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Land use and land use change - Implications on biogenic carbon balance

Importance of model assumptions for a case study of a tissue product

Master's thesis in Industrial Ecology

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MASTER’S THESIS 2019

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In cooperation with Essity

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Abstract

The biogenic carbon’s environmental impact due to land use and land use change (LULUC) in a tissue product was investigated using landscape and stand level perspectives, with tissue fibres sourced from productive Swedish forestland. The analysis was extended to include soil carbon, which was not included in the original Life Cycle Assessment of the tissue product. The implications of using a stand or landscape perspective in the assessment was discussed. Furthermore, the two certification schemes FSC and PEFC were examined for criteria that could safeguard the soil carbon pools in the forest. The results showed that the soil sequestration impact, relative to the reference LCA emissions, could be significant for both the stand and landscape level assessments. However, the uncertainties in the soil carbon sequestration data affect the results significantly and the results should therefore be interpreted with that in mind when interpreting the impact. The temporal and spatial boundaries of the soil data matched the delimitations of a landscape perspective better than a stand perspective making the results more representative in the landscape scenario. Both FSC and PEFC contained criteria that could be interpreted as safeguarding soil carbon.

Key words: Climate change, Land use change, Biogenic carbon, Life cycle assessment, Sweden, Boreal forest

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List of abbreviations

Abbreviations of Organizations, certificates and standards

FSC	The Forest Stewardship Council
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
PEFC	The Programme for the Endorsement of Forest Certification
SNFI	The Swedish National Forest Inventory
SFSI	The Swedish Forest Soil Inventory

Abbreviation of common terms

AGC	Above Ground Carbon
BGC	Below Ground Carbon
CF	Characterization Factor
dLUC	Direct Land Use Change
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWPbio	Biogenic Global Warming Potential
ILCD	The International Reference Life Cycle Data System
iLUC	Indirect Land Use Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
LUC	Land Use Change
LULUC	Land Use and Land Use Change

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1. Introduction

The anthropogenic contribution to climate change is a topic under much research, modelling and debate. The two main greenhouse gases are carbon dioxide and methane, and both are, on the one hand, associated with using or developing land for productive purposes (The World Bank, 2019). On the other hand, increased afforestation and sustainable forest management has the potential to sequester carbon dioxide and become a net sink for carbon-related emissions. The productive forests in Sweden are an important resource for products and are managed to facilitate increased sequestration of carbon dioxide into forest biomass. The increased standing volume of forest has the potential to change the soil's carbon content, as a consequence of the forest management.

The emission of greenhouse gases to the atmosphere is linked to an increased temperature at the earth's surface by perturbing the earth's energy balance (Pierrehumbert, 2011; Stephens et al., 2012). When present in the atmosphere greenhouse gases alter the radiation balance, which is governed by the insolation of sunlight and the outgoing radiation from earth (Pierrehumbert, 2011; Stephens et al., 2012). Greenhouse gases effectively decrease the outgoing radiation by absorbing radiation in wavelength spans unique to the specific greenhouse gases (Pierrehumbert, 2011). Increasing the concentration of the gases in the atmosphere leads to an increased equilibrium temperature at the earth's surface, i.e. global warming (Pierrehumbert, 2011). Methane and carbon dioxide are two greenhouse gases that are a part of the carbon cycle and amplify global warming when present in the atmosphere. Understanding carbon's role, its sources, flows and sinks, in the carbon cycle can help to find measures to reduce the warming.

The increase of greenhouse gases in the atmosphere due to human activities can have several sources. The increased consumption and combustion of fossil fuels is one of the biggest contributors while emissions from land use and land use change, for example deforestation, is another. In 2011 the estimated carbon dioxide emissions from land use, land use change and forestry as a consequence of human activities, including deforestation, was 3.3 Gt CO_2, or 9.5% of the total carbon dioxide emissions (IPCC, 2014). When rainforest is deforested for productive purposes, such as cultivating cropland or establishing pasture, the carbon that is locked in the biomass above ground and the root system below ground is removed. Since pastures and cropland hold relatively small amounts of carbon in the soil and vegetation compared to rainforests, the net result of the land use change, in this case, is a loss of carbon from the land. The biogenic carbon, i.e. carbon from the biological material, that was bound as solid fibres moves from the terrestrial carbon stock to the atmosphere when combusted after use in products, adding to the greenhouse effect. In Sweden however, the terrestrial carbon stock is dominated by forestland that has been managed so that more biomass, is being cultivated more intensively each year (SLU, 2018a; Swedish Environmental Protection Agency, 2018). Contrary to deforestation, the intensified cultivation instead contributes to a carbon sequestering effect, where carbon is removed from the atmosphere and locked in biomass.

The purpose of this thesis is to estimate the environmental impact of soil carbon flows from productive forestland and land converted to productive forestland. These estimates are applied in a life cycle assessment of a tissue product, one of many products derived from Swedish productive forests. The inclusion of soil carbon flows when assessing environmental impact of a forest landscape is valuable as the soil is integral to the forest landscape but are currently not included when products are assessed for environmental impact.

1.1 Thesis background

The forests in Sweden are an important economic and social resource. Companies derive products from productive forestlands and attempt to do so in an environmentally sustainable fashion by following certification schemes by third parties such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). Communicating the latest research from academia on environmental impacts related to forestry with the industrial sector is important to drive and implement change in management towards sustainability.

The thesis is the result of a collaboration between Essity, a global hygiene and health company, and Chalmers University of Technology in order to link the latest research on land use and land use change (LULUC) to forestry and practical applications. Essity has products aiding in personal hygiene such as toilet paper, diapers and feminine products. One of the main sources of raw material to make these products is pulp stemming from sustainable forestry. In 2017, 65% of the 3.7 million tons of fibre sourced by the company was FSC or PEFC certified, and close to 35% met the FSC criteria for controlled wood. Essity is rated industry leader in managing sustainability issues and was one of the early adopters of the Life Cycle Assessment (LCA) methodology for calculating environmental impacts of its products (Dow Jones Sustainability Index, 2018).

Essity’s sustainable business model creates value for both people and nature. Essity’s objective is to develop products and services that contribute toward a sustainable and circular society. To work with sustainability Essity is guided by internal policies, industry standards and directives. More information about the company can be found in Appendix A. The current guidelines on how to handle environmental impacts associated with LULUC are not necessarily congruent due to the lack of scientific consensus in the area or in line with the latest research. Furthermore, few, if any, soil carbon stock calculations pertaining to LULUC following the guidelines have been applied in practice. The calculations are further hindered by the lack of soil carbon stock data in relation to LULUC in the forestry sector. Since LULUC may contribute significantly to a product’s environmental footprint it is important to investigate the topic (Logie, 2014).

1.2 Thesis aim

The main aim of the thesis is to compare methods and model assumptions for calculating biogenic carbon emission’s environmental impact due to LULUC for a selected tissue product produced by Essity. The tissue product consists of fibre sourced from four regions in Sweden, listed from north to south; Northern Norrland (N. Norrland), Southern Norrland (S. Norrland), Svealand and Götaland. The methods’ benefits and drawbacks will be discussed as well as their practical validity, i.e. how the assumptions in the methods compare to forest management in Sweden.

Another task is to calculate soil carbon changes on productive forestland from which pulp for the tissue product is sourced. Whether it is feasible to attribute the change in soil carbon stock to the product and the implications of that allocation will be investigated. Criteria in the two forest certification schemes Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) will be investigated to see whether the certifications contain criteria that can safeguard the soil carbon stock in the forest landscape and thereby can be used as proxies for ensuring the carbon stock in the long term.

To specify the issue under investigation three research questions have been formulated:

1. What methods for calculating biogenic carbon’s environmental impacts related to land use and land use change exist and how do they differ?
2. What are the implications of using the methods to calculate the environmental impact of land use and land use change in forestry?

3. What criteria exist in current forest certification systems, i.e. FSC and PEFC that can safeguard the terrestrial carbon stocks?

1.3 Theoretical Background

1.3.1 The carbon cycle

The research on the global carbon cycle maps and quantifies the flows between the different stocks of carbon and explores the drivers of change in these stocks and flows. This can range from macroscopic change, such as the turnover of dissolved carbon substances in oceans when the surface and deeper water layers mix, to microscopic change in soil due to the microorganism’s rate of respiring dead organic matter to carbon dioxide on the forest floor. The global terrestrial ecosystem’s carbon stock consists of approximately 2070 Gt carbon which varies with the seasons each year (FAO, 2018). During spring and summer there is a net uptake of carbon through photosynthesis in forests which is partially offset by the tree’s constant respiration. Trees respire as glucose from photosynthesis is used for energy and to build new biomass, thereby releasing carbon dioxide (LUSTRA, 2007a). These processes vary with the seasons, during fall the respiration in the biomass continues and photosynthesis drops off. Furthermore, the forest also generates litter, such as needles from coniferous tree species that together with dead wood fall to the forest floor. Microorganisms in the soil respire some of the litter whereas some carbon is accumulated in the top soil layer, the organic horizon (O-Horizon). Larger organisms such as earthworms help mix the carbon in the topmost layer deeper into the ground, where aggregated organic material that is difficult to breakdown accumulates (SLU, 2018b). In Sweden, the soil carbon stock contains approximately double the amount of carbon as the forest biomass above ground (LUSTRA, 2007a). A conceptual flowchart of the carbon cycle process in a forest is shown in Figure 1.

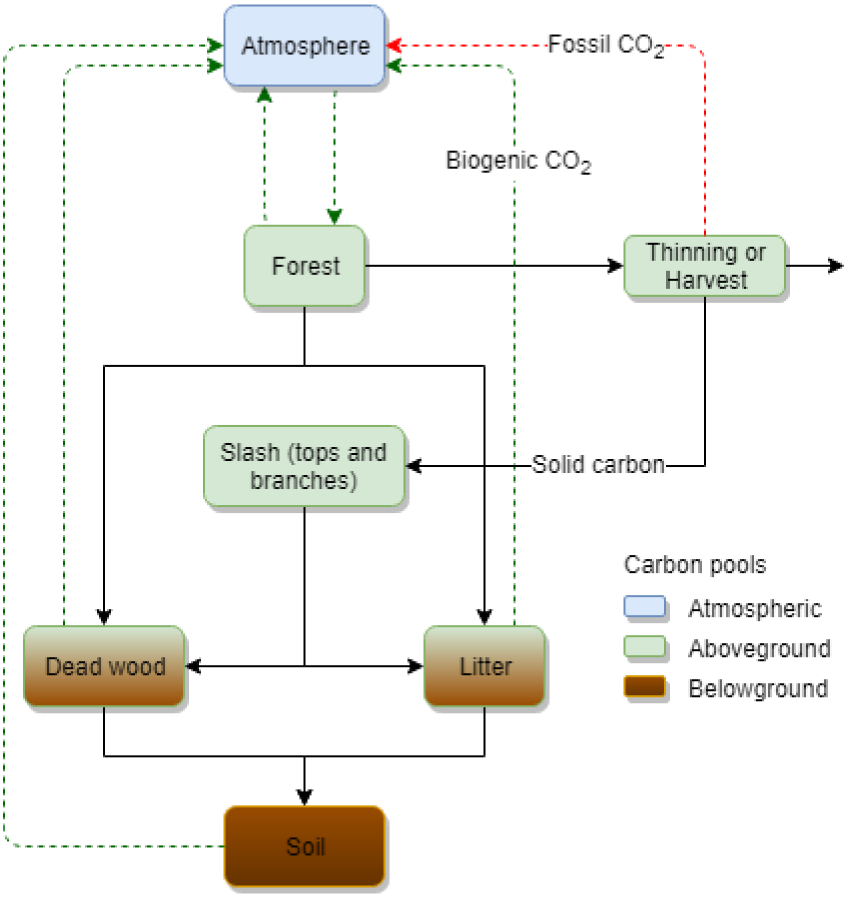

Figure 1: Conceptual model of the productive forest system. Illustrated in red is the fossil carbon dioxide emission involved when thinning or harvesting the biomass.

Other factors that impact the vegetational growth are annual sunlight, precipitation, nutrient availability and herbivory (Huxman et al., 2004; Kathleen C. Weathers, David L. Strayer, 2013). Similarly, the amount of carbon in forest soils depends on the amount of leaf litter, dead wood and forest residues from harvest that is added to the forest floor as well as ecosystem effects that influence the population of degraders (LUSTRA, 2007a; SLU, 2018b). On average, there is a decline in carbon stocks both above ground and in soils when measuring from south to north in Sweden, but the variance within an area can be significant (SLU, 2018c, 2018b).

Over the years, as the trees grow in productive forests, there is a net sequestration of carbon in biomass annually and when the forest is harvested to be used in products, such as in wood, paper or packaging, the carbon leaves the forest system. Simultaneously, parts of the forest residues from harvest are left to degrade and provide suitable growing conditions for the next plantation. Figure 2 shows how the above ground and soil carbon pools change in a modelled scenario of a forest stand over a rotation period of 100 years.

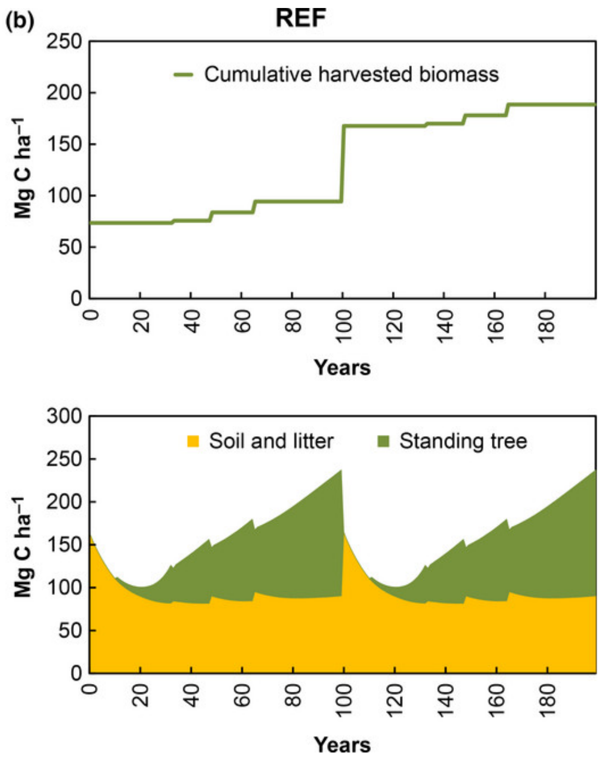

Figure 2: Modelled forest stand level accounting of carbon. Figure cropped from (Cintas et al., 2017), licenced under CC BY 4.0

At the end of the rotation period, when the stand is harvested and aboveground biomass is removed for productive uses, there is a surge of carbon to the soil carbon pool as forest residues are left on the forest floor to be broken down by degraders. In Figure 2, the forest is also thinned three times, as illustrated by the three notches in each harvest cycle, this is common practice in productive forestry where selected trees are felled in order to give the rest of the stand more suitable growing conditions. The top chart in Figure 2 shows the accumulated amount of harvested biomass that is removed for productive uses for the modelled conditions (Cintas et al., 2017). In Sweden, most organic carbon in products is eventually combusted, releasing the carbon as carbon dioxide to the atmosphere, since disposing of organic material in landfills is illegal (Environmental- and energy department, 2001). Categorically, the cause of change in carbon stocks over time can be attributed to the use of land during cultivation or to the change of land use from, for example, silviculture to crop cultivation or vice versa.

1.3.2 Biogenic and fossil carbon

Biogenic carbon is carbon that comes from material of biological origin but excludes carbon in materials that are fossilised or trapped in geological formations (ISO, 2018). Biogenic carbon is treated differently to carbon from fossil sources as biogenic carbon is a part of the circular and fast domain of the carbon cycle whereas fossil carbon is continually added to the atmosphere from sources where the carbon has been locked for millions of years (IEA Bioenergy, 2019). An illustration of the different carbon flows can be seen in Figure 3.

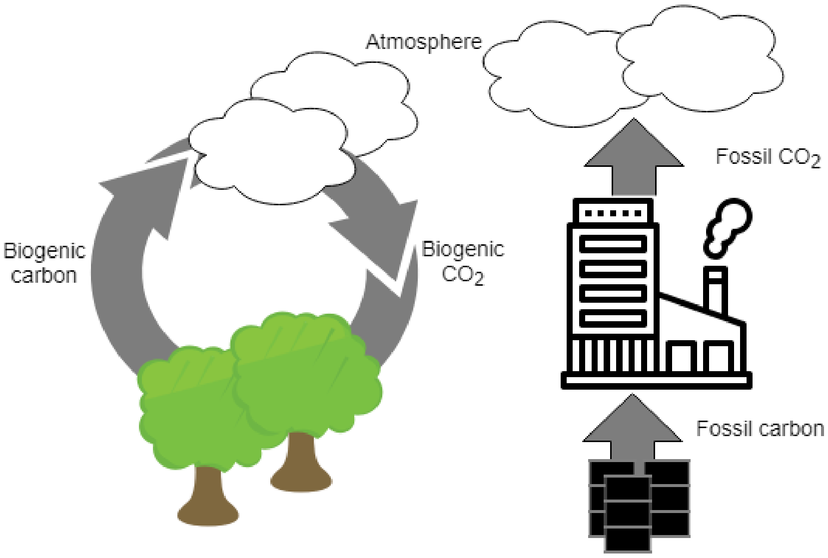

Figure 3: Illustration of biogenic and fossil carbon flows

The circular flow of biogenic carbon does not contribute to a net enlargement of the atmospheric, oceanic and vegetational carbon pools, whereas the linear fossil carbon flow from geological storage does. Carbon in products derived from forestry, that are eventually combusted, is a part of the fast domain of the carbon cycle. The fast domain represents the carbon pools with rapid turnover rates, such as vegetation and soils with 10 to 100 and 10 to 500 year turnover respectively (Berndes et al., 2016)(Ciais et al., 2013). To exemplify, a tree in a forest may be used for products that are eventually combusted to carbon dioxide. The location of the harvested tree can be used to regrow another tree which, over its rotation period, absorb the same amount of carbon when growing to the same size as the previous tree before harvest. Because of the circular nature of biogenic carbon, it has been considered carbon neutral under certain circumstances, such as over a full rotation period with full regrowth of biomass. Critically, the carbon flow neutrality over the harvested stand has led to the misconception that biogenic carbon has no added impact on climate change when translating flows to carbon dioxide equivalents ($CO_{2,eq}$). This has been disputed recently by for example Cherubini et al. (2011), who developed a method and metric for calculation of biogenic carbon impacts on climate change.

1.3.3 Stand and landscape level perspectives

As biobased products have become more popular the research on the environmental impacts, especially climate change, has intensified. This has created two views on how to consider the biomass, in this case productive forest, growth. Stand level approaches, as exemplified by Cherubini et al.'s (2011) GWP_{bio} method, focus on the individual stand from which the forest is harvested and consider the timing of emissions and sequestration as paramount for calculating biogenic impact. Consequently, the method leads to a different impact compared to when using a landscape perspective. Stand level perspectives have been criticised for having unrealistic assumptions, and too narrow temporal and spatial boundaries (Cintas, Berndes, et al., 2016; World Bioenergy Association, 2012) On a stand level, the changes in carbon stocks when harvesting are more dramatic not only for aboveground carbon but also for soil carbon (Eliasson, Svensson, Olsson, & Ågren, 2013). In a landscape perspective the other stands, that are not harvested, compensate for the dramatic changes in carbon stocks on a stand plot since harvest only occurs once per rotation period.

Landscape perspectives focus on carbon flows in the entire forest landscape, which is composed of many individual stands of varying age. In theoretical landscapes, used for modelling, the age distribution can be uniform meaning that the growth of the stands in the landscape is the same over time. In reality, stands vary in age nonlinearly and this affects the sequestration in the landscape as the sequestration in an individual stand varies with age. This is illustrated in Figure 4, where the slope of the line at any location indicates the growth at that time. The landscape perspective reflects the coordination to provide a continuous flow of wood, whereas the stand level reflects forest operations (Cintas, Berndes, et al., 2016). With the landscape perspective forest litter is continually being added to the forest floor adding carbon to the soil, but the rates among individual stands vary significantly as younger trees release less litter than older ones (SLU, 2018b).

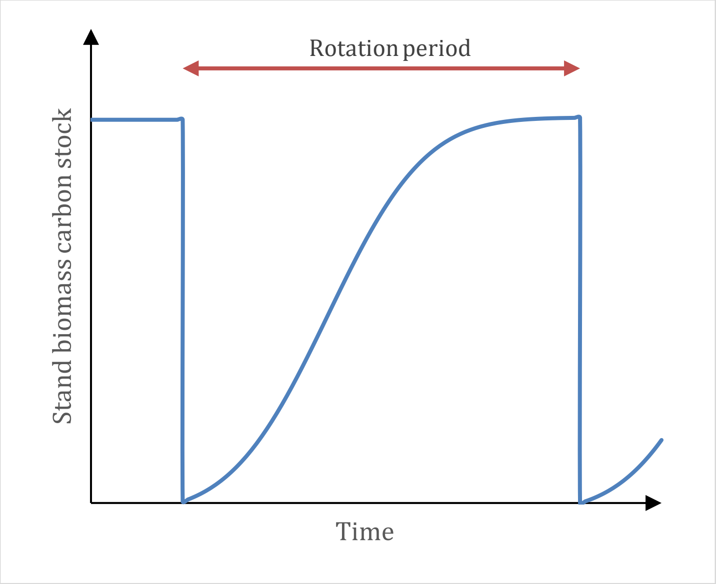

Figure 4: Modelled approximation of stand biomass growth over a rotation period

Exemplified in the figure is an approximated S-shaped function for forest growth that has been tested on boreal forests (Rossi, Morin, & Tremblay, 2010). The growth curve is nonlinear, which impacts the sequestration rate at the individual stand, however having an even aged distribution of stands would yield an average sequestered rate over the landscape highlighting one of the differences of between the two perspectives.

The GWP_{bio} method represents the stand level perspective in this thesis. The method considers the emissions and sequestration of biogenic carbon as biomass from a stand is burnt after usage and is sequestered to the same stand by the next generation of biomass. Since there is a delay between when the carbon dioxide is emitted to when it is all sequestered, i.e. the rotation period, there will be a climate impact due to the heat absorbed by the carbon dioxide in the atmosphere. The IPCC uses the Bern carbon cycle model to translate the emissions to impacts with so called characterization factors. Cherubini's GWP_{bio} characterization factor is based on that there will be significant removal of carbon to the same plot of land that has been harvested by the next generation of biomass. This gives lower characterization factors compared to the IPCC's, that depend on the rotation time. Longer rotation time means longer time to sequester the carbon meaning that the carbon dioxide has an impact in the atmosphere longer. The modelling is complex as the carbon that is emitted from the stand initially enters the atmosphere but quickly is distributed to the ocean, where an equilibrium sets in, and the removal by other terrestrial vegetation as well as the stand. The growth of the stand can be described as an S-curve which means that the sequestration of carbon dioxide varies with the stand's age, see Figure 4. To complicate issues further the ocean-atmosphere equilibrium of carbon dioxide depends on the concentration of carbon dioxide in the atmosphere as governed by Henry's law (Jones & Atkins, 2010). The equilibrium and rate of carbon dioxide transfer therefore shifts depending on whether the atmospheric concentration is 200, 300 or 400 ppm. The method provides modified characterization factors, i.e. the factors that influence impact when multiplied with the carbon flow, that depend on rotation period, so that comparisons can be done with the conventional GWP metric (Cherubini et al., 2011).

The landscape perspective was represented with Essity's method for calculating impact. The method, governed by their internal guidelines, is congruent with a landscape perspective where net changes in carbon stocks should be allocated to the product. By contrast, the implication in the GWP_{bio} method is that net carbon changes are 0 since the impact is measured until the same carbon has been fully sequestered by the next generation of trees. However, soil carbon flows are not included in either perspective and the impact of including these flows will be measured as well.

1.3.4 Forest management

In Sweden, productive forests make up an area of 22.7 million hectares (Mha) and have an output of approximately 85 million m^3 wood per year (Mm^3/year) (SLU, 2018a). Swedish productive forests are managed as a mosaic of even-aged stands that, when harvested, are regenerated by replanting (Cintas, Hansson, et al., 2016). During the growth of a stand in a productive forest thinning is common practice, which is when individual trees are removed from the stand to benefit the growth of the entire stand. Besides obtaining wood from harvest (final felling) and thinning 'other harvest' is another category. This category contains wood that is removed because of other factors such as windfall, removal of pre-dominant trees and seed trees. Predominant trees are trees that have been left since previous harvesting periods and seed trees can be removed if planting is preferred. The three categories, final felling, thinning and 'Other harvest' make up the harvested volume. By volume in 2015, the harvested wood was used by the sawmill industry, 46.7 Vol%, pulp industry, 45.4 Vol% and firewood and others, 8 Vol% (Skogsindustrierna, 2015). Residue flows from the sawmill and pulp mill industries are used for energy to drive processes, and a significant volume of residual wood is sold as woodchips from the sawmills to the pulp mills (Cintas, Hansson, et al., 2016; Skogsindustrierna, 2015). Furthermore, the harvested volume in Sweden is mainly from pine and spruce, which are favoured by the boreal climate (SLU, 2018c).

1.3.5 Land use and land use change

Change in forest carbon stocks can be a result from management during occupation of the land or from the land use being changed from one use to another. Land use (or land occupation) and land use change (or land transformation) (LULUC) can be divided in to three categories: land use (LU), direct land use change (dLUC) and indirect land use change (iLUC). Land use refers to the land use category not changing over time, for example forest remaining forest, which can affect the carbon stock depending on how the land is managed over rotation periods. Aboveground biomass can be increased, as seen in productive forests in Sweden, and soil carbon may also change depending on management practices (SLU, 2018a).

Direct land use change (dLUC) refers to the change from one land use category to another at a specific location. An example of dLUC is the deforestation of rainforests to cultivate productive cropland, which leads to a net removal of carbon from the terrestrial system, including soils, to the atmosphere as rainforests typically have more carbon bound in biomass than crops (Ann-Sofie Morén et al., 2007). Work on how to assess LULUC has been done by Milà i Canals et al. (2007) and is shown in Figure 5.

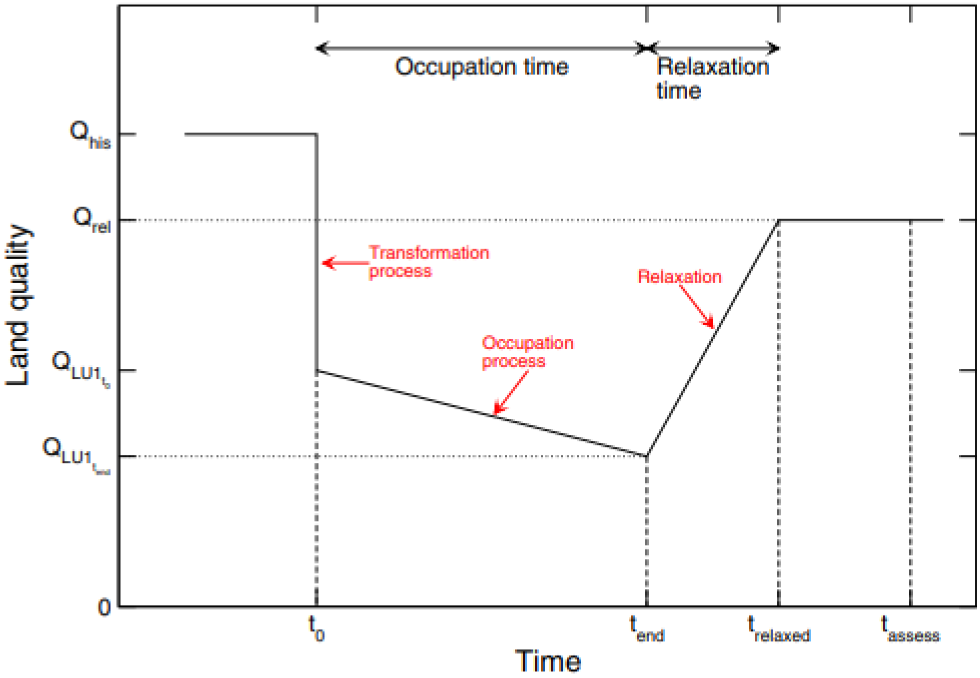

Figure 5: Change in land quality over time for a given area, used with permission from the authors (Liptow, Janssen, & Tillman, 2018)

The figure shows a transformation process, analogous to dLUC, at t_0 and land occupation from t_0 to t_{end} which degrades the land quality. Following the land use, the land is left to relax until a steady state in quality is reached at $t_{relaxed}$. Milà i Canals et al. (2007) discuss soil carbon as a metric for land quality. Land quality is often overlooked when assessing environmental impacts of products (Milà et al., 2007). The change in carbon stocks stemming from LULUC can be either immediate or delayed. Depending on the type of land transformation, the carbon stock change can differ in both magnitude and direction (i.e. a net emission or sequestration) (Deng, Zhu, Tang, & Shangguan, 2016). While the removal of aboveground biomass results in an immediate loss of carbon, soil carbon changes may be much slower.

Indirect land use change (iLUC) is the change from one land use category to another as a result of another land use change. For example, if an area of productive forestland were to expand in Sweden, compromising cropland, the food production would decrease. Assuming the demand for food is the same globally, another actor in e.g. Brazil may proceed to clear rainforest in order to grow soybeans to compensate for the loss of food supply. The initial expansion of forestland has led to an indirect land use change effect in Brazil in this example. At the global scale, indirect land use change may decrease or increase the total terrestrial carbon stock. Another possibility is that the types of products and their mix sourced from the area changes. In forestry there might be a surge in biofuels sourced from wood in Sweden, forcing the wood demand to increase globally increasing the iLUC at other locations. However, the indirect effect is hard to quantify and allocate, and no method is widely accepted.

1.3.6 The life cycle assessment tool

Life cycle assessment (LCA) is a methodological framework and a tool for determining a product or service’s environmental performance over its life cycle. LCA has become the standard within industry, with ISO 14040 and 14044 as important guiding documents, when environmental performance of a product or a service needs to be quantified and compared to other similar goods and services. An LCA consists of four steps, goal and scope definition, inventory analysis, impact assessment and interpretation (Baumann & Tillman, 2004). The goal and scope definition aims to describe the problem and the way LCA is modelled, including but not limited to functional unit, system boundaries, etc. Inventory analysis includes building a model for the system and gathering the relevant data that describe the system. The impact assessment translates environmental loads due to the functioning of the system with characterization factors into an environmental impact. When assessing the climate change impact category translating greenhouse gas flows to carbon dioxide equivalents, i.e. GWP, is recommended. (ILCD, 2010) The interpretation step runs concurrent to the three other steps and allows for corrections and additions to the process. The interpretation is usually done with many stakeholders and the opinions of the stakeholders are constantly iterated in the process (Baumann & Tillman, 2004). The LCA methodology is shown in Figure 6 below.

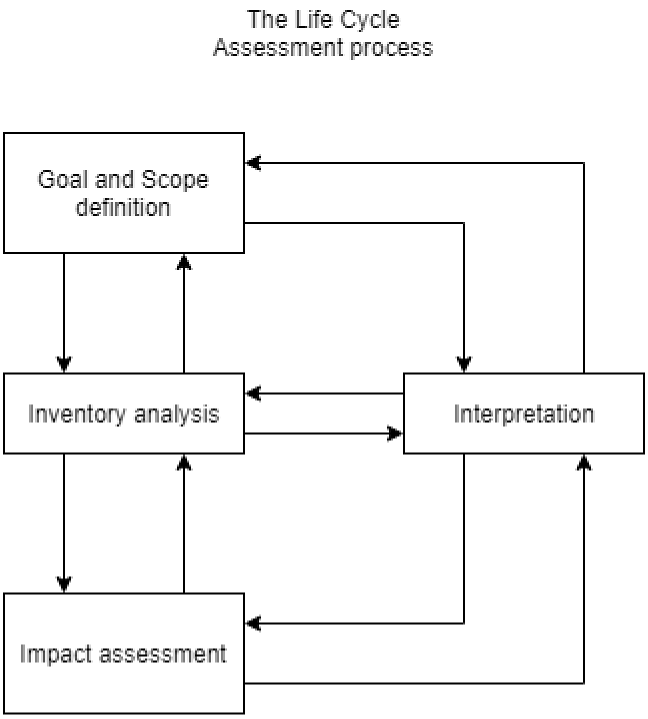

Figure 6: Conceptual model of the LCA process

2. Method

To reiterate the aim of the thesis is:

1. What methods for calculating biogenic carbon's environmental impacts related to land use and land use change exist and how do they differ?
2. What are the implications of using the methods to calculate the environmental impact of land use and land use change in forestry?
3. What criteria exist in current forest certification systems, i.e. FSC and PEFC that can safeguard the terrestrial carbon stocks?

The first two thesis aims will be answered by using existing biogenic carbon impact methods together with life cycle assessment as a tool. The LCA will be used as a tool since Essity has widely used this in the past and it is important to put the results in perspective to previous work at Essity. To be able to use the data in contexts outside LCA, and for transparency, the carbon stock data will also be presented in traditional metrics, i.e. m^3/ha for forestry data and ton C/ha/yr for soil data. The third aim, concerning forest certification and soil carbon stocks, will be assessed through review of forest management literature and the FSC and PEFC certification criteria.

2.1 Working procedure

The working procedure consisted of several steps that are summarized in Figure 7.

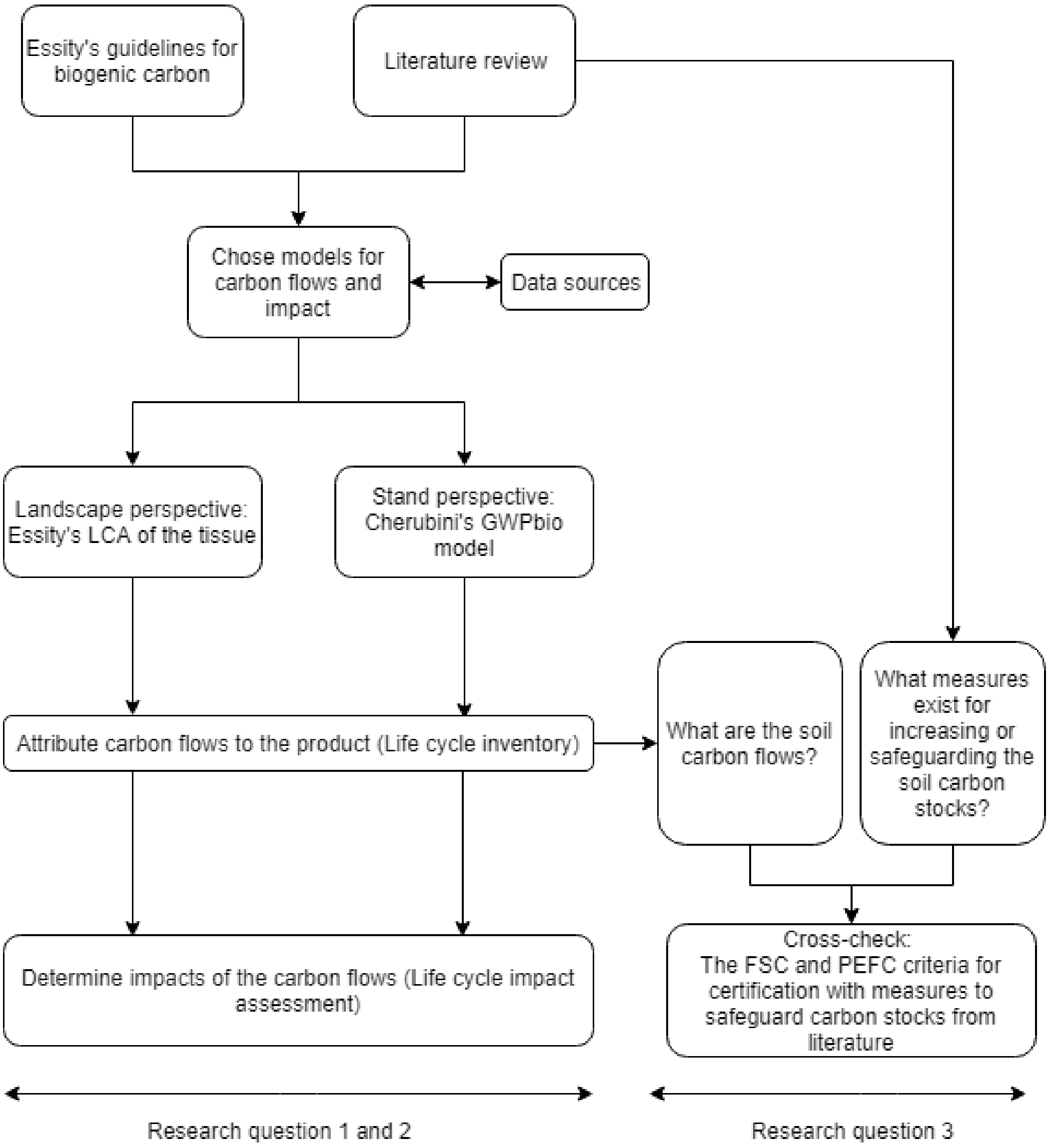

Figure 7: Flowchart of the working procedure

The working procedure consisted of conducting a literature review of the mechanics of the carbon cycle as it relates to the interactions between carbon in the atmosphere, forest biomass and soil. This included reading published books, scientific articles and case reports on forest- and soil management specifically, and the carbon cycle. The information obtained in the initial literature review served as a background for how stocks and flows of carbon interact and the chemical and biological processes that govern the exchange.

Next, Essity’s guidelines were studied in order to identify how Essity works with above ground biogenic carbon, i.e. biomass from trees, and soil carbon as it relates to forest land use and land use change. This included identifying how carbon flows were calculated and the environmental impacts the carbon emissions were calculated to have. It was important to identify the starting point of the project, and to identify how Essity deals with biogenic carbon flows and impacts, so that comparisons to the most recent methods in the scientific literature could be done.

Subsequently the methods for calculating carbon flows within forest systems and soils specifically were mapped and investigated. This included forest management models and calculations from empirical data. Models identified and considered for the calculation of soil and forest carbon flows included the Q, PlanWise, Yasso07 and Coup models, but none were used considering the time restrictions of the thesis. Instead the basis for the carbon flows came from the LCA done by Essity of the product. This reference LCA considers fossil and biogenic carbon flows attributed to the product, but the biogenic carbon category does not include soil carbon. The soil carbon flows were taken from other studies on soil carbon specifically and attributed to the product. Concurrently, techniques for calculating the environmental impacts of using the biogenic carbon from forest biomass in products were examined. This was done in order to outline the techniques that were available in literature to calculate biogenic carbon flows and impacts. It was decided that one landscape and one stand level model should be presented, with and without soil impacts for a total of four impacts. An overview of some stand level perspectives considered can be found in Liptow et al. (2018), including the GWP_{bio} method by Cherubini et al. (2011) and the weighting factor method by Väisänen et al. (2012).

The reference LCA of an average tissue product, which Essity already had done, served as the basis for calculations as carbon flows had been divided up into fossil and biogenic. The internal guidelines for calculating these flows were congruent with a landscape perspective and served as the representative case for this scenario. Soil carbon flows were investigated and added to each of the perspectives since soil carbon changes over time are not accounted for in reference LCA provided by Essity. The carbon flow calculations and the accompanying impacts are described in more detail in 2.3 Life cycle assessment section.

After the methods for calculating the impact of biogenic carbon had been selected, the data requirements for conducting the calculations were analysed. Simultaneously, appropriate data sources were surveyed and the feasibility of using the methods with the available data was assessed. The most important data sources are described in *2.2 data sources* section. Standing wood volume data were gathered from the Swedish National Forest Inventory (SNFI) and some soil data were gathered from the Swedish Forest Soil Inventory (SFSI). However as mentioned earlier, modelling was excluded due to time restrictions and most soil carbon data were gathered from other studies with similar temporal and spatial boundaries as the thesis.

Above ground changes in carbon from annual forest harvest statistics together with soil carbon changes were related to the product in the Life Cycle Inventory, which is described in more detail in the LCA section. As discussed by Mila I Canals et al. (2007), the soil (or land) quality can be described with carbon flows attributed to an area. Net carbon flows from the land were therefore used to assess LULUC impacts. The impacts due to these flows were assessed with the 'Climate Change' impact category, as recommended by the International Life Cycle Data system (ILCD) (ILCD, 2010). The carbon flows attributed to the product are characterized with different characterisation factors, which translate the carbon flows to impact. The landscape assessment uses the Intergovernmental Panel on Climate Change's characterisation factors, as recommended by the ILCD and the GWP_{bio} stand level method has characterization factors unique to the method see Cherubini et al. (2011).

The impact of the tissue product in the reference LCA, representing the landscape scenario without soil carbon allocated, is compared with the impact calculated for the stand scenario without soil allocated and the two perspectives with soil carbon flows attributed and displayed in a normalized graph. The relative size of the impact carried by different types of emissions are shown, divided in to biogenic carbon emitted and sequestered, fossil carbon and soil carbon. The results are then discussed and compared with the two first research questions.

Lastly, the criteria for obtaining the FSC and PEFC certification were identified and compared with the findings of the carbon stock and impact calculations. This was done in order to see whether the two certifications' international criteria already had measures that potentially safeguards the soil carbon stock or increases it implicitly. The results of the first two research questions are mainly quantitative and do not answer what can be done in order to Depending on the amount of measures that safeguard the carbon stocks in the criteria the certifications may be used as proxies for this purpose.

2.2 Data sources

The main data source for carbon stored above ground in forest biomass came from Riksskogstaxeringen, the Swedish national forest inventory (SNFI), where national Swedish forest statistics are compiled every year, including the harvest statistics. Harvest statistics have been measured since 1926 and other metrics have been added over time (SLU, 2018c).

The national inventory report (NIR) for Sweden was also helpful for obtaining data. Some of the data is compiled from SNFI and aggregated to conform to the NIR reporting standards. These data were useful for cross-referencing stocks and flows with the data from SNFI. The NIR reports national greenhouse gas emissions, including effects of land use and land use change on those emissions (Swedish Environmental Protection Agency, 2018).

The main source of data for soil carbon was Markinventeringen, the Swedish forest soil inventory (SFSI), a database of soil statistics that have been measured since 1983. The data obtained from this source were available as aggregated between two time periods, corresponding to the two initial soil inventories, 1983-1987 and 1993-2002 (SLU, 2018b).

2.3 Life cycle assessment

LCA will be used as a tool in the thesis in order to contextualise and tie the carbon flows and the related impacts to the product. An LCA is performed in four steps:

1. Goal and scope definition
2. Inventory analysis
3. Life cycle impact assessment
4. Interpretation

The two initial steps will be covered in the method section, the third in the results section and the interpretation will be addressed in the discussion section. The results from the LCA study will primarily serve as the basis for answering the two first research questions in the thesis. The third research question will be solved by using the carbon flows from the LCA study together with literature on measures that increase the carbon stocks. This will then be compared to the criteria for FSC and PEFC certification for overlap.

2.3.1 Goal and scope definition

The goal of the LCA is to (1) allocate soil carbon stock changes to the functional unit, one tissue product; and (2) calculate the biogenic carbon impact on climate change with the stand level GWP_{bio} method and the landscape perspective. The GWP_{bio} and landscape methods were chosen to represent two current and conflicting views of biogenic carbon flows and impacts to illustrate the implications these have. The biogenic carbon impact results will be compared to the reference impact, Essity's current GWP impact for the tissue product which has a landscape and carbon neutral perspective.

In terms of scope, the LCA will be restricted to pulp from productive forests in Sweden. The fibre used in the tissue product is assumed to be all fresh fibre and the product is incinerated after use. Since the tissue products are used and incinerated shortly after the pulp has been sourced and produced, relative to the rotation cycle, the carbon dioxide emission from the incineration will be approximated as a pulse after harvest. The functional boundary will be the production and allocation of resources to the tissue product, from the forest raw materials to incineration of the product, as illustrated in Figure 8 below.

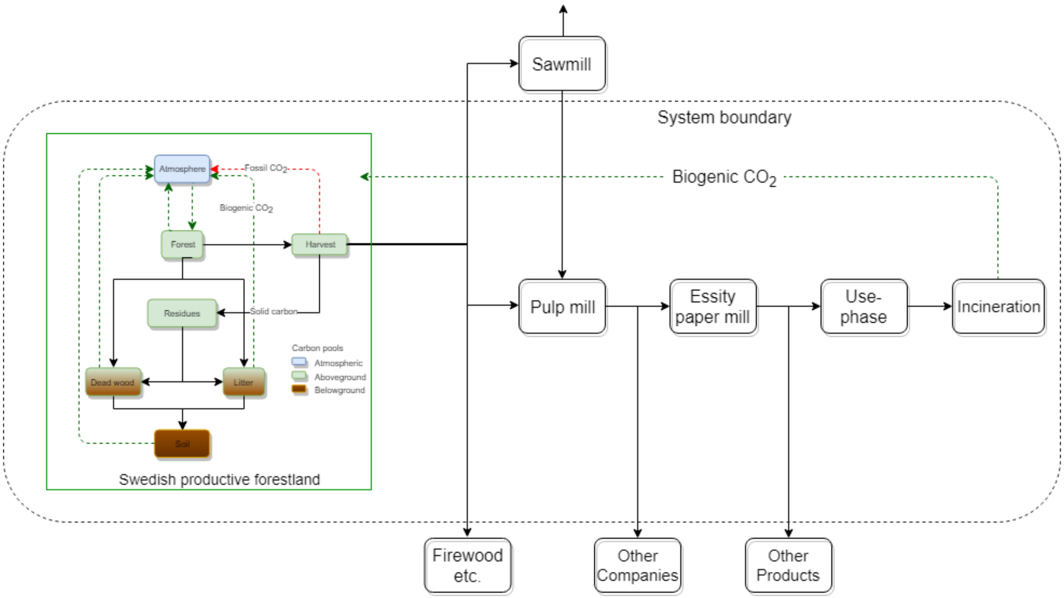

Figure 8: Conceptual flowchart of the forest biomass distribution in Sweden.

The system contains the forest and soil from which the pulp is eventually harvested, in Sweden forests are grown as even-aged stands that are harvested at the same time. The harvested wood is transported to the pulp mill where, together with wood chip residues from the sawmill, pulp is produced. The pulp is then used to make the tissue product in a paper mill, often with the final converting into end products at the same mill. The emissions related to the use-phase are negligible in the context of the life cycle. The system contains fossil emissions from transportation and energy resulting from the production of the tissue product, however a significant portion comes from bioenergy which is considered carbon neutral. There are also biogenic carbon emissions resulting from the incineration of the tissue product after end use. Methane emissions are minimal since drained soils are omitted to the extent possible and a landfill end use scenario is not considered, see the discussion section for more details.

The spatial boundary was set to productive forests in Sweden, which was divided into four subregions; Northern Norrland (N. Norrland), Southern Norrland (S. Norrland), Svealand and Götaland. The division was done since forest site quality, i.e. growth rate, standing forest volume amongst other qualities vary in the regions. As for the temporal boundaries, data from forest statistics in Sweden exist from 1926 and soil data have been sampled since 1983, and these have been used together with soil carbon changes from literature to quantify net carbon stock flows. The biogenic carbon impacts timeframe was set to 100 years for calculations as this covers a full rotation cycle of productive boreal forest in Sweden. This corresponds to the timeframe of the unit in the impact category chosen, GWP_{100}.

The emissions related to the carbon cycle that were studied were emissions of carbon dioxide that result from LULUC. Nitrous oxide is a greenhouse gas that can be emitted from LULUC related to both managed and unmanaged forest, especially in land where wet and anoxic conditions are common. However, nitrous oxide is not a part of the carbon cycle and will not be discussed in the thesis even though the contribution to global warming could be significant (LUSTRA, 2007a). Nitrous oxide emissions are common from drained land, which make up 7-10% of productive forest land, and to the extent possible peatlands will be excluded from the calculations (LUSTRA, 2007a; SLU, 2018b).

2.3.2 Life cycle inventory

The inventory consists of mapping and quantifying the carbon flows within and across the system boundaries, seen in Figure 8, and then allocating the flows, by mass, to the product. Since the tissue product is an existing product with a completed LCA, most of the inventory data related to the product was obtained from that LCA. The product’s LCA did not include soil carbon since land use is not included in Essity’s model for pulp and paper making, the data was therefore obtained from Swedish forest soil inventory (SFSI) and literature. The procedure for attributing the soil carbon flows to the reference LCA's carbon flows, thus establishing the LCI including soil carbon, is shown in Figure 9.

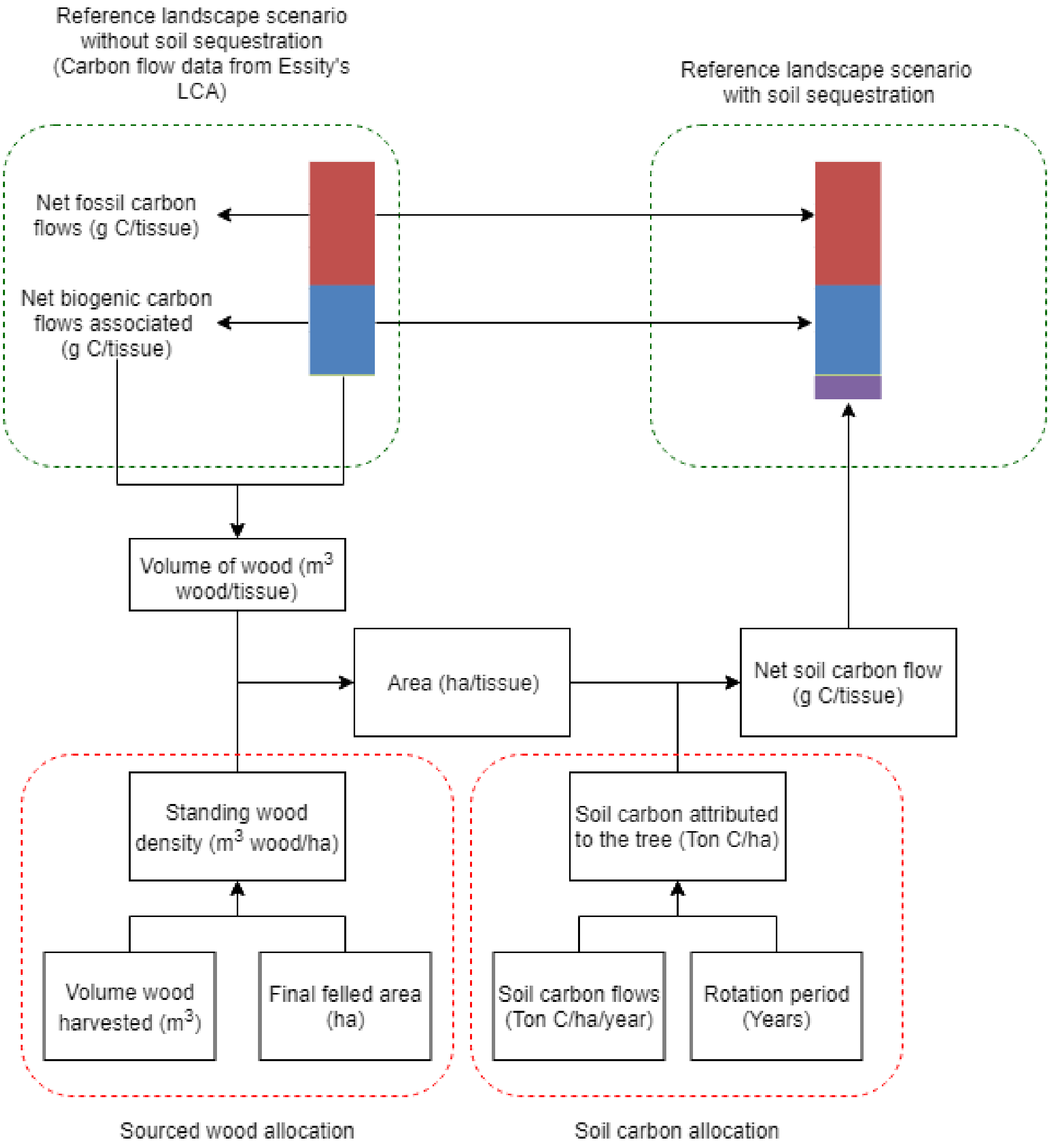

Figure 9: Carbon flow allocation to the product and the procedure for including soil carbon flows. The green dashed rectangles indicate flows attributed to the tissue product, the reference LCA to the left excluding soil carbon and including soil carbon to the right. The red dashed rectangles indicate allocations which are discussed later.

In order to allocate the soil carbon flows to the tissue product productive forestland harvest data, seen in the "sourced wood allocation"-box in Figure 9, was used to establish the area needed to produce one tissue product. The soil data are given or adapted to ton carbon per hectare and year from the data sources. A rotation period must therefore be assumed in order to quantify how many years of soil carbon sequestration that is allocated to the area, seen in the "Soil carbon allocation"-box in Figure 9.

It is important to note that the standing volume per hectare varies between the four regions, higher forest densities are found in the south. Different areas are therefore needed to produce the wood for the tissue product, depending on which of the four regions is chosen to source the wood. Similarly, the difference in the spatial boundaries between the landscape and stand perspective matters as well. The landscape perspective has a spatial boundary that includes the entire landscape, which includes all the harvesting categories; final felling, thinning and other harvest. The volume from each category is therefore allocated to the final felling area to get a standing volume density, displayed in the “sourced wood allocation”-box in Figure 9. For the stand perspective, the spatial boundary is limited to only the stand, which is the wood that is sourced from the final felling area i.e. only the volume from the final felling category. The difference between the perspectives are shown in Figure 10.

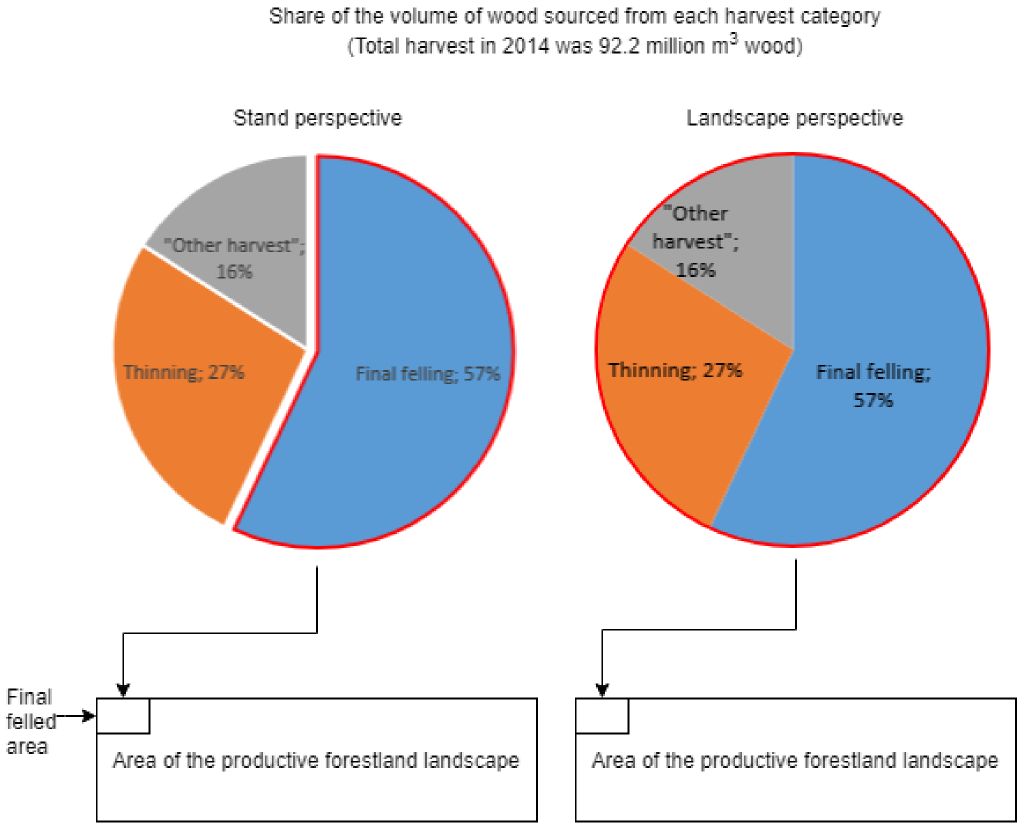

Figure 10: Wood volume allocation for the stand and landscape perspectives

A large volume of the harvested wood in Sweden comes from thinning and “other harvest” categories that are not allocated in the stand perspective, which leads to lower standing volumes for the stand level perspective.

The soil carbon flow attributed to the product therefore depends on three key factors; (1) The region from which the wood is sourced, (2) whether a landscape or stand perspective is used and (3) what soil data is used.

2.3.3 Life cycle impact assessment

In the impact assessment step, the carbon flows that have been allocated to the product are translated to environmental impacts. There are several ways to measure environmental impact and when investigating GHGs' effect on global warming climate change is the recommended impact category (ILCD, 2010). The impact is measured in carbon dioxide equivalents ($CO_{2,eq}$) by translating the flows of carbon with characterization factors (CF) to their global warming potential (GWP). It is recommended to follow the latest GWP data from the IPCC when translating the carbon flows to environmental impacts (ILCD, 2010). The recommendation was followed for the landscape scenario where net changes in carbon flows over the timeframe are calculated and the IPCC CF's are applied. The GWP_{bio} method by Cherubini et al. (2011) has developed unique characterisation factors for carbon dioxide stemming from biogenic carbon and those will be used for the stand perspective.

An issue with the GWP_{bio} method is that the biogenic carbon considered is only the biogenic carbon that is burned. The method measures impact of the carbon in the atmosphere until it is sequestered again and does not include soil carbon. Soil carbon in the landscape perspective is treated as another flow of carbon and can therefore be treated as any other carbon flow. The soil carbon flows will therefore be treated with +1 kg CO_2-eq/kg CO_2 CF for carbon dioxide emissions and -1 kg CO_2-eq/kg CO_2 CF for carbon dioxide associated with sequestration for both cases. This is addressed further in the discussion.

GWP measures the amount of heat a greenhouse gas, such as carbon dioxide, methane or nitrous oxide, absorbs over a certain time frame relative to carbon dioxide is normalized to 1 (IPCC, 2013). The GWP values vary depending on time scale considered. The IPCC lists characterization factors for 20-, 100- and 500-year GWP time horizons, and it allows for comparison of the relative heating effect of gases, which is measured in mass of carbon dioxide equivalents during the selected time horizon. The relative heating depends on how long the gas exists in the atmosphere before it decays and how much heat it absorbs during that time relative to carbon dioxide (IPCC, 2013). Since the greenhouse gases decay at different rates and absorb different amounts of heat the GWP values change depending on the time horizon chosen. GWP over a 100-year time horizon was chosen since this matches the temporal boundary for the thesis the best and allows for comparison with the original LCA, which also is measured in GWP_{100}.

3. Results

The results are divided up and will be discussed in terms of the three LULUC categories; direct land use change (dLUC), indirect land use change (iLUC) and land use. Findings from the soil data calculations will be presented where applicable and biogenic carbon impacts from the landscape and stand perspectives will be presented against the reference scenario for the tissue product.

3.1 dLUC results

To establish the extent of carbon stock changes over time due to direct land use change, the area change of productive forestland over time must be established. Data for direct land use change was obtained from the Swedish national forest inventory (SNFI), where the area productive forestland has been measured since 1983 (SLU, 2018c). The distribution of productive forestland is displayed for each of the four regions over time together with the total productive forestland change for Sweden in Figure 11. The data are available as 5-year averages over the middle year, i.e. the datapoint for 1985 is the average over the period 1983-1987 (SLU, 2018c).

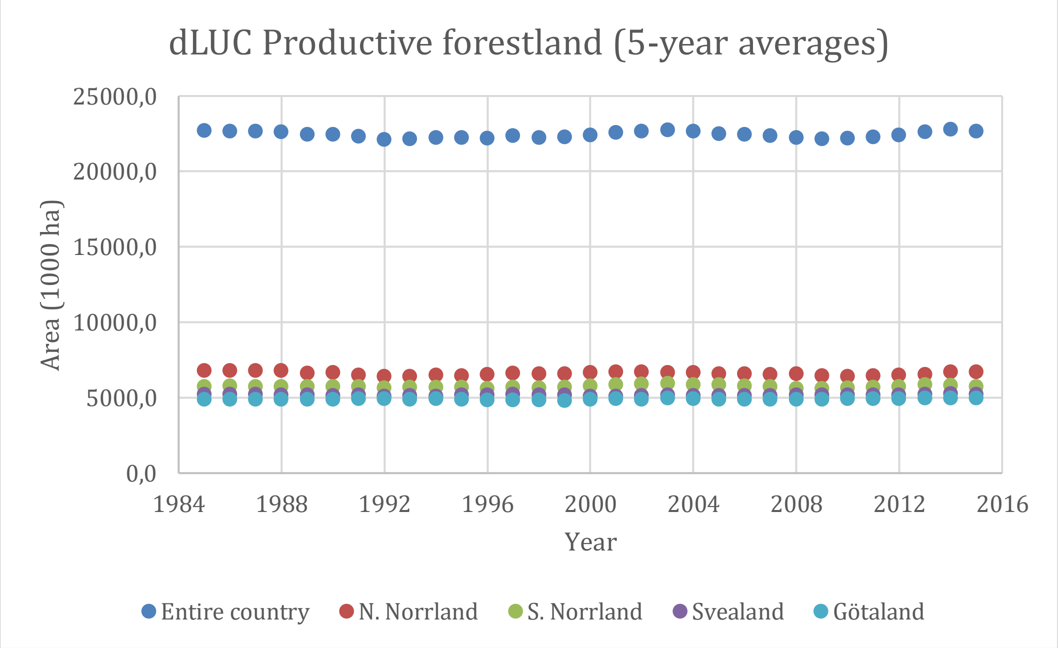

Figure 11: Change in productive forestland area over time for Northern Norrland, Southern Norrland, Svealand, Götaland and Sweden.

The results show no significant dLUC in either of the regions or in the country. Milà I Canals (2013) presented a framework for working with land transformation and the authors suggest to not include land transformation effects if none have occurred during the last 20 years (Milà I Canals et al., 2013). Since the forest land area has not changed in the 20-year time horizon no dLUC effects are included and there is no further investigation into the carbon stock changes resulting from dLUC.

3.2 iLUC results

Indirect land use change (iLUC) occur if the product mix of the land changes or as a consequence of dLUC, as discussed in *1.3.5 Land use and land use change* section. The product mix from the forest area is assumed to be the same over the assessed timeframe so no iLUC is considered from that source. Since the dLUC results indicate that there is minimal dLUC in either of the regions investigated or in Sweden as a whole (see Figure 8) it is unlikely that significant iLUC changes occur outside Sweden. Although Milà I Canals (2013) do not address iLUC specifically it is assumed that land transformation, as discussed the author's paper, implicitly covers iLUC and therefore no further investigation on iLUC was performed (Milà I Canals et al., 2013).

3.3 Land occupation

Biogenic carbon flows and impacts from land occupation are derived from soil data from the Swedish forest soil inventory and forest data from the Swedish national forest inventory, which are tied together by the carbon and amount of land required for one tissue product, the functional unit.

3.3.1 Soil carbon

Representative empirical data on soil carbon was difficult to find, and this will be further addressed in the discussion section. The data that were used came from the Swedish forest soil inventory and was soil carbon for the O-horizon, i.e. the layer in the soil with highest content of organic material (SLU, 2018b, 2019). The data were sampled over two periods, 1983 to 1987 and 1993 to 2002, for each of the four regions and the annual soil carbon change was taken as the average change between the middle years of the sampling. The results are shown in Table 1 under "The Swedish forest soil inventory" category.

Since the empiric soil data obtained may give a misleading picture of annual soil carbon changes a literature review was performed to investigate soil carbon changes from models and empirical calculations over time in Sweden from other sources. The data from the reviewed studies are shown in Table 1.

Table 1: Compilation of soil data used in the thesis, with temporal and spatial included if stated.

Source	**Time covered in study**	**Region covered in study**	**Change in soil carbon (ton C/ha/year)**	**Soil depth (m)**
Ortiz et al. (2013)	1926-2016	Sweden	0.075	0.5
		Sweden	0.062	0.5
LUSTRA (LUSTRA, 2007a)	-	Northern Sweden	-0.08	-
		Southern Sweden	0.09	-
Lundmark et al. (2014)	1926-2004	Sweden	0.07	1
	2005-	Sweden	0.04	1
Ågren et al. (2008)	1926-2000	Sweden	0.12	1
		Sweden	0.13	1
	2014	Sweden	0.075	1
Liski et al. (2002)	1950-1990	Sweden	0.09	0.2
de Wit et al. (2006)	1990	South-east Norway	0.08	1
The Swedish forest soil inventory (SLU, 2019). *O-Horizon*	1984-2002	N. Norrland	0.320	0.1
		S. Norrland	0.384	0.1
		Svealand	0.528	0.1
		Götaland	1.150	0.1

The compilation of soil carbon data in Table 1 shows that annual soil carbon changes are greater for the datapoints in the organic horizon than those found in literature. Most values found in the data sources stem from calculation in forest and soil models but the SFSI data is empirically calculated. Furthermore, the time period covered, and the region covered was also included for each of the soil data to contextualise the values since they depend on both these factors when calculated. For more information about how the individual values are calculated, see the relevant sources.

A statistical analysis was done on the soil values and in coming calculations and the median soil value was elected as the representative value. The median was used since most of the data are concentrated around the mean but the presence of outliers, mainly the O-horizon data, skew the mean. The statistical distribution of the soil data for both landscape and stand level perspectives are included in Appendix B. An analysis on the soil data used is found in the Sensitivity analysis section below and is also addressed further in the discussion.

3.3.2 Biomass carbon

Wood from Swedish productive forests come from three sources (values from 2014); final felling (57 vol.%), thinning (27 vol%) and other harvest

(16 vol%) (Skogsstyrelsen, 2018). These volumes must be allocated to an area in order to connect the aboveground carbon from harvest with soil carbon, which is calculated per hectare, see Figure 9. The three-year moving average for area that was final felled in Swedish productive forestland in 2014 was 197 800 ha and 303 000 ha was thinned, no data were found for the ‘other harvest’ category’s area.

How to allocate these volumes depends on whether a landscape or a stand level perspective is used. In a landscape scenario the thinned volume can be seen as a by-product of forest management and can therefore be allocated to the land area of final felling. The allocation is consistent as the area from which the final felled forest is taken has been thinned earlier in the rotation period and has therefore been allocated to another final felled area the year of the thinning. With a stand level assessment, the thinned volume is outside the system boundary and cannot be allocated to the final felling area. Only the final felled volume is allocated to the final felled area, which is the year’s “stand”. In Table 2, the volume of wood sourced per hectare is shown for the two perspectives in each of the regions.

Table 2: Volume of wood sourced per hectare for the four regions and Sweden as a whole, for the landscape and stand perspectives

Region	**Landscape wood volume sourced per hectare (m^3/ha)**	**Stand wood volume sourced per hectare (m^3/ha)**
N. Norrland	236	165
S. Norrland	433	242
Svealand	446	273
Götaland	710	351
Sweden	448	255

As seen in Table 2, the volume of wood sourced per hectare is greater for the landscape scenario compared to the stand scenario. This is due to the thinned and other harvested wood categories, which make up 43% of the wood volume sourced in Sweden and are allocated to the final felled area in the landscape perspective, see Figure 10.

3.3.3 Biogenic carbon

The total amount of biogenic carbon flows that can be attributed to the tissue product is calculated by linking the soil carbon and the biomass carbon from the sections above. The tissue product is composed of a certain amount of carbon which can be translated to a volume of wood required, which in turn can be allocated to an area with the sourced wood densities from Table 2. The forest area is proportional to soil carbon uptake or release, but the forest area required to produce one tissue product depends on whether a landscape or stand perspective is used and which region is considered.

The volumes of wood in Table 2 were used to calculate the area required to produce the tissue product, which yielded different areas per region. The areas required were then multiplied with the different soil values obtained from calculations and literature review, see Table 1. Since some of those soil values are calculated for certain spatial boundaries, they are only applicable to, and used for, some of the regions listed in Table 1. For example, the LUSTRA soil values are divided into northern and southern Sweden and in the calculations the northern values are not used on the two southern regions and vice versa. This is important as the soil carbon flows depend on the region for which they are calculated as site quality differs between regions.

3.3.4 Impact assessment

The carbon flows associated with the product was characterized and normalized to the emissions of the reference LCA on the tissue product. In the landscape scenario flows that sequester carbon, i.e. the reabsorbed carbon dioxide after incineration of the tissue product and soil carbon changes, are multiplied with negative characterization factors for carbon dioxide since the carbon is sequestered through photosynthesis, which converts carbon dioxide to biogenic carbon. For the landscape perspective characterization factors of +1 kg CO_2-eq/kg CO_2 are used for carbon dioxide emissions and -1 kg CO_2-eq/kg CO_2 for carbon dioxide associated with sequestration.

For the stand level perspective Cherubini et al.'s GWP_{bio} method was used wherein the characterization factor for combusted biogenic carbon depends on the time horizon of the impact assessment and rotation period of the stand. As mentioned in the method section, the time horizon was set to 100 years for the impact assessment and a rotation period of 80 years was used. In the GWP_{bio} method, the amount of carbon dioxide emitted due to the combustion of the biomass is multiplied with the GWP_{bio} characterization factor, in this case 0.34 (Cherubini et al., 2011). The GWP_{bio} model does not consider soil carbon and in this thesis the carbon that is sequestered in soil is considered to come from sequestration of carbon dioxide and is therefore given a characterization factor of -1 kg CO_2-eq/kg CO_2, this is addressed further in the discussion.

The reference impact is the GWP impact in the original LCA of the tissue product, which was provided by Essity. The impact is divided into emissions from biogenic and fossil carbon sources as well as the sequestration of carbon from the regrowth of biomass in the landscape. The impact has been normalized to the emissions of the reference scenario (see Figure 12). The stand level perspective is also shown; note that since the resequestration of carbon is included in the GWP_{bio} emission impact, this is not displayed as a separate category. Added to these two perspectives are the impacts of forest regrowth and soil sequestration, which are shown separately in Figure 12.

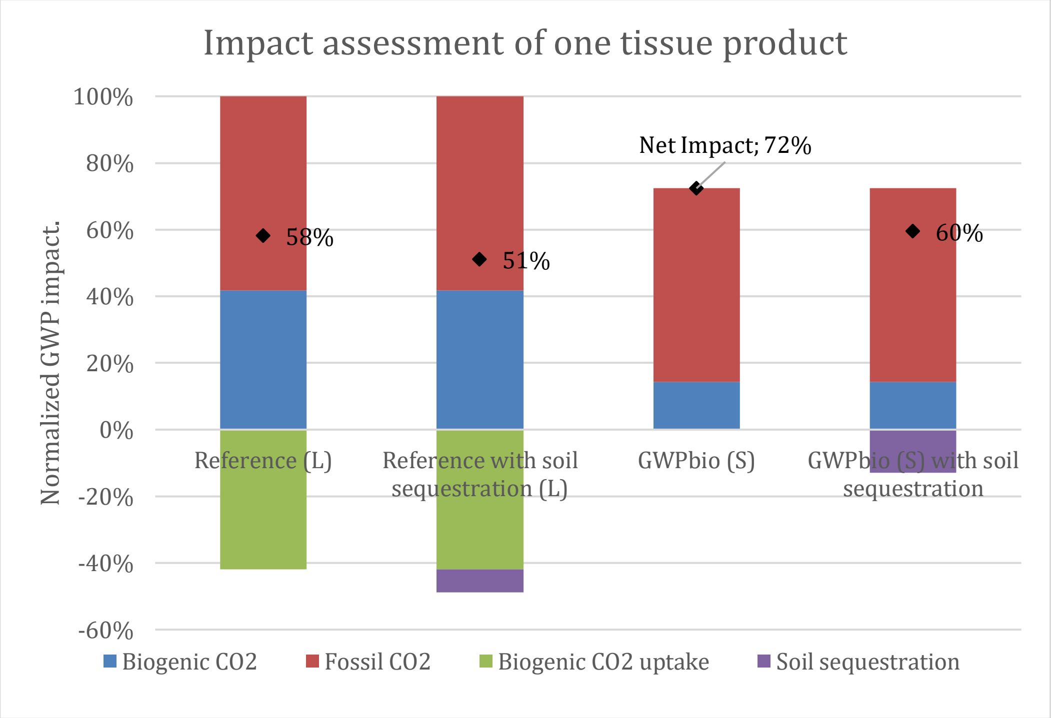

Figure 12: Normalized impact of the tissue product for the four cases, two stand level perspectives and two landscape perspectives divided up in the emission and sequestration constituents. (L) indicating a landscape perspective and (S) a stand perspective,

In Figure 12, negative values indicate sequestration of carbon, i.e. a removal from the atmosphere, and positive values indicate emissions. All results are compared to the emissions of the reference, i.e. the sum of the blue and red bars in the “Reference (L)” series in Figure 12.

The fossil impact is the same for all four cases, 58% of the reference emission impact, as it is unaffected by the variables changed or whether a landscape or stand perspective is used. Moreover, the biogenic carbon emissions and uptakes are the same within the stand and landscape perspectives respectively as these do not change when soil sequestration is included in the impact assessment. This translates to 42% of the reference emission impact for landscape and 14% for the stand perspective. The effect of including soil sequestration can also be seen in Figure 12, when the contributing process is added to the stand and landscape perspectives. The soil sequestration impact is -7 % for the landscape perspective and -13% for the stand perspective. There is a greater area needed to make a tissue product with the stand level perspective since less wood is sourced per hectare when thinned and ‘other harvest’ sources are not included. The impact of soil sequestration is therefore greater at the stand level since the soil has a net sequestering effect that scales with area, a larger area means more carbon sequestered. The greater area needed to make a tissue product in the stand perspective would likely change the fossil carbon dioxide impact as well, but this was not investigated.

3.4 Sensitivity analysis

To investigate how sensitive the impacts are to changes in variables, a sensitivity analysis was done on three variables; soil carbon content, rotation period and future forest harvesting and growth scenarios. Three growth and harvesting scenarios are used with 90, 100 and 110% forest harvesting projections (Skogsstyrelsen, 2015). The three scenarios were tested on both the landscape and stand level perspectives and the effect on the impacts are calculated.

3.4.1 Soil data sensitivity

As seen in Table 1, the soil data varied in both magnitude and sign, i.e. whether the soil carbon process was an emission or sequestration of carbon. This contributed to a spread in the impact depending on which soil carbon data were used. Since most of the data points were close to the average, and the data contained outliers, the most representative soil data point was the median. In Figure 13 the relative impact on the results of changes in the soil carbon, on the landscape level.

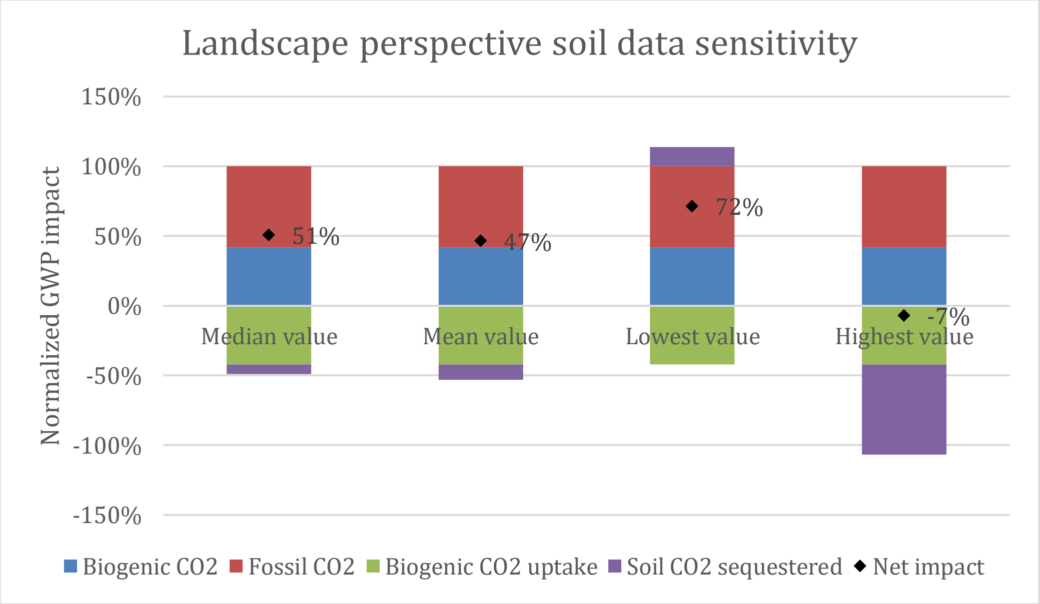

Figure 13: The effect of soil data chosen on the impact of using one tissue product for the landscape perspective.

The soil data used in the “Highest value” of soil sequestration is the O-horizon value for southern Sweden, i.e. Götaland, from Table 1. When the highest value is used for soil sequestration the GWP impact exceeds -100% which means that the product has a net positive impact when measured with in GWP. In other words, the tissue product sequesters more carbon than it emits, even when including the emissions from fossil sources. The “lowest value” is an emission, i.e. that the soil is losing carbon to the atmosphere, which was reported by one source, Table 1.

When using the same soil data but applying it to a stand level perspective the impact due to soil carbon is larger than for the landscape perspective. This is due to a greater area being needed to produce the tissue product as the amount of wood sourced per hectare is lower for the stand perspective. Soil carbon changes are measured per hectare and are therefore magnified, as seen in Figure 14.

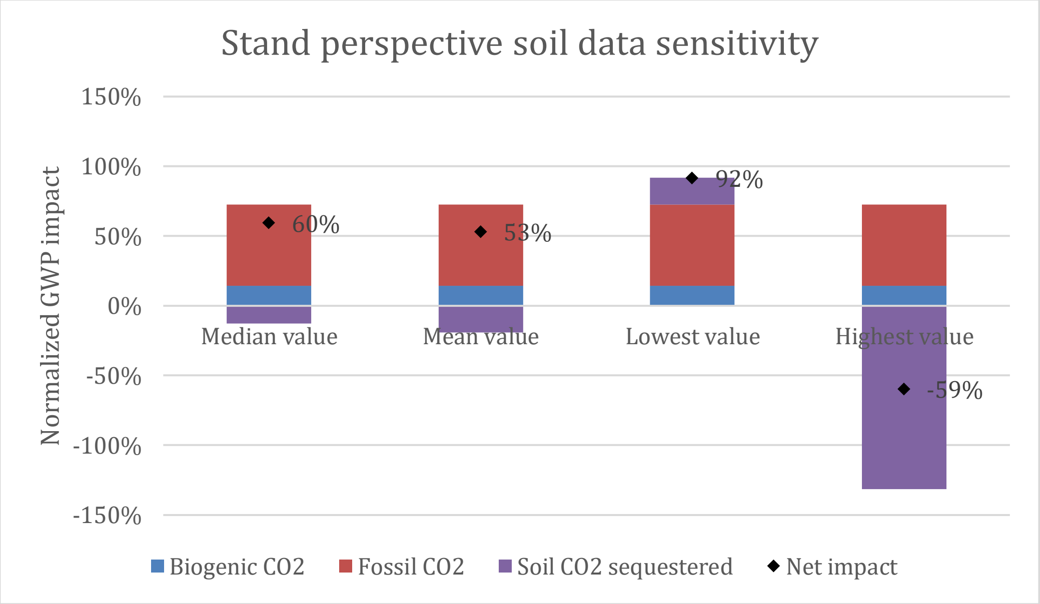

Figure 14: The effect of soil data chosen on the impact of using one tissue product for the stand perspective.

When the “Highest value” for the soil data is used in the stand perspective the sequestration of carbon in the soil is greater than the carbon emissions associated with producing and using the product. Similarly, to the landscape perspective, the “lowest value” represents a net loss of carbon from the soil, and thus an emission of carbon to the atmosphere.

3.4.2 Rotation period sensitivity

The GWP_{bio} method for calculating biogenic impacts on a stand level depends on the rotation period of the species (Cherubini et al., 2011). Similarly, soil carbon sequestration depends on time as well, longer rotation periods yield more carbon sequestered. This is displayed in Figure 15 for both stand and landscape level assessments. The percentages indicate how large a percentage of the impact the soil sequestration and stand biogenic carbon have on the reference emission depending on rotation period.

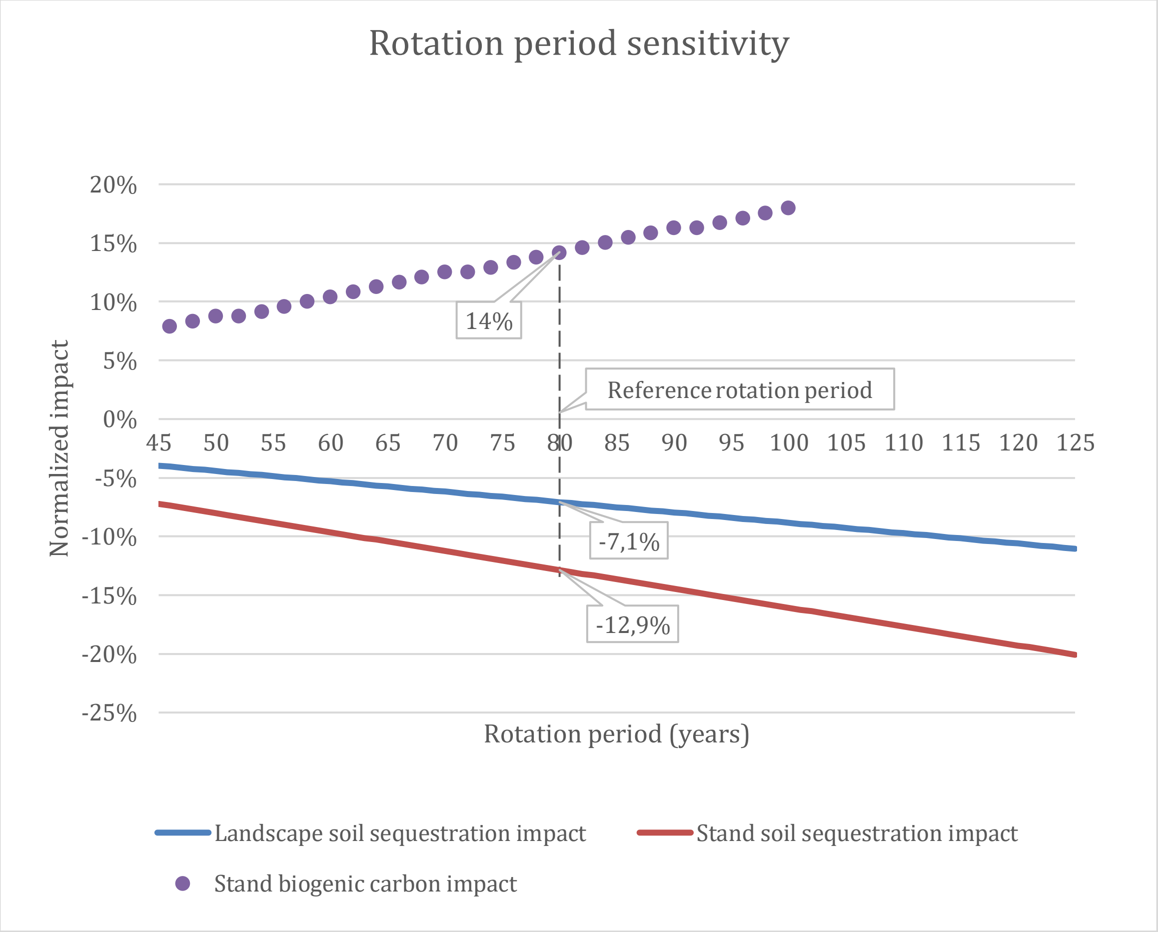

Figure 15: Relative impact of soil sequestration and stand biogenic carbon impact when increasing the rotation period of the productive forest.

The dashed line indicates the rotation period of the case study (80 years) but forests are eligible for final felling at a rotation period between 45 and 125 years in Sweden which is the domain for this analysis (Sveaskog, 2015). The soil sequestration percentage impact increases as the rotation period gets longer, as mentioned earlier more soil carbon is then absorbed. Conversely, the characterization factor for the GWP_{bio} model increases, meaning that the biogenic carbon impact gets larger with increasing rotation periods. The impact of stand biogenic carbon is plotted for the listed rotation periods provided in Cherubini et al. (2011), where rotation periods up to 100 years are listed.

3.5 Scenario analysis: Forest harvest and growth scenarios

The Swedish forestry agency put together three harvesting scenarios for the next century, some data from these scenarios were used to show how the soil impact would change for the product under the scenarios. The data from the scenarios replaces the data that was obtained from SNFI. The data used for the scenario analysis were gross felled volume, final felling area, and final felled volume. These three factors change the amount of wood that is sourced per hectare which in turn changes the biogenic impacts of the tissue product. An example of the data used when plotting the 90% harvesting scenario over time for the landscape and stand perspectives can be seen in Table 3.

Table 3: Scenario data used to calculate soil carbon impacts in the landscape and stand perspectives

90% Harvesting scenario	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Final felling area (1 000 ha/year)	240	240	245	233	225	233	238	235	262	236
Gross total harvest (1 000 000 m^3/year)	79	82	88	92	96	102	104	107	111	111
Final felling harvest (1 000 000 m^3/year)	50	53	56	58	62	67	70	73	77	77

As mentioned earlier, the spatial boundaries of the stand and landscape scenarios differ which means that the total harvest is allocated to the final felling area for the landscape scenario. Only the final felled volume, which is a subset of the total area, is allocated to the final felling area for the stand scenario, see Figure 10. This means that row 3 and 1 were used for the stand perspective and row 2 and 1 were used for the landscape perspective in order to get standing volume densities (m^3 wood/ha). The data in Table 3, along with the same category of data for the 100% and 110% harvesting scenarios, were used as the basis for calculating soil sequestration impact.

An analysis on how this impacts soil sequestration was done for both landscape and stand level perspectives. All other variables remained the same, the landscape impacts are shown in Figure 16. For reference, the impact from soil sequestration was -7%, which is represented as a process in the “Reference with soil sequestration (L)” series in Figure 12.

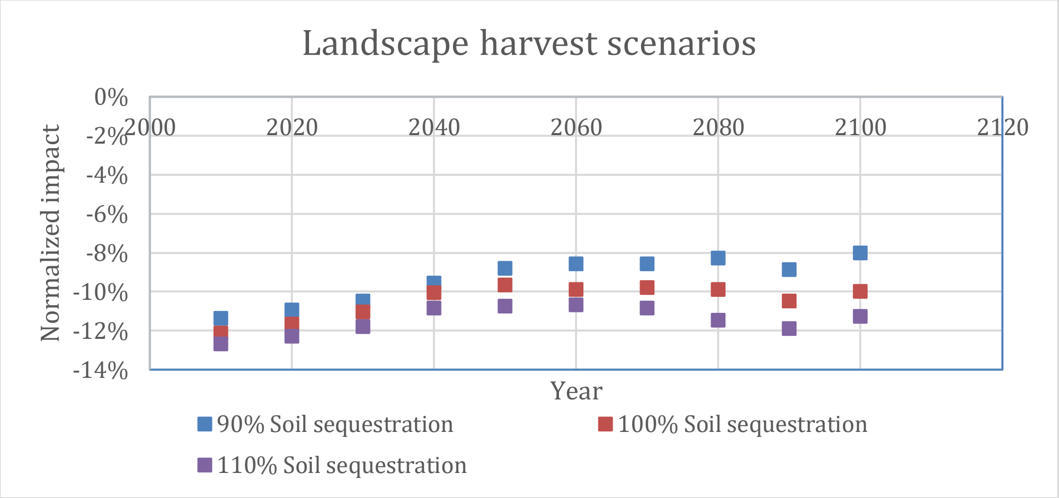

Figure 16: Effects of future harvesting scenarios on soil sequestering's relative impact when producing the tissue product, with a landscape perspective.

Negative values indicate a sequestration effect, i.e. carbon is removed from the atmosphere. In Figure 16, it is difficult to draw any conclusions from the scenarios as the three variables used from Skogsstyrelsen's projections change simultaneously in each time-step for which they are calculated. However, what is seen is that the high harvest scenarios yield a higher impact from soil carbon sequestration of the tissue product's total impact than the lower harvesting scenarios. The analysis was also done on the stand perspective, Figure 17.

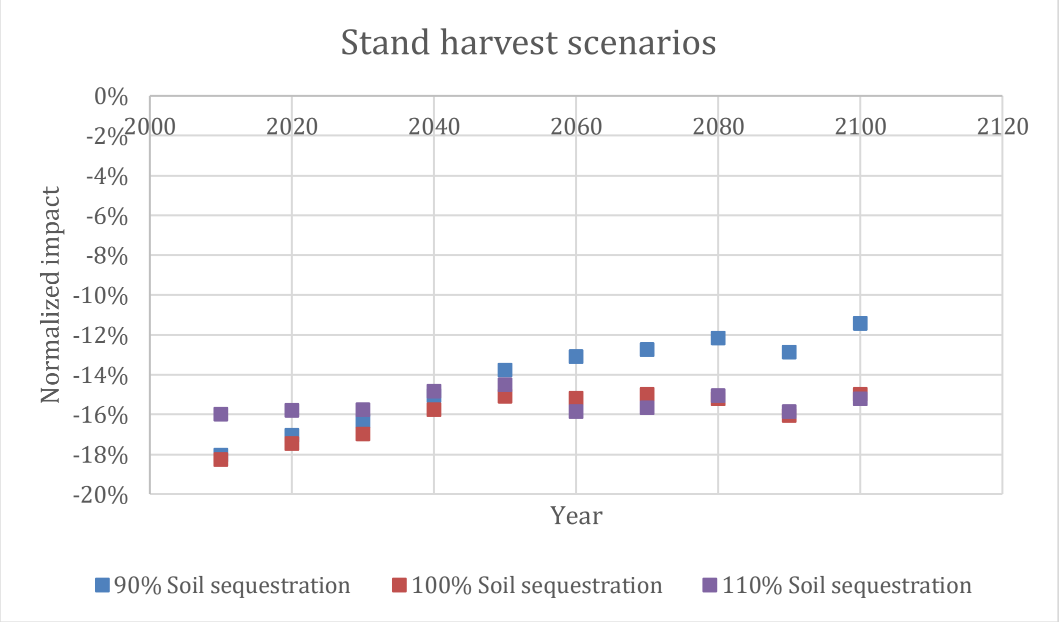

Figure 17: Effects of future harvesting scenarios on soil sequestering's relative impact when producing a tissue, with a stand perspective.

For reference, the soil sequestration was -13% of the relative impact as can be seen in their compartments in the "Cherubini (S) with soil sequestration" series in Figure 12. As with the landscape analysis of these scenarios it is hard to draw any trends or conclusions as multiple variables change with each ten-year interval.

Comparing landscape and stand perspectives reveals that the relative impact is higher for the stand level perspective than the landscape perspective. This is due to less wood being sourced per hectare in a stand perspective, and consequently more area is needed for the tissue product to be produced with the stand perspective. This affects the soil carbon sequestered as more soil carbon is sequestered when a large area is needed and a higher impact from soil carbon on the tissue product's environmental impact is calculated.

4. Discussion

1. What methods for calculating biogenic carbon's environmental impacts related to land use and land use change exist and how do they differ?

There are many methods to calculate biogenic carbon impact, categorically these methods can be divided up into stand and landscape perspectives, which have different spatial boundaries, and static as well as dynamic modelling. Stand perspectives focus on dynamics and impacts of biogenic carbon at a stand, usually meaning that the biomass is of the same age and it is all harvested at once within the stand which is then allowed to regrow, sequestering carbon over the next generation of biomass' rotation period. Cherubini et al.'s (2011) GWP_{bio} method was chosen for comparison with a landscape point of view in this thesis as this was the first stand method published, for examples of stand perspectives see Liptow et al. (2018).

There are also a variety of landscape models which consider the whole landscape as a mixture of even-aged plots that are harvested at different times. The landscape perspectives have a focus on the biogenic carbon flows where the combustion of one plot may get sequestered by the whole landscape's biomass. These models vary in the amount of compartments they use to calculate the flows as well as the mechanisms governing the exchange of carbon between compartments. In the thesis, the reference case for the LCA on the tissue product was considered a landscape perspective which did not include soil sequestration of carbon. The biogenic carbon in the tissue product was considered carbon neutral since sustainable harvest practices are in place so that the growing forest sequesters the carbon in the forest landscape.

On top of dividing the biogenic carbon methods spatially, the differences between static and dynamic modelling need to be addressed. The GWP_{bio} method is a dynamic way of calculating impact, which means that the impact may change non-linearly with time depending on the mechanisms that drive the exchange of carbon between the oceanic, atmospheric and terrestrial compartments as well as the amount of carbon in each. In the calculations the issue was solved by using the characterization factors provided in Cherubini et al. (2011). The landscape perspective used in this analysis as well as the soil data were applied as static changes. This was mainly due to time restrictions that did not allow for the application of a dynamic model for calculation of soil and biomass fluxes of carbon. One of the reasons for the creation of the GWP_{bio} method by Cherubini et al. (2011) was to discuss the importance of considering the timing of the emissions and the time required for complete sequestration of biogenic CO2 emitted due to the combustion of biomass. In this thesis the landscape perspective and soil calculations the flows are assumed to be linear, i.e. the rate of change of carbon is constant.

4.1 Interpretation of LCIA results

2. What are the implications of using the methods to calculate the environmental impact of land use and land use change in forestry?

When using a stand level perspective, the spatial boundaries exclude the utilization of 43% of the wood volume from thinning and other harvest, which is outside the system boundaries. The stand perspective only looks at the wood harvested during the final felling at the stand, whereas thinned and “other harvested” wood is excluded. The wood that is excluded in the stand perspective is a by-product of forest management, to increase the yield during final felling. Since not all wood is included in the allocation in the stand perspective it implies that the discarded wood is not used for any productive purpose. This is in conflict with how sustainable forestry is managed in reality. It would not only be wasteful in an environmental sense but also economically, which could be argued is the main driver for productive forest management. Furthermore, the stand perspective implies that the area under analysis is treated uniformly, i.e. when there is harvest, the whole area gets harvested. It implies that economic value only can be realized to cash flows at the end of each rotation period, once every 80 years, which is not economically sustainable.

Another implication of using the stand level GWP_{bio} is the view of sequestration to the same stand, the burnt biomass’ carbon is sequestered to the same stand, which takes 80 years. The sequestration results in a gradual removal of the carbon dioxide emitted by the products from the stand over the next generation of biomass's growth. The impact is given a modified characterization factor and translated to impacts, GWP_{bio}. In reality the next generation of biomass at the stand absorbs carbon from the atmosphere, but so does the rest of the landscape which is of varying age and varying sequestration rates depending on its age, see Figure 4.

The net impact from biogenic carbon when using the GWP_{bio} approach was 13% of the reference emission from the tissue product, which is higher than the reference where the biogenic carbon emission impact cancels out with the sequestration to zero net emissions from biogenic carbon. The difference stems from the viewpoints of the perspectives; landscape level considers the flow of carbon in the whole landscape and uses traditional characterization factors for the net flow, and the stand perspective looks at the carbon flows over the stand alone and attributes a dynamic characterization factor depending on how long it takes to sequester the carbon emitted from harvest.

The landscape perspective is similar to the current management of forests in Sweden. The allocation of thinned and other harvest volumes to the area of final felling implies that all wood is used for products. Furthermore, with the landscape perspective not all the forest is harvested each year but is instead partitioned to guarantee a continuous flow of wood out of the system annually. In reality the forest sequesters carbon, and wood is removed at a rate which is governed by demand for wood or wood derived products. Currently the demand is lower than the regrowth which means a net sequestering effect in productive forests in Sweden. The flow of carbon in this landscape system allows for a constant or slightly increasing flow of wood based products out of the system which is more in line with economic growth prospects and extraction of wood in reality.

The implication of including soil carbon in the impact assessment suggests that the carbon sequestered in the soil is a result of the forest management practices of the forestland from which the tissue product is produced. The sequestered carbon is allocated to the product, which was done in both the landscape and stand level calculations. As mentioned by Ågren et al. (2008) the soil carbon equilibrium has not been reached yet, meaning that the soil will keep sequestering carbon in the future but not at the same high rate it is currently. If the soil keeps sequestering the allocation may be valid but the difficulty in measuring and evaluating the sequestration rate makes it hard to estimate a value. Uncertainties with soil data is addressed further below.

Moreover, the data that were used had varying spatial and temporal boundaries which means that some data are more applicable to the thesis than others. Some of the soil data that were used were calculated or aggregated for productive forestlands in Sweden. These data may therefore be more applicable to a landscape point of view as it is more similar to reality than the stand view. A stand level perspective would benefit from soil carbon measurements over the regrowth of the stand, in a dynamic fashion to correlate the impacts with the modified GWP_{bio} impact.

Similarly, the temporal boundaries of the soil data from the scientific articles may not be valid currently since they are extrapolated from the data in the study. The change reported in the studies are assumed to be the same currently which may not be true. As mentioned earlier Lundmark et al. (2014) expects the rate of soil sequestration to decrease if biofuels are extracted, whereas Ågren et al. (2008) expects the rate to increase with current litter production, until an equilibrium is reached. Some data are calculated within the temporal boundaries, establishing an average rate of change per year and some studies calculate the annual change in the last year. This means that the results from the soil impact have to be interpreted carefully depending on which data are used. The results should therefore be interpreted as an approximation of the magnitude of soil carbon's effect on the impact on the tissue products total emission impact rather than as an exact result. One of the points of the study was to include soil sequestration as a separate category to investigate its effect which has not been done before.

4.1.1 dLUC and iLUC results

The results from the land use change calculations showed no significant change in either of the two categories, direct or indirect land use change. The dLUC results showed no change in area of one land use category to another, but that depends of what is counted as land use change. In the thesis the IPCC's good practice guidelines were used where forestland is one category and changes from productive forestland to non-productive forestland would not count as land use change. LUSTRA reported that up to 1.5 million ha of current forestland has been drained in the process of making the forestland productive. This does not count as land use change by the definition but is rather a management practice that could give large emissions of methane and nitrous oxide, both strong greenhouse gases (LUSTRA, 2007b). Milà i Canals et al. (2013) suggested a method for calculating land use change effects if present and current IPCC guidelines suggest attributing land use change effects on the land to the next 20 years (IPCC, 2003; Milà I Canals et al., 2013). Potential future scenarios where economics or supply and demand change for wood products may result in land use change effects in Sweden, but this assessment was outside the scope of the thesis. In the sensitivity analysis harvesting scenarios were investigated but this analysis focused on soil carbon impacts. The harvesting scenarios from Skogsstyrelsen did not specify whether any land use change occurred in either of the three scenarios modelled. Therefore, any area change was assumed to either have remained productive forest or changed to non-productive forest. Neither of these two alternatives would have constituted land use change with the IPCC’s good practice guidelines.

Moreover, the conclusion of the iLUC results was that there is no iLUC change since there is no LUC in forestland in Sweden. However, the effects of iLUC could potentially be large, but there needs to be some land use change in Sweden to force iLUC in another area and the system boundaries need to be expanded beyond the country level (Milà I Canals et al., 2013).

3. What criteria exist in current forest certification systems, i.e. FSC and PEFC that can safeguard the terrestrial carbon stocks?

The FSC’s Principles and Criteria for Forest Stewardship contain 10 principles that serve as criteria for obtaining the FSC certification (FSC, 2015). Some principles could be interpreted as proxies for safeguarding the carbon pools, especially as soil organic carbon is vital for soil fertility. By diminishing the soil carbon pools of the forests, the sustainability aspect would be impacted through limited growth, impacting both economic and environmental aspects of forest management. In FSC criteria the principles concerning Benefits of the Forest, Environmental Values and Impacts, High Conservation Values and Implementation of Management Activities contain criteria that can be interpreted to safeguard the soil carbon pool. For example, the Benefits of the forest criteria discuss externalities of operation. Carbon dioxide is a pollutant with negative externalities and by increasing the soil carbon stocks over rotation periods the net emissions from biobased products can be decreased. The criteria in the FSC certification are general and soil carbon is not discussed explicitly. Therefore, it depends on the interpretation of the criteria whether soil carbon should be included. Environmental values are also discussed, of which soil is one. Therefore, criteria pertaining to reducing impacts on these values can be interpreted as safeguarding the carbon stocks. For example, criteria 10.11 states that “The Organization* shall manage activities associated with harvesting and extraction of timber and non-timber forest products* so that environmental values* are conserved…” (FSC, 2015) which can directly be interpreted as conserving soil carbon stocks.

PEFC is another internationally recognized certification scheme for forest management, sharing similarities with FSC. PEFC has over 300 criteria which are adapted to local conditions (PEFC, 2018, 2019). The PEFC criteria, like the FSC criteria, are general which leads to interpretation of the criteria. The PEFC mentions measures which are in line with conserving soil carbon such as promoting sustainability, if soil carbon is removed constantly growth will be impaired. Furthermore, criteria 8.1.2 mentions that "…the capacity of the forest to capture and store carbon shall be safeguarded in the medium and long term…". Depending on whether soils are considered a separate compartment or a part of the forest the criteria could be interpreted as safeguarding or increasing carbon stocks.

Techniques to increase soil carbon in forests through forest management have been studied and the measures can be linked to the certification schemes. Stendahl et al. (2010) found that plantations of spruce can yield 22% more soil organic carbon in soils compared to pine over several harvest cycles when modelled. The difference was mainly due to a larger amount of forest residues associated with harvesting spruce. Norway spruce is recommended over Scots pine if the goal is to increase soil organic carbon in soils (Stendahl et al., 2010). To promote sustainable silviculture, like the certification schemes, it is important to replenish the carbon stocks by leaving forest residues on the land after harvest. The organic horizon in the soil is sensitive to silvicultural practices and change quickly after harvest, whereas the deeper layers of the mineral soils change slowly (Byrne et al., 2006; James & Harrison, 2016). Other studies however, indicate that harvesting leaves no general trend towards lower soil carbon (Johnson, 1992; Johnson & Curtis, 2001). This may indicate that the soil carbon changes in the organic horizon are transient and change over the rotation period. When looking at longer time scales meta-analyses have concluded that increasing forest productivity while minimizing soil disturbances and whole-tree harvesting tends to increase soil carbon stocks (Byrne et al., 2006; Johnson & Curtis, 2001).

4.2 Allocation

There were two main points of allocation in the thesis, the first concerned the allocation of the wood output from productive forests in Sweden to an area and the other was the allocation of soil carbon over time. In the wood output allocation, the difficulty was that 43% of the wood volume comes from other areas than final felling; i.e. areas that are not completely harvested but where only a few trees are harvested over large areas. Including these large areas would give an overrepresentation of carbon sequestered in the soil as the soil values scale with area. In order to remedy this issue, the thinned and ‘other harvest’ volume, i.e. 43% of the volume, was allocated to the final felling area in the landscape scenario. The reasoning behind this was that all the volume must be allocated properly, i.e. neither excluded nor double-counted, and in this way the thinned and ‘other harvest’ volumes are viewed as forest management procedures which all parts of the landscape experience during the growth phase. The allocation is complete as the thinned and ‘other harvest’ volume is allocated to the final felled area during the year when the management procedures are implemented. Different stands are thinned and used for ‘other harvest’ every year and are allocated to the area of the felling that year.

The allocation of the wood volumes conflicts with the system boundaries of the stand level perspective. This conflict arises from the stand level perspective only considering the dynamics of the fully harvested stand and not the entire landscape. Thinning, for example, is a routine procedure in forest management in order to increase the growth on the local plot of forest by removing some trees in order to benefit the entire stand. In the allocation the thinned and ‘other harvest’ volumes were treated as if they were outside the system boundaries and not allocated to the product. This means that 43% of the forest volume remains unallocated. This is not addressed in the article by Cherubini et al (2011) from which the method was derived.

The other allocation issue is the temporal allocation of soil carbon which partly has been covered. The soil carbon changes are calculated on a yearly basis, sometime averaged over long time periods and sometimes given as the rate of change the final year of analysis. By allocating the soil carbon changes over the rotation period this change inevitably gets treated as an average constant change that is multiplied with the rotation period. Soil carbon changes are dynamic and depend on a variety of factors, see Figure 2 for the modelling of carbon changes over a rotation period by Cintas et al. (2017). When allocating this way, the perspective that should be expected to work best is the landscape perspective as it is representative of the whole Swedish productive forest area. Similarly, soil data corresponding to the Swedish productive forestland over the same time frame of the rotation period would be the most accurate. The stand perspective implies that area under analysis is harvested at the same time, which is unrealistic when analysing the entire productive forestland in Sweden. Most of the soil data is calculated for the entire landscape which make the results from the stand perspective less reliable.

4.3 Addressing assumptions and delimitations

Nitrous oxide emissions were excluded when analysing productive forestland in Sweden and when excluding wetlands, where anoxic conditions exist from which nitrous oxides emerge. Similarly, some methane emissions, which are large from wet soils that are drained are also not considered by excluding wetlands (LUSTRA, 2007a). It was however reported that as much as 1.5 million hectares has been drained since 1850 to create forestland (LUSTRA, 2007b). Some of that forestland is productive today, and how to allocate all these emissions are outside the scope of this thesis. Since the emissions of these anoxic compounds occur gradually, some methane will be released from soils within the spatial and temporal boundary considered here and these are not accounted for. The area which is currently releasing methane as a part of the transition to forestland would be hard to estimate along with the fluxes of methane from those areas.

If methane emissions were considered within the spatial boundaries the environmental impact would not be accurately assessed with the stand level GWP_{bio} method. The GWP_{bio} method only considers the carbon dioxide that is sequestered through photosynthesis by the biomass in the stand and does not provide characterization factors for methane. There would be a mix of characterisation factors that have different physical basis, as described earlier was for carbon dioxide in relation to soil carbon. Methane and carbon dioxide from soil reactions use IPCC's characterization factors and aboveground reactions use the GWP_{bio} modified characterization factors.

Another source of methane emission, which was excluded from the thesis, was methane associated with anoxic reactions in landfills. As mentioned earlier, landfilling organic material is illegal in Sweden but it still occurs. Considering the landfill end-use scenario would have resulted in methane emissions with a potentially large impact because of the large heat absorption relative to carbon dioxide. The GWP_{bio} stand level approach does not address how to deal with methane emissions which is a drawback in the method. In a landscape scenario the methane emission would be included as a carbon flow over the rotation cycle and the GWP-impact would be calculated with IPCC's characterization factors.

Conflicting evidence on whether methane emissions from terrestrial sources occur has also been studied. There is no consensus to the extent of methane release, or whether there are any at all. Keppler et al. (2006) reported aerobic methane emissions from living plants of between 62 to 236 Tg/year and between 1 to 7 Tg/year from plant litter whereas Dueck et al. (2007) reported 0.3% of the total amount reported by Keppler et al. (2006). The possibility of methane emissions during the growth of the forest would also need to be included in the impact assessment.

Another working assumption was that a rotation period of 80 years for the harvested wood. The length of the rotation period was chosen as it is a representative age for harvested wood in Sweden. However there is a large variance in felling age. Sveaskog reported that trees between the ages of 45-125 years are eligible for felling with shorter rotation periods being required in southern Sweden (Sveaskog, 2015). As investigated in the sensitivity analysis, increasing the rotation period increases the carbon sequestered by the soils in both landscape and stand perspectives. The amount of carbon sequestered by soils is sensitive to rotation period as the normalized soil sequestration impact can double for both perspectives over the span of the rotation period, see Figure 15. The GWP_{bio} CF is also sensitive to rotation period where the normalized impact doubles over the 46 to 100-year rotation period for which GWP_{bio} characterization factors are provided. Longer rotation periods increase the GWP_{bio} impact since the carbon dioxide is in the atmosphere longer before sequestration by the next generation of forest at the stand.

Another assumption used in the thesis was that only fresh fibre is used which gives a higher impact. Recycling cellulose fibre from biomass is common and where used the GWP-impact is distributed over each use of the fibre. This would result in lower impact of biogenic carbon for the tissue product since the biogenic carbon is the cellulose fibre which is reused. The fossil carbon emission impact will probably increase in absolute terms over all the lifecycles of the fibre since energy is required to reassembly products but decrease per tissue product.

Another assumption was that the tissue product is combusted immediately when the forest is harvested, and the emission can be approximated as a pulse. Similarly, when approximating a greenhouse gas' radiative forcing, a pulse is also assumed, making the real case like the model. However, when wood is harvested there are lag times between harvest and use. Furthermore, tissue products that are sourced from the landscape will not all be used simultaneously, and the emission will not approximate a pulse. Some tissue products will be used immediately, and some will be stored, meaning that the emission from the combustion of the tissue products are probably more normally distributed than the approximated pulse assumed when calculating GWP. Since the GWP_{bio} method's impact is sensitive to how long time the carbon spends in the atmosphere the distribution and timing of the emissions is important. The timing and distribution of the emissions in a stand perspective changes the fluxes between the different sinks. Since the carbon has impact until it is completely reabsorbed in the next generation of forest at the stand the impact will be hard to predict. The timing and distribution are likely important for the landscape perspective as well, but with a landscape perspective, storing carbon in products is beneficial as the carbon causes no impact when it is stored. The landscape perspective is also easier to comprehend with respect to timing and distribution of emissions as it is the net flows from the different environmental sinks and sources that are multiplied with the characterization factor.

LCA, which was chosen as a tool to analyse impact, also has its limitations. LCA was used as a tool since Essity utilizes it to assess their product's environmental performance and the results from this thesis would then be easier to communicate. It was also picked in order to make the problem less abstract by comparing the results and calculations to the tissue product. However, it is important to realize that LCA is not a complete measure of environmental impact, and in this study only GWP was studied quantitatively. Another issue within LCA was that the 100-year time frame may be limiting when considering forest landscapes. The results and analysis show that a landscape perspective is preferable to the circumstances of this theses and a longer perspective may be needed. Another issue to consider in LCA is the context of the data that are used, especially when considering large scale systems such as the productive forests in Sweden. The data that were collected and used for the original tissue product were not examined in detail, and there may be conflicts in the data's context when comparing to the analysis done in the thesis.

4.4 Data uncertainty

The estimated random error in sourced wood volumes on the national scale is 8.0 %, which is estimated through statistical analysis (SLU, 2018a). The errors occur as a consequence of the random sampling when collecting forest data by the SNFI (SLU, 2018a). The SNFI also expects data to be influenced by systematic error, but the size of the error is difficult to quantify (SLU, 2018a). Furthermore, most of the forest data are presented as averages over 3 or 5 years in order to reduce the random error. This is particularly important at the regional level as there are fewer measurements and statistical basis for the measured volumes (SLU, 2018a). The random errors affect the standing volumes and the areas from which the harvesting occurs, both at the national level and the regional level. Since most of the analysis is done on a regional basis, that is N. Norrland, S. Norrland, Svealand and Götaland, the error could be significant, but no analysis was done to quantify this error in the thesis.

It is difficult to measure soil carbon changes and therefore to get a trend from the data. This is due to the relatively small changes in annual carbon flows compared to the size of the carbon stock. In northern boreal forests the annual carbon stock change has been estimated to be less than 1% of the total carbon stock (Ågren et al., 2008; Ortiz et al., 2013; Peltoniemi et al., 2006). This makes it hard to make conclusions on changes in soil carbon stocks from measurements as the uncertainties can be of the same magnitude as the change (Ortiz et al., 2013). These uncertainties arise from systematic errors, measurement errors and the large spatial variation of soil carbon (Ortiz et al., 2013). In order to minimize the errors, and to perform calculations that yield reliable results, a large sample size of data is required (Birdsey, 2004). By the same token, applying large scale sampled data on a specific location may also yield erroneous results because of the large spatial variation in soil carbon (Birdsey, 2004). Comparing to the thesis, the soil carbon change data were taken from a wide variety of sources with large spatial boundaries with most of them focusing on Swedish productive forestland. The soil data is therefore best suited to be applied at the national level. In other words, the soil carbon data obtained are better suited for the landscape perspective rather than the local stand level perspective. Birdsey (2004) mentions that developing equations or models for local circumstances may give better results on specific locations, where aggregate data should not be applied. This alternative may be a better alternative for assessing soil carbon changes in with a stand assessment.

4.5 Method uncertainty

On a spatial scale, the stand level perspective focuses on specific forest management procedures such as final felling or thinning over a few harvest cycles, Cintas et al (2017) suggested that a landscape perspective can be of greater utility when a constant flow of wood is desirable from the landscape (Cintas et al., 2017). The large net flows in and out of the stand level system depending on whether growth or harvest is occurring is not observed at the landscape level where the emission of newly harvested plots are sequestered by the forest in the surrounding landscape (Cintas et al., 2017). Temporally, the stand level approaches often assume that the biomass is burned at the start of the assessment period and the stand is therefore in a state of ‘carbon debt’ until the forest has fully regrown. The World Bioenergy Association (2012) (WBA) has criticised this viewpoint as it assumes that the biomass is burned before it is grown, which is unrealistic (World Bioenergy Association, 2012). The stand level approach has also been critiqued of using too narrow spatial and temporal boundaries and the greater picture is overlooked. The carbon that is absorbed at the local stand is carbon that has been emitted by previous stands at other locations and is a part of the carbon cycle (World Bioenergy Association, 2012). Furthermore, the GWP_{bio} method only assesses the burned biomass and does not consider soil carbon changes. In the thesis the soil carbon impact is simply added to the impact of the GWP_{bio} method to establish the relative size of soil carbon sequestration. Ideally the GWP_{bio} method could be extended to include soil carbon.

5. Conclusions

To conclude, no direct or indirect land use change was found in productive forestlands in Sweden therefore no impacts from LUC was attributed. The biogenic carbon impacts attributed to the occupation of the land was investigated and for the landscape perspective the soil sequestration impact, was -7% of the reference emission. In other words, the soil sequestration offset 7% of the impact from the reference LCA. The corresponding value was -13% for the stand level perspective, with negative values denote sequestration of carbon. The difference between the perspectives is attributed to the spatial boundaries, resulting in lower volumes of wood sourced per hectare and higher soil carbon sequestration per hectare in the stand level perspective. This gives unrealistic results that are misleading: the soil carbon sequestration impact is magnified.

The accuracy of the soil data is hard to assess since it has large uncertainties especially due to spatial variation and measurement uncertainty. The results from allocating soil carbon to the tissue product in the thesis should therefore not be interpreted as definite but as approximations of relative size of the impact. The soil data should be interpreted in its context as spatial and temporal boundaries affect the outcome. The landscape perspective matches the temporal and spatial boundaries to a greater extent than the stand perspective and is therefore more likely to give accurate results.

Criteria in the two forest certification schemes FSC and PEFC were general and measures to protect soil carbon was not mentioned explicitly. However, both FSC and PEFC contained criteria that could be interpreted as safeguarding soil carbon. Criteria in the certification systems highlight sustainability, which soil carbon can be interpreted to be essential to. Other silvicultural practices which overlap with the certification criteria include leaving harvesting residues, increasing productivity and minimizing soil disturbances.

Further studies would need to be done to investigate whether it is reasonable to attribute soil carbon in this manner. The main issue would be to investigate whether the soil carbon changes are permanent or transient. Also, studies analysing the impact of methane and nitrous oxide with a landscape and stand level assessment could also be beneficial as carbon dioxide is the only greenhouse gas analysed in the thesis, which is only one part of the total GHG impact of the forest system.

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7. Appendix A

Essity is a leading global hygiene and health company dedicated to improving well-being through products and solutions, essentials for everyday life. The name Essity stems from the words essentials and necessities. Our sustainable business model creates value for people and nature. Sales are conducted in approximately 150 countries under the leading global brands TENA and Tork, and other strong brands, such as JOBST, Leukoplast, Libero, Libresse, Lotus, Nosotras, Saba, Tempo, Vinda and Zewa. Essity has about 47,000 employees and net sales in 2018 amounted to approximately SEK 118.5bn (EUR 11.6bn). The headquarters is located in Stockholm, Sweden, and the company is listed on Nasdaq Stockholm. More information at www.essity.com.

8. Appendix B

Statistical distribution of soil carbon sequestration when applied to the assessed regions.

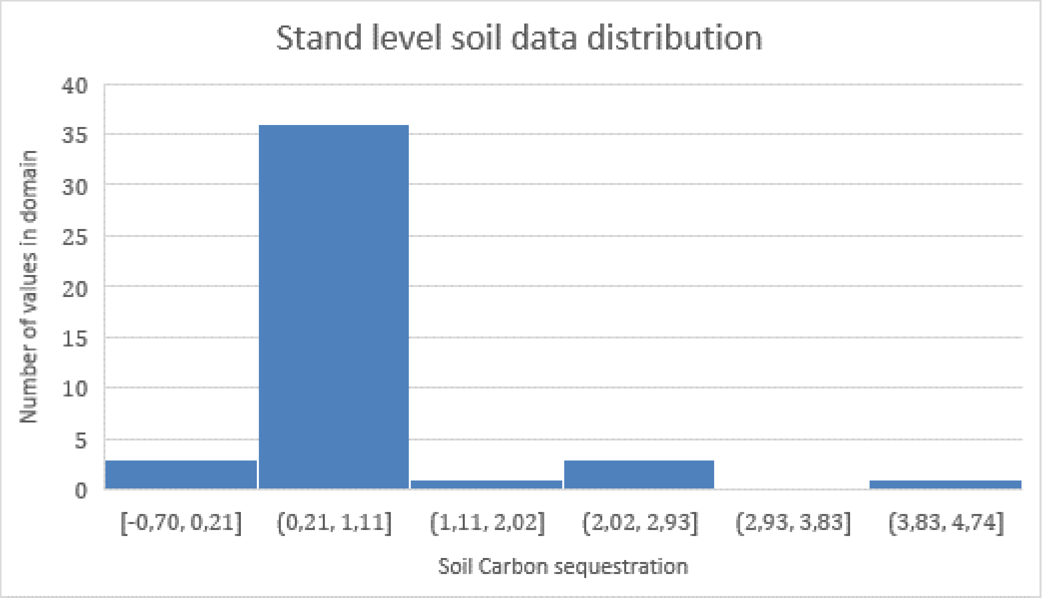

Figure 18: Statistical distribution of the soil data when factored in with the regions, at the stand level

Six equally sized bins to show the distribution of soil data, similarly for the landscape level:

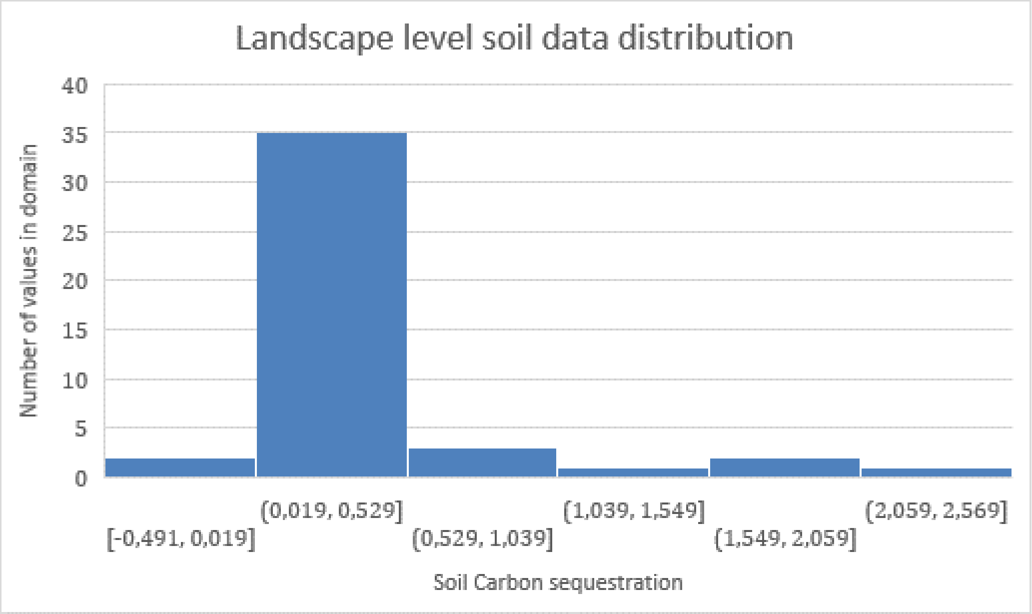

Figure 19: Statistical distribution of the soil data when factored in with the regions, at the landscape level

The number of datapoints are the same in both analyses and the domains are of equal size percentually. The most data is centred around the mean in both cases, but outliers exist in both perspectives

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Gothenburg, Sweden 2019