CHALMERS
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Overcoming limitations in life cycle assessment of bio-based products

A case study of Bermocoll produced by AkzoNobel

Master's thesis in Industrial Ecology

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Gothenburg, August 2015

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Abstract

Renewable resources have become a key concept within the field of sustainability as a means to reduce greenhouse gases (GHG) and to minimize the dependency on fossil alternatives. To quantify the benefits from an increased use of renewable materials is essential for companies as it enables the communication of environmental results. Such quantification can be performed with life cycle assessment (LCA) since it is possible to evaluate the environmental performance of a product for its whole life cycle. However, aspects identified in recent research, which are rarely accounted for in LCA of bio based products, target limitations in the LCA methodology. The exclusion of these aspects increases the risk of an incorrect interpretation of the product's environmental performance. This study has therefore investigated how the climate impact for a bio based product, exemplified with AkzoNobel's cellulose ether Bermocoll, differs if unconventional aspects like *timing of emission, carbon sequestration including credits for carbon stored in the product, biogenic carbon emissions, soil disturbances* and *the albedo effect* are included in an LCA. Further, the appropriateness of incorporating the aspects into an LCA of Bermocoll was evaluated.

For Bermocoll, two LCAs were conducted, one according to common LCA practices and one assessment including unconventional aspects, which were identified in literature as suitable to incorporate in LCA methodology. The method used in the assessment according to common practise was under the assumption of climate neutral biogenic carbon dioxide emissions. The unconventional impact assessment method included the following aspects: timing of emissions, carbon sequestration including credits for carbon stored in the product, biogenic carbon emissions, soil disturbances and the albedo effect. This was done in order to evaluate whether such aspects are possible and important to include in an LCA assessment for Bermocoll. When the results from the two assessments were compared, only a minor difference in climate impact for Bermocoll was seen. This result indicates that the biogenic carbon emissions linked to Bermocoll' s life cycle are indeed climate neutral, which was assumed in the assessment based on common practise. However, this conclusion can only be drawn for assessments under the same assumption as in this study and for similar systems. Moreover, it was concluded that the accuracy of the results are highly dependent on the availability of site-specific data and if the product under consideration has a well-described end-of-life. Although this study proved the feasibility of including some unconventional aspects in climate impact assessment of bio based products, a greater range of products need to be assessed before the potential for incorporating these aspects into LCAs can be entirely evaluated.

KEYWORDS: Bio-based products, life cycle assessment, carbon stored in product, climate neutrality, carbon sequestration, soil disturbances, timing of emissions, albedo effect.

Abbreviations

AOGCM – Coupled Atmospheric Ocean General Circulation Model

CFC – Chlorofluorocarbons

CH_4 – Methane

CO_2 – Carbon dioxide

EoL – End-of-Life

GHG – Greenhouse Gas

GWP – Global Warming Potential

GWP_{albedo} – GWP for albedo

GWP_{bio} – GWP for biogenic CO_2

ILUC – Indirect Land Use Change

IPCC – Intergovernmental Panel on Climate Change

IRF – Impulse Response Function

LCA –Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

N_2O – Nitrous Oxide

NEP – Net Ecosystem Productivity

NPP – Net Primary Production

SOC – Soil Organic Carbon

WTH – Whole tree harvest

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1 Introduction

Within recent years, climate change has been given an increased focus. There is a need for a reduction of greenhouse gas (GHG) emissions in order to mitigate the climate impact and to become more sustainable (Brandão et al., 2013). Bio-based products will play an essential role towards a more sustainable society since they can be used as a replacement of fossil fuels and reduce the dependence of non-renewable resources. It is therefore likely that the production of forest products and biofuels will increase (Røyne et al., 2014). However, a replacement of non-renewable resources to renewable alternatives can also bring negative effects. One example is that an increased use of biomass might reduce carbon stocks, which would result in a temporary increase of CO_2 in the atmosphere until the forest is regrown (Brandão et al., 2013) (Helin et al., 2013). It is therefore important to properly assess the environmental performance of a bio-based product in order to fully understand the impact it has on the environment (Røyne et al., 2014).

A life cycle assessment (LCA) can be used to assess the environmental performance of a service or a product (Baumann and Tillman, 2004). However, recent research has noted methodological shortcomings when bio-based products are evaluated, which result in problems to capture the products' dynamic carbon flows. Several authors have identified aspects, usually not included in common LCA studies of bio-based products, that can have a significant impact on the result (Helin et al., 2013, Brandão et al., 2011) (Bright et al., 2012) (Røyne et al., 2014) (Guest et al., 2013a) (Brandão et al., 2013). Some of these aspects are timing of GHG emission, carbon sequestration including credits to carbon stored in the product, biogenic carbon emissions, climate impact from soil carbon disturbances and the climate impact of the albedo effect. These aspects can influence the result in both a negative and positive way (Bright et al., 2012) (Røyne et al., 2014) (Guest et al., 2013a). If theses aspects are excluded there is a risk that the environmental benefits with forest-based products are over- or underestimated. It is therefore of interest to study how the environmental impact of a bio-based product will change if these aspects are included.

2 Background

AkzoNobel is a major producer of speciality chemicals and one of the leading producers of paints and coatings in the world. Sustainability is a core value within AkzoNobel's business and they are one of the leading industries in the Dow Jones Sustainability Indices (Dow Jones Sustainability Indices, 2014), an index for global sustainability benchmarking who tracks the world's leading companies' economic social and environmental performance (Dow Jones Sustainability Indices, 2015). It has become more important to incorporate sustainability into the business during the recent years, since the cost of environmental impacts is expected to grow over the next years. Resources are getting more scarce and it is likely that governments will implement stricter legislations and policies regarding sustainability in a not too distant future. If companies do not work towards a more sustainable business there is a risk that they will lose competitive advantages since the cost of fossil fuels, energy and water are expected to increase and due to a damaged reputation (KPMG, 2012). There are many ways in which a company can work with sustainability. One way is to perform an LCA in order to evaluate their products or services from an environmental perspective.

Performance additives, a sub business unit within AkzoNobel, is producing high quality cellulose derivatives, speciality polymers, redispersible polymer powders and specialty additives and have business within paint and building and construction (AkzoNobel, 2015a). One of their products is Bermocoll, a product used mostly as a thickener, stabilizer and water-retaining agent for water based decorative paints as well as for building products (AkzoNobel, 2015b). The main component in Bermocoll is cellulose derived from wood or cotton (AkzoNobel, 2015c). As mentioned sustainability is a key value for AkzoNobel and Performance additives wishes to get more insight of the environmental performance of Bermocoll, produced at their production site in Örnsköldsvik. A comprehensive assessment of Bermocoll, where also unconventional climate aspects related to bio-based products are incorporated into an LCA, is therefore of interest to conduct.

2.1 Purpose

The aim of this Master thesis is to assess how the climate impact for AkzoNobel's product Bermocoll differs if several aspects are accounted for which are often excluded in LCAs. Further, the feasibility and relevance of implementing these aspects in an LCA for Bermocoll is evaluated.

From this, three goals are developed:

- The first goal is to identify and gain knowledge about these aspects through a literature review, and identify methods, suitable for integration of the aspects into LCA.
- The second goal is to conduct an LCA and calculate the climate impact for Bermocoll when the aspects are incorporated and evaluate if and how the result differ from an assessment where the aspects are not included.
- The third goal is to assess if the aspects are relevant and feasible to implement into an LCA of Bermocoll.

2.2 Delimitations

The overall delimitation for the study is stated in this section. Delimitations and limitations for the case study can be found in chapter 4.4.8 Case study limitations and delimitations.

- Sustainable development is consisting of three main areas, economic development, social development and environmental protection. The thesis focuses on the environmental part, the two other parts will not be examined.
- There are many impacts categories that can be evaluated in an LCA. In this thesis the focus has been on examining the impact that Bermocoll has on climate change. Therefore, only aspects that contribute to global warming, in either a positive or a negative way, are examined.
- The GWP_{bio} metric, which is used in this study to incorporate the unconventional aspects of carbon sequestration including credit to carbon stored and biogenic carbon emissions are limited to assessing biogenic carbon dioxide. Other GHG emissions are therefore assessed with the standard GWP metric used in common LCA practice.

2.3 Method

The procedure for carrying out this project is described below as well as the data that has been used and how it has been gathered. Based on recent findings within the field of LCA, an area of research

for this project was established, a process that was facilitated by the examiner at Chalmers university of Technology and the supervisors at AkzoNobel. A comprehensive literature study was conducted in order to identify and better understand aspects not commonly included in climate impact assessment in LCAs. The main focus was to find articles that described and identified aspects further and suggested ways to assess the climate impact related to them as well as identify essential data for the impact calculations. From literature, a couple of methods were selected for aspect implementation into LCA and the site specific information these methods required were obtained from questionnaires sent to Performance additives cellulose suppliers. However, additional generic data from literature was used when supplier information was insufficient. As a means to examine how the unconventional aspects would influence the result from an LCA, a case study was performed on AkzoNobel's product Bermocoll. Supervisors at AkzoNobel and other employees provided Bermocoll specific information, additional data sources were also obtained from previously performed studies. The LCA was based on ISO 14040 standard and conducted in the LCA software GaBi, a tool that was introduced by AkzoNobel's sustainability department in Bohus, who continued to support the project whenever needed. The aspect related calculations were performed in Matlab and in Excel and thereafter implemented as an extension of the assessment performed according to common praxis.

3 Theory

The theory chapter is divided in two main parts and will act as a basis for the case study. The purpose of the first part is to clarify tools, theories and concepts used within the study. The second part introduces the unconventional aspects that are identified.

3.1 Climate change

Earth's climate system is highly related to the solar radiation and the factors that influence the solar radiation. The average amount of energy that reaches the top of the atmosphere over the entire planet is 342 W/m^2, of which approximately 30% is reflected back to space. Most of this reflected solar radiation, two-thirds, is reflected back due to clouds and aerosols (small particles in the atmosphere). The rest is reflected by light-coloured surfaces of the Earth, like snow and ice-covered land areas. The energy that is not reflected back to space is absorbed by the atmosphere and surface (IPCC, 2007b). The Earth is emitting about the same amount of energy in longwave radiation back into space as a way to balance the incoming energy flow. A part of this energy is emitted back to Earth due to greenhouse gases that act like a blanket for longwave radiation. The blanketing effect is also known as the natural greenhouse effect (IPCC, 2007b).

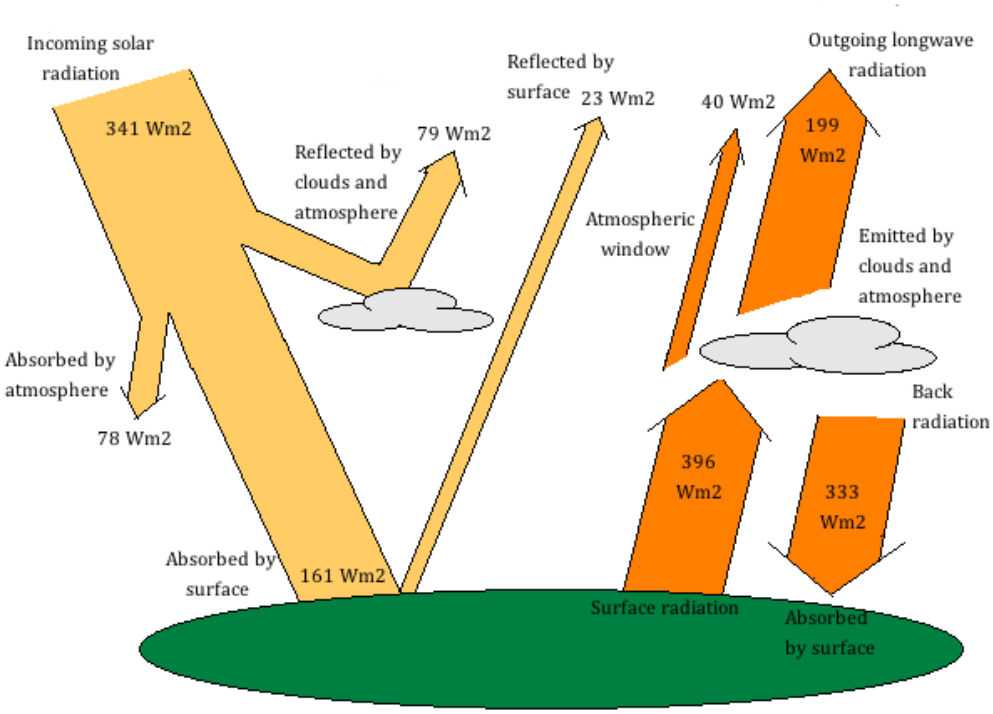

Figure 1 Earth's global mean energy flows (Kiehl and Trenberth 1997)

There are principally three ways that the radiation balance of the Earth can change.

1. If there is a change in the incoming solar radiation
2. If there is a change in the fraction of solar radiation reflected back to space. This can occur due to changes in e.g. cloud cover, atmospheric particles and vegetation
3. If there is a change in the longwave radiation from Earth back to space, which can occur due to a higher concentration of greenhouse gases in the atmosphere (IPCC, 2007b).

Human interference and volcanic eruptions can disturb the GHG balance in the atmosphere and thereby also the amount of radiation that is re-emitted (IPCC, 2007b). Gases that contribute to the greenhouse effect include water vapour, carbon dioxide, methane, nitrous oxide and chlorofluorocarbons (CFCs) (NASA, 2015a). Different GHGs have different capacities to absorb longwave radiation, and thus heat, in the atmosphere (Baumann and Tillman, 2004). Water vapour is the most abundant greenhouse gas and it is involved in the natural climate regulation. An increase of Earth's temperature will increase the amount of water vapour in the atmosphere. The possibility of cloud formation will also increase with increasing amount of water vapour (NASA, 2015a). Clouds can have an blanketing effect but that is generally offset by their reflectivity (IPCC, 2007b). Carbon dioxide can be released to the atmosphere both due to natural events like volcanic eruptions and by human activities such as burning of fossil fuel, deforestation and land use change. Since the industrial revolution, carbon dioxide levels in the atmosphere have increased with about one third due to human activities. This makes carbon dioxide one of the greenhouse gases that have the most influence on global warming (NASA, 2015a). Methane is a more active greenhouse gas than carbon dioxide but it is short-lived and not as abundant in the atmosphere. Methane is released to the atmosphere both by natural and human activities. Another powerful greenhouse gas is nitrous oxide. It is mainly emitted to the atmosphere as an effect of cultivation of crops and by the use of fertilizers. Chlorofluorocarbons (CFCs) are nowadays strictly regulated and as a result, the presence of CFCs in the atmosphere is declining (NASA, 2015a)

3.2 Carbon cycle models

In order to quantify how large a fraction of an anthropogenic CO_2 emission is still present in the atmosphere after a certain time after release, a carbon cycle model can be utilized. These models simulate uptake and exchange of carbon for different compartments and can be used for calculating the relation between the anthropogenic emission and the CO_2 concentration in the atmosphere (Cherubini et al., 2011a). Oceans are important compartments due to their great carbon absorbing capacity and approximately 15-20% of the CO_2 released to the atmosphere will enter and remain in the oceans permanently. Oceanic circulations determine the uptake capacity and its sensitivity for changes in the global average temperature will probably generate lower rates in the future and result in less carbon in the ocean and more CO_2 in the atmosphere (Joss, 1997). For a better adaptation to terrestrial compartments, turnover rates and initial carbon levels in for example leaves and branches are accounted for, and the atmospheric exchanges are simulated with the net primary production (NPP) (Cherubini et al., 2011a).

One alternative for conducting comprehensive climate change studies is to use the combination of AOGCM (coupled atmosphere ocean general circulation model) and the three-dimensional models of the carbon cycle (Hoos et al., 2001). However, as the AOGCM comprises an extensive data set it is not feasible to use for more simple studies. A better option is then the IRF (impulse response function) that are suitable for all kinds of forcing scenarios. There are a few existing IRF model alternatives and the one used within this study is the *Bern 2.5 CC model* as it considers both terrestrial and ocean compartments (Cherubini et al., 2011a).

3.3 LCA methodology

Life cycle assessment (LCA) is tool for assessing a product's or service's environmental impact during its lifetime and it can act as a tool to support decision-making in research and development projects (Sandin et al., 2014). Since an LCA accounts for all stages in a product's lifetime, from

cradle-to-grave, it can be used to identify “hot-spots”, i.e. activities that cause the greatest environmental impact. It is also a suitable tool when comparing the environmental burden of two different products or services or when evaluating alternative actions in the product's life cycle (Baumann and Tillman, 2004). An LCA study is called accounting if the focus is to determine the studied product’s or service’s environmental load during its lifetime. If the focus is instead to assess the environmental impact of alternative options for a product it is called a change-oriented LCA (Baumann and Tillman, 2004). An international standard, ISO 14040, has been developed as guidelines for how to conduct an LCA and address what an LCA should include (Baumann and Tillman, 2004).

The life cycle assessment method is divided into four different phases - goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation. The first phase of an LCA is the goal and scope, which states the purpose and goal of the study and the system or product that will be evaluated. In addition, the functional unit is defined as well as the system boundaries, data requirements and delimitations. The second phase is LCI, where data collection makes possible the determination of the system flows and a calculation of emissions from each life cycle stage is conducted. During the impact assessment, the environmental burden for a product or service is calculated related to a certain impact category. The result from the inventory is multiplied with characterisation factors unique for each impact category and the emission within the impact category. This is done in order to increase the understanding of the result from the LCI. Non-mandatory parts as weighting and normalization can be conducted at this stage as well. The last phase is the life cycle interpretation. At this phase, the results and data from the previous stages are quantified and evaluated. Additionally, it is during this stage that results are concluded and communicated. An LCA is an iterative process and the steps are interrelated, there might therefore be a need to move between and return to previous steps, see figure 2 (Baumann and Tillman, 2004).

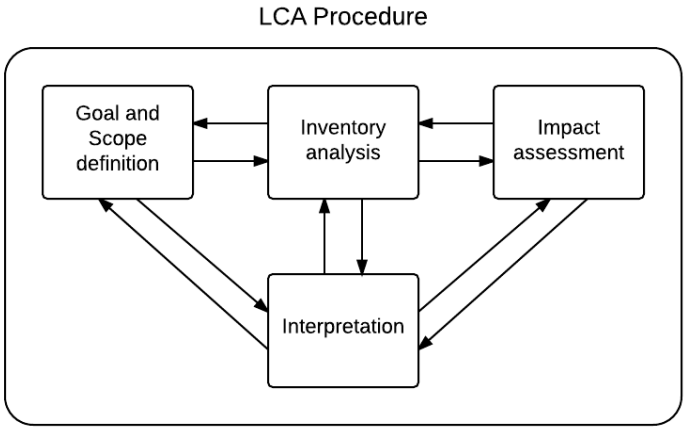

Figure 2 The four phases of the LCA procedure (Baumann and Tillman 2004)

3.3.1 Characterisation methods

Characterisation methods are used to transform the environmental load from emission (or resource use), related to a product or service, into impact categories. By using equivalency factors, also called characterisation factors, emissions that affect the same impact category can be compared and summarized. The characterisation factors are scientifically based and derived from physical-chemical

properties of the different substances (Baumann and Tillman, 2004). The only impact category considered in this study is global warming; other impact categories are therefore not addressed.

Global warming potential (GWP) is a metric used to compare the climate impact of different greenhouse gases (GHGs) and it relates the impact of a GHG emission to the impact that an equal amount of carbon dioxide emission would give rise to (KTH, 2014). According to IPCC, the GWP metric "compare[s] the integrated radiative forcing over a specific period from a unit pulse emissions" (IPCC, 2007a). GHGs have different lifetimes and the impact related to them is therefore changing depending on the time frame. GWPs have therefore been calculated for different time horizons where the most common are 20, 100 and 500 years. Most LCA studies use a time horizon of 100 years as default; this is mainly an effect of political decisions and the fact that the time period of 100-years was used in the Kyoto Protocol (Brandão et al., 2013).

As a consequence of the complexity of the environmental systems, several different characterisation models have been developed. This thesis bases the impact assessment on the most widely used and by many seen as the most complete characterisation mode, CML 2001 (with updated values from 2010), developed by the Institute of Environmental Science at the University of Leiden in the Netherlands (Solidworks, 2015). CML groups the LCI results into mid-point categories based on common mechanism, like global warming, or groupings like ecotoxicity. (GaBi, 2015).

3.3.2 Limitations of LCA methodology

Life cycle assessment can be a useful tool from many perspectives. However, several problem areas within LCA methodology have been identified by e.g. Reap et al. (2008a), where the most severe are allocation, spatial variation, local environment and data availability and quality. According to Baumann and Tillman (2004), allocation problems occur as a result of multifunctional processes where either several inputs or outputs have to share the impact among each other. The consequence might be that the result, and thereby the conclusions, may vary depending on the chosen allocation method. ISO recommends the following procedure for handling allocation problems (Baumann and Tillman, 2004):

1. Avoid allocation by increasing the level of detail or by system expansion.
2. Allocate based on physical relations between materials or products.
3. If physical allocation is not possible, allocate on the basis of other relationships between materials or products, like economic value.

Other critical areas in LCA methodology are the lack of consideration of spatial variations and local environment uniqueness. Spatial variation is for example the difference in topography, meteorological conditions and geology between land areas and local environment uniqueness refers to measures specific for a site, for example soil pH (Reap et al., 2008a). An emission can be more harmful in one place than on another as the local ecosystem can react differently to emissions, as a result of different spatial conditions and local environmental uniqueness. Inaccurate estimates of potential environmental damage can be a result of not taking the above into account (Reap et al., 2008a). The lack of data of high quality is one of the major reasons to uncertainties in LCA studies, which may be a result of data gaps, poorly measured data and unrepresentative data. Lack of ability to represent the accurate impact of the product or service examined in the LCA study can be an effect of low quality data (Reap et al., 2008a). It is important for LCA practitioners to be aware of data gaps and data quality issues and ensure transparency in the data communicated.

The fact that LCA does not assess social or economic impacts limits the tool's comprehensiveness. The exclusion of these areas is problematic if the purpose is to assess the sustainability of the product (Reap et al., 2008b). Recent studies (Brandão et al., 2013) (Helin et al., 2013) (Røyne et al., 2014) have also identified that when it comes to assessing forest and bio-based products, the LCA methodology is limited, which reduces the capacity for managing the carbon flows in a product system. The accuracy of the assessment may therefore be questioned and it may lead to that inefficient products are supported (Røyne et al., 2014).

3.4 Unconventional aspects

In this part of the theory chapter, aspects that can have a significant impact on the LCA result are presented in more detail. These aspects are not usually included in LCA studies of bio-based products.

3.4.1 Timing of biogenic carbon and carbon neutrality

Life cycle assessment studies have as a standard a fixed time horizon of 100 years when impact calculations are performed (Røyne et al., 2014). There is a risk that with such standardization, the relative importance among the different GHGs induces a factor of uncertainty when the result is interpreted. A short time horizon of 20 years ignores impacts forward in time and short-lived GHGs will, be assessed with a higher importance relative to long-lived GHGs, as the greenhouse effect already has occurred then. With a long time horizon of 500 years, a higher relative importance is assigned to long-lived GHGs (Levasseur et al., 2010). Another problem with fixed time horizons is the inability to account for timing of emission (Røyne et al., 2014). With a fixed time horizon of 100 years, the impact of an emission, released 50 years after the time for which the study is made, is integrated from 50 to 150 years. This interval is however not consistent with the chosen 100-year time horizon for the study and the impact for the delayed emission will therefore not represent the study under consideration (Levasseur et al., 2010).

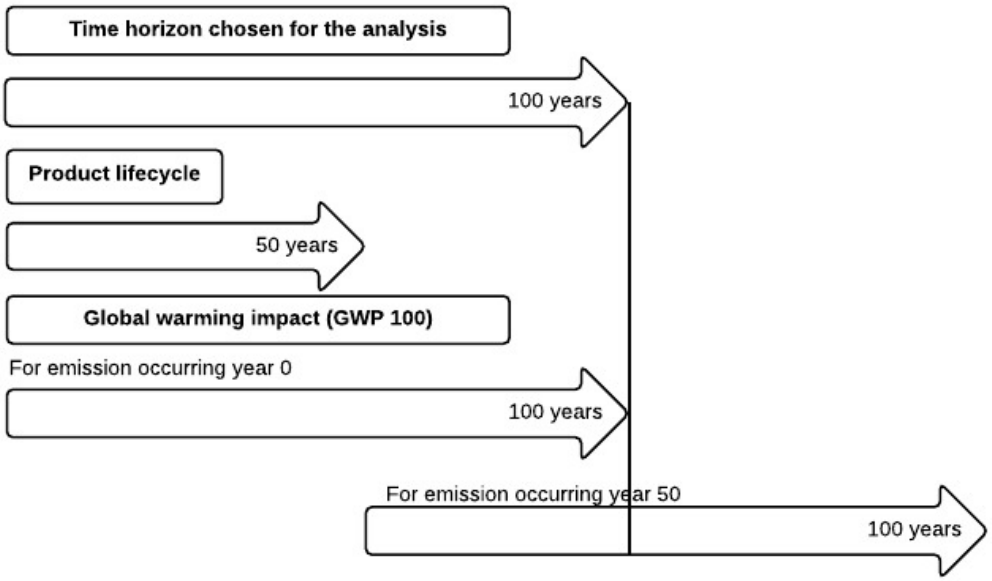

Figure 3 Inconsistency in time frames for global warming LCIA with example of a 50 years lifetime of a product.

To overcome timing problems, a characterization method called dynamic LCA, with flexible time horizons is proposed by Levasseur et al. (2010). Instead of a fixed time window, the integration

interval for each emission pulse is determined by the time of its occurrence in the life cycle (Røyne et al., 2014). Timing of emissions can also be taken into account by giving credits to carbon temporary stored in bio-based products for the avoided radiative forcing it implies. Stored carbon is also beneficial since there is a possibility for developing more efficient mitigation technologies during the storage period which may reduce the amount of carbon released at the product end of life (Levasseur et al., 2013). However, when the temporarily stored carbon is sequestered, it reduces the CO_2 gradient between the atmosphere and the carbon reservoirs. It entails that less carbon is stored in the reservoirs and more carbon is present in the atmosphere, thus higher CO_2 concentration is achieved when the temporarily stored carbon is emitted compared to non-temporary storage. The risk for passing critical tipping points increases and can be altered even further if the climate has become more sensitive to perturbations during the storage period. Therefore, it is essential to account for timing of the impact that also facilitates the establishment of more efficient temporary carbon sinks, closer in time to the impact (Kirschbaum, 2003). Discounting of emission is one method for considering the timing of the impact; it is not necessary, though, if just a short time perspective is chosen for the study (Røyne et al., 2014).

The assumption that the amount of biogenic carbon dioxide sequestered at the forest level equals the amount of biogenic carbon dioxide emitted at the product's end of life is commonly accepted by LCA practitioners and entails that biogenic carbon can be considered carbon neutral. This is a controversial assumption, which lack consistency with reality as the reduction in carbon stocks during harvest is ignored. Carbon neutrality does not imply a climate neutral system, since the lack of timing between the carbon sequestered and the emission released at the product's end of life temporarily increase the CO_2 concentrations in the atmosphere (Røyne et al., 2014).

3.4.2 Indirect land use change

Indirect land use changes (ILUC) is described as "When there is a competition for land, land use at one location could displace an alternative use of land to another location where it can cause land use change, referred to as indirect land use change" (Røyne et al., 2014). An increased demand for cotton in a country can for example result in indirect land use change as the competition for land at one place may force food growing farmers to transform a piece of land somewhere else into food crops, which can result in emission of a significant amount of carbon, especially if the land converted into food cropland formerly were a natural forest or grassland. Emissions from indirect land use change are commonly excluded in life cycle assessment, as these emissions are difficult to quantify with existing methodology (Røyne et al., 2014).

3.4.3 The albedo effect

Biogeophysical effects like changes in evapotranspiration, surface roughness and albedo can have a significant effect on the Earth's surface temperature (Jorgensen et al., 2014). Of these biogeophysical effects, changes in surface albedo has been identified as the greatest impact contributor to temperature variations on a global scale (Cherubini et al., 2012a).

The albedo effect can be described as the ratio at which sunlight is reflected from the Earth's surface back into space. The albedo effect is greater on snow covered surfaces and clear-cut land since these are white and smooth and absorb less solar radiation, while dark surfaces like oceans or forestland absorb more solar radiation. The albedo is measured on a scale from 0 to 1, where 0 is total absorption and 1 is total reflection (Bright et al., 2012). The albedo can have a substantial effect on global warming and vice versa. If the temperature rises, ice and snow covered surfaces will decrease and more land and ocean will be uncovered, which has a lower albedo due to that it leads to a darker

surface. The effect will be that more solar radiation is absorbed and surface and water temperature will rise even further and more ice will melt as a consequence; this is called a positive feedback. On the other hand, since the albedo can have a cooling effect on surfaces that are light and smooth, it can play a significant role when it comes to the climate impact from forest-based products, due to the fact that forest products are related to land use and may lead to land use change (Cherubini et al., 2012a) (Røyne et al., 2014). When a forest is harvested, it can create a cooling effect since clear-cut surfaces has a higher albedo than a forest. Another aspect is that open landscape generally has more snow coverage than forested land, which also causes a higher albedo effect (Bright et al., 2012). Since the albedo effect can influence the global warming for bio-based products, it can be important to address the albedo changes in LCA studies concerning those types of products, something that is not commonly done today (Røyne et al., 2014).

3.4.4 Soil carbon disturbances

Excluding impacts from below ground carbon pools have been identified as a common procedure in life cycle assessment (Røyne et al., 2014). These carbon pools store a lot of SOC (soil organic carbon), which can be emitted to the atmosphere depending on the land use and the management practice in place. In a short term perspective, a fossil based product can be favourable, from a climate impact point of view, compared to a renewable alternative, if soil carbon emissions are taken into account (Guest et al., 2013b).

Soil carbon changes in a managed forest is affected by the final felling but contributions from other management practices also need to be accounted for (Winiewisk and Lugo, 1992). One other management practice which effects the soil carbon levels is the decision to either leave forest residues it on site to decompose or remove it (Guest et al., 2013b). There are one main harvesting technique commonly used in forest management called clear cutting and one alternative method is whole tree harvesting (WTH) (Roxby et al., 2015). WTH removes all above ground biomass including residues, while clear-cutting only extracts the stem. On a clear-cut site, forest residues are thus left to decompose, which is not the case for WTH (Johnson et al., 2002) (Timmermann and Janka, 2014). According to Repo et al. (2011), it is a more favourable practice from a soil carbon perspective to leave the forest residues to decompose. However, emissions occurring from the decomposition of residues are important to account for, as it is the main emission source when residues are left on site (Kilpelainen et al., 2011) Quantification of these emissions is possible with the help of ecosystem models like SIMA, Coupmodel or Yasso07 (Svensson et al., 2008) (Kilpelainen et al., 2011) (Didion et al., 2014). Representative outputs are only achieved when the models are calibrated with site-specific input parameters and it is therefore useful to first conduct a comprehensive data inventory over the site under consideration (Svensson et al., 2008).

4 Methodology

This chapter presents the methodologies used to compute and incorporate the aspects into the LCA study, which are described in the theory chapter 2.4.

4.1 GWP_{bio}

How to quantify the climate impact for biogenic carbon is not obvious and different guidelines can be found in the existing literature. The most common approach is to assume that biogenic carbon has zero impact and thus is climate neutral. One alternative recommendation is to not distinguish between fossil and biogenic carbon, which then are assigned the same impact. However, it can be argued that a biogenic emission pulse results in a temporary increase of CO_2 in the atmosphere, which is not accounted for in these two approaches (Cherubini et al., 2011a).

Cherubini et al. (2011a) propose a climate metric, GWP_{bio}, developed with the purpose to quantify the climate impact of a biogenic emission pulse without ignoring its residence time in the atmosphere. The GWP_{bio} metric relates the time evaluation for the instantaneous radiative forcing from a pulse of biogenic CO_2 to the radiative forcing of the same amount of anthropogenic CO_2 over a fixed time horizon (Cherubini et al., 2012b). The metric generates characterisation factors, in the same way as regular GWP factors that are to be multiplied with the amount of biogenic carbon emissions in order to obtain the GWP in CO_2 equivalents. The metric GWP_{bio} can be applied on all biomass types and it is site specific as it depends on the biomass rotation period. The methodology was developed under the conditions that an evenly aged biomass stand is clear cut and directly revegetated with the same biomass type after harvest (Cherubini et al., 2011a).

A more detailed presentation of the GWP_{bio} metric and how it is computed is presented below as is also an extension of the method that incorporates storage of CO_2 in products. The GWP_{bio} metric is calculated through:

$$GWPbio = \frac{C_0 \int_0^{TH} \alpha_{CO_2} f(t)}{C_0 \int_0^{TH} \alpha_{CO_2} y(t)} \quad (1)$$

where $y(t)$ is the IRF (impulse response function) or decay function for an anthropogenic emission, $f(t)$ is the IRF or decay function for a biogenic emission, C_0 is the intensity of the emissions and α_{CO2} is the radiative efficiency of CO_2 (Guest et al., 2013a).

4.1.1 IRF for anthropogenic emission pulse

Impulse response functions (IRF) determine the fraction of an emission that is still present in the atmosphere at any time after the release (see chapter 2.2. Carbon cycle models). The emission will degrade along an exponential path as a result of carbon uptake in different compartments. The IRF for an anthropogenic CO_2 emission is in this case simulated with the Bern 2.5 carbon cycle model recommended in IPCC's fourth assessment report, which is seen in equation (2) (Cherubini et al., 2011a).

$$y(t)_{CO2} = A_0 + \sum_{i=1}^{3} A_i e^{-t/\beta_i} \quad (2)$$

A_0 is the asymptotic airborne fraction of CO_2 that remains in the atmosphere because of the equilibrium response of the ocean-atmosphere system, A_i is the relative capacity of the other sinks

that are filled up with atmospheric CO_2, β_i is the rate at which the different sinks can sequester CO_2 and t is the time since the release (Cherubini et al., 2011a).

4.1.2 IRF for biogenic emission pulse

Sequestration in growing biomass results in a more complex IRF function for a biogenic CO_2 emission in the atmosphere. The Bern 2.5 CC model is combined with a growth function to represent the decay of a biogenic CO_2 emission in a more proper way. However, the Bern 2.5 CC model is still applicable in case of no replantation after harvest as sequestration in growing biomass is not possible in such cases (Cherubini et al., 2011a).

The growth function simulates sequestration over rotation periods, namely from replantation until harvest. This enables that the decay function accounts for the temporal increase of biogenic CO_2 in the atmosphere since the exchange between the CO_2 emission and the sequestration is generated over time and combined with the anthropogenic IRF, as can be seen in equation (3) and (4) (Guest et al., 2013a).

$$f(t) = \int_0^t [C_0 e(t') - C_0^* g(t')] y(t - t') dt' \quad (3)$$

or

$$f(t) = \int_0^t e(t') y(t - t') dt' - \int_0^t g(t') y(t - t') dt' \quad (4)$$

where t' is the integration variable from the time since harvest, t is the time dimension, C_0 is the intensity of the emissions, C^* is the intensity of the removal flux, $e(t')$ is the emission function, $g(t')$ is the CO_2 removal rate from the atmosphere due to biomass regrowth, $y(t)$ is the IRF from the Bern 2.5 CC model and $f(t)$ is the fraction of the biogenic CO_2 emission still present in the atmosphere at any time after the release (Cherubini et al., 2012b). The standard case for $f(t)$ is simplified as follows (Cherubini et al., 2011b)

1. C_0 and C_0^* is assumed to be unit pulses and therefore equal to 1. It entails that the system is carbon neutral.
2. The emission function $e(t) = \delta(t)$. A delta function is zero for all points in time despite the one where the release occurs.

$$\delta(t) = \infty t = 0 \quad (5)$$

$$\delta(t) = 0 t \neq 0 \quad (6)$$

3. The delta function has a shifting property

$$\int \delta(t) y(t - t') dt' = y(t) \quad (7)$$

Equation (5) can now be written in terms of

$$f(t) = y(t) - \int_0^t g(t') y(t - t') dt' \quad (8)$$

4.1.3 Growth functions

There are several models that are used in literature for determining the growth in biomass. The GWP_{bio} values can be based on the Gaussian growth model and the Schnute growth model, both will be described in the section below. A normal distribution function, Gaussian, can simulate the growth in biomass, according to the following equation (Cherubini et al., 2011a):

$$g(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(t-\mu)^2/2\mu^2} \quad (15)$$

where the variance σ and the mean μ simulates the forest growth. It is assumed that carbon sequestration reaches maximum capacity after half a rotation which corresponds the mean $\mu = r/2$. The variance describes deviations in distribution from the mean and it is assumed to be $\sigma = \mu/2$.

The Schnute growth model is used to determine the accumulation of carbon in a growing forest and the equation can be seen below (Cherubini et al., 2011b):

$$G(t) = (\alpha + \beta e^{\gamma t})^{\delta} \quad (9)$$

$$\alpha = y_1^b + \frac{y_2^b / y_1^b}{1 - e^{-a(T_2 - T_1)}} \quad (10)$$

$$\beta = \frac{e^{aT_1}(y_2^b - y_1^b)}{1 - e^{-a(T_2 - T_1)}} \quad (11)$$

$$\gamma = -a \quad (12)$$

$$\delta = \frac{1}{b} \quad (13)$$

where t is the time dimension, T_1 and T_2 is the initial and final age, y_1 and y_2 is the corresponding values of the function at T_1 and T_2, a is the constant acceleration in growth rate and b is the incremental acceleration in growth rate (Cherubini et al., 2011b). The function is tailored with values from the IPCC guidelines for GHG inventories. A constant tree density is assumed and the value of y_2 represents the amount of carbon sequestered in above ground biomass under a period of two rotations for a natural forest. The values of a and b are estimated through numerical approximation with the help of two different conditions: that an average amount of carbon of 40tC/ha is stored in the above ground biomass at the end of one rotation and that half of this amount is reached after half a rotation period (Cherubini et al., 2011b). The cumulative growth is obtained from equation (9) but since the growth rate is essential, the following derivate is utilized:

$$g(t) = \rho e^{\gamma t}(\alpha + \beta e^{\gamma t})^{\delta - 1} \quad (14)$$

where $\rho = \delta\beta\gamma$

A third growth model alternative is NEP (net ecosystem productivity), which compared to the previous growth models has the capability to utilize site-specific parameters. The net balance between the amount of carbon dioxide sequestered through photosynthesis and the carbon dioxide emitted through respiration in soil or decomposition of dead wood result in the net ecosystem productivity, NEP. The model simulates the growth in a stand and negative values are normally generated after harvest since the decomposition rate of forest residues exceeds the sequestration in biomass. However, as a consequence of a decreased decomposition rate and more sequestration in biomass, a positive NEP value will be obtained over time (Cherubini et al., 2012a). For simulating growth in biomass, computer based models can also facilitate the calculations. Mutti is a software for stand simulations and it is calibrated after Scottish pine, either in a mixed, young or managed stand. Mutti, can,

compared to the other growth models, simulate different intensity levels of forest management and in addition account for a comprehensive set of carbon fluxes. These fluxes are sequestration in growing stock and carbon released from dead wood including natural mortality and logging residues (Helin et al., 2015).

4.1.4 Carbon stored in product

Guest et al. (2013a) assessed the climate impact of a biogenic pulse emission, delayed due to storage in the antroposphere, which extended the concept of GWP_{bio} to include credits given to carbon permanently stored. A development of the above described decay function, equation (8), is presented based on the same concepts and models and can be seen in equation (16) below:

$$f_{total} = \begin{bmatrix} f1(t) = -\int_0^{\tau} g(t')y(t-t')dt' & 0 \leq t \geq \tau \\ f2(t) = y(t-\tau) - \int_{\tau}^{t} g(t')y(t-t')dt' & t \geq \tau \end{bmatrix} \quad (16)$$

$f1(t)$ is the storage period for which credits are given, starting with replantation and ending when the biomass from the previous rotation period enters the atmosphere through an emission pulse, $f2(t)$ defines the gradual decay of the biogenic emission pulse from τ until the chosen time horizon (TH) where τ is the time spent in the antroposphere, namely the life length of the product (Guest et al., 2013a). The decay function according to Guest et al. (2013a) assumes that there is no delay between harvest and replantation. Guest et al. (2013a) calculates GWP_{bio} values for storage and rotation periods from 0 to 100 years. For a time horizon of 500 years, the Gaussian distribution function is utilized. The GWP_{bio} characterisation values, which account for both the impact from a biogenic pulse emission and storage time, is presented in table 1.

Table 1 GWP_{bio} for a 500 year time horizon

Rotation period (year)	**Storage period in the antroposphere (year)**										
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
1	0.003	-0.012	-0.027	-0.042	-0.057	-0.072	-0.087	-0.10	-0.12	-0.13	-0.15
10	0.008	-0.007	-0.022	-0.037	-0.052	-0.067	-0.082	-0.10	-0.11	-0.13	-0.14
20	0.015	0.001	-0.014	-0.029	-0.044	-0.059	-0.075	-0.090	-0.11	-0.12	-0.14
30	0.023	0.008	-0.007	-0.022	-0.037	-0.052	-0.067	-0.082	-0.10	-0.11	-0.13
40	0.031	0.016	0.001	-0.014	-0.029	-0.044	-0.059	-0.074	-0.090	-0.11	-0.12
50	0.038	0.024	0.009	-0.006	-0.021	-0.036	-0.052	-0.067	-0.082	-0.10	-0.11
60	0.046	0.031	0.016	0.001	-0.014	-0.029	-0.044	-0.059	-0.074	-0.090	-0.11
70	0.054	0.039	0.024	0.009	-0.006	-0.021	-0.036	-0.051	-0.067	-0.082	-0.10
80	0.062	0.047	0.032	0.017	0.002	-0.013	-0.028	-0.044	-0.059	-0.074	-0.090
90	0.069	0.055	0.040	0.025	0.010	-0.005	-0.021	-0.036	-0.051	-0.067	-0.082
100	0.077	0.062	0.047	0.032	0.017	0.002	-0.013	-0.028	-0.043	-0.058	-0.074

In table 1 it can be seen that long storage times in the antroposphere and short rotation periods result in the most negative GWP_{bio} factors and is therefore the best combination from a climate impact perspective. A longer storage time in the antroposphere means that more CO_2 is sequestered in growing biomass, which gives a net reduction in radiative forcing in the atmosphere. Short rotation periods are related to rapid growth and quick sequestration of biogenic carbon released from the end-of-life of a product, which minimize the residence time for the biogenic emission in the atmosphere

and thereby the temporary increase in radiative forcing (Guest et al., 2013a). The net reduction in radiative forcing for which credits are given offsets the temporary increase in radiative forcing in the atmosphere since the delayed emissions are released closer in time to the fixed time horizon and the time spent in the atmosphere is therefore reduced. This results in negative GWP_{bio} values and the biogenic emissions are considered climate neutral. However, it is important to stress that the biogenic emission becomes climate neutral as a result of storage and regardless of storage time, the emission pulse will still initiate a temporary increase in radiative forcing in the atmosphere when it is released at its end of life (Guest et al., 2013a). The general expression for GWP_{bio} according to Guest et al. follows the equation below:

$$GWP_{Bio} = GWP_{BP} - GWP_C \quad (17)$$

where GWP_{BP} is the global warming for a biogenic pulse and GWP_c is the global warming for carbon stored in a product (Guest et al., 2013a)

4.2 GWP_{albedo}

To assess the impact that the albedo effect has on global warming, it can be translated into a GWP characterization factor, GWP_{albedo}, where the radiative forcing that the harvest of 1 m^2 of biomass contributes to, is set in relation to one pulse of 1 kg anthropogenic carbon dioxide emission over the same time horizon (Cherubini et al., 2012a). The method used in this thesis for calculating the GWP_{albedo} metric is based on the methods that Bright et al. (2012) and Cherubini et al. (2012a) present in their papers and it will be presented below. It is assumed that the biomass assessed is harvested via clear-cutting technique, that no thinning takes place before final felling and that biomass is replanted on the site directly after harvest. It is further assumed that the same planting density is applied for all rotations (Bright et al., 2012).

The instantaneous radiative forcing that a change in albedo from biomass contributes to can be described as (Bright et al., 2012):

$$RF_\alpha = -R_{TOA}\Delta\alpha_p \quad (18)$$

R_{TOA} is the incoming solar radiation at the top of the atmosphere (TOA) and $\Delta\alpha_p$ is the change in planetary albedo. The variations in planetary albedo, $\Delta\alpha_p$, is linearly related to the variation in surface albedo, $\Delta\alpha_s$, by a two-way atmospheric transmittance parameter, f_a. The two-way atmospheric transmittance parameter accounts for absorption and reflection of solar radiation in the atmosphere. RF_α can therefore be written as (Bright et al., 2012):

$$RF_\alpha = -R_{TOA}f_a\Delta\alpha_s \quad (29)$$

where $\Delta\alpha_s$ is the difference between the starting albedo (surface albedo of standing biomass) and the new albedo after harvest (albedo of clear-cut surface) (Bright et al., 2012):

$$\Delta\alpha_s = \alpha_{s,new} - \alpha_{s,old} \quad (20)$$

Surface albedo data for a specific location and time period is collected via the MODIS Data Subsetting and Visualization Tool (DAAC, 2015) by using the product BRDF/MCD43A. The MODIS tool provides cloud-clear albedo data for images measured every eighth day from February 2000

(Cherubini et al., 2012a). The two-way atmospheric transmittance parameter is a product of the clearness index, K_t, and an atmospheric transmittance factor, T_a. The clearness index, K_t, is the ratio of the incoming solar radiation at the top of the atmosphere that reaches Earth's surface after reflection from clouds and absorption by the atmosphere. T_a can be described as the fraction of the radiation that is reflected back from Earth's surface that reaches the top of the atmosphere (Bright et al., 2012).

$$f_a = K_t T_a \tag{21}$$

Values for K_t for a given location is collected from a database provided by NASA (NASA, 2015b) which is based on satellite measurements of solar insolation at Earth's surface measured every day from July 1983 to June 2005. An average global value is used for the atmospheric transmittance factor, T_a, of 0.845 (Lenton and Vaughan, 2009). The radiative forcing at the top of the atmosphere, R_{TOA}, is calculated, for given Julian day from 1 to 365, d_i, by the following expression (Bright et al., 2012), where R_{sc} is the solar constant with a value of 1.367 kW/m^2 (Atikins and Escuider, 2013):

$$R_{TOA,i} = \frac{R_{sc}}{\pi}\left(1 + 0.33\cos\frac{360 d_i}{365}\right) \cdot \left(\cos L \cos\delta \sin\omega + \frac{\pi\omega}{180}\sin L \sin\delta\right) \tag{22}$$

To obtain R_{TOA}, the latitude of the evaluated location, the declination angle, δ, and the sunset hour angle, ω, all in degrees, must be known. The declination angle and the sunset hour angle are calculated with equations (23) and (24) (Bright et al., 2012).

$$\delta = 23.45 \sin\left(360\frac{284 + d_i}{365}\right) \tag{23}$$

$$\omega = \cos^{-1}(-\tan L \tan\delta) \tag{24}$$

The mean annual radiation at the top of the atmosphere is then calculated by using equation (25) (Bright et al., 2012).

$$R_{TOA,ann} = \frac{\int_{i=1}^{i=365} R_{TOA,i}}{365} \tag{25}$$

Since the new surface albedo change is only temporary and will eventually go back to its old state, pre-harvest, an expression is introduced that describes the decay of the new surface albedo as a function of time:

$$\Delta\alpha_s(t) = y_\alpha(t)\Delta\alpha_s \tag{26}$$

where $y_\alpha(t)$ is a value between 0 and 1 and describes the time evolution of the initial albedo change and is dependent of the dynamics of the vegetation type that is planted. $y_\alpha(t)$ is always site-specific. Since no data of the dynamics of the vegetation type on the sites studied in this thesis could be found, it has been modelled with the help of an exponential function (Bright et al., 2012).

$$y_\alpha(t) = e^{-t/\tau} \tag{27}$$

where τ is defined as one fifth of the rotation period (Cherubini et al., 2012a).

To get the local mean annual instantaneous radiative forcing values for the mean annual radiative forcing at TOA, $R_{TOA,ann}$, mean annual values for the two-way atmospheric transmittance parameter $f_{a,ann}$ and the surface albedo change, $\Delta\alpha_s$, together with $y_\alpha(t)$ is inserted into equation (19):

$$\Delta RF_{\alpha,ann}(t) = -R_{TOA,ann} f_{a,ann} \Delta\alpha_s y_\alpha(t) \quad (28)$$

To be able to compare the radiative forcing that a change in surface will contribute to in relation to that of a pulse of CO_2, equation (28) needs to be multiplied with the affected area, here set to 1 m^2, and divided by the area of the Earth's surface, in m^2, in order to get the global mean annual radiative forcing.

$$\Delta RF_{\alpha}^{Global}(t) = \frac{-R_{TOA,ann} f_{a,ann} \Delta\alpha_s y_\alpha(t) A_a}{A_e} \quad (29)$$

The GWP_{albedo} characterisation values can now be calculated with the following expression for the desired time horizon (Cherubini et al., 2012a):

$$GWP_{Albedo} = \frac{\int_0^{TH} \Delta RF_\alpha(t)\, dt}{\int_0^{TH} \Delta RF_{CO_2}(t)\, dt} \quad (30)$$

where $\Delta RF_{CO_2}(t)$ is the radiative fording that one pulse of 1 kg anthropogenic CO_2 gives rise to and can be described by the equations below:

$$\Delta RF_{CO_2}(t) = k_{CO_2} y_{CO_2}(t) \quad (31)$$

where y_{CO_2} is the Bern 2.5 CC function described in the methodology chapter 3.1.1 and k_{CO_2} is the radiative efficiency of CO_2 per kg of emission (the same as the parameter α_{CO_2} that is described in chapter 3.1) and can be calculated by the following expression:

$$k_{CO_2} = \frac{a_{CO_2}}{1 \cdot 10^{-6}\, M_{CO_2}/M_{air} M_a} \quad (32)$$

where M_{CO_2} is the molecular weight of CO_2 and has a value of 44.009 kg/kmol, M_{air} is the molecular weight of air with a value of 28.97 kg/kmol, M_a is the mass of the atmosphere and equal to $5.1441 \cdot 10^{14}$ m^2 and a_{CO_2} is the radiative efficiency of CO_2 in W m^{-2} $ppmv^{-1}$ and described further below, where CO_2' is the background concentration of CO_2 with a value of 378 ppm (Bright et al., 2011):

$$a_{CO_2} = 5.35 * \ln(CO_2' + 1/CO_2') \quad (33)$$

The characterisation factors derived by using equation (30) are given in kg CO_2/m^2. To obtain the impact the albedo change contributes to per functional unit, the GWP_{Albedo} values are multiplied with the acquired clear-cut area (in m^2) per functional unit.

The method developed by Bright et al. (2012) has been updated by Cherubini et al. (2012a) for computing the global radiative forcing, where the global radiative forcing is calculated by using monthly mean values of the two-way atmospheric transmittance parameter, $f_{a,}$ the radiative forcing at TOA, R_{TOA}, and the surface albedo change, $\Delta\alpha_s$, as can be seen in the equation below:

$$RF_{\alpha}(t) = \frac{\sum_{m=1}^{m=12} -\bar{R}_{TOA}(m)\overline{f_{\alpha}}(m)\Delta\bar{\alpha}(m)A_A}{M} y_{\alpha}(t)A_E^{-1} \quad (34)$$

The impact from radiative forcing from a change in surface albedo is especially significant in regions that have seasonal snow cover. Cherubini et al. (2012a) stated that the forcing from change in surface albedo is between 1.5 to 5 times more effective than CO_2 in affecting the global surface temperature. To calculate for these effects, Cherubini et al. (2012a) suggest the use of climate efficacies, *E*, that are derived from numerical climate simulations. Values for the climate efficacies are E_{CO_2}=1 for $C0_2$ and E_{albedo}=1.94 for changes in albedo.

The GWP_{albedo} characterisation values can now be calculated with the following expression for the desired time horizon (the time horizons studied in this thesis are 20, 100 and 500 years):

$$GWP_{albedo} = \frac{\gamma^{-1}\int_0^{TH} E_{Albedo}\Delta RF_{\alpha}(t)\,dt}{\int_0^{TH} E_{CO_2}\Delta RF_{CO_2}(t)\,dt} \quad (35)$$

where γ is the carbon yield of the biomass standing, used to convert the albedo values from kg CO_2-eq/m^2 to kg CO_2-eq/kg CO_2 (Cherubini et al., 2012a).

5 Case study

The upcoming chapters will introduce the case study and provide a case specific description of all the mandatory parts in an LCA.

5.1 Case study introduction

To assess the impact contribution from the unconventional aspects stated in the theory chapter, a case study was conducted for Performance additive's product Bermocoll produced at their site in Örnsköldsvik. Bermocoll is a thickening and water-retaining agent used in paint and building materials (AkzoNobel, 2015c). The main component in Bermocoll is cellulose derived from cotton and wood (AkzoNobel, 2015b), which makes it a suitable product to study since the aspects are particularly relevant for bio-based products. Two LCAs were performed to assess the contribution from the aspects not usually included in an LCA, one standardised assessment according to AkzoNobel's praxis and one where the unconventional aspects were included. The aspects potentially affect the whole life cycle of the product and therefore it is essential to conduct a full cradle-to-grave assessment. The LCAs focus only on the global warming impact and are of an accounting type since the purpose is to evaluate the climate impact for which Bermocoll can be held responsible from a cradle-to-grave perspective. As Bermocoll is a component in paint, which is consumed on a global market, two different gate-to-grave scenarios were assessed upon request from AkzoNobel. The first was simulated according to the Indian market and the second according to the German market. In both cases, Bermocoll is assessed as a part of a pure acrylic based exterior paint, which is painted on a house with cement-based plasters.

5.2 Case study goal

The goal for the case study is to evaluate how the climate impact for Bermocoll Prime and Bermocoll EBS in paint differs when unconventional LCA aspects are taken into account compared to if Bermocoll is assessed according to common praxis, when the paint is utilized in India respectively Germany. The unconventional aspects evaluated in the case study are, *timing of biogenic carbon dioxide emission, carbon sequestration including credits for carbon stored in the product, how to assess biogenic carbon emissions, soil disturbances* and *climate impact of the albedo effect.*

5.3 Case study scope

Four different scenarios were assessed in the case study, two for each country. These are referred to as scenarios 1, 1a, 2 and 2a from hereon:

Scenario 1: A cradle-to-grave where Bermocoll Prime in paint is used in *India* and assessed according to *common practice*

Scenario 1a: A cradle-to-grave where Bermocoll Prime in paint is used in *India* and assessed with the unconventional aspects.

Scenario 2: A cradle-to-grave where Bermocoll EBS in paint, is used in *Germany* and assessed according to common practice

Scenario 2a: A cradle-to-grave where Bermocoll EBS in paint is used in *Germany* and assessed with the unconventional aspects.

5.3.1 Functional unit

The functional unit is a crucial part of an LCA as it facilitates the comparison of different products on the same scale (Baumann and Tillman, 2004). In this study, the comparison measure is the amount of Bermocoll (kg) required to coat a square metric meter (m^2) of wall with paint on a house with a lifetime of 100 years to a satisfying end-user demand.

5.3.2 Flowcharts

The flowcharts for scenarios 1 and 1a, Bermocoll Prime utilized in India, and scenarios 2 and 2a, Bermocoll EBS utilized in Germany are illustrated in figure 4. The flowcharts illustrates the life cycles of Bermocoll from crade-to-grave. The difference between the systems is the composition of raw material, the use phase and the end-of-life, where the paint in scenarios 1 and 1a is landfilled while in scenarios 2 and 2a, the paint is incinerated or recycled.

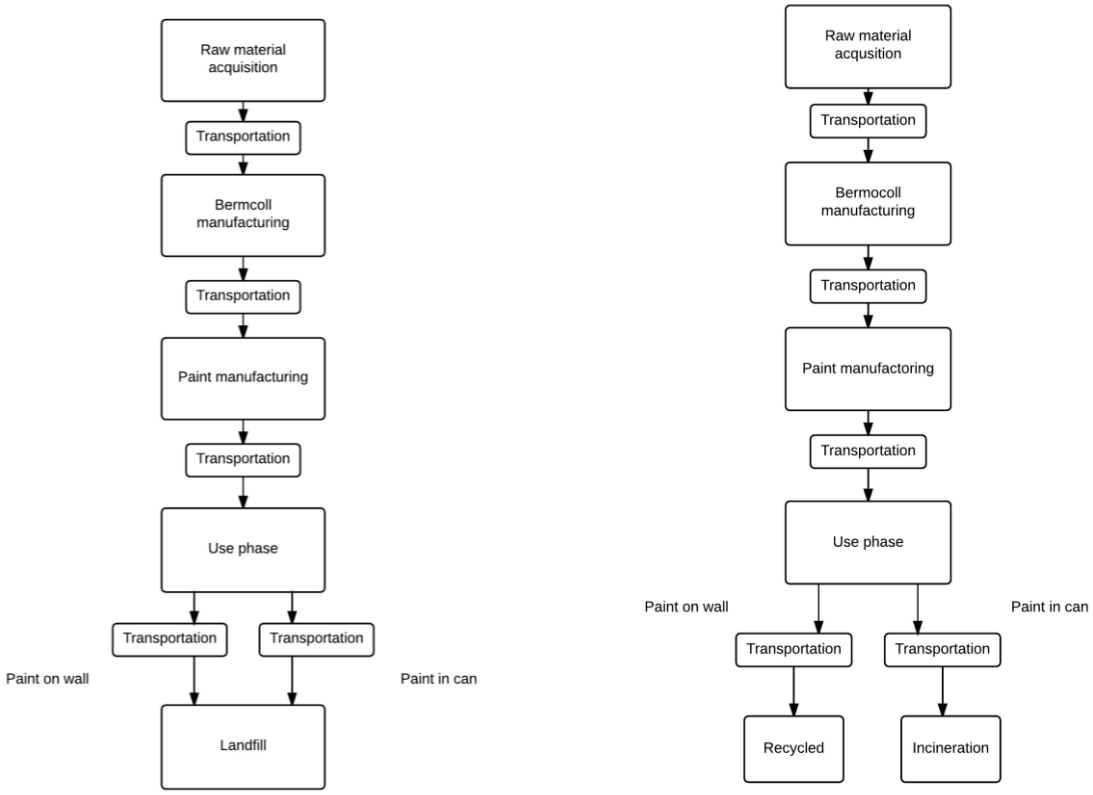

Figure 4 Flowchart of Bermocoll from cradle-to-grave for scenario 1 and 1a (India) respectively scenarios 2 and 2a (Germany)

5.3.3 Technical description of Bermocoll's cradle-to grave

Bermocoll is a water soluble cellulose ether and a component in decorative paints and building products due to favourable thickening, stabilizing and water retaining properties (AkzoNobel, 2015c). Cellulose is the major component in Bermocoll and substituents like ethyl chloride, methyl chloride and hydroxyethyl groups give water soluble properties (AkzoNobel, 2015c) Enzymatic resistance and thickening efficiency are also determined by the substituents, which are selected based on the desired Bermocoll properties (AkzoNobel, 2015c). Performance additives purchases three types of cellulose, derived from wood or cotton linters, depending on the required Bermocoll viscosity. Cotton linters are small fibres that cover the cottonseed and a by-product from cotton extraction. The extracted cellulose is, in order to be in an appropriate form, processed in a pulp mill and transformed into pulp. Two Bermocoll products are assessed in this case study, Prime and EBS. Bermocoll Prime is based on two different types of pulp derived from wood and Bermocoll EBS is based on cotton linters pulp.

Assumptions regarding Bermocoll are presented below, except for assumptions regarding the unconventional aspects, which will be presented in chapter 4.5. If no literature reference is stated, assumptions are based on information provided by AkzoNobel's suppliers and employees at AkzoNobel.

5.3.3.1 Production of Bermocoll

The main raw material needed to produce Bermocoll is cellulose, which originates from wood or cotton linters. The wood pulp is in this case derived from wood extracted from plantations in USA and Norway and the cotton linters originate from cotton fields in China. The wood and cotton linters must be transformed into pulp in a pulp mill in order to be used in production of Bermocoll. Other important raw materials are ethyl and methyl groups which are produced either in-house or purchased from external suppliers (AkzoNobel, 2015c). The production of Bermocoll is a business secret and cannot be described in detail. In short, the pulp is dissolved into cellulose, which thereafter is transferred to a reactor where it reacts with the other raw materials and becomes Bermocoll. The product is then washed, dried, milled and packed in bags, which are delivered to paint producers.

5.3.3.2 Production of and paint

A detailed description of the paint production is not made, just the step when Bermocoll is added. The addition of Bermocoll takes place in a tank at high mixing speed. The Bermocoll can be added as either a dry powder or a slurry to unthickened paint. The environmental impact linked to Bermocoll during the paint production is assumed to be negligible in relation to the impact from the other phases of Bermocoll's life cycle.

5.3.3.3 The use phase

The wall to be painted is, in this case, assumed to be covered with cement-based plaster. The paint that is used in all scenarios is water based and contains a pure acrylic binder. The paint is also suitable for exterior use and the fraction of Bermocoll in the paint is 0,3% in all scenarios. The density of the paint is 1280 kg/m^3, in both cases (General Paint Technical Department, 2012) and the paint covers 6 m^2/l and two coatings are required each time the wall is painted (Center for advanced maintenence technology, 2007). The durability of the paint varies depending on the climate. In India the colour is assumed to be durable for 7 years and 14 re-paintings are thus required during the lifetime of the building and in Germany the paint is durable for 15 years which corresponds to 7 re-paintings during the lifetime of the house. It is assumed that the house is only repainted to improve the durability of the paint, not due to any damages of the plaster. It is further assumed that no paint will be removed

between the paintings and that there are no losses of paint during the lifetime of the house, i.e. no old paint is considered to be removed or eroded. All paint, once painted on the wall, is thereby attached to the wall at the time of demolition. After each painting, there is 12.9% paint left in the can, which will never be used (Lee et al., 2011).

5.3.3.4 End-of-life

It is reasonable to assume the same end-of-life for Bermocoll and paint, since the addition level of Bermocoll in paint is less than 1% and separation of such a small fraction seems very unlikely. When the wall is coated with paint, it is assumed that no migration of Bermocoll from the wet or dry paint film takes place since there is no scientific evidence for such a thing to happen. It is further assumed that the paint has the same end-of-life as the material it is attached to, in this case cement based plaster. Waste regulations in Germany and India have been used for developing end-of-life scenarios and two separate waste streams are described, one for the Bermocoll in the paint left in can and one for the Bermocoll in paint applied to the wall.

Germany

Paint on wall

The paint on the wall, when the building should be demolished, is assumed to be a part of demolition waste. In Germany, it is prohibited to dispose demolition waste at the landfill. Most of the demolition waste is recycled and used as filling materials in roads and mines after being crushed into smaller particles This approach is common for concrete-based demolition waste and it is assumed that the cement is recycled in this way since concrete and cement have similar properties (Weisleder and Nasseri, 2006). Since Bermocoll is assumed to be a part of the cement residue, it is thus recycled and assumed to be permanently stored as filling material in a road or a mine. Permanent storage entails that no emissions are released over the assessment period of this study, which is 500 years.

Paint in can

Waste management in Germany is adapted to a five-step waste hierarchy. The hierarchy prioritizes several waste management options from an environmental point of view. The most preferred option is prevention followed by preparation for recycling, recycling, energy recovery and finally disposal (Umwelt Bundesamt, 2014). Energy recovery through incineration is assumed for the paint left in can since the first three management options in the waste management hierarchy are considered to be unreasonable options for this type of waste.

India

Paint on wall

In India, 91% of municipal solid waste ends up at the landfill. Separation of waste is non-existent which means that demolition waste containing paint residues also ends up at landfill and will be mixed with household waste (Ministry of Environment and Forest India, 2010, Annepu, 2012). Thus it is assumed that Bermocoll eventually will be degraded under anaerobic conditions when landfilled (Themelis and Ulloa, 2007). The generated emissions go right into the atmosphere since all attempts to develop landfill stations with recovery facilities have so far failed in India (Joshi et al., 2013).

Paint in can

Due to the poor separation of waste, cans with paint residues are also left at the landfill. (Ministry of Environment and Forest India, 2008).

5.3.3.5 Transportation

All transportation of Bermocoll during its life cycle is assumed to be by boat or truck. Different boat and truck types have been assumed, depending on the country in which the transport is made and also depending on the type of goods transported. In all cases, has the nearest route been estimated since there is no existing information of the exact transport routes of Bermocoll. A more detailed assessment of the environmental impact from the transportation of Bermocoll was never made since it was not the main focus of the study.

5.3.4 Case study methodology

Several different types of Bermocoll are produced at the site in Örnsköldsvik and assessing them all would be too time-consuming. The products were therefore divided into groups, based on similar input data, which resulted in six product groups for paint and seven product groups for building and construction. Among the 13 groups, two groups for paint were further investigated: Bermocoll Prime and Bermocoll EBS, as they were identified to be regularly used in paint, in India and Germany.

5.3.5 System Boundaries

The case study is limited to Bermocoll produced in the manufacturing plant in Örnsköldsvik. Two product groups of Bermocoll, suitable for pure acrylic-based exterior paint, were assessed from a cradle-to-grave perspective. The gate-to-grave phase simulates the conditions of paint use in Germany and India, respectively. Emissions related to acquisition and production of raw materials for Bermocoll, manufacturing of Bermocoll, waste disposal and transport of Bermocoll is included in the assessment while emissions connected to packaging material are excluded. Emissions linked to the process in the paint production, in which Bermocoll is dissolved, are assumed negligible as well as emissions from preparation and maintenance work of the surface to be painted. Emissions from personnel, production facilities, transportation vehicles and equipment are excluded.

Bermocoll is distributed on a global market and geographical boundaries are therefore crucial. The unconventional aspects are to a large extent site-specific and thus sensitive to the location of the cellulose suppliers. Three suppliers located in Norway, USA and China are included as these represented different cellulose types suitable for Bermocoll production.

Temporal boundaries are important to define for a consistent impact assessment. The lifetime of the house, which is coated with paint containing Bermocoll, is 100 years. After demolition, some part of Bermocoll ends up at a landfill and some is assumed to be recycled (scenarios 2 and 2a), which extends the storage time for Bermocoll in the antroposphere. The time horizon for the analysis has therefore been chosen to 500 years, which is sufficiently longer than the estimated storage time for Bermocoll. (Guest et al., 2013a)

5.3.6 Reference flow

The reference flow is based on the functional unit. In scenarios 1 and 1a, the house is painted 14 times during its lifetime. The amount of paint needed per square meter is 0.213 kg but since 12.9% of the paint is left in the can, 0.245 kg paint is required. The reference flow for the functional unit can thereby be calculated based on the amount of Bermocoll in paint. For scenarios 2 and 2a, calculations are based on the same measures as in scenarios 1 and 1a, except that the house is repainted 7 times during its lifetime.

$$15\ times * 2\ coatings * 0.003\ amount\ bermocoll\ in\ paint * 0.245 \frac{kg\ paint}{m^2}$$
$$= 0.0206 \frac{kg\ Bermocoll}{m^2}\ \ for\ 100\ years$$
$$7\ times * 2\ coatings * 0.003\ amount\ bermocoll\ in\ paint * 0.245 \frac{kg\ paint}{m^2}$$
$$= 0.0103\ \frac{kg\ Bermocoll}{m^2}\ \ for\ 100\ year$$

5.3.7 Impact categories

This case study focuses only on the impact category global warming. For the four scenarios fossil carbon emissions, including biogenic methane, are assessed with an impact assessment method based on characterization factors from CML 2010 according to AkzoNobel praxis for carbon reporting. However, CML 2010 factors for the time horizon of 500 years were not available in GaBi, which entailed the usage of CML 1996 for this time horizon. The data set CML 2010 excludes impacts related to biogenic carbon. Nevertheless, according to AkzoNobel praxis, biogenic CO_2 is assumed to be climate neutral. This way of assessing biogenic CO_2 will be used in scenarios 1 and 2. The impact for biogenic carbon in scenarios 1a and 2a are calculated based on metrics and methods that account for unconventional aspects, which will be further explained in coming chapters.

5.3.8 Case study limitations and delimitations

The case study limitations and delimitations are stated in this section to highlight areas outside of the scope:

- Assumptions regarding end-of-life scenarios are based on current conditions. No consideration has been taken to possible changes or improvements in the future.
- Carbon dioxide emissions related to ILUC is not assessed in the case study due to difficulties to find a suitable methodology for evaluating such emissions.
- Carbon emitted to the atmosphere from decomposing residue, left on the plantation sites, is not accounted for.

5.3.9 Allocation

For processes with a multi input or a multi output, it is essential to allocate the emissions between them in a relevant way. Allocation problems can be handled with different methods, which in this case study was performed according to the ranking system for allocation methods in the ISO standard, when possible. In the scenario where Bermocoll is utilized in Germany, a part of the disposed paint is incinerated. The incineration process is a multifunctional process, it performs waste handling and heat and power production. Partitioning or system expansion with substitution can be used for allocation of the environmental impact due to incineration (Baumann and Tillman, 2004). System expansion with substitution implies that the heat from the incineration process substitutes heat production from another fuel and thereby also the emissions the other fuel should have generated. The avoided emissions from the replaced fuel are thus subtracted from those created by the system that performs waste handling (this is one possibly relevant approach if the waste handling can be seen as the main function in that study). However, since this is an accounting LCA and the purpose is to report the actual emissions connected to the product, substitution is not a suitable method to use, since by using substitution, emissions which never actually occur is accounted for (Brander and Wylie, 2011). Baumann and Tillman (2004) recommends partitioning as allocation method for accounting LCAs. However, since no partitioning factor for how to allocate emission from the incineration of Bermocoll

could be identified, an allocation method which implies that the main product bears all burden, which is Bermocoll, is used (Sandin et al., 2015).

5.3.10 Data quality requirements

Plenty of data has been gathered in order to create four cradle-to-grave assessments for Bermocoll. Data quality variations are unavoidable for such an amount of data, especially since they represent different parts of a life cycle. Data that represent the production of Bermocoll is expected to have a higher quality since it is in-house information provided by AkzoNobel, and this process can be considered to be part of the foreground system. Data for the rest of the supply chain is in general based on assumptions that reduce the quality level as this data is based on questionnaires and information from literature. The cradle-to-gate phase is modelled in GaBi from existing processes for raw material production in the software database. However, these processes are in some cases not detailed enough to be suitable for describing the production of Bermocoll. One example is the processes for wood cellulose, which do not include flows and emissions for the production of wood pulp. However, updating processes in GaBi was outside the scope of this study due to time limitations. If there were no available process for a raw material, it was replaced with a similar raw material or left out. However, excluding raw materials was done on the premise that it was only a small portion of Bermocoll's composition. Data for the unconventional aspects was gathered by questionnaire sent out to the cellulose suppliers. This was made in order to get more site-specific information regarding the cellulose extraction. Average data from research articles was used as a complement in cases when the information from the cellulose suppliers was not sufficient enough to be used for the impact calculations. Average data was also used for the end-of-life scenarios since it was not possible to find specific data describing Bermocoll's end-of-life in India and Germany.

5.4 Aspect calculations

The following sections describe aspect specific calculations and assumptions conducted for deriving the impact related to each unconventional climate aspect applied in the case study.

5.4.1 Biogenic carbon - GWP_{bio}

The characterisation metric GWP_{bio}, based on Guest et al. (2013a), presented in chapter 3.1.4, is the metric used in order to account for timing of emissions and carbon sequestration, credits for carbon stored in the antroposphere and for including biogenic carbon emissions. The decay function for a biogenic emission, according to Guest et al. (2013a), describes how these aspects are incorporated in the metric. The aspect *credit for carbon temporarily stored in the antroposphere* is taken into account since credits are assigned to temporarily stored carbon for the reduction in radiative forcing it implies. The magnitude of the credit is determined from the avoided radiative forcing when CO_2 is sequestered in growing biomass during storage. As a result of the stored carbon, the *timing of emission* is also accounted for, in line with conclusions by Røyne et al. (2014). The temporary radiative forcing from the release of a delayed emission at the product's end of life is gradually sequestered in the growing biomass over the time horizon, which result in a consistent assessment since the impact for the delayed emission is integrated over the time it is present in the atmosphere. The fact that the temporal increase of CO_2 is considered, implies that Guest et al. (2013a) does not assume *carbon neutrality of biogenic carbon* and the growth function describes the growing biomass over time, which indicates that timing of *carbon sequestration* is accounted for.

In order to calculate GWP_{bio}, table 1 in chapter 3.1.4 is used, according to Guest et al. (2013a). This table requires that the storage period in the antroposphere and the rotation time for the evaluated

biomass are known. Thus, the storage time for Bermocoll in the antroposphere and the rotation periods were determined. Variations in storage time were identified since fractions of Bermocoll have different end-of-life depending on if it is a part of the paint applied on the wall or in the paint left in the can. In addition, storage time variations were a consequence of the number of times the house was repainted during its lifetime, which is 100 years. For example, Bermocoll in paint applied to the wall at the first application is stored for a longer time in the antroposphere compared to the amount of Bermocoll in paint applied to the wall during the first repainting. Since the house was repainted with equal amounts of paint every 14 years in scenarios 1 and 1a and every seven years in scenarios 2 and 2a, it is assumed that an average storage time can represent Bermocoll in paint applied to the wall.

As already mentioned, storage time variations are a result from different end-of life-processes for Bermocoll. Assumptions in the goal and scope describe which end of life that represents Bermocoll, either in paint left in can or in paint applied on the wall. In scenarios 1 and 1a, where the paint is used in India, Bermocoll is assumed to end up at a landfill regardless of it is in paint left in a can or in paint applied onto the wall. After every repainting, Bermocoll in paint left in the can is landfilled while Bermocoll in paint applied to the wall is landfilled when the house is demolished. Landfilled Bermocoll is assumed to linearly degrade during a century (Baumann and Tillman, 2004) and the emissions are assumed to be emitted in one pulse, which result in an average storage time on 50 years. In scenarios 2 and 2a, where Bermocoll is used in Germany, Bermocoll in paint applied to the wall is recycled, and the part left in the can is incinerated. Recycled Bermocoll is assumed to be permanently stored, which implies no degradation during the assessment period of 500 years. Storage for Bermocoll in paint left in the can is insignificant as it is incinerated within a short time period after repainting. The average storage time for Bermocoll in the antroposphere can be seen in table 2.

Table 2 Time Bermocoll spends in the antroposphere in the different scenarios depending on how it is disposed of

	Storage time in the antroposphere			
	Incinerated	**House wall**	**Recycled**	**Landfill**
Scenarios 1 and 1a	0 years	54.5 years		50 years
Scenarios 2 and 2a	0 years	55 years	>500 years	50 years

Species type, rotation periods and the supplier location were obtained from questionnaires sent to the suppliers. The rotation period for the supplier in USA is based on information found in literature (Louppe et al., 2008) as no such value was provided in the questionnaire. Species and rotation periods for the biomass types at the supplier locations can be seen in table 3 below.

Table 3 Location, species and rotation period for the three cellulose types studied

Biomass type	Location	Species	Rotation period
Wood	USA, Florida, Madison County	Slash pine	25 years
Wood	Norway	Norway spruce	90 years
Cotton linters	China, Xinjiang, Hami	Average cotton plant	1 year

The process which provides steam for the production of Bermocoll generates a considerable amount of biogenic carbon dioxide and was therefore assessed with the GWP_{bio} methodology. Steam is locally produced and since spruce is a common species in Sweden, it was assumed to represent the wood used for fuel in the steam process. The rotation period for spruce in Sweden is on average 100 years (SkogsSverige, 2001) and no storage was assumed since wood is combusted. A minor amount of biogenic carbon is emitted from other processes connected to the production of Bermocoll. However, this is such a small amount that the impact from these emissions is assumed negligible. GWP_{bio} factors for the different scenarios were derived from Guest et al. (2013a) for bio-based products stored in the antroposphere, see table 1 in chapter 3.1.4.

The values for GWP_{bio} were multiplied by the biogenic carbon emissions from Bermocoll's end of life. How these emissions were calculated is described below. The renewable percentage of Bermocoll was first calculated. From previous production data for Bermocoll, values for the molar substitution and the degree of substitution could be derived. These were multiplied with the molecular weight of the substituents and added to the molecular weight for cellulose and the total molecular weight for Bermocoll was achieved. The molecular weight of cellulose was divided by the molecular weight of Bermocoll and the renewable percentage was achieved, which is 66% for Bermocoll Prime and 58% for Bermocoll EBS. To calculate the emissions from the fraction of Bermocoll that was landfilled, the following equation was used:

$$C_aH_bO_c + \left(a - \frac{b}{4} - \frac{c}{2}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4}\right)CO_2 \quad (36)$$

The emissions from the incinerated part of Bermocoll was computed by equation (37).

$$C_aH_bO_C + \left(a + \frac{1}{4b} - \frac{c}{2}\right)O_2 \rightarrow aCO_2 + \frac{b}{2}H_2O \quad (37)$$

These equations explain the molar relationship between Bermocoll and incineration or landfill reactants and products. The molar equivalency was used to determine the amount of CO_2 and CH_4. The total amount of CO_2 was multiplied with the renewable percentage of Bermocoll and the biogenic CO_2 was derived.

5.4.2 The albedo effect - GWP_{albedo}

The suppliers that produce wood cellulose, use wood from forest plantations in Norway and USA and the cotton linter pulp supplier use cotton linters from plantations in China. Based on information given by the suppliers, geographical areas were identified for the forest and cotton plantations, from which the three different cellulose types are derived from. No exact locations were given so Google Earth was used to estimate more precise coordinates. Two locations for the wood based cellulose types were located, one with standing biomass and one site with open landscape (used instead of clear-cut site). The two locations were chosen so they were not too far apart, not more than 20km, in order to simulate similar conditions. Coordinates for the different locations can be found in table 4. Cotton is an annual crop and no reference site was therefore needed since clear-cut conditions can be obtained for the cotton plantation site.

Table 4 Coordinates for the studied plantation sites

	Standing biomass		Open landscape	
Location	**Latitude**	**Longitude**	**Latitude**	**Longitude**
USA, Florida (wood)	30.427	-83.493	30.498	-83.322
Norway (wood)	59.385	10.93	59.355	10.824
China, Xinjiang (cotton linters)	42.855	93.41		

As a first step towards calculating the instantaneous radiative forcing that arise due to a surface albedo change, the radiation at the top of the atmosphere, R_{TOA}, was computed for all sites with standing biomass according to equation (22) descried in 3.2. The next step was to compute the two-way atmospheric transmittance parameter, f_a, according to equation (21) as in chapter 3.2. Values for the insolation clearness index, K_T, were obtained from NASA's database *NASA Surface meteorology and Solar Energy* (NASA, 2015b). Data from July 1983 to June 2005 were collected and a mean monthly insolation clearness index was calculated. Data for K_T were collected for all sites identified as standing biomass based on their coordinates in table 4.

The difference in monthly mean surface albedo was obtained by using the MODIS Land Products Subsetting and Visualization Tools and the product *(MCD43A) MODIS/Terra+Aqua BRDF and Calculation Albedo* (DAAC, 2015). Albedo data MODIS black sky shortwave broadband with optical depth set to 0.2, solar zenith angle set to *local*, the spatial boundaries set to 0 km between February 2000 to June 2015 were collected for all sites, for standing biomass and open landscape. To ensure that the sites studied had consistent land cover over the time frame that the albedo values were measured, the function historical imagery in Google Earth was used. Some of the data in the data set consisted of invalid observation values and were therefore not taken into account. A mean monthly albedo was calculated based on the acceptable measured data for all years, in order to avoid uncertainties related to annual variability. The difference in mean surface albedo, $\Delta\alpha_s$, for cellulose produced from wood was found by subtracting the albedo values derived for each month from open landscape with the albedo derived from standing biomass according to equation (20). For cellulose produced from cotton linters, a minimum and maximum value was computed based on average monthly values, derived from data for all years. This was done since cotton is an annual crop and starting albedo (standing biomass) and new albedo (clear-cut) is occurring during the same year. It is assumed that the lowest albedo occurs right before the time of harvest and that the highest albedo is right after harvest.

A global radiative forcing for an albedo change, $\Delta RF_{\alpha}^{Global}$, was calculated according to Cherubini et al. (2012a) for cellulose derived from forest, using equation (34). For cellulose derived from cotton linter, $\Delta RF_{\alpha}^{Global}$ was computed from equation (29) since no monthly annual albedo values were calculated. With $\Delta RF_{\alpha}^{Global}$ computed, the characterisation factor for surface albedo could be calculated according to equation (30), together with the radiative forcing from anthropogenic CO_2, ΔRF_{CO2}, according to equation (31) found in the methodology section 3.2. The characterisation factor was computed for the time horizon of 500 years. The result can be seen in chapter 5.2.

The albedo values and the clearness index were derived by calculations made with Excel and the rest of the calculations were performed using Matlab. The Matlab scripts used can be seen in appendix A. Equation (35) for calculating GWP_{albedo} suggested by Cherubini et al. (2012a) was not used since no adequate data for carbon yields could be found.

To obtain the impact that the albedo change contributes to, the clear-cut area required to produce the desired amount of product, in this case study cellulose in the form of pulp, was computed. The area is related to the amount of pulp required for the functional unit chosen for this study. The clear-cut area needed to produce the required amount of pulp was computed by multiplying the biomass yield for each site with the required amount of biomass needed to produce pulp for the functional unit for each Bermocoll product. Biomass yields for each site, wood densities and biomass-to-pulp yields can be found in table 5. The wood-to-pulp yields for the biomass originating from Norway was given by the supplier and included the whole tree, with bark. Stem volume density per hectare and wood density for Norway spruce were taken from literature (Bright et al., 2012) (The Wood Database, 2015). For the biomass originating from USA, the yield values were found in litterature. The wood-to-pulp yield was given for dry wood chips and the biomass yield for the site was given in cubic meter per hectare, for a whole tree (Louppe et al., 2008) (Briggs, 1994). It is assumed that 90% of the yield is used for making pulp. To obtain the amount of wood chips acquired from a square meter, the bark volume had to be accounted for, which is 18% for slash pine, as well as the density of oven dry slash pine (Miles and Smith, 2009).

Table 5 Characteristics for the different species types from which the cellulose is extracted

	USA	**Norway**	**China**
Type of biomass	Slash Pine	Norway Spruce	Cotton seed
Yield/ha	375 m^3/ha	275 m^3/ha	0.11 kg/m^2
Wood density	540 kg/m^3	405 kg/m^3	
Biomass-to-pulp yield	50%	40%	50%

The area needed to produce the required amount of cotton linter pulp was calculated in a similar way as for wood pulp. For each square meter cotton cultivated, 0.11 kg cotton seed is obtained, of which 8,35% is cotton linters (NCPA, 2002). However, cotton linter is a by-product from cotton cultivation and the impact resulting from a change in surface albedo must thereby be allocated between all the by-products. Economic allocation was used as much as possible but since economic values for all by-products could not be found it was partly allocated by weight. The calculations can be seen in appendix A. The area of forest land or the area of the cotton crop that is required to produce the amount of cellulose per functional unit can be seen in table 6

Table 6 Area required per functional unit in the different scenarios

Scenarios 1 and 1a - Bermocoll Prime		**Scenarios 2 and 2a - Bermocoll EBS**
USA	Norway	China
4.05E-04 m^2/FU	2.23E-03 m^2/FU	7.14E-03 m^2/FU

5.4.3 Soil carbon disturbance

In order to account for the soil carbon, either lost or sequestered, from wood or cotton extraction, site-specific information from the cellulose suppliers was gathered. Additional literature was used to find complementary data necessary to describe the site specific soil conditions in a more detailed way. However, in the existing literature, emission based calculation methods for soil disturbances were seldom explained in detail enough to be useful for this study. Efforts to use ecosystem models, proposed and used in literature, were conducted without any success. A more detailed assessment of the Coupmodel developed at the Royal Institute and Technology (2015) were performed; it simulates all carbon flows in soil. However, the model required site-specific input data, which finally resulted in a decision to limit the soil disturbance aspect to only use soil carbon values from literature instead of using soil carbon model for calculating these values. The main conclusions from three articles acted as a basis for the impact estimations for soil disturbances and the findings are described below

In a literature study by Johnson and Curtis (2001), the effects from forest management on soil organic carbon were investigated in North America. From the study, it could be concluded that whole tree harvesting (WTH) reduces soil carbon stock with 6%; this is a commonly used harvesting method in USA (Johnson and Curtis, 2001) (Roxby et al., 2015). Different species were investigated and for slash pine, soil carbon changes were evaluated over 15 years after harvest (Johnson et al., 2002). As the cellulose from the supplier in USA was derived from slash pine, it was assumed that the findings from Johnson's studies could be representative in this case (Roxby et al., 2015).

From a soil organic carbon perspective, Brandao et al. (2011) emphasized the advantage of leaving forest residues to decompose on site in a spruce stand. The result from Brandao et al. (2011) study indicated that from a hectare of land in a spruce forest, more carbon was sequestrated than lost as a result of degradation. The Norwegian supplier, which produces cellulose from spruce trees, stated that residues are left on site after harvest (see table 7) and on this basis, data from Brandao et al. (2011) were utilized.

For the cotton supplier in China, it was assumed that the soil carbon changes were in line with findings from a study by Tang et al. (2010) that evaluated a cotton crop in China, Changes in soil carbon were assessed from results generated from a model that simulates carbon sequestration and SOC changes. Table 7 summarizes the most important information obtained from the cellulose suppliers and SOC changes from Johnson et al. (2002), Brandao et al. (2011) and Tang et al. (2010)

Table 7 Harvesting practices and site specific information for the three plantation sites. Note that a positive delta SOC value represents that more carbon is sequestered than lost and for negative values is more lost than sequestered

	Norway	**USA**	**China**
Species	Norwegian Spruce	Slash pine	Cotton linters
Harvest practices	Clear cutting	WTH	Cotton cultivation
Residues left on site	Yes	No	Yes
∆SOC	0.32 tC/ha	-2.16 tC/ha	-1.12 tC/ha

The climate impact for soil disturbances was calculated from the SOC values in table 7 above. The area of forest land or cotton land required for producing the amount of cotton linters or wood cellulose needed per functional unit was computed, which is the same area as was used to calculate the impact from changes in albedo. That area together with the ratio between the molecular weight for carbon dioxide and the molecular weight for carbon was multiplied with the SOC values, and CO_2 emissions were obtained per functional unit. GWP_{bio} values were taken from table 1 and multiplied with the CO_2 emissions. It was assumed that the probable effects on SOC from management practices only appeared over a year since there was no information from the suppliers regarding management practices in subsequent years, which implied GWP_{bio} values with no storage. GWP_{bio} values with no storage means that all emissions from disturbances of the soil are released during the first year after the final felling of the forest. Emissions occurring after the first year are a result from other management practice like thinning and these are considered to have a minor impact on the soil thus excluded. However, the rotation periods for the different suppliers were still the same.

In order to calculate the annual soil carbon changes for the supplier in USA, a literature value was used, which represents average soil carbon content in Ultisols 180 tC/ha (Buringh, 1984), since this is the most common soil type in the area where the American supplier operates (Watts and Collins, 2008). This value was multiplied with the percentage loss due to WTH according to Johnson and Curtis (2001). As the numbers from Johnson et al. (2002) were based on a time period of 15 years, it was assumed that they could be divided with 15 years to achieve the annual change. As described in the theory chapter 2.4.4, other management practices can affect carbon stored in soil but in this case, only the SOC changes from harvest of a forest or cultivation of a cotton crop are included. Losses due to soil degradation were assumed to be emitted in the form of CO_2 to the atmosphere. The climate impact from fertilizers was excluded.

6 Case study results

The following chapter presents the obtained GWPbio and GWPalbedo factors and the impact from soil carbon disturbances. In addition, the global warming impact for the scenarios and a variation analysis comparing different end-of-life options is presented. The impacts are assessed over the time horizon 500 years.

6.1 Characterisation factors for GWP_{bio}

The GWP_{bio} characterisation factors used for calculating the impact from biogenic carbon emissions in scenarios 1a and 2a can be seen in table 8 respectively table 9. The factors are obtained from Guest et al. (2013a) and are based on the biomass rotation period and the storage time Bermocoll spends in the antroposphere. The storage time, and thereby the GWP_{bio} factors, is highly dependent on the end-of-life process for Bermocoll, which can be seen in table 8 and 9.

Table 8 GWP_{bio} factors for biogenic carbon in scenario 1a (Bermocoll Prime used in India)

	Bermocoll in can	Bermocoll on wall	Steam	
GWP_{bio}	-0.0168	-0.0932	0.077	kg CO2eq/kg

Table 9 GWP_{bio} factors for biogenic carbon in scenario 2a (Bermocoll EBS used in Germany)

	Bermocoll in can	Bermocoll on wall	Steam	
GWP_{bio}	0.003	-1	0.077	kg CO2eq/kg

For producing Bermocoll Prime with a desired cellulose quality, wood cellulose from both Norway and USA is required. The GWP_{bio} factor has therefore been normalized to represent both these sites. The normalisation factor is calculated as the weight percentage of cellulose extracted from either Norway or USA to produce Bermocoll Prime per functional unit.

In chapter 4.5.1, it is further explained how the factor was derived and which rotation periods and storage time they are based upon. The derived GWP_{bio} factor was multiplied with the biogenic emission connected to each EoL, which can be found in appendix B and C. The relative impact that the factors contributed to in scenarios 1a and 2a can be seen further down in this chapter.

6.2 Characterisation factors for GWP_{albedo}

The surface albedo for the sites with standing biomass can be seen in figure 5 below. The figure shows that the albedo values for the sites in China and Norway are higher during the winter months due to snow cover during these months. The site in USA is located in Florida where the climate is mild and snow is rare and marginal deviations in surface albedo are obtained during a year. Figure 5 shows that the site in China has a higher albedo, which is a result of that cropland in general has higher surface albedo than forest. The exact numerical values for all sites can be found in appendix A.

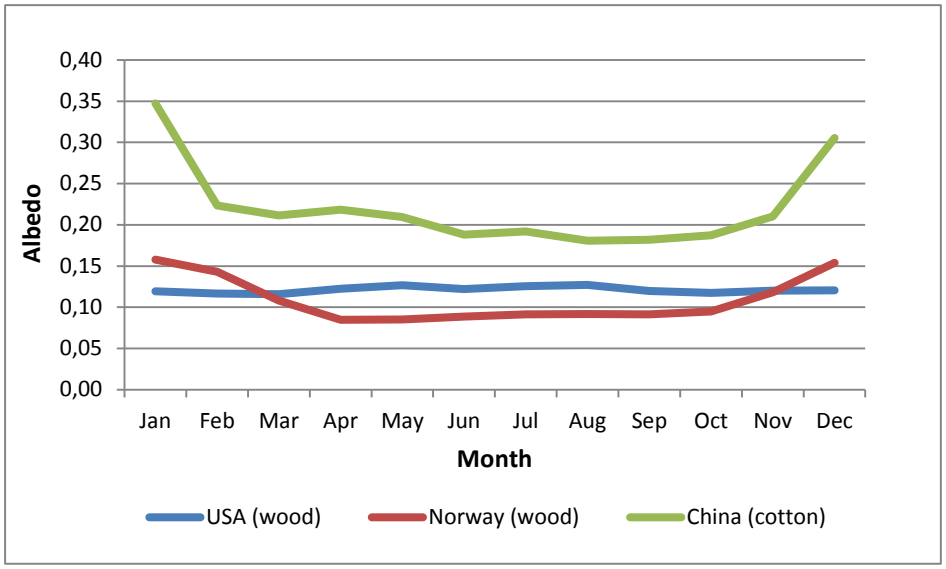

Figure 5 Variation in surface albedo during a year for the studied biomass plantations.

GWP_{albedo} values for all sites studied was derived by the method described in chapter 3.2 and 4.5.2. The values are shown in table 10.

Table 10 GWP_{albedo} factors for the plantation sites studied

	China, cotton linters	USA, wood	Norway, wood	Unit
GWP_{albedo}	-0.0381	-0.2885	-0.8056	kg CO2eq/m2

The negative values in table 10 imply that for every square meter harvested, a negative radiative forcing is induced, due to a change in albedo, that has a cooling effect on the temperature (Bright et al., 2012). Table 10 shows that the GWP_{albedo} values for the cotton linters are significantly lower compared to the forest plantation sites. This is due to the fact that cotton linters is derived from an annual crop, which induce only a short-lived change in surface albedo due to the fact that the normal albedo state is reached aging quickly after harvest. The site in USA has the lowest variation in surface albedo, which can be seen in figure 5, due to absence of seasonal snow coverage, something that should imply low GWP_{albedo} values. However, compared to the other sites, the site in USA is located closer to the equator, causing higher radiative forcing at top of the atmosphere, $R_{TOA,}$ which offsets the result somewhat. The main reason for the higher GWP_{albedo} factor for the site in Norway is the assumption that it takes longer time for the albedo to return to its old state after harvest with longer rotation times. Another reason is the seasonal snow cover, which increases the albedo during these months and thereby the variation in surface albedo.

The GWP_{albedo} factor for the two products, Bermocoll Prime and Bermocoll EBS were derived based on the properties of each cellulose type used in the products and the GWP_{albedo} factors from table 10. The GWP_{albedo} values used to calculate the impact from a change in albedo for Bermocoll Prime and EBS in scenarios 1a and 2a, is shown in table 11.

Table 11 GWP_{albedo} factors for scenarios 1a and 2a

	Bermocoll Prime – Scenario 1a	Bermocoll EBS – Scenario 2a	Unit
GWP_{albedo}	-0.685	-0.038	kg CO2eq/m2

6.3 Soil carbon disturbances

Soil carbon changes for the three suppliers can be seen in table 12. The Norwegian supplier has a negative value since more carbon was sequestrated in soil as a result of that forest residues are left on the forest floor after a clear cutting. It is important to stress that sequestration in this case means that the amount of CO_2 in residue, left in the forest after harvest, is supplied to soil. However, during WTH, no residues were left on the site, which resulted in that carbon soil was lost, hence the positive value for slash pine. In China, more carbon was lost than sequestrated during cultivation and therefore the positive value.

The SOC values in table 12 can only signify the soil carbon changes in connection to harvesting; potential changes from other forest operations occurring one year after harvest are therefore excluded. The soil carbon changes would have been more representative for the study if they could express soil carbon changes over one rotation instead of over one year. However, finding such values in literature was not possible.

Table 12 Global warming impact from soil carbon disturbances for the plantation sites

	Cotton crop China	Slash pine USA	Spruce Norway	Unit
ΔSOC	$2.40 \cdot 10^{-12}$	$-1.96 \cdot 10^{-12}$	$-4.83 \cdot 10^{-12}$	kg CO_2eq/FU year

For producing Bermocoll Prime with a desired cellulose quality, wood cellulose from both Norway and USA is required. The soil carbon changes occurring when the cellulose for producing Bermocoll Prime is extracted therefore need to be normalized to represent soil disturbances at two different sites. The normalisation factor is calculated as the weight percentage of cellulose extracted from either Norway or USA to produce Bermocoll Prime per functional unit.

Table 13 Global warming impact from soil carbon disturbances for scenarios 1a and 2a

	Bermocoll Prime – Scenario 1a	Bermocoll EBS – Scenario 2a	Unit
ΔSOC	$-4.29 \cdot 10^{-12}$	$2.40 \cdot 10^{-12}$	kg CO_2eq/FU year

6.4 Impact assessment results

In this part of the result chapter is the global warming impact from the different scenarios presented and compared. The global warming impact is presented in normalised values due to confidentiality and since the relative contribution of the unconventional aspects is in focus. The result from the assessment, which incorporates unconventional aspects, is compared to LCA results where biogenic carbon is assumed to be climate neutral. Even if the biogenic carbon emissions in scenario 1 and scenario 2 are assumed to be climate neutral is the impact from these emissions still visualised in the charts in figure 6, 7, 9 and 10, in order to show the possible impact of these emissions. Nevertheless, the total impact for the biogenic emissions in scenario 1 and 2 are still zero, thus climate neutral since there is a red negative impact bar, which is eliminating the positive biogenic impact. In scenario 1a and 2a, where the unconventional aspects are included in the assessment, is the biogenic carbon not assessed as climate neutral.

6.4.1 Results for Scenarios 1 and 1a

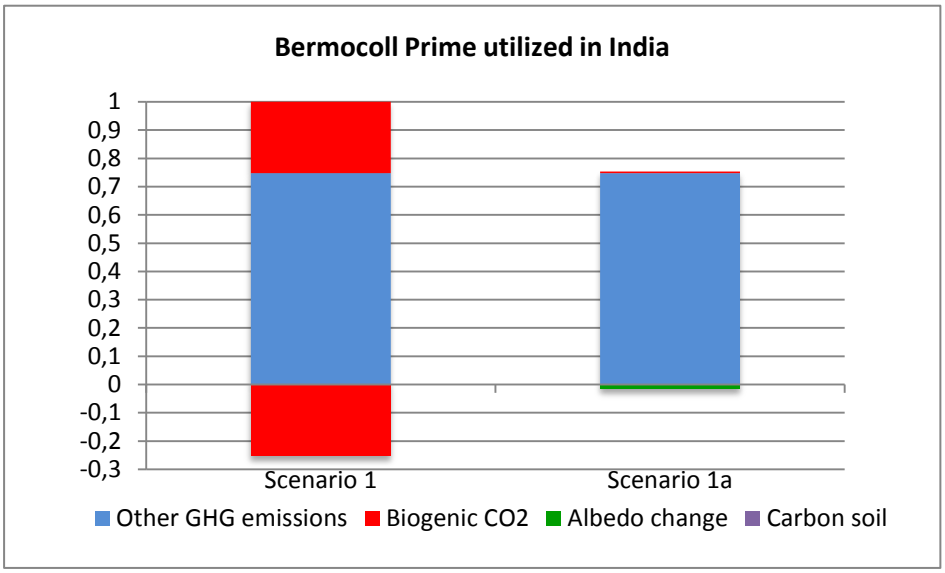

Figure 6 The relative global warming impact for scenario 1 compared to scenario 1a

For Bermocoll Prime used in India, the impact from biogenic carbon is increased with 1 % in scenario 1a compared to scenario 1, under the assumption that in scenario 1, biogenic carbon is considered climate neutral. The result in scenario 1a was influenced by the incorporation of the GWP_{bio} metric. The GWP_{bio} metric accounts for storage of biogenic carbon in the anthroposphere for an extensive time and is therefore given, in this case, a negative credit. Credits are given since it is assumed that biomass starts sequestrating carbon before the product is disposed and the stored carbon released, thus creating a net reduction of carbon in the atmosphere. However, the total impact from biogenic carbon was not negative in scenario 1a, which is due to the fact that there are biogenic carbon emissions connected with the process that generates steam, which is needed to produce Bermocoll. These biogenic emissions are created when wood fuel are incinerated and are therefore immediately released into the atmosphere, which entails no credit for carbon stored. Changes in surface albedo have a minor effect on the result and contribute with a cooling effect that reduces the global warming impact from scenario 1 with 2%. The low influence from changes in surface albedo is an effect of that only a small area of forestland is required to produce the acquired amount of cellulose. Soil carbon changes

had a negligible effect on the result. In total the inclusion of the unconventional aspects have reduced the global warming impact with 1% compared to scenario 1.

6.4.2 Results for Scenarios 2 and 2a

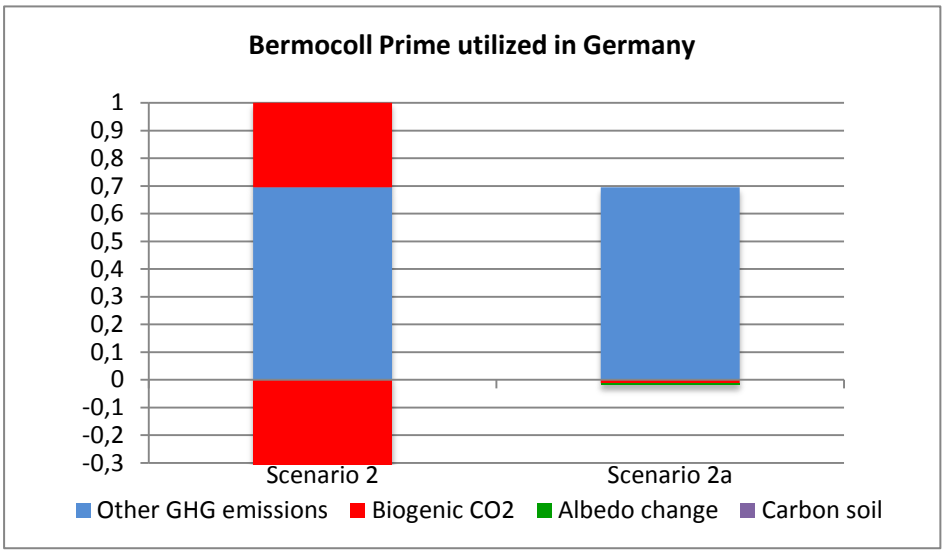

Figure 7 The relative global warming impact for scenario 2 compared to scenario 2a

For Bermocoll EBS used in Germany is the impact from biogenic carbon reduced with 2 % in scenario 2a compered to scenario 2, which is a result from that inclusion of the GWP_{bio} metric used in scenario 2a. This is mainly an effect of that the majority of Bermocoll EBS is recycled at its end-of-life and assumed to be stored the antroposphere for longer than 500 years. The carbon dioxide related to the recycled fraction of Bermocoll is therefore given a credit of -1. Changes in surface albedo contribute to a cooling effect that impact the result with about 1 % in this scenario. This is slightly less than in scenario 1a and it is due to the fact that Bermocoll EBS is based on cellulose derived from cotton linters, which is an annual crop, and therefore has little cooling effect on the climate due to short rotation times. Impact from carbon soil is negligible. In total the inclusion of the unconventional aspects have reduced the global warming impact with 3 % compared to scenario 2.

It is important to emphasise that the negative GWP values in scenario 1a and 2a do not imply that additional carbon sinks are created. In the case of GWP_{bio}, the negative values is a result of that it is assumed that regrowth begins when the proposed time frame starts, which implies that CO_2 from the atmosphere will be sequestered before the carbon stored in the product is emitted, which results in a negative radiative forcing. Longer storage periods also imply that less radiative forcing will be created, due to the emission pulse from the biogenic carbon is stored in the product, during the fixed time frame, in this case 500 years (Guest et al., 2013a). Regarding the GWP_{albedo} factor, a negative value implies that there will be a cooling effect on the surface temperature, due to that a temporary increase in surface albedo occurs.

6.4.3 Comparisons of the global warming impact from all scenarios

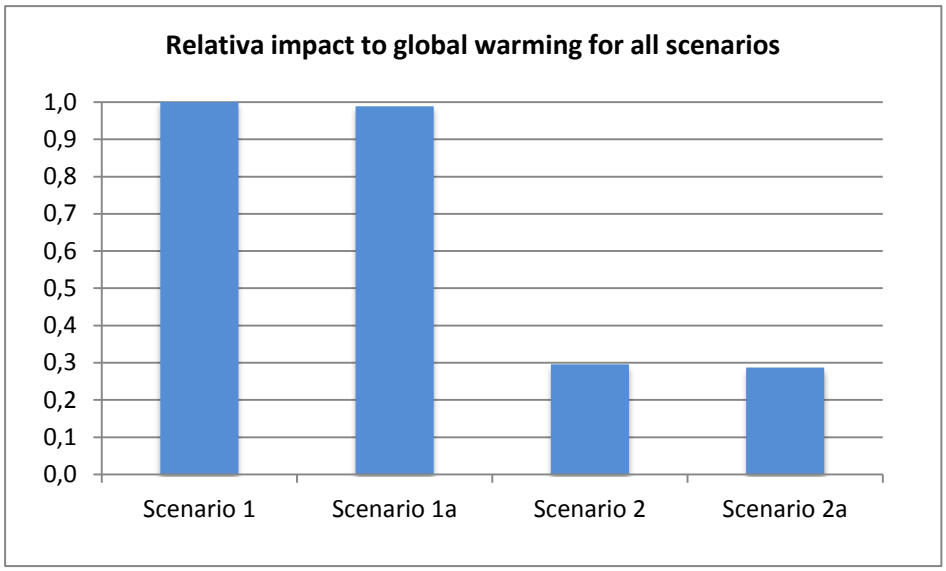

Figure 8 The figure shows the relative global warming impact from all scenarios

In figure 8, it can be seen that the global warming impact for Bermocoll in scenario 1 and 1a, used in India, is more than three times higher than for scenario 2 and 2a, Bermocoll used in Germany. This is due to the fact that twice as much Bermocoll is required in scenarios 1 and 1a in order to coat a square meter of wall with paint of 100 years. It is also and effect of that Bermocoll ends up at a landfill at its end-of-life in these scenarios, which generates a significant amount of emissions, especially from methane. If the same amount of Bermocoll were used in scenarios 1 and 1a as in scenarios 2 and 2a, the result would only differ by a third since the impact from the production phases is about the same. As can be seen in figures 6 and 7, the majority of the global warming impact is related to non-biogenic emissions.

6.6 Variation analysis

When AkzoNobel is assessing the global warming impact of their products is incineration normally used as end-of-life. A variation analysis was therefore performed in order to evaluate the global warming impact from different end-of-life scenarios. The analysis was conducted based on the same assumptions except that the storage time was 55 years for the paint, attached to the wall, due to the fact that the paint is incinerated directly after the house is demolished.

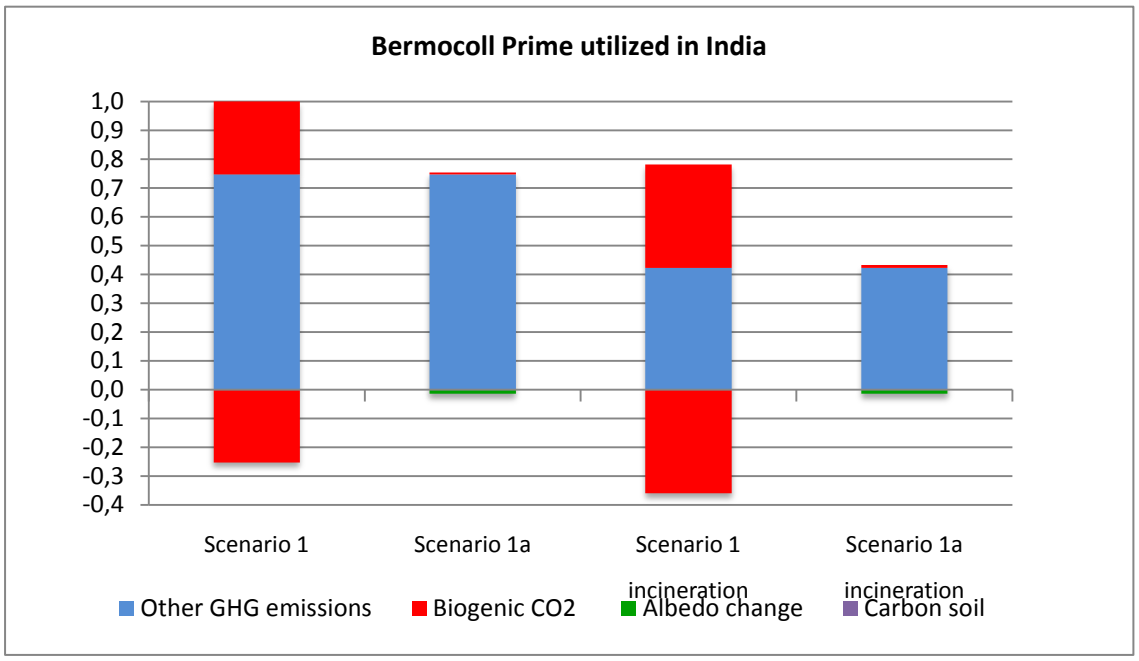

Figure 9 The relative global warming impact Bermocoll Prime used in India if landfilled or incinerated.

Figure 9 shows the global warning impact of Bermocoll Prime, scenarios 1 and 1a, if it is landfilled or incinerated. Incineration of Bermocoll results in lower global warming impact, in both scenario, compared to if Bermocoll is landfilled, since no methane emissions are formed. This aspect contributes to a reduction of the global warming impact with 1% regardless of end-of-life scenario. However, since incineration generates more biogenic carbon than landfilling a greater amount of biogenic carbon emissions is reduced in total when Bermocoll is incinerated. The albedo effect and carbon soil have the same impact regardless of end-of-life scenario.

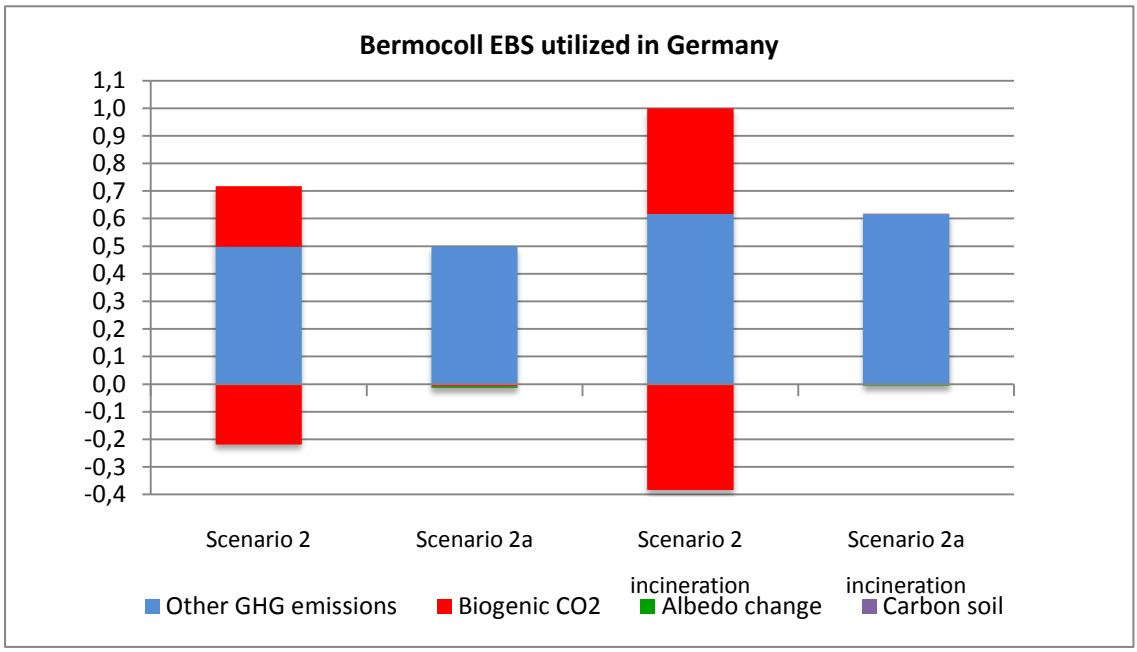

Figure 10 The relative global warming impact of Bermocoll EBS used in Germany if recycled or incinerated

When the same comparison is made for Bermocoll EBS, incineration is an unfavourable end-of-life option since it is compared to recycled Bermocoll, which is assumed permanently stored and therefore are no emissions is released. Regarding the unconventional aspects, the overall reduction in global warming impact is 0.5 % when Bermocoll is incinerated and 3% reduction when Bermocoll is landfilled as a result of including the aspects. In scenario 2a incineration is the biogenic carbon not entirely negative as it is in 2a. This is due to the fact the biogenic carbon is assumed to stay in the antroposphere for a shorter time if incinerated than recycled and therefore given a lower credit. The albedo effect and carbon soil have the same impact regardless end-of-life scenario.

7 Discussion

The main objective of this thesis has been to implement unconventional climate aspects to an LCA of a bio-based product and to compare the global warming impact result of such assessment with the result from an LCA conducted according to common praxis. The results show a marginal change in global warming impact between scenario 1 and 1a and between 2 and 2a. However, the study showed that the impact from biogenic carbon emission in scenario 1a and 2a, in which unconventional aspects were incorporated, were close zero and thus the results from these assessments confirm the climate neutrality assumption made in scenario 1 and 2. Reaching climate neutrality by implementing unconventional aspects, e.g. credits to carbon stored in a product, results in a more trustworthy description of the carbon flows in a products life cycle which should be seen as an advantage compered to assume climate neutrality, which is currently done by AkzoNobel.

The estimated storage times for Bermocoll in the antroposphere was the determined factor for the climate neutrality result for biogenic carbon in scenario 1a and 2a since the carbon credit for the net reduction in radiative forcing during storage was greater than the temporary increase in radiative forcing from the biogenic emissions released at Bermocoll's end-of-life. In addition was biomass regrowth a contributing factor to the climate neutrality result since it implies a gradual sequestration of the biogenic emission when it is released into the atmosphere. The influence on the results from biomass regrowth was higher in scenario 2a than 1a since shorter rotation periods, as for cotton crop, implies faster sequestration and reduced residence time of the biogenic emission in the atmosphere.

The lifetime of Bermocoll was a challenge to estimate since the path through the antroposphere is uncertain. In the scenarios based on German conditions it has been assumed that all Bermocoll in construction debris is recycled so many times in the antroposphere that there are no emissions released during the assessment period, which implies that it can be considered as permanently stored and assigned a maximum credit for carbon stored. Perhaps, Bermocoll could be emitted before 500 years since there is no clear evidence of whether Bermocoll is degraded or not. Difficulties in predicting the lifetime of Bermocoll was also experienced in scenarios 1 and 1a when Bermocoll ends up at a landfill, especially when it was attached to a non-degradable material. This indicates problems in making reasonable assumptions regarding Bermocoll's lifetime in the two gate-to-grave scenarios assessed, which reduce the accuracy in the storage time estimations. The storage time was mentioned above as one of the aspects that affected the result in a significant manner, which increases the uncertainty level of the result in this thesis and stresses the importance of assessing a product with a well described end-of-life to avoid an over- or underestimation of the amount of credit given for carbon stored since it affects the LCA result to a great extent. However, if Bermocoll would be incinerated at its end-of-life, the storage time estimations would have been easier to predict and a higher accuracy level would probably have been obtained if a wooden house had been assessed in the case study, at least in Germany where demolition waste from a wooden house is incinerated. As wood is landfilled in India, it would not lead to any significant impact difference since wood also ends up at a landfill site. However, it would be easier to assume a degradation time of Bermocoll since it would be attached to a biodegradable material instead of a cement plaster.

Implementation possibilities for the GWP_{bio} metric within LCA can be discussed from different points of view. From an LCA practitioner perspective, the selection of growth model is critical since it depends on the data availability and the scope of the study. An assessment including many biomass

suppliers would probably yield a more reliable result if a less site-specific growth model were used, like the Schnute growth model or the Gaussian distribution model. The workload would in addition be reduced since less data needs to be gathered compared to if a more site specific NEP would be used. However, if the purpose was to calculate the GWP_{bio} for a specific supplier and collection of site-specific data is possible, a more accurate result would be achieved with NEP. From the perspective of a multinational company like AkzoNobel, a less site-specific model like the one used in this study would be more favourable. The fact that the GWP_{bio} methodology covers many of the unconventional aspects makes it a comprehensive alternative to common praxis. Alternative methods like the ILCD storage method suggested by the European Commission (2010) and dynamic LCA according to Levasseur et al. (2010) can only target one aspect each and in order to create a competitive alternative to GWP_{bio}, a combination of many different methods is necessary, which complicates an assessment. However, to incorporate many unconventional aspects into one method is not straightforward as they may be difficult to combine. Such a situation occurs for assessments with infinite time horizons since the credit for stored carbon then disappears. An infinite time horizon starts when the product is disposed and the emissions are released into the atmosphere. This leads to no recognition of the time period for which the emissions are stored in the product and no credits can therefore be given (Guest et al., 2013a). The aspect of stored carbon has another implication as it postpones emissions and relies on the ability of future generations' capacity to reduce GHGs (Kirschbaum, 2003) and the development of mitigating technologies (Levasseur et al., 2013).

A limitation of the study was the inconsistency in the impact assessment between biogenic carbon and the other GHGs over the fixed time horizon. All emissions stored in Bermocoll are delayed, to a time period that starts when the product is disposed of. The impact of the emissions is equal to the effect on the radiative balance over the years they reside in the atmosphere to the fixed time horizon at the end of said time period. This was the case for biogenic carbon assessed with GWP_{bio}, while the impact from the other GHGs is computed from the original GWP metric. The original metrics are developed without accounting for timing of emissions, which is further explained in theory chapter 2.4.1. The fact that GWP_{bio} values, according Guest et al. (2013a) has been developed to assess only biogenic carbon is problematic as it implies that timing of other GHG are excluded, which perhaps may complicate the possibilities to incorporate this methodology in common LCA praxis. Guest et al. (2013a) address this problem and explain that it would be more preferable from an LCA perspective to combine their method with a dynamic approach, which can handle all emissions independent over time and they therefore recommend an adaption to the Levasseur et al. (2010) dynamic LCA. Nevertheless, since the timing of biogenic emission is excluded in the AkzoNobel assessment, as it is assessed with the standard GWP metric, and then included in the GWP_{bio} assessment will the contribution from timing of emission of biogenic CO_2 still be visualized even if the timing of the other GHG are ignored.

Soil disturbances did not influence the result, which probably is an effect of difficulties to incorporate the aspect in the assessment. A different result would have been obtained if soil models were utilized since these simulate the complex system of carbon flows in soil. Soil carbon data, which represented the soil conditions at the location of the three suppliers, was instead taken from literature. In the case of the Norwegian supplier, the result was based on a study conducted in Great Britain. Thus, the result is uncertain and for a more reliable assessment, it would be necessary to collect more site-specific data from the suppliers. The literature emphasizes that management practices affect if CO_2 is sequestered in soil or lost to the atmosphere. From a soil carbon perspective, it is better to leave forest residues on site, which was practised by the Norwegian supplier since clear-cutting technique was

utilized. However, for the cotton plantations in China was more carbon lost than sequestered despite that residues were left on place, which likely can be explained with the intensified tillage. More losses would possibly have been expected if the impact from fertilizers had been taken into account. For the supplier in USA, WTH management was assumed which reduced soil carbon stocks with 6% (Johnson et al., 2002). The result would have change if SAW, a clear cutting technique where only the stem is removed from the plantation site, was implemented instead since it increases soil carbon with 18% (Johnson and Curtis, 2001). Another remark worth mentioning is that a short rotation period is favourable from a biogenic carbon point of view as these emissions are sequestered more rapidly in growing biomass. However, it implies more frequent harvesting of forestland, which from a soil disturbance perspective would intensify the carbon fluxes in soil and result in either sequestration in soil or losses, depending on management practices in place (Cherubini et al., 2011b).

A minor cooling effect due to changes in surface albedo was detected, which seems to be a result of a combination of circumstances like short rotation times for the cotton crop and lack of snow at the location for the American supplier. This is in line with Cherubini et al. (2012a) that makes the assessment that the albedo change forcing is negligible for fast growing biomass and for biomass growing in areas with out seasonal snow coverage. If all cellulose used would have been derived from biomass from non-annual crops and from areas with seasonal snow cover the albedo effect would probably influence the result to a greater extent. Another factor that influenced the result is the site's location; a site located closer to the equator has higher incoming solar radiation flux at the top of the atmosphere. The biomass yield of the site are also a factor that influence the result since the GWP_{albedo} values are to be multiplied with the area acquired for the functional unit. A high yield will result in lower cooling effect from surface albedo compared to low yields. Another parameter that can influence the result is the definition of the "decay function", $y_{\alpha}(t)$. The function $y_{\alpha}(t)$ is in reality site specific but no such data could be found and it is therefore a source of uncertainty for the final GWP_{albedo} result. The fact that this study is assessed over a time horizon of 500 years impact the magnitude of GWP_{albedo} values greatly. If the time horizon had been shorter the inclusion of the albedo effect would have a greater influence on the global warming impact reduction. The accuracy of changes in surface albedo is sensitive to the availability of site-specific data. To find an optimal reference area was difficult since the majority of the land at the identified locations were covered with forest or cropland. Cropland was used to represent a clear-cut site, which results in some uncertainties since the variation in surface albedo for a clear-cut site might be slightly different. As the aspect of surface albedo requires site specific data, it is complicated to assess the albedo effect of Bermocoll since the cellulose used in Bermocoll originates from a range of suppliers located all around the world. In some cases the suppliers do not own the biomass plantations themselves, which impedes the accessibility for important albedo data. Although there are impediments related to the albedo effect, variations in surface albedo is an aspect that has potential to reduce the global warming impact especially for locations where species with long rotations grow and where seasonal snow cover is common, which are possible conditions for the Norwegian supplier.

As a final remark, the aspect of ILUC (indirect land use change) is discussed, which was identified by Røyne et al. (2014) as one unconventional climate aspects that might need to be included. Methods for assessing ILUC were not identified during the conducted literature study and therefore excluded in the case study. However, the aspect is still crucial and probably a major contributor to the global warming impact for Bermocoll. Strategies were presented in the theory chapter 2.4.2. for avoiding or mitigating the ILUC effect and one of them was to utilize residues as products. Cotton linters are not residues from cotton harvesting more a by-product, but in cases where the cotton plantation is

harvested for the sole purpose of the cotton lint, cotton linters can be considered as low ILUC risk product's. For the wood suppliers, it can become difficult, though, since forest residues have been identified as beneficial to leave at site since it may increase soil carbon. This leads to a situation where the LCA practitioner has to choose between lowering the ILUC impact by removing the residues and use them as raw material for a product or lowering the soil carbon impact by leaving the residues on site.

8 Conclusions

In the following list, the conclusions are stated

- The climate impact for Bermocoll EBS used in Germany was reduced by 3% when the unconventional aspects were incorporated and the climate impact for Bermocoll Prime used in India was reduced by 1%. The long storage time in the anthroposphere for Bermocoll was the decisive factor since it implies a major credit for carbon stored.
- Changes in surface albedo had a minor effect on the climate impact for Bermocoll EBS and Bermocoll Prime as a result of lack of seasonal snowfall where the American supplier operates and short rotation time for the cotton crop in China.
- Inclusion of the aspect of soil disturbances had a negligible impact as a result of difficulties to model this aspect with sufficient methods.
- The renewable part of Bermocoll can be considered climate neutral when the unconventional aspects are incorporated, if the assessment is conducted under the same assumptions and methods as in this study.
- Cellulose for producing Bermocoll is extracted from several plantation sites located in different pasrts of the world and there are many different suppliers who sell the cellulose to AkzoNobel. This reduces the accessibility for site-specific data and thus reduces the possibilities to assess the overall impact for albedo changes. The aspect is therefore not (yet) appropriate to implement in an LCA of Bermocoll.
- It is not possible, from the result in this study, to say anything about how appropriate the aspect of soil disturbances is to implement in an LCA of Bermocoll since no method could be found to calculate soil emissions.
- From a Bermocoll perspective, it can be concluded that the aspects timing of emission, carbon sequestration, climate neutrality and credit for carbon stored in products are essential to assess since Bermocoll has a long storage time in the atmosphere and a major percentage is renewable. However, more research is necessary in order to find an optimal method for incorporating these aspects with a higher accuracy when Bermocoll is assessed from a cradle-to-grave perspective.
- The accuracy of credits given to carbon stored in product is sensitive to the chosen end-of-life scenario since it defines the time that Bermocoll spends in the antroposphere. Different end-of-life scenarios are possible for Bermocoll depending on the product it is a part of and the country it is consumed in. However, with an end-of-life scenario that is not well defined, it can be questioned if it is appropriate to include the aspect into an LCA of Bermocoll

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Appendix A - Albedo calculations

Table 14 below shows the values for the clearness index, K_t, for all three sites. The clearness index values, K_t, was obtained by using NASA's database NASA Surface meteorology and Solar Energy (NASA, 2015b).

Table 14 Mean values of Kt, the clearness index.

Kt values														
		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Annual**
Hami City, Xinjiang, China	**Cotton**	0.634	0.668	0.637	0.600	0.590	0.543	0.542	0.571	0.604	0.628	0.626	0.608	0.604
Madison County, Florida, USA	**Forest**	0.501	0.512	0.535	0.563	0.557	0.494	0.499	0.497	0.504	0.541	0.539	0.516	0.521
Sarpsborg Norway	**Forest**	0.360	0.431	0.462	0.472	0.518	0.486	0.508	0.486	0.464	0.393	0.379	0.331	0.441

The table 15, 16 and 17 show the surface albedo values for standing biomass, open landscape and the change in surface albedo for the studied sites. The albedo values were obtained by using MODIS Land Products Subsetting and Visualization Tools (DAAC, 2015).

Table 15 Mean surface albedo values for standing biomass for the sites studied

Average albedo values for standing biomass														
		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Annual**
Hami City, Xinjiang, China	**Cotton**	0.119	0.117	0.116	0.122	0.127	0.122	0.125	0.127	0.120	0.117	0.120	0.120	0.121
Madison County, Florida, USA	**Forest**	0.158	0.143	0.108	0.085	0.085	0.089	0.091	0.092	0.091	0.095	0.118	0.154	0.109
Sarpsborg Norway	**Forest**	0.348	0.223	0.211	0.218	0.210	0.188	0.192	0.181	0.182	0.187	0.210	0.305	0.221

Table 16 Mean surface albedo values for open landscape for the sites studied

Average albedo values for open land														
		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Annual**
Madison County, Florida, USA	**Forest**	0.181	0.182	0.177	0.173	0.176	0.175	0.175	0.171	0.171	0.172	0.176	0.177	0.175
Sarpsborg Norway	**Forest**	0.391	0.393	0.216	0.123	0.133	0.154	0.156	0.152	0.143	0.133	0.240	0.370	0.217

Table 17 Mean values for the change in surface albedo for the sites studied

		Change in surface albedo (delta albedo)												
		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Annual**
Madison County, Florida, USA	**Forest**	0.062	0.066	0.061	0.051	0.049	0.053	0.049	0.044	0.052	0.054	0.056	0.056	0.054
Sarpsborg Norway	**Forest**	0.234	0.250	0.108	0.038	0.048	0.065	0.064	0.060	0.051	0.038	0.122	0.216	0.108

The GWP_{albedo} values were obtained by using Matlab, and the scripts used are found below. The first script is for computing the GWP_{albedo} factors for the sites with wood and is calculating the global radiative forcing for an albedo change, $\Delta RF_{\alpha}^{Global}$, according to Cherubini et al. (2012a). For cellulose derived from cotton linter was $\Delta RF_{\alpha}^{Global}$ computed according to Bright et al. (2012) and the second scrip was used to calculated the GWP_{albedo} factors for the site with cotton linter.

Matlab script for calculating the GWP_{albedo} values for the sites with wood

```
%% Input values

L=X;            % Latitude of measured place in degrees
Rsc=1367;       % Solar constant in W/m2
Ta=0.854;       % The fraction of the radiation reflected from the surface
                   back to the top of the atmosphere (TOA)
Aa=1;           % Local area affected
Ae=5.10e14;     % Area of Earth's surface
r=X;            % Rotation period of biomass
tau=r/5;        % Fraction of the rotation period (Cherubini et al, 2012)


%% Rtoa - incoming solar radiation flux at the Top Of the Atmosphere (TOA)

Rtoa=@(di)(Rsc/pi)*((cosd(L)*cosd(23.45*sind(360*(284+di)/365)).*sind(acosd(
-tand(L)*tand(23.45*sind(360*(284+di)/365)))))+(pi*acosd(-
tand(L)*tand(23.45*sind(360*(284+di)/365)))/180)*sind(L).*sind(23.45*sind(36
0*(284+di)/365)));

Rtoa_int=quadl(Rtoa,1,365); % Integration over the Julian days of the years
                              from 1 to 365
Rtoa_ann=Rtoa_int/365;      % Mean annual extraterrestrial radiation at TOA

Rtoa_int_jan=quadl(Rtoa,1,31)/31;    % Mean extraterrestrial radiation at
                                       TOA in January
Rtoa_int_feb=quadl(Rtoa,32,59)/28;   % Mean extraterrestrial radiation at
                                       TOA in February
Rtoa_int_mar=quadl(Rtoa,60,90)/31;   % Mean extraterrestrial radiation at
                                       TOA in March
Rtoa_int_apr=quadl(Rtoa,91,120)/30;  % Mean extraterrestrial radiation at
                                       TOA in April
Rtoa_int_may=quadl(Rtoa,121,151)/31; % Mean extraterrestrial radiation at
                                       TOA in May
Rtoa_int_jun=quadl(Rtoa,152,181)/30; % Mean extraterrestrial radiation at
                                       TOA in June
Rtoa_int_jul=quadl(Rtoa,182,212)/31; % Mean extraterrestrial radiation at
                                       TOA in July
Rtoa_int_aug=quadl(Rtoa,213,243)/31; % Mean extraterrestrial radiation at
                                       TOA in August
```

```
Rtoa_int_sep=quadl(Rtoa,244,273)/30; % Mean extraterrestrial radiation at
                                       TOA in September
Rtoa_int_oct=quadl(Rtoa,274,304)/31; % Mean extraterrestrial radiation at
                                       TOA in October
Rtoa_int_nov=quadl(Rtoa,305,334)/30; % Mean extraterrestrial radiation at
                                       TOA in November
Rtoa_int_dec=quadl(Rtoa,335,365)/31; % Mean extraterrestrial radiation at
                                       TOA in December

Rtoa_m=[Rtoa_int_jan Rtoa_int_feb Rtoa_int_mar Rtoa_int_apr Rtoa_int_may
Rtoa_int_jun Rtoa_int_jul Rtoa_int_aug Rtoa_int_sep Rtoa_int_oct
Rtoa_int_nov Rtoa_int_dec];

%% Delta albedo - Change in surface albedo

delta_a=[x1 x2 x3 x4 x5 x6 x7 x8 x9 x19 x11 x12]; % Difference in monthly
mean surface albedo between standing and biomass and clear cut site. Values
are specific for the chosen location and were obtained by using the MODIS
tool.


%% fa - Two-way atmospheric transmittance parameter

Kt=[x1 x2 x3 x4 x5 x6 x7 x8 x9 x19 x11 x12]; % Clearness index, the average
fraction of Rtoa that reaches the earths surface in each month. Values are
specific for the chosen location and provided by NASA's Solar Surface Energy
project.

fa=Kt*Ta;


%% RF_albedo_Global - Local mean annual instantaneous albedo radiative
forcing

y_t=@(T)exp(-T/tau); % y_alfa (albedo decay function) defines the temporal
profile for the return of albedo to the pre-harvest level owing to forest
re-growth

y_alfa_20=quad(y_t,0,20);   % integration over 0 to time horizon 20 years
y_alfa_100=quad(y_t,0,100); % integration over 0 to time horizon 100 years
y_alfa_500=quad(y_t,0,500); % integration over 0 to time horizon 500 years

RF_albedo=sum(-Rtoa_m.*fa.*delta_a)/12;

RF_albedo_20=RF_albedo*Ae^-1*y_alfa_20;   % RF_albedo for time horizon 20
                                            years
RF_albedo_100=RF_albedo*Ae^-1*y_alfa_100; % RF_albedo for time horizon 100
                                            years
RF_albedo_500=RF_albedo*Ae^-1*y_alfa_500; % RF_albedo for time horizon 500
                                            years

%% Bern 2.5CC function

A0=0.217;  % variables taken from literature for the Bern 2.5CC function
A1=0.259;
A2=0.338;
A3=0.186;
B1=172.9;
B2=18.51;
```

```
B3=1.186;

yCO2=@(t)(A0+(A1*exp(-t/B1))+(A2*exp(-t/B2))+(A3*exp(-t/B3)));
% Bern 2.5CC function

yCO2_20=quadl(yCO2,0,20);  % integration over 0 to time horizon 20 years
yCO2_100=quad(yCO2,0,100); % integration over 0 to time horizon 100 years
yCO2_500=quad(yCO2,0,500); % integration over 0 to time horizon 500 years




%% kCO2 - Radiative efficiency of CO2 per kg emission

kCO2=(5.35*log((378+1)/378))/(1e-6*(44.009/28.97)*5.1441e18);


%% RF_CO2 - Instantaneous radiative forcing from 1 kg of bionic CO2
emissions

RF_CO2_20=yCO2_20*kCO2;   % RF_CO2 for time horizon 20 years
RF_CO2_100=yCO2_100*kCO2; % RF_CO2 for time horizon 100 years
RF_CO2_500=yCO2_500*kCO2; % RF_CO2 for time horizon 500 years


%% GWP Albedo per m2

GWP_20=RF_albedo_20/RF_CO2_20;    % GWP albedo for time horizon 20 years
GWP_100=RF_albedo_100/RF_CO2_100; % GWP albedo for time horizon 100 years
GWP_500=RF_albedo_500/RF_CO2_500; % GWP albedo for time horizon 500 years
GWP_albedo=[GWP_20 GWP_100 GWP_500]
```

Matlab script for calculating the GWP_{albedo} values the site with cotton linters

```
%% Input values

L=X;       % Latitude of measured place in degrees
Rsc=1367; % Solar constant in W/m2
Kt=X;      % Clearness index, the fraction of Rtoa that reaches the earths
           surface. The value is a mean annual value and is specific for the
           chosen location and provided by NASA's Solar Surface Energy
           project.
Ta=0.854; % The fraction of the radiation reflected from the surface back to
           the top of the atmosphere (TOA)
Aa=1;           % Local area affected
Ae=5.10e14;     % Area of Earth's surface
alfa_s_new=X;  % Albedo after harvest. The value is specific for the chosen
                location and was obtained by using the MODIS tool.
alfa_s_old=X;  % Albedo before harvest. The value is specific for the chosen
                location and was obtained by using the MODIS tool.
r=X;       % Rotation period of biomass
tau=r/5;  % Fraction of the rotation period (Cherubini et al, 2012)


%% Rtoa - Incoming solar radiation flux at the Top Of the Atmosphere (TOA)

Rtoa=@(di)(Rsc/pi)*((cosd(L)*cosd(23.45*sind(360*(284+di)/365)).*sind(acosd(
-tand(L)*tand(23.45*sind(360*(284+di)/365)))))+(pi*acosd(-
tand(L)*tand(23.45*sind(360*(284+di)/365)))/180)*sind(L).*sind(23.45*sind(36
0*(284+di)/365)));

Rtoa_int=quadl(Rtoa,1,365); % Integration over the the Julian days of the
                              years from 1 to 365
Rtoa_ann=Rtoa_int/365;     % Mean annual extraterrestrial radiation at TOA

Rtoa_int_jan=quadl(Rtoa,1,31)/31;    % Mean extraterrestrial radiation at
                                      TOA in January
Rtoa_int_feb=quadl(Rtoa,32,59)/28;   % Mean extraterrestrial radiation at
                                      TOA in February
Rtoa_int_mar=quadl(Rtoa,60,90)/31;   % Mean extraterrestrial radiation at
                                      TOA in March
Rtoa_int_apr=quadl(Rtoa,91,120)/30;  % Mean extraterrestrial radiation at
                                      TOA in April
Rtoa_int_may=quadl(Rtoa,121,151)/31; % Mean extraterrestrial radiation at
                                      TOA in May
Rtoa_int_jun=quadl(Rtoa,152,181)/30; % Mean extraterrestrial radiation at
                                      TOA in June
Rtoa_int_jul=quadl(Rtoa,182,212)/31; % Mean extraterrestrial radiation at
                                      TOA in July
Rtoa_int_aug=quadl(Rtoa,213,243)/31; % Mean extraterrestrial radiation at
                                      TOA in August
Rtoa_int_sep=quadl(Rtoa,244,273)/30; % Mean extraterrestrial radiation at
                                      TOA in September
Rtoa_int_oct=quadl(Rtoa,274,304)/31; % Mean extraterrestrial radiation at
                                      TOA in October
Rtoa_int_nov=quadl(Rtoa,305,334)/30; % Mean extraterrestrial radiation at
                                      TOA in November
Rtoa_int_dec=quadl(Rtoa,335,365)/31; % Mean extraterrestrial radiation at
                                      TOA in December

Rtoa_years=[Rtoa_int_jan Rtoa_int_feb Rtoa_int_mar Rtoa_int_apr Rtoa_int_may
Rtoa_int_jun Rtoa_int_jul Rtoa_int_aug Rtoa_int_sep Rtoa_int_oct
```

```
Rtoa_int_nov Rtoa_int_dec];

%% Delta albedo - Change in surface albedo

delta_a=alfa_s_new-alfa_s_old; %Difference in mean surface albedo between
                                standing and biomass and clear cut site

%% f_a - Two-way atmospheric transmittance parameter

f_a=Kt*Ta;

%% Bern 2.5CC function

A0=0.217; %variables taken from literature over the Bern 2.5CC function
A1=0.259;
A2=0.338;
A3=0.186;
B1=172.9;
B2=18.51;
B3=1.186;

yCO2=@(t)(A0+(A1*exp(-t/B1))+(A2*exp(-t/B2))+(A3*exp(-t/B3)));
%Bern 2.5CC function

yCO2_20=quadl(yCO2,0,20);  % integration over 0 to time horizon 20
yCO2_100=quad(yCO2,0,100); % integration over 0 to time horizon 100
yCO2_500=quad(yCO2,0,500); % integration over 0 to time horizon 500

%% kCO2 - radiative efficiency of CO2 per kg

kCO2=(5.35*log((378+1)/378))/(1e-6*(44.009/28.97)*5.1441e18);

%% RF_CO2-Instantaneous radiative forcing from 1 kg of bionic CO2 emissions

RF_CO2_20=yCO2_20*kCO2;   % RF_CO2 for time horizon 20 years
RF_CO2_100=yCO2_100*kCO2; % RF_CO2 for time horizon 100 years
RF_CO2_500=yCO2_500*kCO2; % RF_CO2 for time horizon 500 years

%% RF_albedo_Global - Local mean annual instantaneous albedo radiative
forcing

y_t=@(T)exp(-T/tau);       % y_alfa (albedo decay function) defines the
temporal profile for the return of albedo to the pre-harvest level owing to
forest re-growth

y_alfa_20=quad(y_t,0,20);   % integration over 0 to time horizon 20 years
y_alfa_100=quad(y_t,0,100); % integration over 0 to time horizon 100 years
y_alfa_500=quad(y_t,0,500); % integration over 0 to time horizon 500 years

RF_albedo_20=-Rtoa_ann*f_a*delta_a*Ae^-1*y_alfa_20; % RF_albedo for time
                                                     horizon 20 years
RF_albedo_100=-Rtoa_ann*f_a*delta_a*Ae^-1*y_alfa_100; % RF_albedo for time
                                                      horizon 100 years
RF_albedo_500=-Rtoa_ann*f_a*delta_a*Ae^-1*y_alfa_500; % RF_albedo for time
                                                      horizon 500 years

%% GWP albedo per m2
```

```
GWP_albedo_20=RF_albedo_20/RF_CO2_20;     % GWP albedo for time horizon 20
                                            years
GWP_albedo_100=RF_albedo_100/RF_CO2_100; % GWP albedo for time horizon 100
                                            years
GWP_albedo_500=RF_albedo_500/RF_CO2_500; % GWP albedo for time horizon 500
                                            years

GWP_albedo=[GWP_albedo_20 GWP_albedo_100 GWP_albedo_500]
```

The area required to produce the acquired amount of cellulose for the chosen functional unit for each site was obtained by using the parameters in table 18. The amount of each cellulose type acquired for 1 kg Bermocoll Prime and EBS is seen in table 19. To obtain the acquired amount of cellulose for the function unit the figures in table were multiplied by the reference flow for Prime, 0.0206 kg, and EBS, 0.0103 kg.

Table 18 Characteristics for the different species types from which the cellulose are extracted

	USA	**Norway**	**China**
Type of biomass	Slash Pine	Norway Spruce	Cotton seed
Yield/ha	375 m^3/ha	275 m^3/ha	0.11 kg/m^2
Wood density	540 kg/m^3	405 kg/m^3	
Biomass-to-pulp yield	50%	40%	50%

Table 19 Amount cellulose acquired for 1 kg Bermocoll

Amount cellulose acquired for 1 kg Bermocoll				
	Cellulose Norway	**Cellulose USA**	**Cellulose China**	**Total**
Prime	0.483	0.147	0	0.630
EBS	0	0	0.533	0.533

The required area from the site in Norway was calculated by the equation below, the figures are taken from table 18 and 19.

$$\frac{0.483\frac{kg\ pulp}{kg\ BMC} * 0{,}0206\frac{kg\ BMC}{kg\ FU}}{0.4} \Bigg/ \frac{275}{10000}\frac{m^3}{m^2} * 405\frac{kg}{m^3} = 0.00223\ \frac{m^2}{kg\ \ FU}$$

The required area from the site in USA was calculated by the equation below, the figures are taken from table 18 and 19. The bark volume of the tree is also accounted for which is 18% of the total volume of the tree. More information about the parameters used is found in chapter 4.5.2

$$\left.\frac{\frac{0.483\frac{kg\ pulp}{kg\ BMC} * 0.0206\frac{kg\ BMC}{kg\ FU}}{0.4} \Big/ 540\frac{kg}{m^3}}{(100\% - 18\%)} \right/ \frac{375}{10000}\frac{m^3}{m^2} * 90\% = 0.000405\frac{m^2}{kg\ \ FU}$$

The required area to produce cotton linters was calculated by the equation below, the figures is taken from table 18 and 19.

$$\left.\frac{0.553\frac{kg\ pulp}{kg\ BMC} * 0.0103\frac{kg\ BMC}{kg\ FU}}{0.5} \right/ 0.11\frac{kg}{m^2} * 8.35\ \% = 1.185\ \frac{m^2}{kg\ \ FU}$$

However, cotton linter is a product obtained when cottonseed are processed, which is a by-product from cotton lint production. The area required must therefore be allocated in relation to the other products to obtain the impact from a change in surface albedo that is connected to the cotton linter cultivation. The cottonseed has a total value of 15% of the total cotton crop. Form cottonseed is cotton oil, meal, hull and linters extracted. Of these product is oil the most valuable and stand for about 50% of the value of all products obtained from cottonseed and cotton meal stands for about 33% of the value. Economic values for cotton hull and linters could not be found but the weight percent of cotton hull is 27% for the cottonseed and for cotton linter it is 8.35% (NCPA, 2002).. The value for cotton hull and linter together is 17% and since no information was found of how this value were divided between the product it was assumed to correspond to the weight of the products. The value of cotton linter of the total value of all products form the cottonseed is therefore 4.02%. This value was multiplied with the value that cottonseed have of the total crop production to obtain cotton linters value based on the total cotton crop product, which is 0.60%.

$$\frac{8.35\%}{8.35\% + 27\%} * (100\% - 50\% - 33\%) * 15\% = 0.60\%\ Value\ of\ cotton\ linter\ of\ the\ total\ cotton\ crop$$

To obtain the area that induces a change in surface albedo connected to cotton linters the required area to produce the acquired amount of cellulose is multiplied with the value of cotton linter of total cotton crop.

$$0.60\% * 1.185\frac{m^2}{kg\ \ FU} = 0.00714\frac{m^2}{kg\ \ FU}$$

Appendix B - Emissions from end-of-life processes

The table below shows the molecular composition of Bermocoll EBS and Prime. These values were used to obtain the emissions generated from Bermocoll when landfilled or incinerated.

Table 20 Molecular composition of Bermocoll EBS and Prime

	C	H	O	Renewable part
EBS	12	22	7.20	58%
Prime	10.16	18.32	6.5	66%

To calculate the emissions from Bermocoll that was landfill the following equations was used.

$$C_aH_bO_c + \left(a - \frac{b}{4} - \frac{c}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4}\right) CO_2$$

The emission from the incinerated part of Bermocoll was computed by the equation below.

$$C_aH_bO_C + \left(a + \frac{1}{4b} - \frac{c}{2}\right) O_2 \rightarrow aCO_2 + \frac{b}{2} H_2O$$

The emissions from 1 kg landfilled Bermocoll Prime can be seen in table 20. To obtain the emissions generated per functional unit and for each EoL process the values in table 20 were multiplied by the fraction for each EoL process which is seen in table and the reference flow which is 0.0206 kg for Prime and 0.0103kg for EBS.

Table 21 kg emissions for 1 kg Bermocoll if landfilled

kg emissions from Landfill per kg Bermocoll			
	Biogenic CO_2	Non-biogenic CO_2	CH_4
Prime	0.528	0.268	0.376

Table 22 EoL process for the Bermocoll Prime

EoL processes Prime		
	Tot amount BMC	Landfilled
Paint in can	12.9%	12.9%
Paint wall	87.1%	87.1%
Tot	100.0%	100.0%

Table 23 show the emissions generated when Bermocoll Prime is landfill for the chosen functional unit

Table 23 kg emissions from Bermocoll Prime per functional unit if landfilled

Emission Prime if Landfilled kg/functional unit			
	Biogenic CO_2	Non-biogenic CO_2	CH_4
Landfill can	0.0014	0.0007	0.001
Landfill wall	0.0095	0.0048	0.007

The emissions from 1 kg incinerated Bermocoll EBS and Prime can be seen in table 24. To obtain the emissions generated per functional unit and for each EoL process the values in table 24 were multiplied by the fraction for each EoL process which is seen in table 25 and the reference flow, which is 0.0206 kg for Prime and 0.0103kg for EBS.

Table 24 kg emissions from 1 kg Bermocoll if incinerated

kg emissons from Incineration per kg Bermocoll			
	Tot CO_2	Biogenic CO_2	Non-biogenic CO_2
EBS	1.878	1.082	0.796
Prime	1.830	1.214	0.616

Table 25 EoL process for the Bermocoll EBS

EoL processes EBS		
	Incinerated	Recycling
Paint in can	12.9%	0.0%
Paint wall	0.0%	87.1%
Tot	12.9%	87.1%

A big fraction of the Bermocoll used in scenario 2 and 2a, Bermocoll EBS, was recycled and the emission was assumed to be permanently stored over the assessed time horizon. The carbon dioxide preserved in the recycled fraction was found by multiplying the reference flow for Bermocoll EBS with the fraction of Bermocoll recycled and the molecular weight of carbon dioxide divided by the molecular weight of Bermocoll EBS, which is seen in the equation below.

$$0.0103 * 87.1\% * \left(\frac{44}{281.2}\right) = 0.00140376$$

The emission generated when incinerating Bermocoll EBS for scenario 2 and 2a as well as the fraction carbon dioxide preserved in the recycled part of Bermoocll is shown in Table 26.

Table 26 kg emissions from Bermocoll EBS per functional unit if incinerated and recycled

Emission EoL EBS kg/functional unit		
	Biogenic CO_2	Non-biogenic CO_2
Incineration	0.0014	0.0011
Recycling	0.0014	0

For the variation analysis was it assumed that both Bermocoll EBS and Prime was incierated at its EoL. The kg emissions generated per functional unit for this process cen be seen in table 27

Table 27 kg emissions from Bermocoll EBS and Primes per functional unit if incinerated

kg emissons from Incineration per functional unit			
	Tot CO_2	Biogenic CO_2	Non-biogenic CO_2
EBS	0.019	0.011	0.008
Prime	0.038	0.025	0.013

Appendix C – Impact assessment

The impact from biogenic carbon for scenario 1a is seen in table 28 and for scenario 2a in table 29. The GWP_{bio} values were obtained according to the description in chapter 4.5.1 and 5.1 and the biogenic carbon emissions according to appendix B.

Table 28 Impact to global warming from biogenic carbon with aspects included for scenario 1a

Impact from biogenic carbon for scenario 1a			
	GWP_{bio} 500	CO_2 emissions (kg)	Tot impact from biogenic CO_2 (kg CO_2eq/kg FU)
For BMC in can	-0.018	0.0014	-2.35E-05
For BMC on wall	-0.093	0.0095	-0.0009
For Steam	0.077	0.0225	0.0017

Table 29 Impact to global warming from biogenic carbon with aspects included for scenario 2a

Impact from biogenic carbon for scenario 2a			
	GWP_{albedo} 500	CO_2 emissions (kg)	Tot impact from biogenic CO_2 (kg CO_2eq/kg FU)
Incineration	0.003	0.0014	4.31E-06
Recycling	-1	0.0014	-0.0014
For Steam	0.077	0.0225	0.0017

The table below shows the impact to global warming from soil carbon disturbances and variation in the surface albedo

Table 30 Impact to global warming from soil carbon disturbances and variation of surface albedo scenario 1a and 2a

	Impact from change in surface albedo	**Impact from soil disturbances**	
Scenario 1a	-0.0019	-4.29E-12	kg CO_2 eq/kg FU
Scenario 2a	-0.0003	2.40E-12	kg CO_2 eq/kg FU

Table 31 shows the total impact to global warming for all scenarios. The fossil impact and the impact from biogenic carbon form scenario 1 and 2 is derived by using GaBi

Table 31 Total Impact to global warming for all scenarios

	Fossil	Biogenic	Albedo	Soil	Total	
Scenario 1	0.099	0.0336			0.042	kg CO_2eq/kg FU
Scenario 1a	0.099	0.0008	-0.0019	-4.29e-12	0.029	kg CO_2eq/kg FU
Scenario 2	0.029	0.0129			0.133	kg CO_2eq/kg FU
Scenario 2a	0.029	-0.0005	-0.0003	2.34e-12	0.098	kg CO_2eq/kg FU

Appendix D – Variation analysis

A variation analysis was performed in order to evaluate the impact contribution from the aspects, if Bermocoll was incinerated. The figures from that assessment is seen in table 32 to table 35

The impact from biogenic carbon for scenario 1a is seen in table 32 and for scenario 2a in table 33. Biogenic carbon emissions is calculated according to appendix B.

Table 32 Impact to global warming from biogenic carbon with aspects included for scenario 1a

Impact from biogenic carbon for scenario 1a			
	GWP_{bio} 500	CO_2 emissions (kg)	Tot impact from biogenic CO_2 (kg CO_2eq/kg FU)
For BMC in can	0.057	0.003	0.0002
For BMC on wall	-0.024	0.022	-0.0005
For Steam	0.077	0.023	0.0017

Table 33 Impact to global warming from biogenic carbon with aspects included for scenario 2a

Impact from biogenic carbon for scenario 2a			
	GWP_{albedo} 500	CO_2 emissions (kg)	Tot impact from biogenic CO_2 (kg CO_2eq/kg FU)
Incineration	-0.080	0.010	-0.0008
Recycling	0.003	0.001	4.31-06
For Steam	0.077	0.011	0.0009

The table below shows the impact to global warming from soil carbon disturbances and variation in the surface albedo

Table 34 Impact to global warming from soil carbon disturbances and variation of surface albedo scenario 1a and 2a

	Impact from change in surface albedo	**Impact from soil disturbances**	
Scenario 1a	-0.0019	-4.29E-12	kg CO_2 eq/kg FU
Scenario 2a	-0.0003	2.40E-12	kg CO_2 eq/kg FU

Table 35 shows the total impact to global warming for all scenarios. The fossil impact and the impact from biogenic carbon form scenario 1 and 2 is derived by using GaBi

Table 35 Total Impact to global warming for all scenarios for the variation analysis

	Fossil	Biogenic	Albedo	Soil	Total	
Scenario 1	0.056	0.047			0.104	kg CO_2eq/kg FU
Scenario 1a	0.056	0.001	-0.0019	-4.29e-12	0.056	kg CO_2eq/kg FU
Scenario 2	0.036	0.023			0.059	kg CO_2eq/kg FU
Scenario 2a	0.036	9.63e-05	-0.0003	2.40e-12	0.036	kg CO_2eq/kg FU