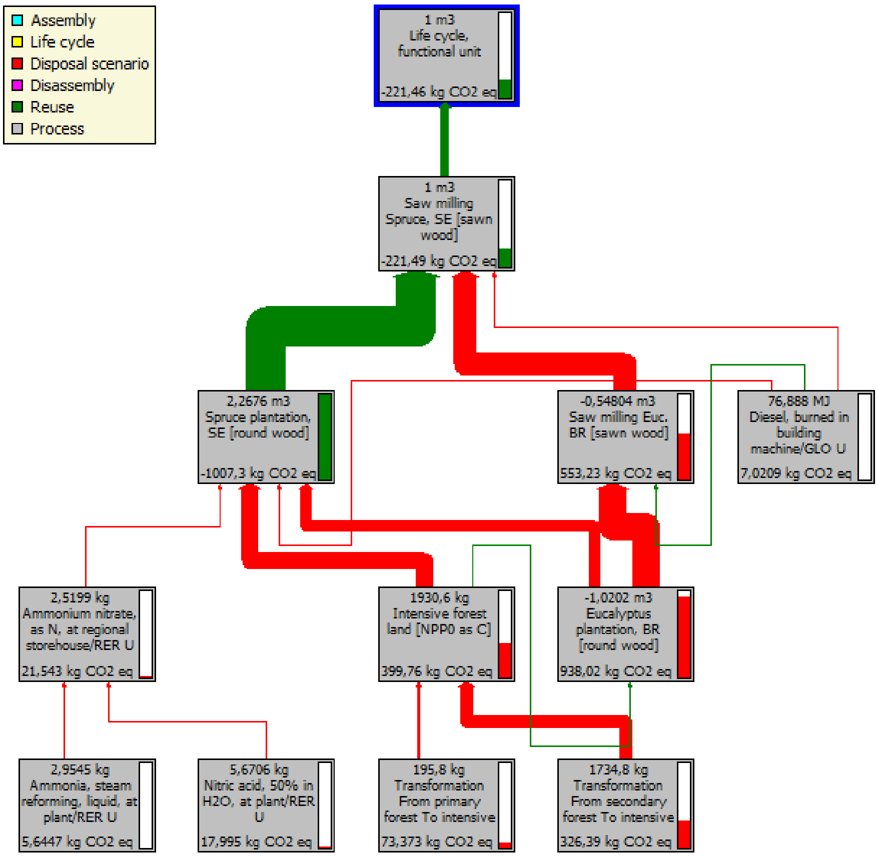

Figure 14 – Result obtained withSimaPro for the first scenario, using a Network calculation function and the cumulative indicator of emissions.

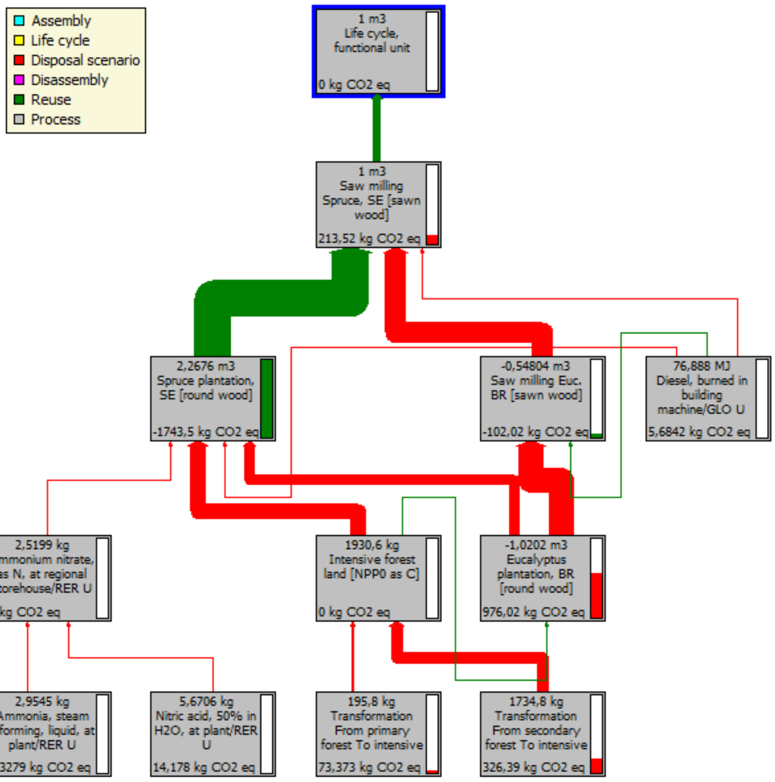

Figure 15 - Result obtained with SimaPro for the first scenario, using a Network calculation function. The emissions reported refer to the single process.

Table 5 – Outcomes of the ten scenarios obtained with SimaPro. The table shows the net contribution in CO_2 emissions (positive value) or uptake (negative value) for each process resulting from the 10 scenarios modeled.

PROCESSES		SCENARIOS 1	2	3	4	5	6	7	8	9	10
P	Spruce plantation SE (kg CO_2 eq)	-1743.5	-1743.5	55.77	-2213.4	-2469.4	-102.43	-2256.3	-2194	-1382.2	-1593.9
R	Sawmilling SE (kg CO_2 eq)	213.52	213.52	130.26	311.99	252.07	184.96	368.46	402.49	213.52	213.52
O	Eucalyptus plantation BR (kg CO_2 eq)	976.02	976.02	937.81	943.31	959.86	1038.7	934.8	934.78	650.86	926.49
C	Sawmilling BR (kg CO_2 eq)	-102.02	-102.02	-70.81	-126.29	-120.55	-83.19	-132.42	-132.43	-102.02	-102
E	Disposal, incineration (kg CO_2 eq)	0	0	0	821.44	966.79	0	966.79	966.79	0	0
S	Transformation from primary forest to intensive forest (kg CO_2 eq)	73.37	0	401.49	14.73	73.37	401.49	14.173	0	74.23	73.37
S	Transformation from secondary forest to intensive forest (kg CO_2 eq)	326.39	0	1786	63.04	326.39	1786	63.04	0	330.21	326.39
E	Other (kg CO_2 eq)	34.76	34.76	34.78	34.26	34.77	34.77	34.757	34.75	34.75	34.79
S	TOTAL	-221.46	-621.22	3275.3	-150.92	23.3	3260.3	-6.7	12.38	-180.65	-121.34

Note that the figures in Table 5 express GHG emissions measured as GWP in terms of CO_2 equivalent. This is not the same as measuring the CO_2 emissions, since the GWP is affected by the timing of GHG emission and sink. For each scenario, the last row of the table (Total) is equivalent to the value of the emission reported in the 'Life cycle functional unit' in Figure 14 (cumulative final net GHG value). The GHG for the single processes correspond instead to the value of the LCA processes shown in Figure 15 (net GHG value for the single processes). A negative final value ('Total' in Figure 15) indicates a net GHG uptake from the system and therefore a positive environmental impact, particularly with regard to climate change mitigation effect. On the contrary, a positive final value indicates a net GHG emission and therefore a negative environmental impact.

At first glance, it can be observed that the range of final results is remarkably wide. The total value of emission is negative for 8 out of the 10 scenarios tested. That means when timber is used as a construction material and the residues employed in the pulp and paper industry, there is a net uptake of GHG, assuming new biomass is replanted to substitute the harvested one. This is in line with the expected results and with the findings of previous studies presented in section 2. The two cases in which a positive result (negative impact) is found correspond with the scenarios where the shortest time horizon is applied (20 years), specifically scenario 3 and 6. Here the emissions caused by the iLUC are higher, since they are distributed on a relatively short timeframe. Moreover the iLUC emissions are not offset by the biomass re-growth, because the short TH does not account for the entire period in which the spruce tree grows. The full-vigor growth phase of trees (25-40 years after tree planting, see section 3.3.1), during which the biomass growth increase exponentially, is not accounted when the 20 years TH is chosen. For this reasons the final results diverge sensibly from the ones obtained in other scenarios.

The following subsections analyze more in detail the results obtained for each group of tested assumptions, as they were presented in Table 4.

4.1 Land use modeling

The first two scenarios in Table 5 (brown variables in Table 4) show how the inclusion/exclusion of the iLUC is tested. The other variables are kept constant, according to the default values, as explained in section 3.6.1. The climate indicator GWP, with TH equal to 100 years, is applied to both scenarios with a dynamic approach. In this study is assumed that the wood used in constructions has a lifetime of 100 years, after which the wood is incinerated. At year 100, the GWP factor is null. The emissions taking place at year 100 are multiplied for the dynamic GWP factor 0. That explains why the disposal process in the first two scenarios is null, as well as in other scenarios with TH equal or minor than 100 years.

Figure 16 shows the results obtained for scenario 1 and 2. The negative values represent GHG uptake while the positive values GHG emissions. It can be observed that the GHG uptake is the same in the two scenarios. In Figure 16 the negative values are equal for the two scenarios. The difference is that scenario 1 has also higher emission than scenario 2. In fact, if the iLUC effect is not modeled, the emissions of attributed to the system are significantly lower, as shown by the column relative to the second scenario in Figure 16. In conclusion, in the case study adopted the choice of modeling the effect of iLUC or not, results in a difference in GHG uptake of approximately 400 kg of CO_2 equivalent.

It is interesting to note that the eucalyptus plantation contributes with a net emission of CO_2 to the C balance.

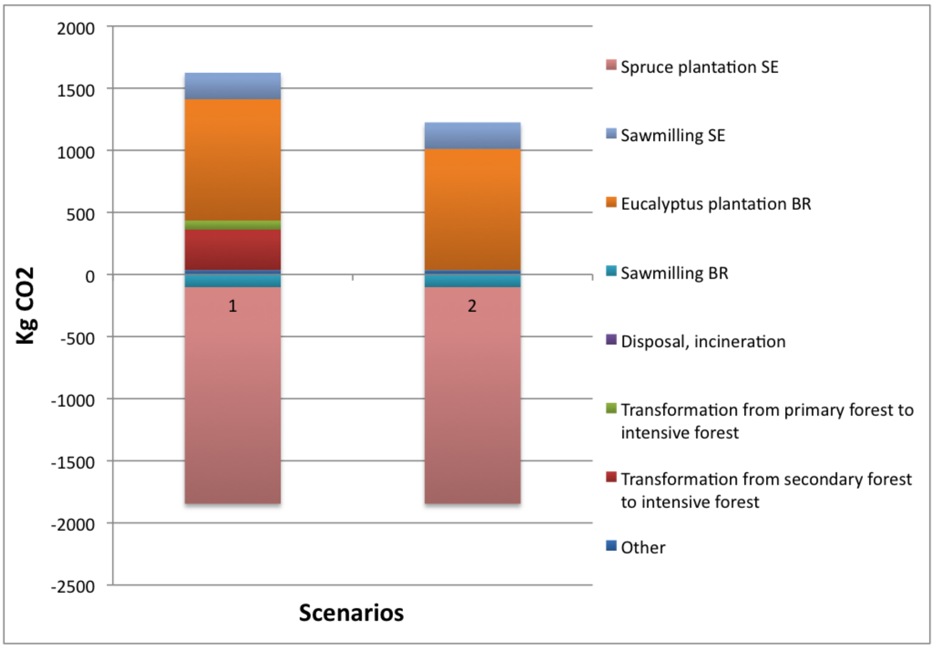

Figure 16 - Comparison of the result obtained for the two land use models tested (scenario 1 and 2).

This result might appear counterintuitive, since from a tree plantation it would be expected a net carbon sequestration effect. The reason of this result is that the Eucalyptus plantation is an avoided process: consequently, emissions from this process are accounted as avoided emissions. CO_2 sequestration from an avoided process is accounted as avoided sequestration, which entails a net emission of C. This is valid also for the results of the other tested scenarios, compared below. Similarly, the sawmilling process is a net CO_2 emitter and the emissions from the Swedish sawmilling process are visible as a positive value in Figure 16. The emission from the avoided process Eucalyptus sawmilling, are instead negative, as they are avoided emissions.

4.2 Climate indicator and time horizon

Due to the strong interdependence between climate indicators and time horizon, the results concerning these two assumptions are here presented and analyzed together. As illustrated in the testing plan, the study tests two approaches concerning the climate indicator and four different TH, where the 1000 years TH is tested only for the static approach. Hence, in total there are seven options comparing these two methodological choices tested respectively in scenario 1, 3, 4, 5, 6, 7 and 8 (red variables in Table 4). The results are shown in Figure 17. The first three scenarios in the figure are relative to the climate indicator GWP based on a dynamic approach. The tested parameter is the TH, assuming respectively value 100, 20 and 500 years. The first scenario does not include the disposal scenario, because the dynamic approach with TH 100 and 20 years weights for a factor 0 the emission of C taking place in year 100. If a dynamic LCIA is adopted the disposal scenario is therefore present only for a 500 years TH.

The most evident result however, is how strongly a 20 years TH affects the result. The iLUC model has an important emission profile. This suggests that in general, the effect of indirect land use change cannot be disregarded. In particular, the results for the GWP20, both with static and dynamic approach (scenario 2 and 6), have a very different profile, because of the higher contribution of the iLUC effect. CO_2 emissions from iLUC are generated both from transformation of primary forest to intensive forest and from secondary forest to intensive forest (red and green colors in Table 4): primary forests (an old-growth forest) have a higher concentration of C in soil, since the soil C decreases by increasing the number of harvesting, as found by Holtsmark (2011).

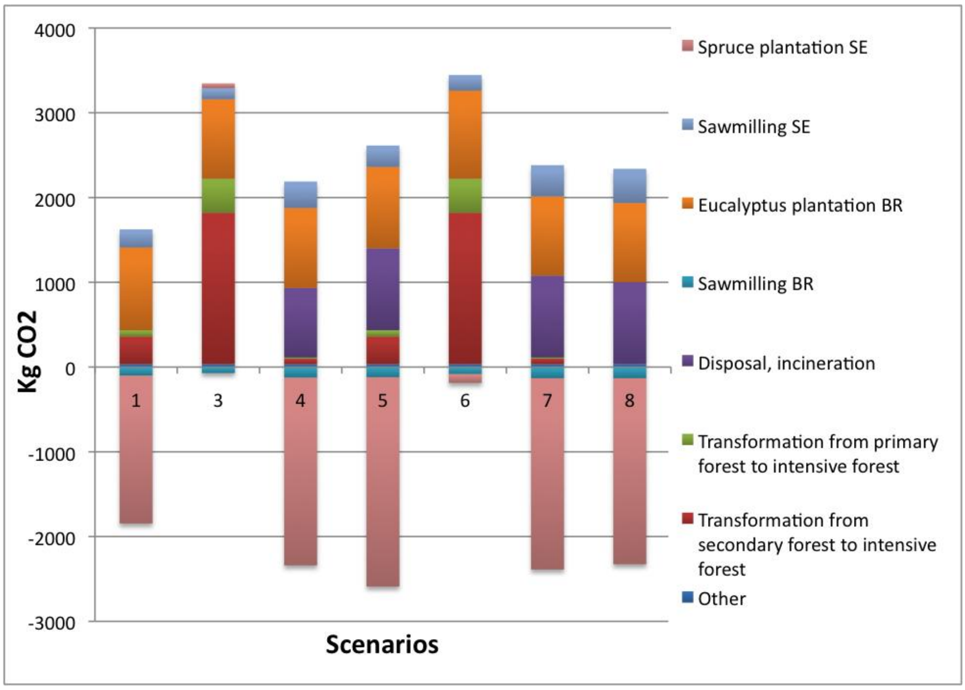

Figure 17 - Comparison of the result obtained testing climate indicators and THs (scenario 1, 3, 4, 5, 6, 7 and 8).

It is also likely that in a primary forest trees are more aged and contain more C than in a younger forest. On the other hand, when a short TH (e.g. 20 years) is considered, the biomass re-growth is included only for the first 20 years and the contribution to GHG sequestration is rather small. The combined effect of iLUC and a 20 years TH leads to a very small contribution of the spruce plantation in C uptake. Albeit only with a small amount, in scenario 3 the spruce plantation contributes for a net positive factor (the net contribution after 25 years is a net emission of GHG). This is due to the emission from biomass decomposition of the previous harvested plantation and the emission from soil preparation and fertilization take place at the beginning of the new rotation time, and are accounted by a TH of 20 years. At the same time, GHG sequestration from biomass takes place in a longer timeframe, thus it is only partially included with a 20 years TH. This is also valid with regard to the scenario 6. Nevertheless, scenario 6 shows a small negative contribution from the spruce trees, as the emissions in this case are not weighted for the time-dependent factor, as it is further explained below.

Extending the analysis of the results also to the scenarios 5-8 allows drawing some considerations regarding the adoption of a static or dynamic approach. In general, Figure 17 shows how a static approach (constant GWP) overestimates the effect of GHG emission uptake/release, since it does not weight them for a time dependent factor. A closer look at the final results though, reveals that using a static or dynamic approach alters the final impact of the system: for instance, scenario 1 and 5 differs only for the climate indicator approach used in LCIA but the final result is an emission uptake for scenario 1 (-221.46 kg CO_2 equivalent) and release of emissions (23.3 kg CO_2 equivalent) for scenario 5. Scenario 5 in particular, shows the highest value of GHG sequestration from the spruce plantation, also higher than scenario one, despite the TH is the same (100 years): the reason is the static approach used in the LCIA, where the emissions/uptake of C are accounted independently on the time factor. GHG sequestered in the first year or at the end of the rotation time are in this case considered in the same way.

The consequence is an overestimation of the positive impact of GHG uptake from the spruce plantation. The total emission uptake in biomass is of course always the same but the method adopted affects its measure. Similar results can be found comparing the fourth and seventh model, with same TH but different LCIA approach. The net effect of using a static approach is therefore not only an overestimation of the environmental impact, whether it is a positive or negative impact. Rather, for the case study investigated, the static approach alters the perception of the impact itself.

The climate indicator affects the model also with regard to the disposal process. As seen above from a first analysis of the results, the product disposal contributes only when a TH of 500 years is selected, given the assumed lifetime of the construction material of 100 years. When a static approach is adopted though, emission from disposal are accounted also for a 100 years TH; according to the definition of static approach adopted here, when a static climate indicator is used, the emission are not weighted for a time dependent factor. To simulate this, the GWP is set to a fixed value (1) for the time considered in the TH, as explained in section 3.6. In other words, while scenario 1 does not have the contribution of the disposal process, because the dynamic GWP100 is 0 after 100 years, in scenario 5 the disposal process contribute to the emission, since the static GWP is set to 1 also at year 100.

The last scenario in Figure 17 models a TH of 1000 years and a static GWP as a climate indicator. The relative results do not differ significantly from results of scenario 7, where another long-term TH of 500 years is adopted. Figure 17 also shows that in scenario 8, the iLUC model does not contribute to CO_2 emission (it can also be seen from Table 5, where the values for transformation from primary and secondary forest to intensive forest land are equal to zero).

4.3 Forest Carbon stock

The last group of modeling assumptions regards three options for modeling the C pool to include in the model. The results are depicted in Figure 18. The contribution from the iLUC model does not have any consequence in this modeling approach, since the iLUC scenario is a ‘frozen variable’ and it is equally applied for the three cases. Similarly, the LCIA approach and TH are kept constant, consistently with the default assumptions. Also, the disposal scenario does not contribute in any of the three models, as the default TH is 100 years.

The choice of C pool to include in the model mainly affects the CO_2 emission/uptake from the spruce plantation in Sweden and eucalyptus plantation in Brazil. As explained in section 3.4, the eucalyptus plantation is an avoided process. Therefore, coherently with the analysis of the results presented in section 4.1, the emissions of an avoided process account as avoided emissions (thus as an emission uptake) and results in a negative GHG value, while the GHG sequestered account as avoided GHG uptake and results in a positive GHG value.

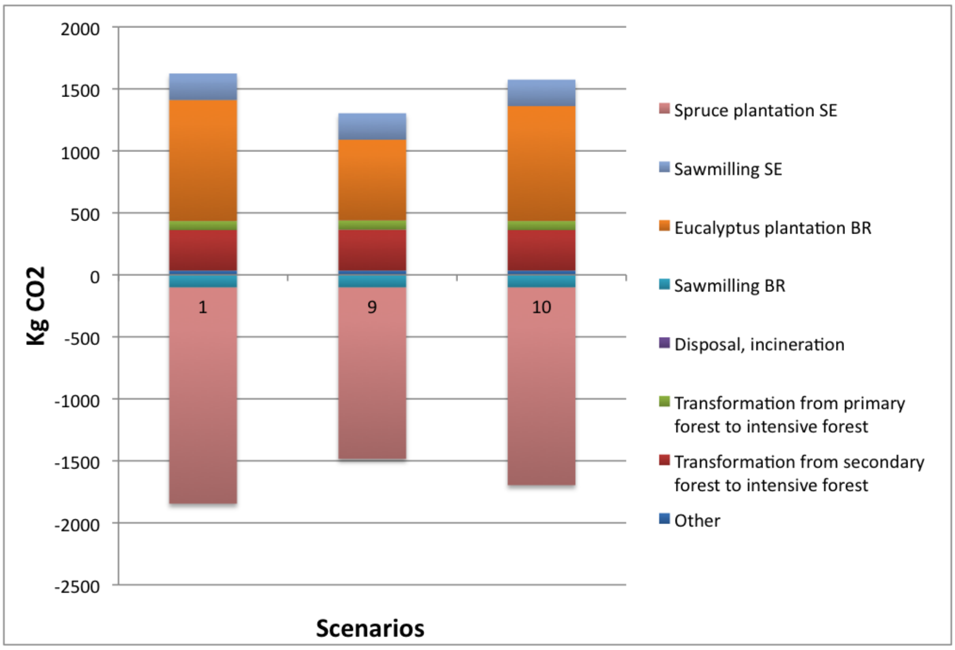

Figure 18 - Comparison of the result obtained testing different carbon stock models (scenario 1, 9, 10).

As expected, scenario 1 has the highest value of GHG sequestered by the spruce plantation, followed by scenario 10 and 9, as in scenario 1 the entire C pool is modeled including both AG and BG biomass. This result is coherent with what expected: in fact the first scenario models the entire C pool, including both AG and BG biomass.

Scenario 10 only models the AG C and does not account for the BG C pool. The C sequestered in BG biomass is not considered. On the other hand, the emissions from BG biomass decomposition are also not accounted. This entails a net increase of the amount of GHG sequestered in biomass during the TH, because a 100 years TH includes the uptake of emission taking place during the rotation time (70 years) while excludes the emissions taking place in 100 years.

The same analysis can be done for scenario 9, where the result is even more significant. In this case the C pool is only the C in stem, an even more limited amount of C. The substantial difference is that with this assumptions no residues are considered at all. There is no contribution from biomass degradation. Anyway, the C in stem is smaller than the C content of the AG C pool, and scenario 9 shows the smallest C sequestration from the spruce plantation. Looking only at the spruce plantation process, the effect of modeling a larger or smaller C pool achieves a scaling up or down of the final result. On the contrary, if the total outcome is analyzed, a different result is realized: scenario 9 results in a higher CO2 uptake than scenario 10, despite the former accounting for C in the stem and the latter for the AG biomass. In conclusion, among the last group of assumptions tested, the most reliable results were drawn from the first scenario.

5. Discussion

The results presented in the previous chapter confirm what suggested by the literature reviewed: different LCA practices in modeling the biogenic C cycle of forests may lead to a wide range of different LCA results. This study only focused on four debated methodological assumptions, compared against each other in ten different combinations and the results obtained, diverge remarkably from each other. This chapter discusses some of the findings and answers the RQ and sub-research questions presented in section 1.4.

The findings shown in Table 5 indicate that the wider variation of the total CO_2 equivalent emission/uptake is caused by the choice of the TH. A 20 years TH turns the system from a net GHG absorber to a net GHG emitter. All the results obtained are formally correct, since the mass flows are in balance in all the processes of the system. This is valid for each scenario modeled (see the Appendices). The wide range of results depends exclusively on the modeling assumptions tested. Different results are obtained both within groups of variable tested and between different groups (the groups here are identified with the colors in Table 4). The most similar results are obtained when testing the models of forest C pools. This group provides for the three cases compared a net GHG uptake, with a variance limited to 100 kg of CO_2 equivalent emission per cubic m^3 of product.

The processes resulting as the highest absorber of GHG is the spruce plantation in eight out of ten scenarios; the two exceptions are found when the 20 years TH is considered as explained in the previous chapter. The highest contribute of GHG emission in eight scenarios is instead the eucalyptus plantation, while appears the highest absorber of GHG in the two cases in which the TH 20 is adopted: the eucalyptus plantation has a much shorter rotation time (6 years) than the spruce plantation (70 years), due to the fast growth-rate of this tree; consequently, in a 20 years TH the eucalyptus plantation undertakes a full rotation time while the spruce plantation does not even complete 1/3 of its the rotation time.

The iLUC model affects the results more significantly when a shorter TH is considered. When the TH 1000 has been modeled the contribution of the iLUC model has been 0. On the other hand, for a 20 years TH the CO_2 equivalent emissions from iLUC, in particular from transformation from secondary forest to intensive forest, are of the same magnitude as the CO_2 uptake in spruce plantation in 100 years. Other sources of GHG emissions are fertilizer application, diesel consumptions used in sawmilling process and transportation etc. These emissions are approximately constant for all the scenarios modeled (35 kg CO_2 equivalent).

Despite the tested variables affect the final results of the LCA, they are not the only methodological assumptions playing a role. They were chosen after an extensive literature review because appeared as among the most debated assumptions and because found in several studies facing the methodological challenges of modeling C cycle in LCA. However, as seen in the literature review, other authors deal with the effect of different assumptions on LCA outcomes, such as accounting for a single or multiple yields (Holtsmark 2012), different protocols modeling the C in soil (Newell and Vos 2012) or the use of different climate indicators than the GWP (Fuglestvedt et al. 2003; Jonker, Junginger, and Faaij 2013; Searchinge r et al. 2008).

It is reasonable to image that any other modeling choice introduced would also affect the modeling of the forest C cycle. Yet, the ten combinations proposed for the comparison of the chosen modeling options do not intend to be comprehensive. Those are only examples of possible comparison, selected in a way to provide some insight to the role played by each of them to the variability of the final results. Other variables may also influence the results. Nevertheless, the conclusion of this study cannot be extended to other methodological assumptions. Rather, the methodology adopted for the comparison and the aim of the study might be extended to test further criteria and assumptions.

This study models as the by-product of the spruce sawmilling process both the sawn chips and slabs (section 3.4). The model is based on UNECE-FAO (2010), which provides aggregated data concerning chips and slabs. However, while wood chips are likely to substitute eucalyptus for the production of pulp and paper, wood slabs can also substitute construction materials (or other long-lived products). If only wood chips were considered as a by-product, the displaced eucalyptus would have been less and the outcome in terms of GHG emission/uptake would have also been affected.

5.1 Main findings of the study

This section begins answering the second and then the first sub-research question, through which eventually answering the main RQ.

Despite the wide range of results obtained, eight out of the ten scenario modeled provide the same indication: they reveal that the production of 1 m^3 of sawn spruce entails a total net uptake of GHG, if used as a construction material, with a lifetime of 100 years and the by-product employed in the pulp and paper industry. These results suggest that the use of wood for long-lived product might play a key role in sequestering C from air in biomass. Nevertheless, when considering a TH of 20 years, the results indicate a different conclusion. If the goal is to reach a reduction of the GHG concentration in air in a short term, the use of wood, also for long-lived product, might actually obstruct the achievement of this goal. The benefit of using wood for long-lived product is in fact not immediate. This study does not estimate the time necessary to offset the emission related to falling a tree. Looking at the results though, specifically comparing the one obtained in scenario 1 with a 100 years TH and 3 with a 20 years TH, it seems that a period of time closer to 100 than 20 years is needed to offset the C emitted from the process. The answer to the second sub-research question:

Does the carbon stored in long-lived products (e.g. timber for construction materials) modify the environmental impact of falling a tree?

is here formulated: the use of wood in long-lived product does alleviate the environmental impact of falling a tree, provided that new trees are re-planted and the by-products of the system are used in the pulp and paper industry. The process may even be beneficial for the environment, contributing to negative GWP, because the GWP from uptake is larger than for emissions. The advantages are only substantial after a period of time longer than 20 years. The outcome of the analysis is inconclusive in regards to the use of a wood-fuel by-product. This lies outside the boundaries of this study. The methods adopted to measure the forest C cycle play a key role in the outcome of the study. Therefore the first sub-research question asked:

What would be a good compromise between an accurate LCA model and an acceptable degree of complexity?

The results underline that in order to reach reliable conclusions a certain degree of complexity of the model is required, since this should keep into account several aspects affecting both the LCI and LCIA phase. In general, increasing the accuracy of the model improves its conformity to the reality and allows reaching more reliable results. Nevertheless, the answer depends on the purpose of the study, its goal and scope, as stated also in the ISO standard (2006). Some of the choices might be neglected in specific conditions with limited consequences on the final result. For example, if a dynamic GWP500 is assumed, the iLUC model might be ignored because its contribution in terms of emissions in this case is little. Yet, if a high percentage of wood residues in the forest are harvested, the C pool could be restricted only to the C in stem or to the AG carbon. This also depends on the location and the context of the study.

This study does not model the effect of intensive forest and repeated harvesting on the C content in soil. Conclusion concerning the importance of modeling the soil C cannot be drawn from the analysis. In the forest C cycle proposed in the study the soil C is only partially accounted when considering the BG carbon stock. The findings suggest that considering only C in stem, or only AG carbon pool may alter the adherence of the model and the final results (see section 4.2). Similarly, considering static LCIA method (not accounting for the timing of emission and sink) alters the result for what concerns the real environmental impact of GHG sequestration and uptake. Simplifications of the model can be done in some cases but which aspect they should involve strictly depends on the circumstances and scope of the study.

In conclusion, the main research question asked:

How to include forest carbon cycle in Life Cycle Assessment of forestry products?

The results of this study suggest that, in order to include the carbon cycle in LCA, it is necessary:

- To account for the effect of the iLUC model, specially for short or medium value of TH
- To adopt a dynamic LCIA indicator accounting for the timing of emission and sink
- To include both AG and BG C stock.

The outcomes do not suggest the use of a specific TH. The most suitable TH depends on the scope of the study: if a short-term analysis is required, a 20 years TH is to be preferred. To gain an overview of the total impact a longer TH, e.g. 500 years, is preferable. In general a 100 years TH appears a reasonable choice. Nevertheless, the outcomes underline the degree of sensitiveness of LCA results to the TH adopted.

Further research is required to improve the model of the biogenic C cycle, but the scientific debate has defined the limits and strengths of some practices. What is likely missing is an updated standard including the issues related to the inclusion of C cycle in LCA, clarifying what aspects are still to be debated and what are becoming consolidated and suggested practices. In absence of these, the outcome of LCA of forestry products is vulnerable to misinterpretation and to the selection of assumptions that might inherently determine them beforehand.

5.2 Interpretation of unexpected results

Emissions from biomass degradation, take place during a long period of time, as seen in section 3.3.2. Therefore it would be reasonable to expect that considering a longer TH the net value of CO_2 sequestered would be lower, because the total amount of emission accounted from biomass decomposition increases with time while the C uptake stops with the rotation time of the plantation, when the trees are chopped down.

The results that have been presented though, pinpoint a different conclusion: when using a dynamic approach, the GHG uptake expressed as CO_2 equivalent, from the spruce plantation (net value resulting from residues decomposition and CO_2 uptake) is higher when the used TH 500 years than when it is 100 years. The explanation for this result, apparently counterintuitive, is the time dependent factor for which the emissions are weighted in the dynamic approach.

Figure 19 depicts the curves followed by the GWP factor for the different TH adopted. The values of the GWP decreases much more rapidly when a 20 years TH is considered than when the TH is 100 or even more 500 years. That implies that the smaller is the TH considered, the smaller is the factor multiplied by the values of CO_2 uptake in trees. As a result, the total uptake from trees will appear smaller when a smaller TH is considered, assuming the application the dynamic GWP as a climate indicator.

The same analysis would lead to different conclusions in case a static GWP is used. In this case the GWP is assumes always value 1 for years included in the TH and 0 otherwise. A 20 years TH still entails a lower value of uptake from the spruce plantation, since the CO_2 sequestered in the biomass until the end rotation time (70 years) is not accounted. However, now the 100 years TH entails a higher value of CO_2uptake compared with the 500 years TH, since the GWP factor does not decrease with time as in case of impact assessment with a dynamic approach.

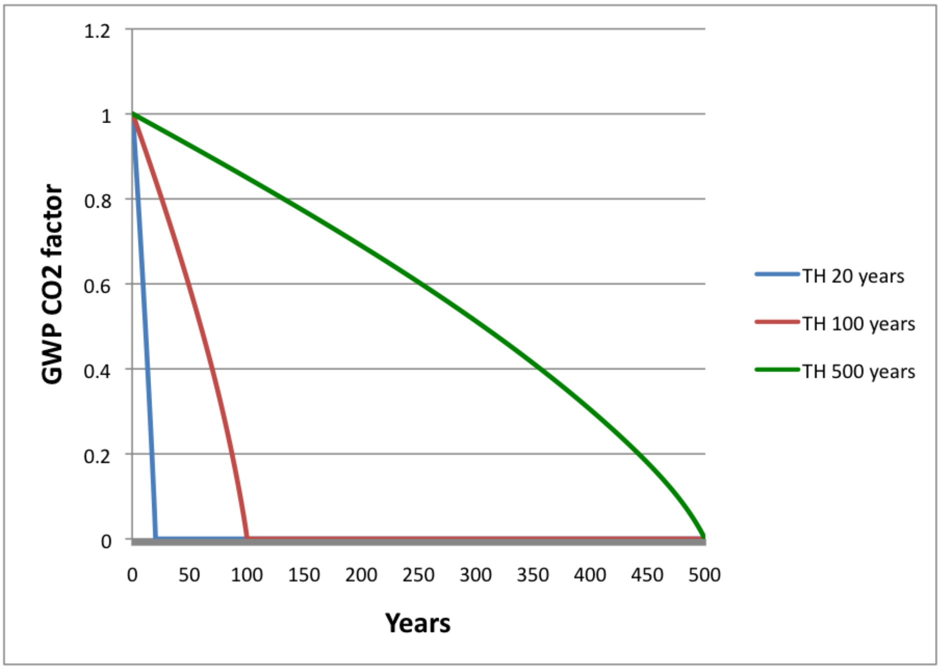

Figure 19 - Comparison between values assumed by GWP factor for CO_2 per year, according to the TH considered

The effect of the by-product on the total CO_2 account is also unexpected. In general, in CLCA it is expected that avoiding a process or a product would entail an environmental benefit. The case study considered here, aimed to model a net-positive system, conceived as a possible option to sequester C in biomass instead of using it as a wood fuel. For this reason, supported by the indications provided by the literature reviewed, the by-product is modeled as employed in the pulp and paper industry and the possibility of being use as a biofuel is disregarded. The results though, show that if an avoided process would also sequester CO_2 from air, as in the case of eucalyptus plantation used for the production of pulp and paper wood, avoiding this process leads to a net positive GWP. This result, despite formally correct, appears as a paradox. If such a system would be implemented in reality there is a potential danger that the production of goods as an output from this process would be perceived as beneficial in terms of environmental impact. However this would be a misleading conclusion, for two main reasons: first, since this study shows that the impact of the FU is only beneficial, in terms of CO_2 emission up-taken expressed as GWP, if a longer TH than 20 years is applied; secondly and most importantly, because this study only aims to account for the impact of the FU in terms of GWP, or its the potential climate change mitigation effect. Other impacts have not been accounted, such as social impact of increasing the wood production, stress added on the land, impact related to chemical treatment of wood before the final use, impact of the construction in which the product is used or any other process in which the wood is employed.

When interpreting the result of this study, it should be kept in mind that any activity has a related environmental impact. This might be reduced or smaller if compared to other systems. But this should not be confused with the idea that increasing consumption and production would be beneficial for the environment. At least this is not a conclusion that could be drawn from this study.

5.3 Limitation and Further possible developments

A limit of this study is not accounting for the entire soil C and the effects of trees harvesting in the soil C pool. The most comprehensive scenario modeled regarding the forest C stock only includes AG and BG carbon. The BG carbon pool though, only includes the C contained in the below ground biomass, not the C contained in the soil. Modeling the soil carbon is rather complex. In the context of this study, a boreal forest, it might be assumed that the C displaced by the multiple harvesting is offset by the one contained in the non-harvested residues decomposing in the forest, since the decomposition process in a boreal forest is rather slow. However this is a quite superficial assumption, without any scientific evidence.

The results presented in chapter 4 do not aim to comprehensively assess the impact of the identified FU. The goal of the study is exclusively to model the forest C cycle to compare different LCA methodologies accounting for the CO_2 emission and sink and the consequent climate change effect.

The research only focuses on four modeling assumptions and eleven options (tested comparing ten scenarios). Therefore, further development can be to extend the comparison both to other assumptions and including more options for each assumption. The number of comparison can also be increased, confronting against each other further variables and methods.

It might be interesting to compare the results obtained by modeling different C decomposition models than the ROTHC-26 utilized here, by setting the same default values assumed in this study. Other iLUC models might be compared to the model proposed by Schmidt (2013) adopted by this study.

In conclusion, this study only identifies as a reference scenario the natural relaxation of the land (section 3.1). Different choices of reference scenario could be considered and compared to evaluate the consequent impact on the final outcomes.

6. Conclusions

Taking as a starting point the increasing attention towards mitigation and adaptation to climate change impact, this study explores the suitability of different existing LCA methodological approaches accounting for direct and indirect impacts related to forestry and forest carbon cycle.

The inclusion of forest C cycle in LCA presents several modeling challenges. The study compares ten LCA scenarios, testing four methodological assumptions, according to a testing plan. The objective is to evaluate their contribution of each assumption to the LCA outcomes. The four methodological assumptions were selected after an extensive literature review and concerned: the impact of indirect Land Use Change iLUC, the timing of CO_2 emission/uptake from forest biomass, the TH considered and the forest C pool included in the model. To ensure the comparability of the results, the case study of producing 1 m^3 of spruce used as a construction material is identified. The case study aims at investigating whether the use of wood in long-lived product rather than for incineration would contribute to reduce the concentration of CO_2 in air.

The study succeeded in modeling a system where the mass flows of C are balanced. The balance includes all the processes involved in the system within its boundary.

The outcomes show a substantial difference between modeling scenarios, both within the same group of assumptions tested and among them. The results show a net uptake of C from air per FU, with the exception of the scenarios in which a TH of 20 years is modeled. A short TH increases the weight of the iLUC impact while accounts only for a minor amount of the C re-sequestered in the re-planted biomass and return as an outcome a net emission of C. However, in general the use of wood in long-lived product reduces the C content in air, mitigating in the long run the adverse impact of climate change.

A certain degree of complexity is required in the model to obtain a model conform to the reality, or at least what could be considered a good approximation of it. The results suggest including the iLUC model in LCA, to include both AG and BG C stocks and to apply a dynamic impact assessment method. The choice of the TH depends on the scope of the study but it has been found that it also strongly affects the final outcome.

In conclusion, due to the missing consensus upon the methods to apply when assessing the impact of using wood product and the challenges of modeling the C cycle of forests, the outcome of LCAs can be remarkably wide. Further research is necessary to improve the model of biogenic C cycle but probably further standardization and guidelines would also help practitioners to define what has still to be debated, what are arbitrary assumptions and which are not advised practices.

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Appendices

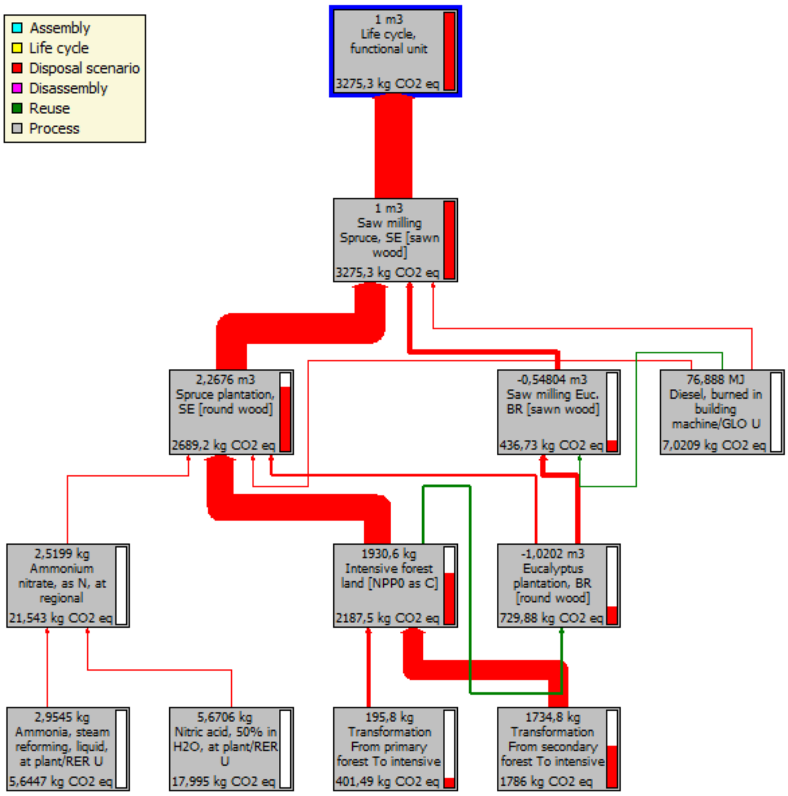

Figure 20 - SimaPro network calculated for scenario 3. Emissions are shown with cumulative indicator

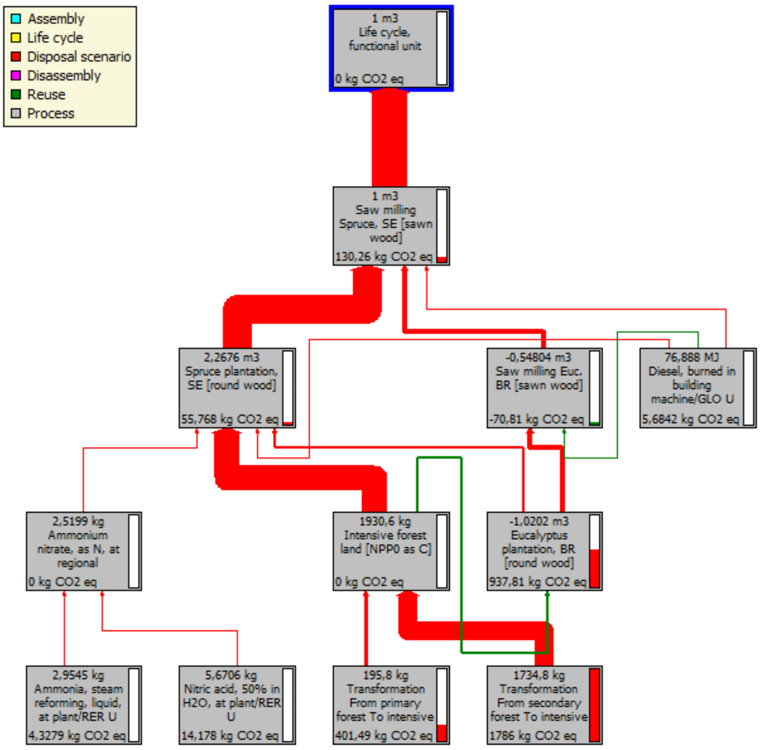

Figure 21 - SimaPro network calculated for scenario 3. Emissions are shown for the single processes

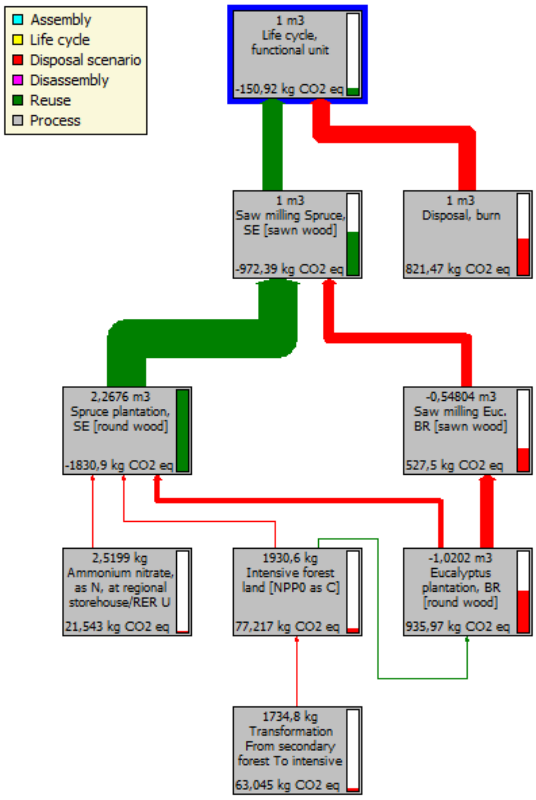

Figure 22 - SimaPro network calculated for scenario 4. Emissions are shown with cumulative indicator

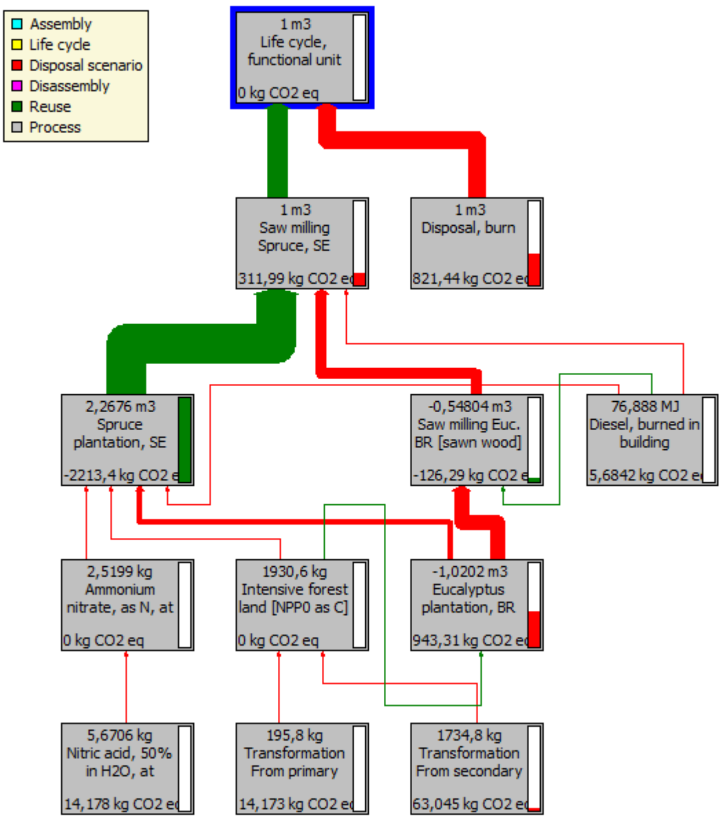

Figure 23 - SimaPro network calculated for scenario 4. Emissions are shown for the single processes

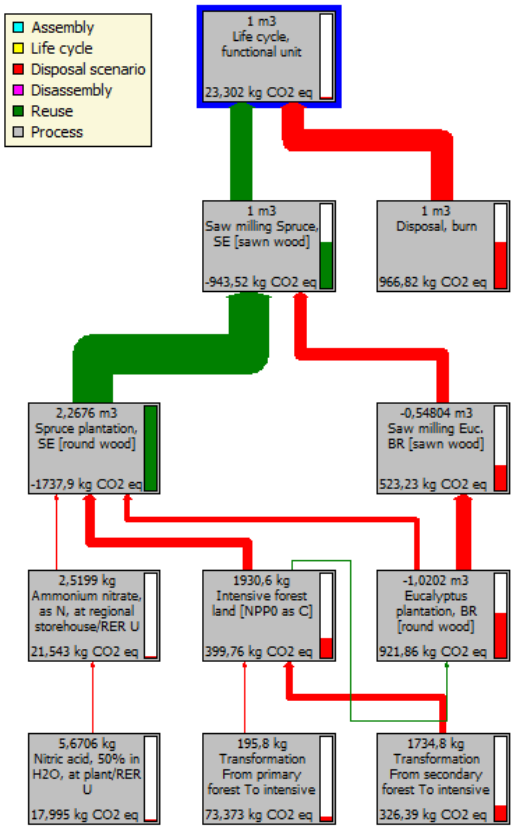

Figure 24 - SimaPro network calculated for scenario 5. Emissions are shown with cumulative indicator

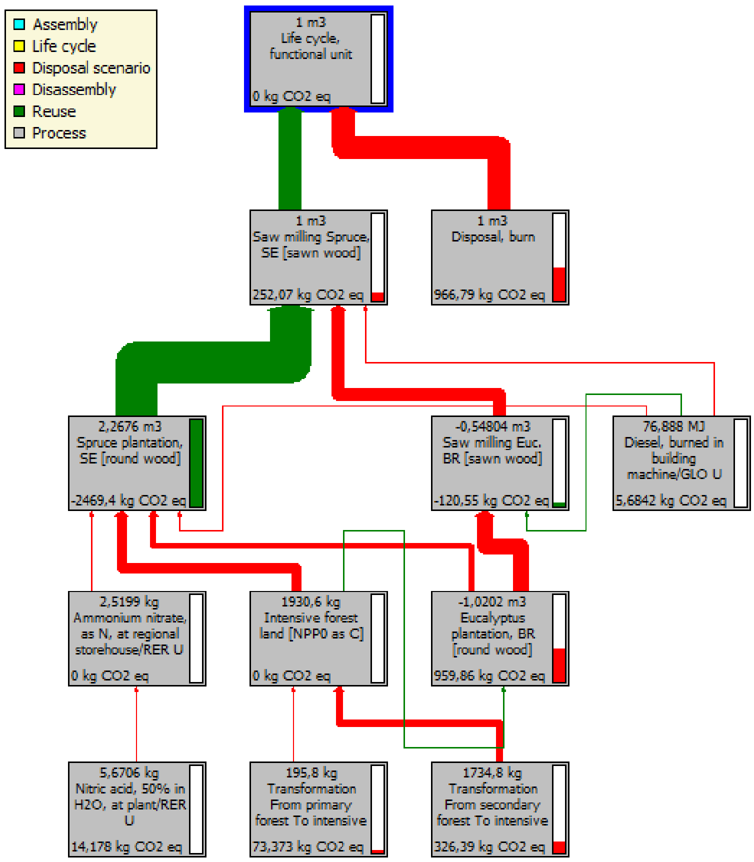

Figure 25 - SimaPro network calculated for scenario 5. Emissions are shown for the single processes

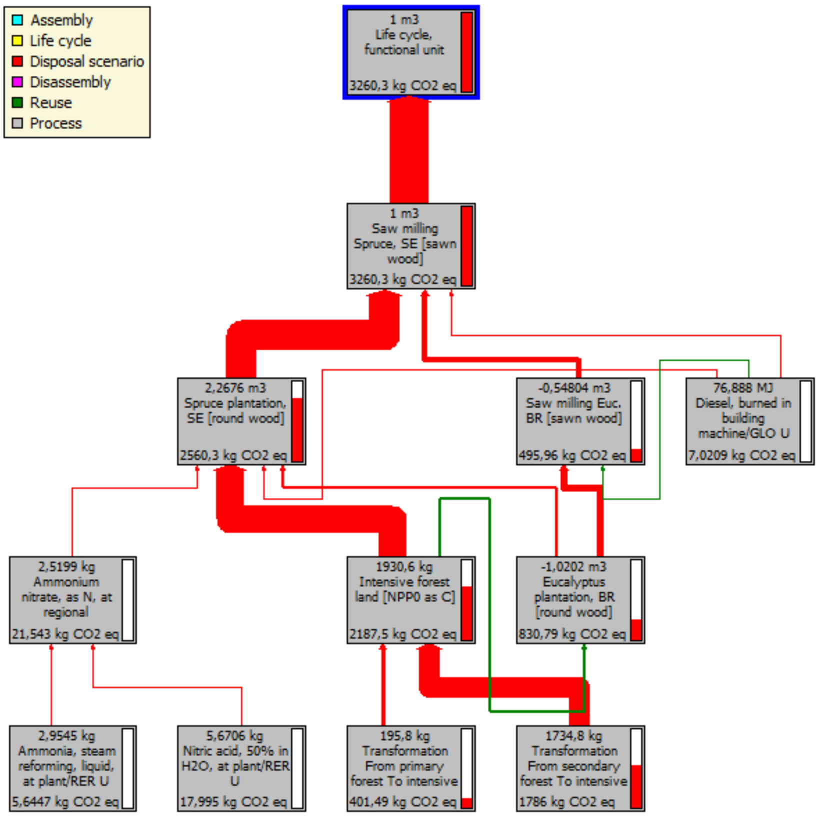

Figure 26 - SimaPro network calculated for scenario 6. Emissions are shown with cumulative indicator

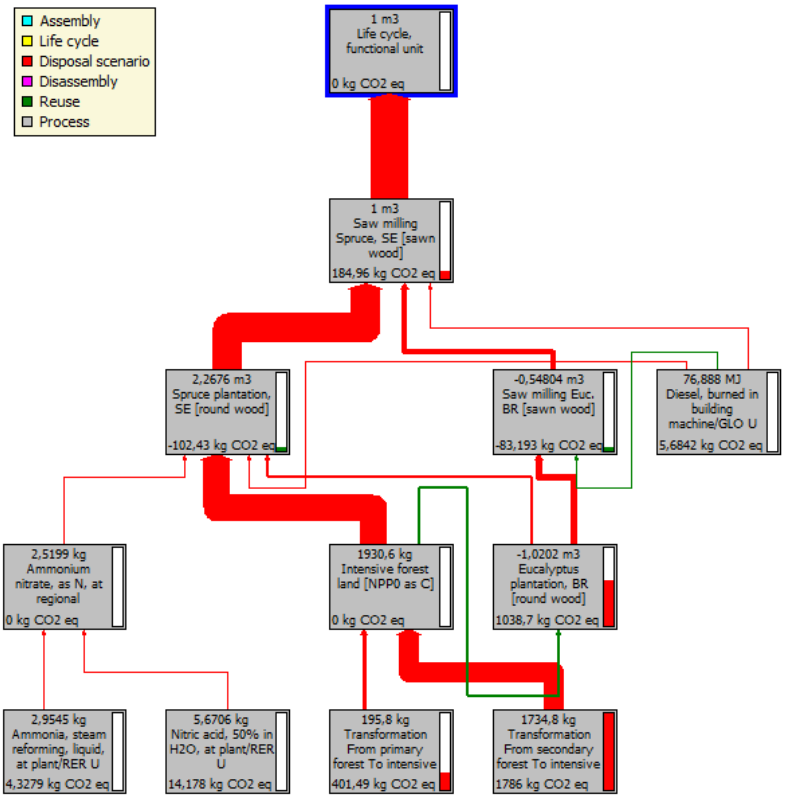

Figure 27 - SimaPro network calculated for scenario 6. Emissions are shown for the single processes

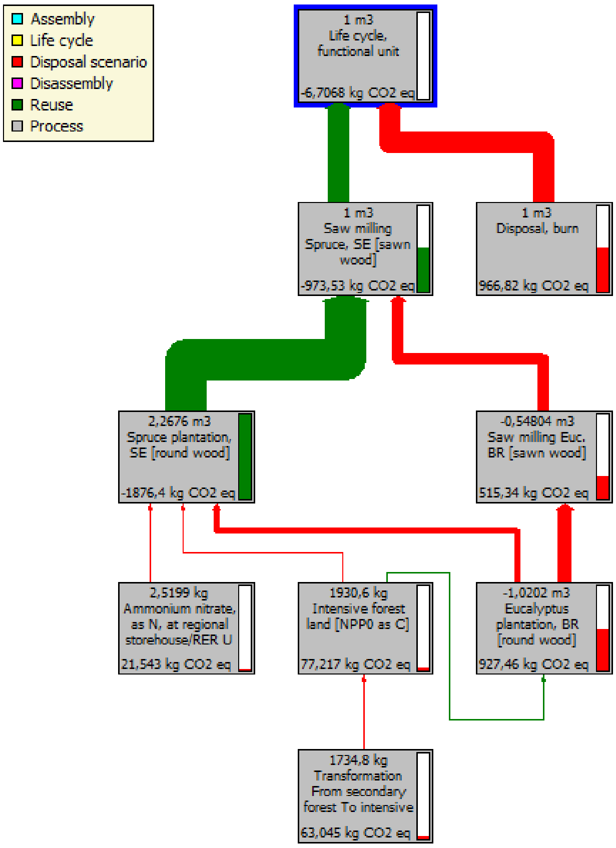

Figure 28 - SimaPro network calculated for scenario 7. Emissions are shown with cumulative indicator

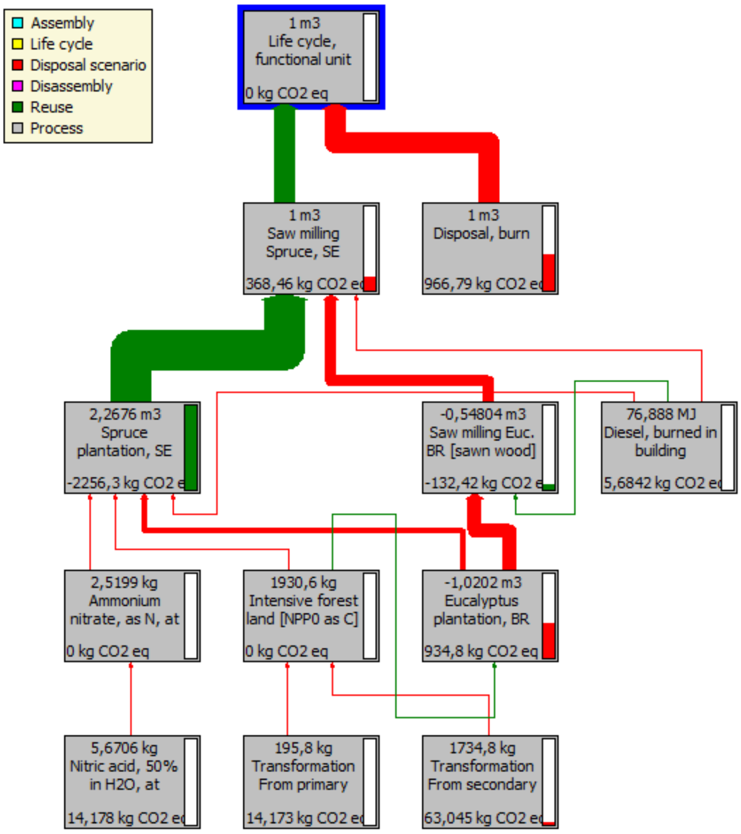

Figure 29 - SimaPro network calculated for scenario 7. Emissions are shown for the single processes

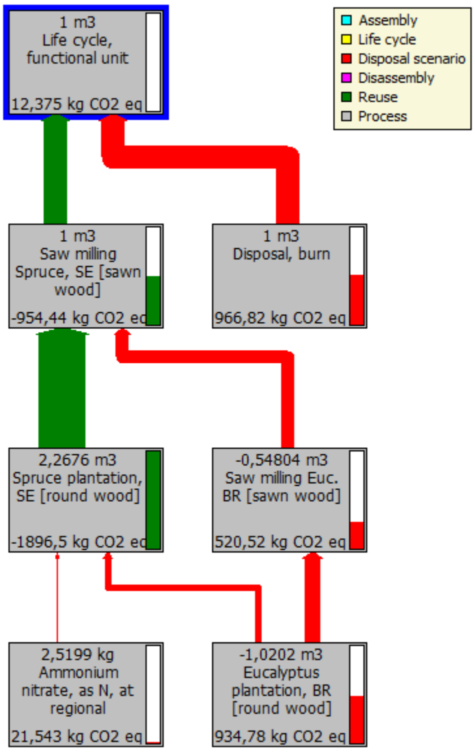

Figure 30 - SimaPro network calculated for scenario 8. Emissions are shown with cumulative indicator

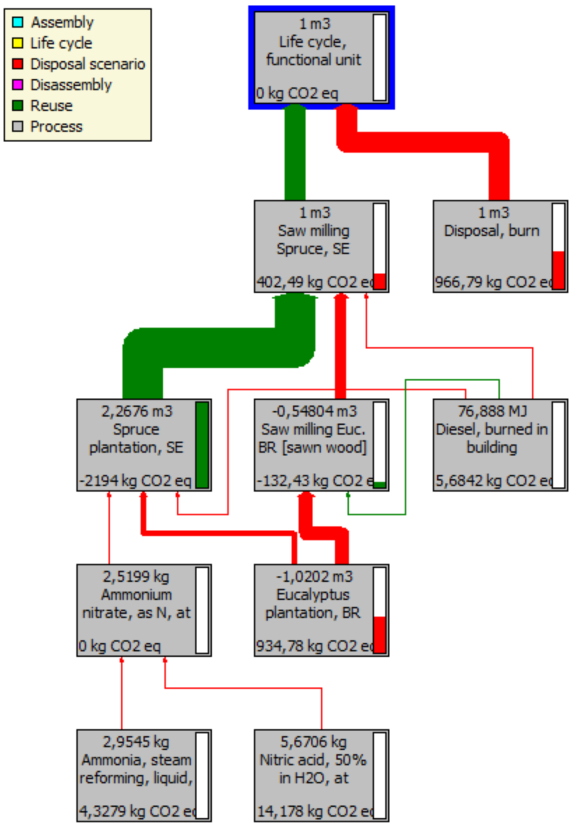

Figure 31 - SimaPro network calculated for scenario 8. Emissions are shown for the single processes

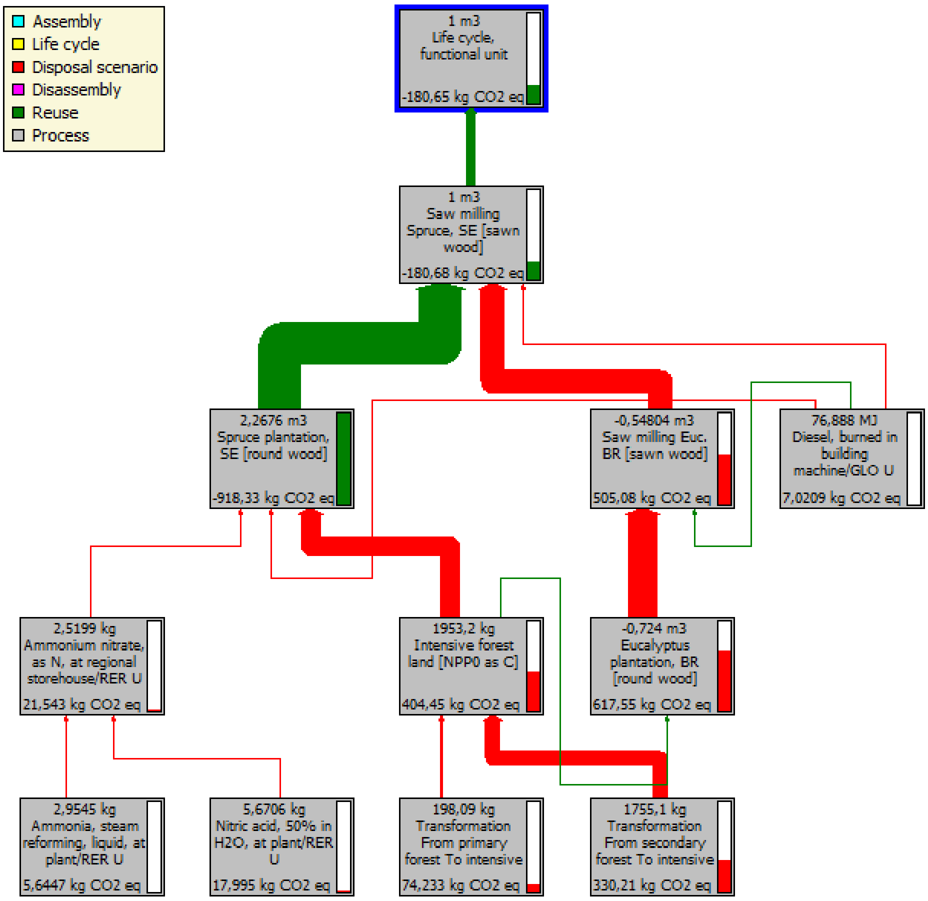

Figure 32 - SimaPro network calculated for scenario 9. Emissions are shown with cumulative indicator

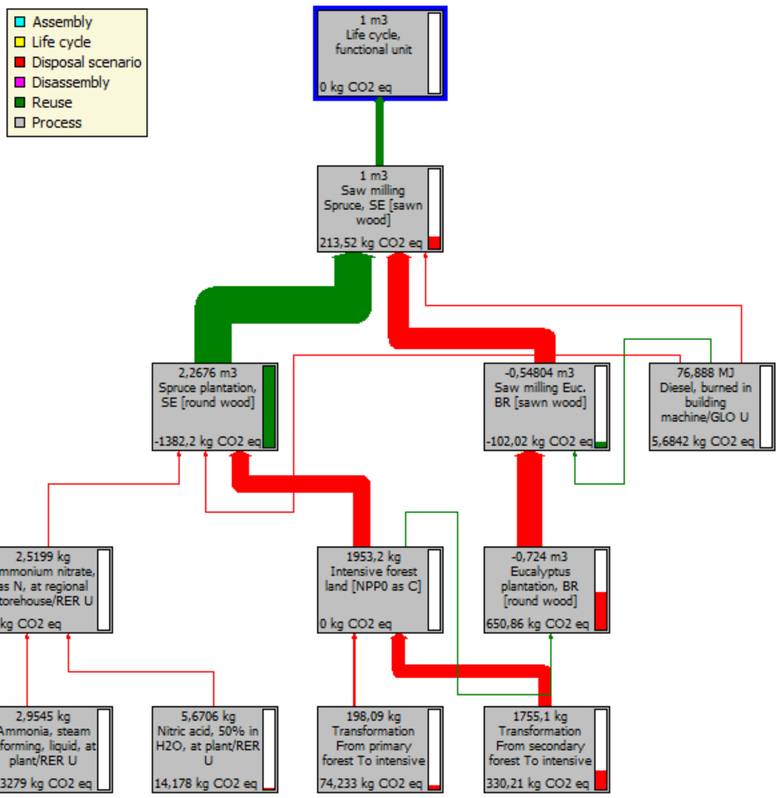

Figure 33 - SimaPro network calculated for scenario 9. Emissions are shown for the single processes

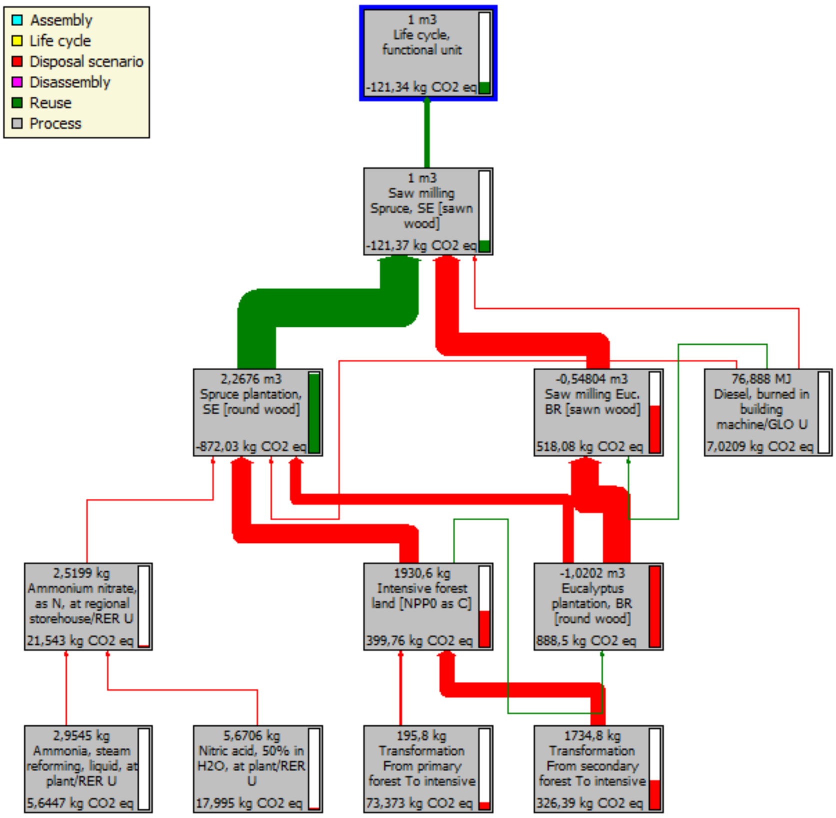

Figure 34 - SimaPro network calculated for scenario 10. Emissions are shown with cumulative indicator

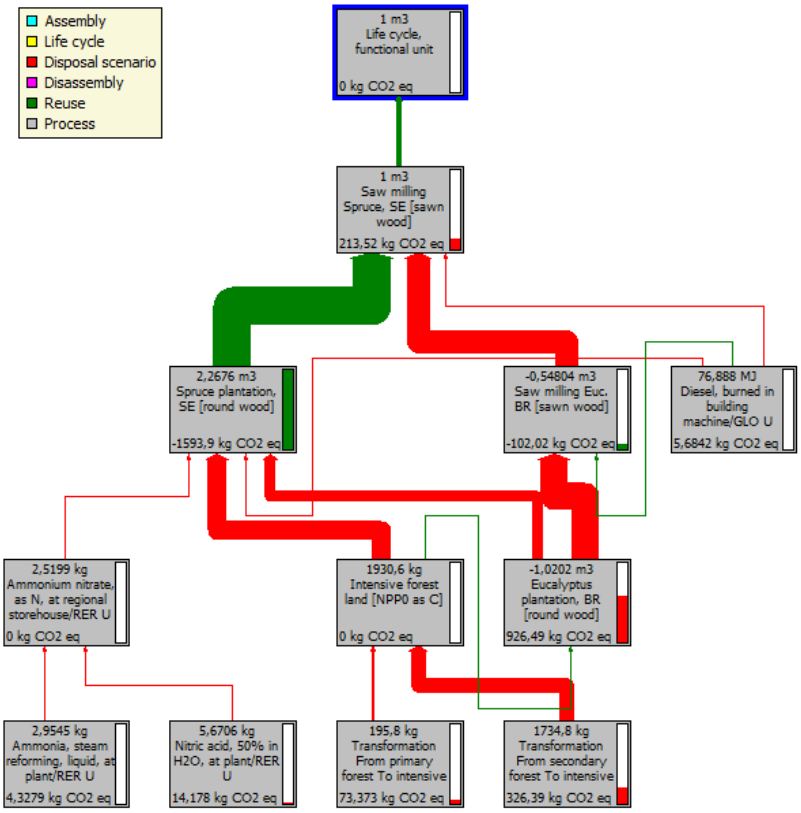

Figure 35 - SimaPro network calculated for scenario 10. Emissions are shown for the single processes