Building materials and their impacts on biodiversity

A comparison of wood and concrete building frames

Master's thesis in Industrial Ecology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

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Report No. E2023:079

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An AI interpretation of the concept ‘Wood, concrete, and biodiversity’. Created using Shutterstock.

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Abstract

The usage of biomaterials in society is increasing due to their environmental benefits and renewability. However, risks involved in using biomaterials include biodiversity loss, conflicts in land use, and carbon storage potential. There are numerous ways to assess the environmental impact of materials, one of which is life cycle assessment (LCA). Biodiversity is a very complex subject as it can be measured on different scales and aspects. Due to the complexity, biodiversity is not yet fully internalised in the LCA framework as no generally accepted method can cover all aspects of biodiversity.

The purpose of this thesis was to assess the environmental impact of the building materials wood and concrete. To do this, the load bearing constructions of two buildings about to be built by Sveafastigheter was investigated using an LCA approach. The main focus of the assessment was to capture the biodiversity impact at species level by using different methods of impact assessment and comparing the results. Biodiversity loss is often caused by anthropogenic activities induced by underlying causes such as production and consumption patterns, population growth, trade, and technological innovation. IPBES have identified five direct drivers: land use change, climate change, pollution, exploitation of species, and invasive species.

Three different methods of impact assessment were chosen due to their connection to the direct drivers behind biodiversity loss. ReCiPe was chosen due to the inclusion of midpoint impact categories covering climate change, pollution, and to some degree land use change. Two separate methods developed by Chaudhary and Brooks, and Kuipers et al., with each looking at land use were chosen since they each look at the impacts of land use more comprehensively than ReCiPe. Completely developed methods of impact assessment was not found for the inclusion of neither exploitation of species, nor invasive species.

Results showed that when including climate change, pollution, and land use via ReCiPe, the concrete-framed building had a higher impact on species loss than the wood-framed building. However, the methods unanimously showed that the wood-framed building had a substantially larger impact due to land use change. Thus, a conclusion can be made that when measuring biodiversity loss due to the usage of different materials, there is a need to develop methods covering all aspects of biodiversity including all five drivers behind biodiversity loss as well as the impact on different levels of biodiversity.

Keywords: Biodiversity, life cycle assessment, methods of impact assessment, wood, concrete.

Acknowledgements

We would like to thank our supervisor Ulrika Palme for the advice and feedback given throughout the writing of this thesis, as well as everybody who has helped us with feedback and ideas.

Martin Christiansson and Theodor Roos
Gothenburg, May 2023

Abbreviations

AP	Acidification potential
C&B	Chaudhary and Brooks method of impact assessment
CF	Characterisation factor
CLT	Cross laminated timber
cSAR	Countryside species-area relationship
ECA	Effectively connected habitat
EP	Eutrophication potential
EPD	Environmental product declaration
FU	Functional unit
GWP	Global warming potential
HF	Kuipers et al. method of impact assessment including habitat fragmentation
IPBES	The Intergovernmental science-policy platform on biodiversity and ecosystem services
ISO	International Organization for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land use
PDF	Potential disappeared fraction
POCP	Formation potential of tropospheric ozone
SETAC	Society of Environmental Toxicology and Chemistry
WDP	Water Deprivation Potential
WWF	World wildlife fund

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1. Introduction
Today there is a strong trend in society towards an increased usage of biomaterials due to their environmental benefits and renewability, both for construction as well as energy production (McCormick & Kautto, 2013). Forestry, in particular, has seen an increase in harvest rates in recent years (Ceccherini et al., 2020). However, risks involved in using biomaterials include biodiversity loss, conflicts in land use, and carbon storage potential.

The International Organization of Standardization (ISO) defines life cycle assessment (LCA) as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (International Organization of Standardization, 2006). As of today, biodiversity is not yet fully internalised in the LCA framework as no generally accepted method can cover all aspects of biodiversity at all levels, i.e. ecosystem, species or genetic (Crenna et al., 2020). Hence such assessments do not always show the full picture of the impacts which can be explained by the complex nature of assessing biodiversity (Damiani et al., 2023). Therefore, impact categories, indicators, and methods need to be evaluated to find a way to internalise biodiversity into the LCA framework more comprehensively. The hypothesis is that wood buildings is better for the environment compared to concrete buildings. While this might be true for environmental impacts such as CO_2-emissions, there is a need for investigation regarding biodiversity and land use which is assessed in this thesis by applying different methods of impact assessment.

1.1. Purpose
Sveafastigheter plans to build two functionally identical buildings with wooden and concrete building frames, respectively. The two materials have different properties and thus different amounts of the materials are needed to build the frames. In order to assess the sustainability of the two options, they need to be assessed regarding their environmental impact throughout their life cycles, LCA is a common way to do this (Crenna et al., 2020). The purpose of the thesis is to present a recommendation of which building material is preferable by using different methods of impact assessment to investigate the impact on biodiversity at species level due to the two buildings.

1.2. Aim
The aim of the thesis is to assess the environmental impacts of wood and concrete as building materials for two functionally identical residential buildings about to be built by Sveafastigheter. The load bearing elements of each building is assessed with an LCA approach, with the main focus being the two materials' impacts on biodiversity through species richness.

ReCiPe is a widely used method of impact assessment in LCA which include midpoint and endpoint impact categories that can be used to measure the loss of species (Winter et al., 2017). The topic of land use transformation and occupation is of interest due to the assumption that the impact on biodiversity due to forestry might be somewhat overlooked or underestimated. To measure the impact due to land use transformation and occupation, a method by Chaudhary and Brooks (2018), as well as a method by Kuipers et al. (2021) is implemented to evaluate forestry and quarrying in connection to wood and concrete as building materials.

Ultimately, by comparing the results of the different methods of impact assessment, the goal is to determine if any of the materials are superior regarding impact on biodiversity. Through these comparisons, recommendations will be formulated and presented to Sveafastigheter regarding which building material would have the lower impact on biodiversity.

1.3. Research questions

Questions to be answered:

- Which impact categories and indicators are relevant to assess biodiversity loss?
- How do different types of land use, intensities, and ecoregions affect the results?
- Which building material is more preferable when assessing biodiversity impact at the species level?

1.4. Limitations

The thesis studies the system with a cradle-to-gate approach, meaning that the assessment starts with extraction of raw materials and ends at the construction of the buildings when they enter the use phase. There are five main drivers to biodiversity loss according to IPBES (2019), these being, terrestrial and aquatic habitat change, climate change, pollution, invasive species, and overexploitation of species. This thesis only evaluates drivers of terrestrial and aquatic habitat change, climate change and pollution, due to limitations in methods available that can be used to evaluate the remaining drivers. Extraction of raw materials, together with all processes in the refinement steps are assumed to be located in Sweden. Due to this, the effects of land use transformation and occupation will be limited to the ecoregions found in Sweden. Since the buildings are about to be built in the Stockholm area, extraction of raw material will be evaluated for this region whenever possible, if no data is available for the Stockholm area is available, average data for Sweden will be used.

The assessment only looks at the load bearing elements of the buildings, in the cases where both buildings contained similar amounts of the same material in the same building parts, these where neglected. The three methods of impact assessment are used to evaluate biodiversity at the species level, meaning that the landscape, ecoregion, and genetic level is not investigated. The impact calculated using ReCiPe is based on EPD-data, meaning that the included impact categories are limited to those in the EPD framework.

2. Background

This chapter introduces the topic of biodiversity, why it is important and how it can be measured. LCA is explained through a brief background, explanation of the steps included and how data could be presented through environmental product declarations, as well as explanations of the methodologies used in the thesis. Furthermore, backgrounds are provided for the product chains of the two assessed materials.

2.1. Biodiversity

Biodiversity refers to the different kinds of life you can find in one area and can be measured on multiple levels and be defined in different ways. One commonly accepted definition was coined by The Convention on Biological Diversity (United Nations, 1992) ”the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems”.

Four commonly accepted scales of biodiversity include from largest to smallest: landscape, ecosystem, species, and genetic (Bracy Knight et al., 2020). These scales can further be categorized into compositional, structural, and functional aspects. Landscapes consist of multiple ecosystems inhabiting different species of various genetics. The compositional aspect covers the richness of the individual levels, structure covers diversity and ranges, and function describes flows and processes within the levels. Because of the complexity of biodiversity, there is no singular way of measuring the total impact. There are numerous ways to measure different aspects, all relying on multiple variables. Species richness for example is a measurement which should incorporate the commonness or rarity of species, endemicity, abundance, as well as the distribution of species (Bosworth et al., 2011). Furthermore, a decision must be made as to which unit species should be expressed in, e.g. numerical species richness or species density, i.e. the number of species in a given area.

Biodiversity is important in order for humans to continue to reap the benefits of goods and services provided by nature. The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2003) briefly describes ecosystem services as ‘the benefits people obtain from ecosystems’. This short description is derived from the definition of ecosystem services by Costanza et al. (1997) “ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits human populations derive, directly or indirectly, from ecosystem functions”. Furthermore, ecosystem services are categorized into provisioning, regulating, cultural, and supporting services (Millennium Ecosystem Assessment, 2003). Some ecosystem services overlap and can be represented in multiple categories.

The provisioning services represent the products that can be obtained from the ecosystem (Millennium Ecosystem Assessment, 2003), such as food from plants and animals, biomass such as wood, freshwater, fuel, and medicines. Regulating services represent the benefits obtained from the regulation of ecosystem processes. Examples of regulating services are climate regulation by the sequestering or emitting of greenhouse gases, water purification, air quality maintenance, and pollination. Cultural services are nonmaterial benefits through e.g., inspiration, aesthetic values, cultural heritage, and recreation. Finally, the supporting services are necessary for the other categories of ecosystem services. This category is made up of services that either take place over a very long timescale or have indirect impacts on people’s well-being. Examples of supporting services are habitat provisioning, nutrient cycling, photosynthesis, and soil formation.

The connection between biodiversity and ecosystem services is represented by functional redundancy (Millennium Ecosystem Assessment, 2003). When it comes to ecosystem functions, many species have similar attributes, meaning that the loss of one species can be covered by another, thus there are no overall loss in ecosystem functions. There are also species which contributes in unique ways to the ecosystem functioning and a loss of such species would be all the more impactful. Minor changes in biodiversity might not have a great impact on the system overall, however, as increased rates of biodiversity loss lead to reduced redundancy and thus a decrease in the production of ecosystem services. Conversely, increased redundancy lead to a more reliable production of ecosystem services.

The drivers behind biodiversity loss are often anthropogenic in nature. IPBES (2019) have identified five direct drivers of biodiversity loss: land-use change, exploitation of species, climate change, pollution, and invasive species. These direct drivers result from underlying causes, or indirect drivers. Indirect drivers include production and consumption patterns, population growth, trade, and technological innovations, among others.

Ecosystem services are often undervalued in commercial markets compared to economic services or manufactured capital, leading to a decreased focus on sustainability (Costanza et al., 1997). In fact, ecosystem services are crucial to the Earth's life support system as well as the economy. While provisioning services are perceived as more concrete, providing physical benefits that can be more easily measured, the same cannot be said for the other categories. The four categories work in symbiosis with each other and the loss of one of the more abstract services can have a great impact on one of the more concrete services.

Due to anthropological intervention, the latest decades have seen substantial increases in agricultural yield and raw timber harvest (IPBES, 2019). At the same time, regulatory contributions from nature have declined e.g. soil organic carbon and pollinator diversity. In fact, IPBES (2019) state that during the last 50-years, nine out of ten presented regulatory ecosystem services have had a negative global trend.

In the Living Planet Report by WWF (2022) it is stated that on average, there has been a 69% decline in the relative abundance of monitored wildlife populations worldwide during the period 1970 to 2018. Land-use change is presented as the biggest threat to nature and biodiversity, leading to the destruction of natural habitats. However, many land-use practices are essential for humanity, providing critical resources such as food, water, and biomass, which presents us with a dilemma (Foley et al., 2005). Land-use change is necessary, but some types of land use degrade the ecosystems, thus resulting in a decline in ecosystem services which reduces the capacity to benefit from the many goods and services nature provides in the future.

The perceived value of nature and biodiversity depends heavily on which worldview is applied. The above mentioned aspects of biodiversity is heavily connected to an anthropocentric worldview, where nature is a tool meant to be used for human benefit. Nature is given an instrumental value and its contributions or natural capital can be replaced with manufactured capital. A biocentric worldview would instead attribute intrinsic value to each and every individual, human, animal, plant, or otherwise. This means that anthropogenic interventions turning natural capital into manufactured capital would be ethically wrong and in the current state of human-nature symbiosis, humans could almost be seen as a parasite leaching off nature for its own benefit. Finally, with an ecocentric worldview, the ecosystem as a whole is given an intrinsic value stemming from the notion that nature in itself is valuable regardless of its contribution to human beings. Here, the value of the system as a whole need to be in equilibrium. One species could technically replace another if it benefits the ecosystem as a whole (Bosworth et al., 2011).

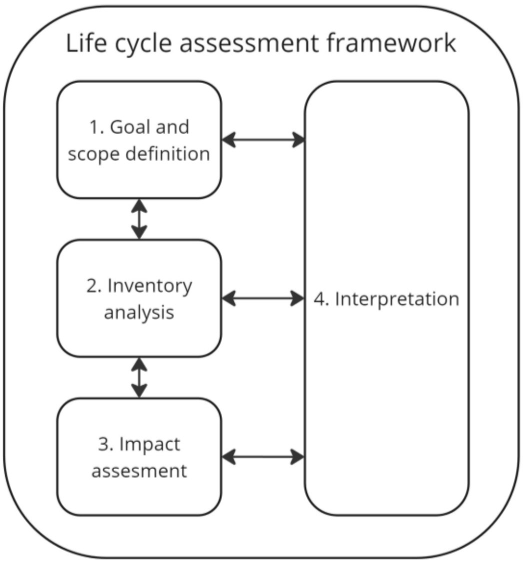
2.2. Life Cycle Assessment

LCA is a widely used and recognised method when evaluating environmental impacts and have seen usage in many different sectors over its' existence (Ekvall, 2020). One of the first examples of LCA being used in the construction sector was in the 1980s with the study by Bekker (1982), in which the focus was the use of renewable resources in the construction of new buildings. The Society of Environmental Toxicology and Chemistry (SETAC) started organising annual conferences in the 1990s by gathering researchers and industry representatives for dialogue to harmonise the framework for practitioners (Baumann & Tillman, 2004; Buyle et al., 2013). 1994 saw the involvement of ISO for the first time, and in 1997, the first standardisation of a general methodological framework for LCA was created in the ISO 14040 standard series (International Organization for Standardization, 2006).

2.2.1. Definition of LCA

The latest definition of LCA as defined by ISO, which was updated in 2006, is "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (Baumann & Tillman, 2004; Hellweg & Milà Canals, 2014). An LCA usually consist of four steps illustrated in Figure 1.

Figure 1: The four steps of the life cycle assessment framework.



Note: Adapted from Baumann and Tillman (2004).

The first step is called 'Goal and scope' and aims at defining the reason for why the study is being conducted, which boundaries exist and the functional unit of the system (Baumann & Tillman, 2004). This is followed by the second step called 'Inventory analysis', or LCI for short, which consists of creating a flowchart according to the system boundaries as well as the input and outputs for each process in the life cycle. The collected data is then used to calculate the environmental loads of the system based on the functional unit defined for that system. In the third step, 'Life cycle impact assessment' (LCIA), the aim is to describe the environmental consequences caused by the environmental loads defined in the inventory analysis. This is done by applying a method of impact assessment and converting the loads into impacts by using characterisation factors (CF) (Baumann & Tillman, 2004). Examples of methods of impact assessment are ReCiPe, CML, or Carbon footprint (Buyle et al., 2013). The fourth and final step, 'Interpretation', aims to evaluate the results gained from the earlier steps in accordance with the defined goal and scope of the study, while also making the information easily digestible.

2.2.2. Environmental Product Declarations

Environmental product declarations (EPD) are a way for companies to concisely and transparently present third party verified, comparable LCA data and other relevant environmental information regarding their products (The Norwegian EPD Foundation, 2019). In order for an EPD to be published, it must follow a set of rules and regulations enacted by EPD programme operators, such as EPD-Norway or the International EPD System.

EPDs include a range of information on the products, such as their intended use, material compositions, functional unit of the analysed system, environmental data, and flowcharts presenting the steps included in the LCA. EPD guidelines for publication states that the EPDs should include environmental impact indicators matching the functional unit for at least the impact categories presented in Table 1 (The Norwegian EPD Foundation, 2019).

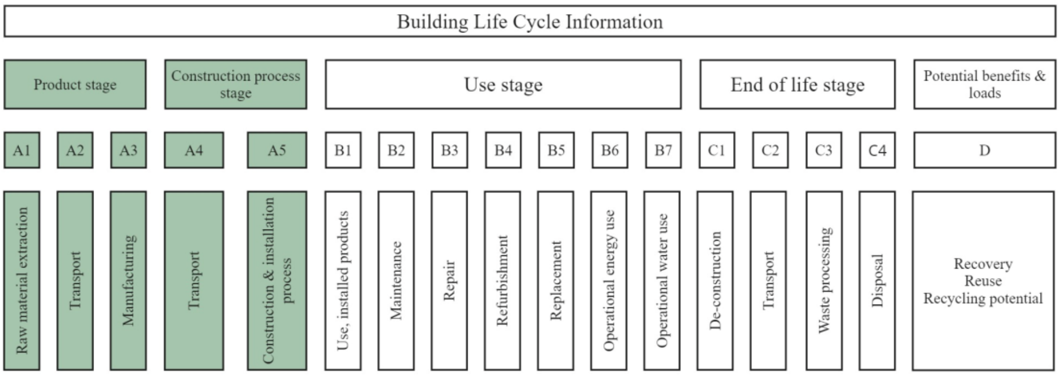
Table 1: Impact categories included in EPDs.

Impact category	Unit
Climate change (GWP)	[kg CO_2 equivalents]
Depletion of stratospheric ozone (ODP)	[kg CFC 11 equivalents]
Acidification (AP)	[kg SO_2 equivalents]
Eutrophication (EP)	[kg $(PO_4)^3$ equivalents]
Formation potential of tropospheric photochemical oxidants (POCP)	[kg C_2H_4 equivalents]
Depletion of abiotic resources	[kg SB equivalents]
Depletion of abiotic fossil resources	MJ

Before publication, each EPD goes through a validation process to make sure data is gathered and presented correctly, that the EPD is comparable to other publications, and that it follows the correct LCA methodology. Each newly published EPD is valid for five years to make sure it is relevant and up to date.

Following the European standard EN 15978:2011 (Swedish Standards Institute, 2011), the life cycle phases in the construction sector are evaluated in four stages which can be seen in Figure 2. This standard starts from the stage Construction Phase (A), followed by the Use Phase (B), End-of-Life phase (C) and the fourth and final phase (D), which accounts for any allocation gained by recycling. Only the construction phase will be evaluated in this case study as the main impact evaluated is biodiversity loss caused by land us change and occupation.

Figure 2: Illustration over the life cycle stages in the construction sector.



Note: Adapted from (Caruso et al., 2020).

2.3. LCA & Biodiversity

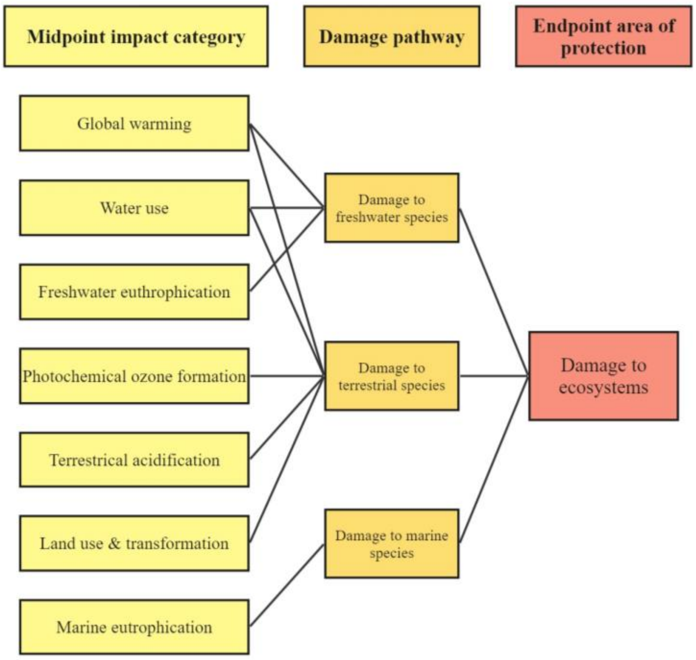
Research of biodiversity in LCA has been ongoing for at least 20 years (Winter et al., 2017), however its' implementation has been limited. Specific drivers behind biodiversity decline, such as land use, climate change, and pollution, are usually represented as midpoint impact categories, which are translated to capture the endpoint impact on biodiversity on a species level. ReCiPe is one method of impact assessment commonly used in LCA, which has multiple midpoint categories, e.g. global warming, acidification, eutrophication, land use or water use, which can be translated into the endpoint 'Damage to ecosystems' expressed in loss of species richness. This way of measuring biodiversity is very general as it does not differentiate between different taxa or geographical differences but rather gives an impact in species loss (Winter et al., 2017). The method of impact assessment developed by Chaudhary and Brooks (2018) applies the countryside species area relationship (cSAR) to study the impact of land use as a driver behind biodiversity decline in five taxa by assessing different types of land use, with different intensities, in a wide range of geographical locations. Kuipers et al. (2021) further expand on the cSAR model to incorporate habitat fragmentation and studies the impact of land use on biodiversity decline for four different taxa due to different types of land use in a wide range of ecoregions.

2.3.1. Biodiversity in ReCiPe

The idea behind the ReCiPe method of impact assessment is to have a single consistent methodology which combines both midpoint- and endpoint-categories (Goedkoop et al., 2013). ReCiPe 2008 started being developed in 2001, after a session in Brighton focused on understanding the strengths and weaknesses of midpoint- and endpoint-methods. Fifty LCA experts were present at the session and their collective opinion was that it would be desirable to have a common framework including both midpoint and endpoint indicators. According to Goedkoop et al., (2013), ReCiPe is based on the midpoint approach from the CML Handbook on LCA and the endpoint approach of Eco-indicator 99. However, almost all midpoint and endpoint characterisation models had to be reworked or redesigned in order to create a combined framework including both midpoint and endpoint indicators.

ReCiPe takes LCI results and translates them via environmental mechanisms into midpoint impact categories (Goedkoop et al., 2013). These midpoint impacts are then further translated into endpoint impact categories via yet another set of environmental mechanisms. ReCiPe 2008 include eighteen impact categories at midpoint level, e.g. Climate change, Ozone depletion, Human toxicity, Eutrophication, and Acidification. At the endpoint level, the midpoint impact categories can be translated to contribute into three categories: 'Damage to human health', 'Damage to ecosystem diversity', and 'Damage to resource availability'. For the purpose of this thesis, we will look at the endpoint 'Damage to ecosystems', utilizing the connected midpoint categories to assess the sustainability of the two building materials. Figure 3 presents the damage pathways for the impact categories included in the thesis.

Figure 3: ReCiPe mid-to-endpoint damage pathway for the area of protection 'Damage to ecosystem'.



Note: Adapted from (Huijbregts et al., 2017).

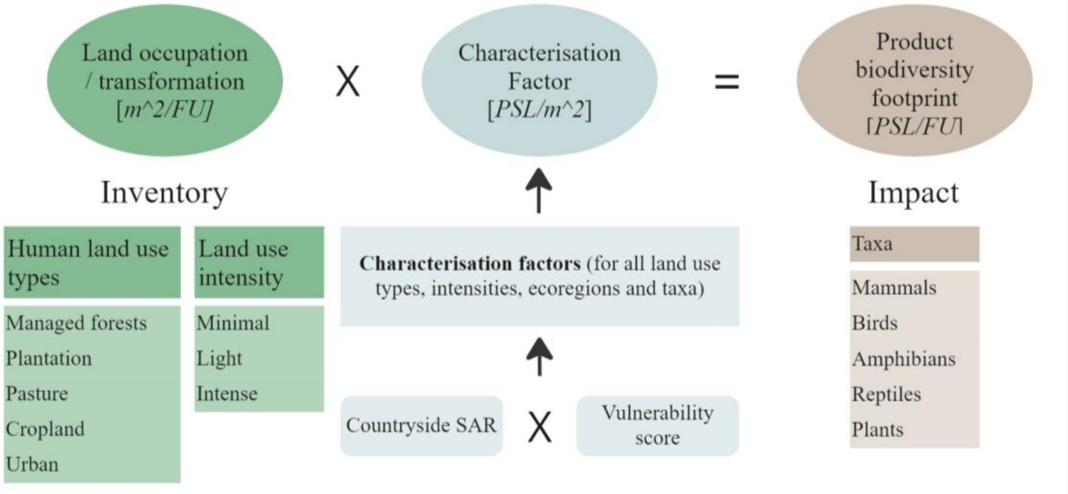
It is worth noting that the impact category 'Global warming', based on CO_2 equivalents, could contain both positive and negative impacts (Larsson et al., 2016). Negative impacts consist of biogenic CO_2 i.e. sequestrated carbon in biobased materials, and there is currently no common consensus on how to report biogenic carbon. The negative impacts occur early on in a products lifecycle, where the sequestration takes place. However, the biogenic CO_2 is later released to air during the later stages of the products lifecycle where the emissions should be accounted for as a positive impact, resulting in a zero-sum emission of biogenic carbon over the entire lifecycle. In cradle-to-gate analyses of buildings, only the stages leading up to and including the construction of the buildings are included. This results in a net negative impact due to biogenic carbon which is not accounted for again in the later stages, resulting in impacts which can be somewhat misleading (Larsson et al., 2016).

Damage to ecosystem diversity is calculated as 'Loss of species during a year' (Goedkoop et al., 2013). This is a somewhat simplified way to measure biodiversity via LCIA. One approach of measuring ecosystem quality is in terms of flows, with high ecosystem quality being represented by little to no disruption of flows from anthropogenic activities. Conversely, if the flows are often disrupted by anthropogenic activities, the ecosystem quality is considered to be low. Furthermore, flows can be measured at many different levels, e.g. ecosystem, species, genetic, material, or energy. Due to the many variables included in the measurements of biodiversity or ecosystem quality, there is a need for a simplification in order to make it feasible for calculation thus presenting the results in 'Loss of species during a year'.

2.3.2. Chaudhary & Brooks method

The Chaudhary and Brooks (C&B) method is an LCIA method that can help visualise the biodiversity impact from land use interventions through potential species loss or potentially disappeared fraction of species (Chaudhary & Brooks, 2018). To achieve this, the method calculates global and regional characterisation factors (CF) for five different taxa; mammals, birds, amphibians, reptiles, and plants, on five different land use types; managed forest, plantations, pasture, cropland, and urban, where each land use type has three levels of intensity; minimal, light, and intense use. Furthermore, the method presents disaggregated CF for 804 terrestrial ecoregions, which corresponds to areas with a distinct collection of species and communities. This method builds upon an earlier version created by Chaudhary et al. (2015) and is the current recommended method by UNEP-SETAC for assessing biodiversity impact within LCA (Koellner et al., 2013). While the C&B method presents the decline of species richness caused by land use interventions, it does not examine any of the other direct drives such as climate change, pollution, overexploitation, or invasive species. Figure 4 is a visual presentation of the C&B method.

Figure 4: Illustration of the methodology developed by Chaudhary and Brooks.

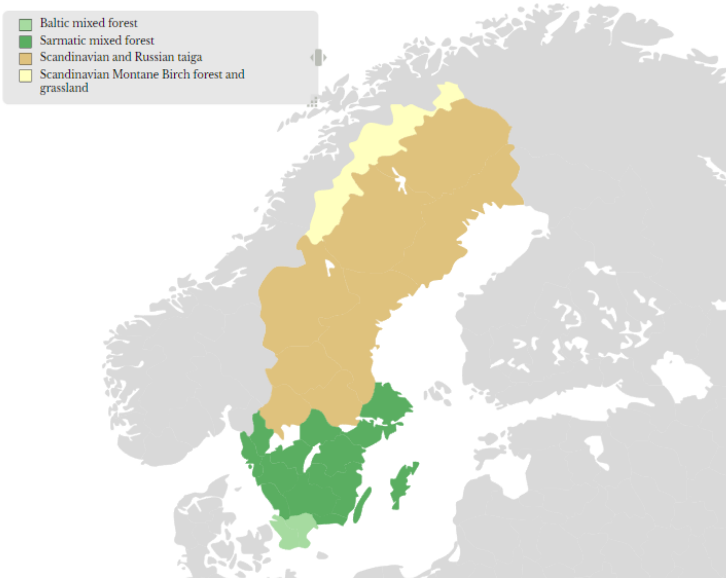


Note: Adapted from Chaudhary and Brooks (2018).

The biodiversity impact is calculated by connecting land occupation and transformation with potential species loss. Land occupation and transformation are based on the land use type and the intensity as well as the amount of area needed to produce the raw material of the investigated product.

The C&B method can be used to measure how different types of land use affect different taxa in different terrestrial ecoregions. Ecoregions consist of areas where the ecosystem is generally similar (Environmental Protection Agency, 2022). Sweden contains four different ecoregions: Baltic mixed forest located at the very south of Sweden, Sarmatic mixed forest covering the remainder of southern Sweden from northern Skåne to Värmland and from Västra Götaland to Stockholm including Gotland, the largest ecoregion in Sweden is Scandinavian and Russian taiga covering almost two thirds of Sweden from Värmland and Stockholm in the south to the very north border between Sweden and Finland, the last ecoregion in Sweden is Montane Birch forest and grasslands covering a thin strip of the north western border between Sweden and Norway. The ecoregions and their locations within Sweden are presented in Figure 5.

Figure 5: Ecoregions and their locations in Sweden



The CFs are based on the countryside species area relationship (cSAR) model and vulnerability scores (Chaudhary and Brooks, 2018). The cSAR model is used to calculate projected species loss $S_{loss,g,j}$ for each taxa, in each terrestrial ecoregion due to current land use according to Equation 1.

$$S_{loss,g,j} = S_{org,g,j} * \left(1 - \left(\frac{A_{new,j} + \sum_{i=1}^{16} h_{g,i,j} * A_{i,j}}{A_{org,j}}\right)^{z_j}\right) \quad (1)$$

In this equation, $S_{org,g,j}$ refers to the number of species per taxa g (g = 1:5; mammals, birds, amphibians, reptiles, and plants) occurring in each ecoregion j (j = 1:804), $A_{new,j}$ refers to the current natural habitat in the ecoregion in m^2, $A_{i,j}$ refers to the area of land use type i (i = 1:16), $A_{org,j}$ refers to the area of each ecoregion before any anthropological intervention, $h_{g,i,j}$ refers to the taxon affinity of taxa g to the land use type i in ecoregion j, and z_j refers to the species area relationship exponent for the ecoregion j (Chaudhary & Brooks, 2018).To incorporate the effect of different land use types, an allocation factor $a_{i,j}$ is applied to $S_{loss,g,j}$, according to Equation 2.

$$S_{loss,g,i,j} = S_{loss,g,j} \times a_{i,j} \quad (2)$$

Equation 2 can be used to calculate how many species extinctions can be allocated to a specific land use type in a certain ecoregion (Chaudhary & Brooks, 2018). The allocation factor $a_{i,j}$ is based on the area of a specific land use type i in an ecoregion j and the taxon affinity of each taxa g to that land use type divided by the sum of total area of all land use types and the taxon affinity, as presented in Equation 3.

$$a_{i,j} = \frac{A_{i,j}(1-h_{g,i,j})}{\sum_{i=1}^{16} A_{i,j}(1-h_{g,i,j})} \quad (3)$$

In order to calculate the regional land occupation CF, $S_{loss,g,i,j}$ from Equation 2 is divided by the area of land use type i in ecoregion j according to Equation 4.

$$CF_{regional,occ,g,i,j} = \frac{S_{loss,g,i,j}}{A_{i,j}} \quad (4)$$

Global CF can be calculated by combining the regional CF gained from Equation 4 and vulnerability scores for each taxa to ecoregion according to Equation 5.

$$CF_{global,g,i,j} = CF_{regional,g,i,j} * VS_{g,j} \tag{5}$$

The vulnerability scores are based on extinction risks and geographical diffusion of species presented on a scale from 0 – 1, where a higher value refers to a more vulnerable position for the species within an ecoregion and are based on the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2015). As an example a vulnerability score of 1 would mean that the species is strictly endemic to an ecoregion and that all the species within that ecoregion is listed as critically endangered (Chaudhary & Brooks, 2018). Global CFs are used to measure potential rather than actual extinctions, thus the results are presented in potential global species loss per m^2. Impacts due to transformation are calculated by multiplying the occupation CFs by half the biodiversity regeneration time.

2.3.3. Kuipers et al. method

This method, hereafter referred to as the Habitat-Fragmentation (HF) method, uses the species-habitat relationship, a reworked version of the cSAR considering both habitat conversion and fragmentation effects, to develop land use occupation and transformation CFs for four taxa (amphibians, birds, mammals, and reptiles, as well as aggregated CF) in 702 terrestrial ecoregions for four different land-use types (urban, cropland, pasture, and forestry) (Kuipers et al., 2021). The HF method generally estimates higher impacts due to land use than its predecessor cSAR, suggesting that land use impacts might be underestimated without the inclusion of fragmentation effects.

The species-habitat relationship was developed by integrating cSAR with effectively connected habitat (ECA), which is a measurement of landscape permeability and species dispersal distances. This way both habitat suitability and connectivity are considered, thus incapsulating the effects of fragmentation.

The potential disappeared fraction of species is calculated by Equation 6.

$$PDF_{g,j,reg} = 1 - \left(\frac{H_{g,j}}{H_{g,j,ref}}\right)^{z_{g,j}} = 1 - \left(\frac{\sum_i h_{g,i,j} * ECA_{g,i,j}}{\sum_i h_{g,i,j} * ECA_{g,i,j,ref}}\right)^{z_{g,j}} \tag{6}$$

Here $PDF_{g,j,reg}$ refers to the potentially disappeared fraction of species in taxa *g* (g=1:4) in ecoregion *j* (j=1:702). *H* refers to the suitable connected habitat and is calculated according to Equation 7.

$$H_{g,j} = \sum_i h_{g,i,j} * ECA_{g,i,j} \tag{7}$$

In this equation *h* refers to the habitat suitability of land use type *i* (i=1:4) to taxa *g* in ecoregion *j*, and *z* refers to the species-habitat relationship slope for taxa *g* in ecoregion *j*. *ECA* refers to the effectively connected habitat of taxa *g* in land use type *i* and ecoregion *j*, and *ref* refers to the reference state. Land type suitability *h* is calculated by Equation 8.

$$h_{g,i,j} = \left(\frac{S_{g,i,j}}{S_{g,j}}\right)^{1/z_{g,j}} \tag{8}$$

Here, *h* is defined as the proportion of species *S* of taxa *g* in land use type *i* relative to the total number of species *S* of taxa *g* in ecoregion *j*, raised to the power of *1/z*. The effectively connected area *ECA* of land use type *i* for taxa *g* in ecoregion *j* is calculated by Equation 9.

$$ECA_{g,i,j} = \left(\sum_{m,n} a_{i,j,m} * a_{i,j,n} * p_{g,i,j,mn}\right)^{0.5} \quad (9)$$

Here, *ECA* is based on the number and size *a* of individual patches *m* and *n*, and *p* refers to the probability of dispersal between each pair of patches *m* and *n*. The probability of dispersal is calculated according to Equation 10.

$$p_{g,i,j,mn} = e^{-w_{g,i,j,mn}/\alpha_{g,i,j}} \quad (10)$$

The least-cost distance *w* refers to the matrix-permeability-weighted length of the route between patches *m* and *n* that results in the shortest distance connecting the two patches, and *α* refers to the median dispersal distance of species of taxa *g* in land use type *i* and ecoregion *j*. Furthermore, the least-cost distance *w* is defined as the distance *d* travelled through matrix-type *k* multiplied by the resistance *r* of taxa *g* in land use type *i* and ecoregion *j* to matrix-type *k* according to Equation 11.

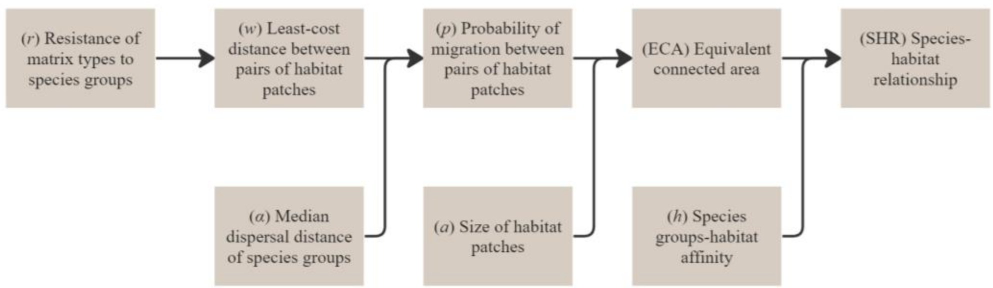
$$w_{g,i,j,mn} = \sum_k d_{i,j,k,mn} * r_{h,i,j,k} \quad (11)$$

The resistance *r* of taxa *g* in land use type *i* and ecoregion *j* to matrix-type *k* depends on the amount of overlapping species *S* between land use type *i* and matrix-type *k* according to Equation 12.

$$r_{g,i,j,k} = 1 - \frac{S_{g,i,j,k}}{S_{g,i,j}} \quad (12)$$

The resistance is expressed as a value between 0-1 where zero represents a full overlap between species in land use type *i* and matrix *k* meaning that the matrix can be crossed without any cost. Figure 6 is a visual representation of the variables leading to the species-habitat relationship.

Figure 6: Visual representation of the species-habitat relationship.



Note: Adapted from Kuipers et al. (2021).

Average occupation CFs are calculated according to Equation (13).

$$CF_{g,i,j,occ} = PDF_{g,j} * A_{lu,j}{}^{-1} * q_{g,i,j} \quad (13)$$

In this equation, *PDF* refers to the damage function from Equation 6, *A* refers to the total area of all land use types *lu* combined, and *q* refers to the distribution factor for attributing the impacts on taxa *g* in ecoregion *j* to land use type *i*.

Lastly, average transformation CFs are calculated by multiplying the average occupation CFs by half the regeneration time *t* of taxa *g* in land use type *i* and ecoregion *j* according to Equation 14.

$$CF_{g,i,j,trans} = CF_{g,i,j,occ} * 0.5t_{g,i,j} \tag{14}$$

Equations 1-9 presents the steps taken to calculate taxa-specific CFs for land use occupation and transformation according to Kuipers et al. (2021). Additionally, the authors present a method for calculating land use specific, taxa-aggregated CFs as presented in Equation 15.

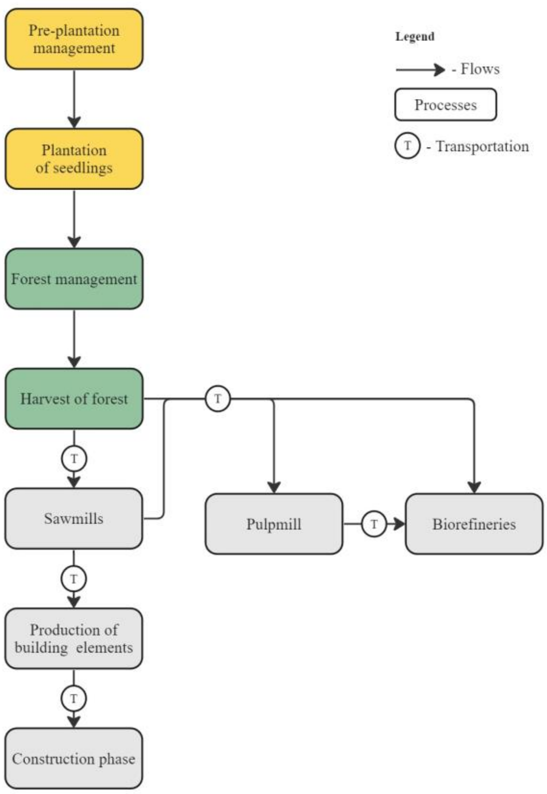
$$CF_{\bar{g},i,j} = \sum_{g}^{N} CF_{g,i,j} * N_j^{-1} \tag{15}$$

Here, *CF* represents the taxa, land use type, and ecoregion specific characterisation factor and *N* is the number of taxa present in that ecoregion *j*. This equation tells us that each taxon is weighted equally, regardless of the number of species per taxa present in the region.

2.4. Swedish Forestry

The dominating management system in Swedish forestry today is even-aged management with tree retention (Roberge et al., 2020). This management system is characterised by its relative even-aged structure of trees within the larger forest, also called a forest stand. These forest stands generally consists of a single cohort and are established through regeneration after clear-cutting at commercial felling. The time between two final fellings, also called “the rotation length”, can vary greatly. For the two major tree species used in Sweden, Norway spruce and Scots pine, the minimum forest ages for clearcutting can be as low as 45 years for the most productive spruce forests, while for less productive forests the age of a forest stand can be up to one hundred years. In Figure 7 presents a simplified visualisation of the forestry industry.

Figure 7: Simple flowchart showing the Swedish forestry industry and its different processes.



After a harvest, the stage of forest regeneration starts as soon as possible and the most commonly form of regeneration is through planting of seedlings at 84 % while the two other options of direct seeding and natural regeneration is at 10 % and 4 % respectively (Roberge et al., 2020). The number of seedlings planted can vary greatly from place to place, but a common amount is 2000-3000 seedlings per hectares (Agestam et al., 2022). Following the establishment of a new forest stand the next intervention is called pre-commercial thinning, which often takes place after a forest stand has reached 5 to 10 years of age, when trees has reached a height of 2 to 3 meter. Pre-commercial thinning is usually a manual labour, done to create spacing for growing forest so that retained trees gets better access to light, water and nutrients and as such an increases growth opportunity.

When trees reach a height of 12 to 14 meters it is recommended to transitions to commercial thinning (Roberge et al., 2020) This involves reducing the number of stems in the forest stand so that the trees that remains can reach proper dimensions. By using commercial thinning, forest owners can increase the value of future timber as the trees of higher quality remains and have improved opportunity for growth while also securing revenue from the felled trees. As opposed to the earlier stage, commercial thinning is a heavily mechanised with single-grip harvester and forwarders, which cut down the trees and moves them to the nearest roads.

As with commercial thinning, the final felling is using heavy machinery to harvest the trees when the forest stand has reached maturity (Roberge et al., 2020). At this stage through the earlier thinning work, the amount of trees still standing normally are in a range at five hundred trees per hectares (Agestam et al., 2022), or a fourth of the initial amount of trees at first thinning. At the cutting site, the harvested trees are normally debranched and cut down to length before forwarders move the newly created logs to the roadside to be collected for transportation to industry sites or abroad as export.

After the final felling, the timber is loaded onto timber trucks at the roadside and then transported to the relevant industries, typically sawmills, pulp mills or paper plants (Roberge et al., 2020; Skogsindustrierna, 2019). In Sweden two-thirds of the domestic transport work by the forest industry’s is done by trucks and one-third by train.

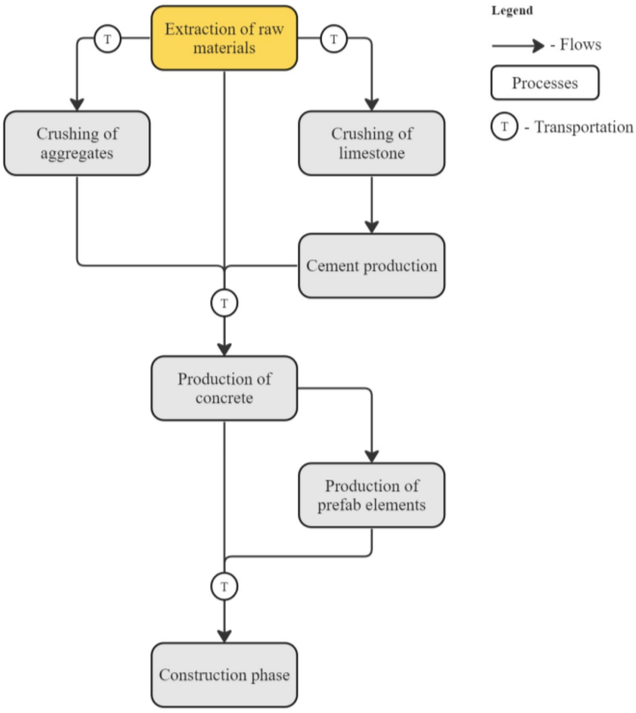
When timber has been transported to sawmills the logs goes through several different processes to refine the raw wood into a finished product that is ready to be used (Svenskt Trä, n.d.). It starts with debarking of the timber, followed by root reduction and sawing. During the sawing of timber, there are substantial losses, meaning that 45% of the timber logs end up as saw goods while the other 55% are lost as sawdust and woodchips (Agestam et al., 2022) . After this a rough sorting takes place before the wood is dried. The drying is followed by another sorting before the sawed products is packaged and then either sent to customers or put into storage.

Unmanaged forests form a wide display of features due to frequent small-scale disturbances and decay. Such features create natural habitats for a variety of species and include decaying trees, large amounts of dead wood, pits and mounds around the roots, and old large trees with knags and crevices. In contrast, managed forests are characterised by lower variability in disturbances leading to a more homogeneous tree composition and environment and thus a potential loss in natural habitats (Paillet et al., 2010).

2.5. Swedish Concrete Production

There are two main ways to build using concrete, either by on site casting of ready-mixed concrete where the concrete is transported to the construction site and pumped into moulds where it is hardened, or by using prefabricated elements where the concrete is moulded into shape at the factory before the finished elements are transported to the construction site (Svensk Betong, n.d.). Figure 8 provides a simplified visualisation of the production of concrete for the construction of buildings in Sweden.

Figure 8: Simple flowchart of Swedish concrete production and its different processes.



Quarries are open-pit mines that are created by exposing rock or mineral through the removal of overburden, i.e. the soil and vegetation covering the material intended for extraction (Axora, n.d.). Different types of concrete have different material compositions based on their intended purpose. The production chain starts with the extraction of raw materials, such as aggregates, limestone, and water. The process of extracting aggregates is usually done by using explosives to remove large rocks from the working face of a quarry. The rocks are then transported by either truck or conveyor to a crusher where it goes through multiple crushing and sifting stages to produce the desired size of gravel depending on the intended use (Cemex, n.d.).

The process of cement production starts with extraction of limestone by using explosives (Heidelberg Materials, n.d.). The extracted limestone is transported in dump trucks with a maximum load of ninety-five tons, to crushers where the material is crushed to a size of maximum 80 mm. After this, the crushed limestone is transported by conveyor to storage. The material is further grinded into a fine powder, consisting of particles smaller than 0,09 mm. The limestone is then mixed with other raw materials before it is dried, preheated, and finally burned in a kiln to create clinker. After the burning process, the clinker is cooled off and stored before it is grounded together with gypsum and limestone to create cement.

The gravel and cement are transported to concrete plants where they are mixed together with water and additives to create the concrete (Marceau et al., 2007). The ready-mixed concrete is either cast at the factory to create prefabricated elements or transported by concrete mixer trucks to be casted at the construction sites.

While quarrying of limestone and gravel are important for the production of cement because of its versatile use in construction of buildings and infrastructure, it also brings with it ecological pressures that are important to consider (Rosvall & Isaksson, 2021). One such ecological pressure is the changing and fragmentation of habitats through land use transformation, by removing overburden to access the resources below ground (Businessandbiodiversity, n.d.). With this land transformation the natural habitat can be either altered or potentially destroyed, which can have negative effect on local species. Land transformation through quarrying can also lead to indirect impacts such as changes to surface or ground water (SustainableBuild, n.d.), which in turn could cause other habitats in the vicinity of the extraction site to dry out or be flooded.

3. Method

The two buildings were investigated through an LCA approach using three different methods of impact assessment. This chapter presents the methodologies and the steps within the different methods used to calculate the biodiversity impacts of the materials.

3.1. Literature search

A literature search was conducted on the topic of biodiversity in connection to LCA, forestry, concrete production, and land use. One intention of the literature search was to find which impact categories in LCA are connected to biodiversity loss and could be implemented in the case study of the two buildings. Another aim was to find relevant characterisation factors connected to biodiversity loss and LCA. The literature search included search engines such as Google Scholar, Scopus, and Web of Science.

Relevant articles were collected partly using keyword searches, partly through the snowball method where references in articles were looked up further. Potential articles were selected based on number of citations and, especially for LCA methodology, date of publication, where more recent articles were preferred. Abstract, conclusion, and keywords were reviewed in order to assess which articles where suitable for the topic after which relevant articles were read more thoroughly. Keywords used in the literature search includes, were not limited to: Biodiversity, LCA, Forestry, Concrete production, Land use, Occupation, Transformation, Quarry.

3.2. LCA

The case study was conducted with an LCA approach using multiple methods of impact assessment to calculate the impact on biodiversity due to different building materials.

3.2.1. Goal & Scope definition

The goal of the thesis was to assess and compare the environmental impacts of the two building-materials wood and concrete, with focus being the materials' impact on biodiversity. Two multi-family buildings are to be constructed and are said to have the same functionality, i.e. providing living space of similar quality while having the same gross floor area. To identify the environmentally preferable choice in building material, the load bearing elements of the buildings were assessed with an LCA approach using different methods of impact assessment. The load bearing elements were of interest due to the fact that this is where the largest flows of the investigated materials exist. Building elements containing similar amounts of the same material which were included in both buildings will not be taken into account, e.g. concrete foundations. This is due to the fact that the aim of the thesis is to compare the differences in impacts of the two building materials. The intention was to contribute to the dialogue in the construction sector about strengths and weaknesses of different building materials by addressing the issue of biodiversity loss.

Functional unit

As the goal of the thesis were to evaluate wood and concrete as building materials used in a multifamily residential building, two different products systems were evaluated based on each building material. The functional unit (FU) was chosen as the total area of the buildings, which Sveafastigheter has put to 1051 m^2 gross floor area, which can be explained as the total space of the whole building in m^2 including the wall thicknesses and other spaces not used as living quarters. According to Boverket, the Swedish National Board of Housing, Building and planning (Boverket, 2019) gross floor area is a recommended unit when calculating impacts of entire buildings.

System boundaries

To make a comparative analysis of the building materials and assess the biodiversity impact, two different products systems were needed, each representing one of the two materials. As described in the limitations, the main evaluation only studied the life cycle stages before use phase, that is the product and construction phases (A1-5) consisting of material extraction, refining of material, manufacturing of goods, transportation, and ends at the construction of the buildings and as such the LCA was a cradle-to-gate assessment.

Geographical boundaries of the assessment were limited to the national boarders of Sweden as the buildings are assumed to be constructed with wood from Swedish forests. Similar logic is true for the concrete production where limestone and gravel were assumed to be extracted from Swedish quarries. The boundary between the technical- and the natural-system were drawn at the extraction of raw materials, which for this study means harvest of mature forest, and excavation of limestone and gravel. The temporal boundary for the assessment was put to 50 years which corresponds to the standards used in LCA-studies on the construction sector when assessing residential buildings and is the recommended time-horizon by (Boverket, 2019).

3.2.2. Inventory analysis

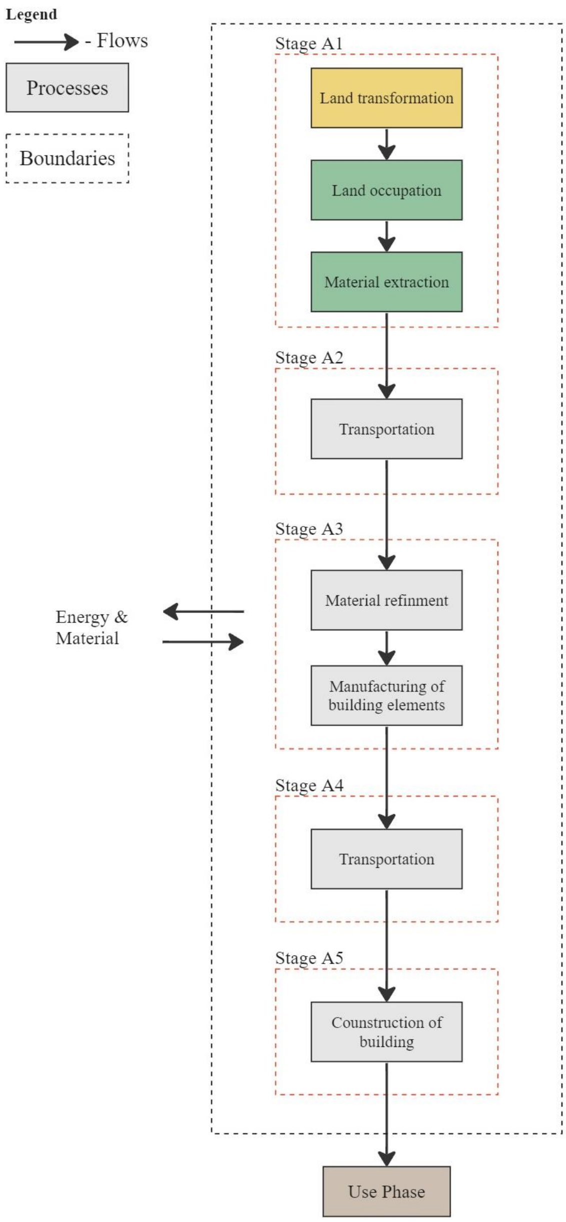
The data on resources needed for construction of the two buildings were supplied by Sveafastigheter. Based on the goal of the study, the resource flows connected to the load bearing elements were extracted from the supplied data. The investigated building elements and their respective weights for the two buildings are presented Table 2.

Table 2: Building elements with weights.

Building material	Element	Weights [ton]
Timber	Timber beams	96,53
	Load bearing interior wall	32,86
	Load bearing outer wall	23,53
Concrete	Hollow concrete beam	263,75
	Load bearing interior wall	193,86
	Load bearing outer wall	205,81

Figure 9 presents a simplified flowchart presenting the different stages evaluated for the two buildings.

Figure 9: Initial flowchart of the cradle-to-gate stages in the two buildings.



The flowchart shows the studied systems of the timber and concrete production from cradle-to-gate, which ranges from A1 to A5, as defined in the ISO framework 14040:2006 (International Organization for Standardization, 2006).

Step A1 consider resource acquisition. For the wood-framed building, A1 starts with plantation of new forest followed by forest management and then harvesting of the forest (Roberge et al., 2020). For the concrete-framed building, A1 starts with creation of quarries followed by extraction of raw material (Marinkovic, 2013). Following the extraction, step A2 covers the transportation of materials to factories to be refined into manufactured goods. The materials delivered to the factories enters the A3 stage and here goes through multiple refinement processes. For the timber production these processes can be explained in short as measuring and sorting of timber logs, debarking, drying, sawing, followed by a second measurement and sorting step before the products are packaged to be sold or stored (Svenskt Trä, n.d.)

For the concrete production, the A3 stage starts with production of cement by collecting and crushing of the limestone (Heidelberg Materials, n.d.). The refining of gravel and limestone consists of crushing, mixing, preheating, filtering, heating, and cooling. The limestone is used to create clinker which is later used to produce cement and the gravel is crushed and filtered to obtain the preferred fractions. Clinker, gravel, water, and additives are later mixed into concrete compounds (Heidelberg Materials, n.d.). The refined saw timber and concrete are thereafter used to produce the elements for each building. Step A4 consist of the transportation of building elements to the construction site and the final step, A5, is the construction of the building.

3.2.3. Estimating land use

To calculate the required land use for the two buildings, the total amount of material included in the building elements and the land use required to produce the respective amounts were calculated.

Land use needed for timber production

The land use connected to the wood building are due to the timber use in the building elements. Table 3 presents the elements of interests as well as their weights.

Table 3: Elements with weights, timber building.

Element	Weight [ton]
Timber beams	96,53
Load bearing interior wall	32,86
Load bearing outer wall	23,53

The elements are made out of cross laminated timber (CLT), which according to EPD's for building elements used in the Swedish market consist of up to 99% timber. The material compositions are used to calculate the amount of material needed for each of the building elements according to Equation 16.

$$m_{wood,e} = W_e * a_i \qquad (16)$$

Here $m_{wood,e}$ is the mass of wood per element *e*, W_e is the weight of elements *e* (*e*=1:3), and a_i is the weight percentage of the wood in the CLT product. The a_i was extracted from EPD for CLT which gave a weight percentage for wood at 98,71%. The product henceforth is referred to as CLT and can be seen in Table 4 with the total weight of wood needed in tons. Tables including material compositions and the amount of material in each element is presented in Appendix A.

Table 4: Total weight of wood, timber building.

Product	a_i [%]	Weight wood [ton]
CLT	98,71	150,96

There are considerable losses in the production chain of wood products where 55% of the material is lost in the form of sawdust and woodchips at the sawmills (Agestam et al., 2022). The outputs of sawdust and woodchips are used for other applications, for example creation of paper in pulp mills, or as an energy source in biorefineries. The losses means that the total wood demand from the forest will increase, which was calculated using Equation 17.

$$Wood\ demand = \frac{\sum m_{wood,e}}{1-0,55} \quad (17)$$

Here $\Sigma m_{wood,e}$ refers to the sum of wood in the building elements, and the denominator reflects the fraction that gives the total wood demand needed as input into the sawmills. The total wood demand is presented in Table 5.

Table 5: Total wood demand, timber building.

Product	Wood demand [ton]
CLT	335,46

To calculate the land user required for wood production, forestry in Sweden was investigated. The Swedish University of Agricultural Sciences presents the yearly mean productions for Sweden in total as well as individually for the four main regions in Sweden: Northern Norrland, Southern Norrland, Svealand, and Götaland (Nilsson et al., 2022). For the purpose of this thesis, the yield for the region of Svealand was used since this is the geographical region of the buildings to be constructed and assumed place of resource extraction.

The yield is presented in m^3sk/ha. *Sk* is a Swedish term, referring to the whole volume of the tree including bark above stump cut (Svenskt Trä, n.d.). This needs to be converted into volume under bark, presented in the unit m^3fub/ha, *fub* referring to cubic meter wood under bark. The average conversion factor from m^3sk to m^3fub for spruce and pine is 0,815 (Skogskunskap, n.d.). Yearly forestry yield for the Svealand region is presented in Table 6.

Table 6: Yearly forestry yield, Svealand region.

Region	Yield [m^3sk/ha]	Yield [m^3fub/ha]
Svealand	6,40	5,22

In order to calculate the yield in tons, the density of the wood products was multiplied with the yield in m^3fub, the yield together with the densities are presented in Table 7.

Table 7: Density of wood product and yield in tons, timber building.

Product	Density [ton/m^3]	Yield [ton/ha]
CLT	0,436	2,27

The total amount of land use needed for the building was calculated by using Equation 18.

$$A_{tot,wood} = \frac{Wood\ demand}{yield} \cdot 10^4 \quad (18)$$

Here $A_{tot,wood}$ refers to the land use needed for the building, *Wood demand* refers to the total weight of wood in the building elements including the additional losses of sawdust and woodchips, *yield* refers for the yearly produced wood material in ton/hectares, and the factor 10^4 were used to convert from hectares to m^2. Total land use needed is presented in Table 8.

Table 8: Total land use needed, timber building.

Product	**A [m^2]**
CLT	1 476 442

In Equation 17, the total wood demand was increased due to losses in the production chain. As such the total land use will be inflated. Since sawdust and woodchips are used as inputs for pulp mills and biorefineries, the land use of these new products will not be taken into account. Thus, only the land use connected to the material that will be used for the construction of the building will be accounted for. The final land use for the timber building is presented in Table 9, reflecting 45% of the total land use.

Table 9: Final land use, timber building.

Product	**A [m^2]**
CLT	664 399

Land use needed for concrete production

The land use connected to the concrete building are due to the gravel and cement in the building elements. Table 10 presents the elements of interest as well as their total weights.

Table 10: Elements with weights, concrete building.

Building element	**Weight [ton]**
Load bearing interior wall	193,86
Load bearing outer wall	205,81
Hollow concrete beam	263,75

EPD's for building elements used in the Swedish market was used to calculate the amount of gravel and cement required for each building element according to Equation 19.

$$m_i = W_e * a_i \qquad (19)$$

Here m_i is the mass of material i (i = 1:2), W_e is the weight of element e (e = 1:3), and a_i is the weight percentage of material i in element j. The total amount of gravel and cement needed for the entire building is presented in Table 11. Tables including material compositions and the amount of material in each element is included in Appendix A.

Table 11: Amount of gravel and cement needed, concrete building.

Material	Weight [ton]
Gravel	494,28
Cement	99,88

To calculate the land use required for gravel production, quarries in the Stockholm area were investigated. Sveriges Geologiska Undersökning release yearly reports on aggregate production in Sweden. Data is available for amount of gravel produced as well as the number of quarries in Sweden in total and individual statistics for each county (Norlin & Göransson, 2021). To calculate the land use associated with gravel, the number of quarries as well as the yearly production in the Stockholm area was assessed. The land use required was calculated using Equation 20.

$$A_{gravel} = \frac{size}{\left(\frac{yield}{n_{quarry}}\right)} \cdot 10^4 \qquad (20)$$

Here A_{gravel} refers to the land use needed to produce the gravel, *size* represents the assumed size of an average quarry in hectare based on measurements of quarries in the Stockholm area used by a larger construction company, estimated to approximately 30 hectares. *Yield* represents the total yearly production of gravel in tons, and n_{quarry} represents the number of quarries. This gives us the land use required to produce one ton of gravel which when multiplied by 10^4 gives us the land use in m^2.

To calculate the land use required for cement production, the cement factory in Slite and the adjacent limestone quarry were investigated (Bergab, 2017). Slite is by far the biggest cement producer in Sweden (Rosvall & Isaksson, 2021), supplying 75 – 80% of the total amount produced in the country. The land use required was calculated using Equation 21.

$$A_{cement} = \frac{size}{yield} \cdot 10^4 \qquad (21)$$

Here A_{cement} refers to the land use needed to produce the cement, *size* represent the size of Slite limestone quarry in hectare which equals 89 hectare (Bergab, 2017), and *yield* represents the yearly cement production in Slite in tons. Multiplying by 10^4 gives us the land use required to produce one ton of cement in m^2. The required land use to produce one ton of gravel and cement respectively is presented in Table 12.

Table 12: Required land use gravel and cement, concrete building.

Material	A [m^2/ton]
Gravel	1,189
Cement	0,356

The total amount of land use associated with the concrete building was calculated using Equation 22.

$$A_{tot,concrete} = \Sigma(A_i \cdot m_i) \qquad (22)$$

Here, A_i represents the land use associated to the production of one ton of each material i, and m_i represents the total mass of material i. The land use associated with each material, as well as the total land use required are presented in Table 13.

Table 13: Total and material specific land use, concrete building.

Material	A [m^2]
Gravel	587,74
Cement	35,56
Total	623,29

3.3. Methods of Impact assessment

To assess the materials impact on biodiversity, three different methods of impact assessment were used. ReCiPe uses environmental impact indicators from EPDs to calculate the impact of the different building elements which is further translated to 'Damage to ecosystems' via ReCiPe endpoint characterisation factors. The C&B method measure biodiversity impact via the land use connected to each building and presents impacts for different taxa in different ecoregions due to several land use types of differing intensities. HF, similar to the C&B method, measure biodiversity impact due to different types of land use in different ecoregions, albeit not taking into account potential differences in intensity of land use. CFs used in the HF method are based on the SHR model which differs from cSAR used in C&B in that it takes into account habitat fragmentation.

3.3.1. ReCiPe

The goal of using ReCiPe as a method of impact assessment is to express biodiversity damage in terms of the endpoint impact category 'Damage to ecosystems'. The building elements together with weights were collected for each building according to Table 14.

Table 14: Building elements with weights.

Element	Timber building weight [ton]	Concrete building weight [ton]
Timber beams/Hollow concrete beam	96,53	263,75
Load bearing interior wall	32,86	193,86
Load bearing outer wall	23,53	205,81

EPD's representative to each building element, intended for use in the Swedish market were used to gather environmental impact indicators for the relevant impact categories according to Table 15.

Table 15: Impact categories used.

Impact category	Unit per ton material
Global warming potential (GWP)*	kg CO_2 eq.
Acidification potential (AP)	kg SO_2 eq.
Eutrophication potential, freshwater (EP,f)	kg P eq.
Eutrophication potential, marine (EP,m)	kg N eq.
Formation potential of tropospheric ozone (POCP)	kg NO_x eq.
Water deprivation potential (WDP)	m^3
Land use (LU)	m^2

*Note: *Global warming potential due to land use and land use change is also included and are added to GWP when calculating endpoint impact*

The EPDs list indicators corresponding to the functional unit of that particular EPD. For the most part, the functional unit was listed as 1 ton. However, in the instance that the functional unit was listed as m^3, the corresponding indicators were converted to match a functional unit of 1 ton. Most EPDs use impact categories matching ReCiPe, however, in the case that the EPD listed impact categories using different units, conversions were needed to get impacts matching the assessed ReCiPe endpoint. Table 16 includes the impact categories as listed in the EPDs, impact categories as needed in ReCiPe, and the conversion factors used to calculate the new units.

Table 16: Impact category conversion factors, ReCiPe.

Impact category	Unit EPD	Unit ReCiPe	Conversion factor
AP	mol h^+ eq.	kg SO_2 eq.	0,032
POCP	kg NMVOC eq.	kg NO_x eq.	0,18
EP,f	kg PO_4	kg P eq.	0,33

POCP and EP,f was converted using data taken from the supplementary data listed by Huijbregts et al. (2017) in connection to the ReCiPe methodology. For AP, such conversion factors were not present and thus some calculations were needed. The calculations were based on the chemical formula presented in Equation 23 (Heijungs, 1994).

$$SO_2 + H_2O + O_3 \rightarrow 2H^+ + SO_4^{2-} + O_2 \tag{23}$$

Based on the equation, the relationship between SO_2 and H^+ tells us that for every mol SO_2, two mol of H^+ can be created. The molecular mass of SO_2 is 64 g*mol^{-1}, and 1 kg SO_2 can create 1000/32 mol H^+, conversely 1 mol H^+ is equal to 1/31,25 kg SO_2 (Heijungs, 1994).

The impact category 'Land use' is not required to be included in the EPDs, hence characterisation factors for this category was gathered from the supplementary data in connection to the ReCiPe methodology (Huijbregts et al., 2017). The ReCiPe methodology includes five different types of land use: managed forest, annual crops, pasture, artificial area, and permanent crops. For the timber building, the land use type 'managed forest' was used. In the case of the concrete building, where the land use was due to gravel and limestone quarrying, the land use type 'artificial area' was used due to this being the recommended equivalent to mineral extraction sites (Huijbregts et al., 2017). The conversion factors for the two land use types are presented in Table 17.

Table 17: Annual crop equivalents per land use type, ReCiPe.

Land use type	Conversion factor (annual crop eq.)
Managed Forest	0,30
Artificial Area	0,73

After conversions and the addition of 'Land use', the midpoint impacts were calculated according to Equation 24.

$$MI_c = W_e * EI_{e,c} \qquad (24)$$

Here W_e refer to the weight of each corresponding element in ton and $EI_{e,c}$ refers to the environmental impact indicator for building element *e* and impact category *c*. The two buildings midpoint impacts for each category are presented in Table 18.

Table 18: Midpoint impacts per building, ReCiPe.

Parameter	Unit	Timber	Concrete
GWP-total	kg CO_2 eq	-2,73E+05	1,10E+05
GWP-LULUC*	kg CO_2 eq	1,34E+02	6,98E+01
AP	kg SO_2 eq	1,13E+00	1,20E+01
EP,f	kg P eq	2,50E+00	5,03E+00
EP,m	kg N eq	6,42E+01	1,33E+02
POCP	kg NO_x eq	2,40E+01	9,61E+01
WDP	m^3	2,21E+04	4,13E+06
LU	m^2	1,99E+05	4,55E+02

*Note: * GWP-LULUC presents the CO_2 emissions due to land use and land use change*

To calculate the endpoint impact, conversion factors for each impact category listed by (Huijbregts et al., 2017) was applied according to Equation 25 and presented in Table 19.

$$IR = \sum(MI_c * C_{end,c}) \tag{25}$$

Here IR refers to the endpoint impact calculated according to ReCiPe, MI_c is the midpoint impact and $C_{end,c}$ is the endpoint conversion factor for impact category c in species.year/midpoint impact. The total endpoint impact was calculated for each building.

Table 19: Endpoint characterisation factors per impact category, ReCiPe.

Ecosystem	Impact category	Unit	Conversion factor
Terrestrial	Global Warming	Species.year/kg CO_2 eq.	2,80E-09
	Photochemical ozone formation	Species.year/kg NO_x eq.	1,29E-07
	Acidification	Species.year/kg SO_2 eq.	2,12E-07
	Water consumption	species.year/m^3 consumed	1,35E-08
	Land use - occupation and transformation	Species/(m^2·annual crop eq)	8,88E-09
Freshwater	Global Warming	Species.year/kg CO_2 eq.	7,65E-14
	Eutrophication	Species.year/kg P to freshwater eq.	6,71E-07
	Water consumption	species.year/m^3 consumed	6,04E-13
Marine	Eutrophication	Species.year/kg N to marine water eq.	1,70E-09

3.3.2. Chaudhary & Brooks method of impact assessment

To calculate the impact on biodiversity using the C&B method, the land use calculations from Section 3.2.3 were applied together with CFs listed by Chaudhary and Brooks (2018) as supplementary data in connection to their methodology for the method of impact assessment. Tables 20 and 21 presents the taxa specific as well as taxa aggregated CFs for ecoregion ‘Sarmatic mixed forests’ and the two land use types ‘Forest intense’ and ‘Urban intense’.

Table 20: Taxa specific occupation and transformation characterisation factors per land use type in ecoregion 'Sarmatic mixed forest', C&B method.

Taxa	**Forest intense**		**Urban intense**	
	CF_{occ} [PSL/m^2]	**CF_{trans}** [PSL*year/m^2]	**CF_{occ}** [PSL/m^2]	**CF_{trans}** [PSL*year/m^2]
Mammals	7,96E-13	3,46E-10	7,62E-13	3,34E-10
Birds	1,25E-12	5,14E-10	1,22E-12	5,01E-10
Amphibians	1,84E-13	7,59E-11	1,59E-13	6,59E-11
Reptiles	6,31E-15	2,60E-12	1,21E-14	5,00E-12
Plants	8,38E-13	3,26E-10	2,64E-12	1,04E-09

Table 21: Taxa aggregated occupation and transformation characterisation factors per land use type in ecoregion 'Sarmatic mixed forest', C&B method.

Land use type	**CF_{occ} taxa aggreg.** [PDF/m^2]	**CF_{trans} taxa aggreg.** [PDF*years/m^2]
Forest intense	1,52E-14	6,38E-12
Urban intense	1,49E-14	6,27E-12

The taxa specific impact was calculated using Equation 26.

$$IC\&B_{g,i,j} = \left(CF_{occ,g,i,j} * A_{i,b}\right) + \left(CF_{trans,g,i,j} * \frac{A_{i,b}}{years}\right) \qquad (26)$$

Here $CF_{occ,g,i,j}$ refers to the occupation characterisation factors for taxa g in land use type i and ecoregion j. $CF_{trans,g,i,j}$ refers to the transformation characterisation factors for taxa g in land use type i and ecoregion j. $A_{i,b}$ refers to the land use needed for land use type i connected to building b. Finally, *years* refers to the 'occupation time' of each land use type and reflects the instant impact caused by transformation over the operational years of a certain land use type. According to Angelstam et al. (2020) the rotation time for a clear-cut forest ranges from 45 to 100 years, leading to the assumed operational year for a forest being 75 years in this calculation. Quarries are assumed to be operational for at least 30 years (Cemex, n.d.), which is used as the 'occupation time' in the calculations. This results in the potential species lost for each taxon due to land use occupation and transformation in a certain ecoregion. In order to calculate the potentially disappeared fraction per taxa, each taxa-specific impact was divided by the species richness $S_{org,g,j}$ per taxa g in ecoregion j. Taxa-aggregated CFs are already in the unit PDF, thus no conversion was needed to calculate the impact across the taxa.

3.3.3. Habitat-Fragmentation method of impact assessment

The calculations for HF method are similar to that of the C&B method. Taxa specific and taxa aggregated land use occupation and transformation CFs are presented for the ecoregion 'Sarmatic mixed forest' in Tables 22 and 23.

Table 22: Taxa specific occupation and transformation characterisation factors per land use type in ecoregion 'Sarmatic mixed forest', C&B method.

Taxa	**Forestry**		**Urban**	
	CF_{occ} [PDF/m^2]	**CF_{trans}** [PDF*year/m^2]	**CF_{occ}** [PDF/m^2]	**CF_{trans}** [PDF*year/m^2]
Mammals	5.99E-13	2.61E-10	6.53E-13	2.86E-10
Birds	3.37E-13	1.38E-10	3.12E-13	1.28E-10
Amphibians	5.84E-13	2.40E-10	3.41E-13	1.41E-10
Reptiles	6.81E-13	2.80E-10	6.81E-13	2.82E-10

Table 23: Taxa aggregated occupation and transformation characterisation factors per land use type in ecoregion 'Sarmatic mixed forest', HF method.

Land use type	**CF_{occ} taxa aggreg.** [PDF/m^2]	**CF_{trans} taxa aggreg.** [PDF*years/m^2]
Forestry	5.50E-13	2.30E-10
Urban	4.97E-13	2.09E-10

Equation 27 combines the CFs with the land use attributed to each building to calculate the taxa specific and taxa aggregated impact.

$$IHF_{g,i,j} = \left(CF_{occ,g,i,j} * A_{i,b}\right) + \left(CF_{trans,g,i,j} * \frac{A_{i,b}}{years}\right) \tag{27}$$

In this equation, *IHF* refers to the impact calculated using the HF method presented in PDF per taxa or taxa-aggregated. *CF* refers to the average occupation & transformation characterisation factors for taxa *g* in land use type *i* and ecoregion *j*, *A* refers to the land use needed for land use type *i* connected to building *b*, and years refers to the occupation time of each land use type.

4. Results & analysis

The aim of the thesis was to assess how the choice of construction material would affect the impact on biodiversity caused by the construction of the two buildings. To answer this, three different methods of impact assessment were used, ReCiPe, C&B and HF. In this section, the results gained through applying each of the three methods are presented individually followed by a comparison between the methods.

4.1. Biodiversity impact using ReCiPe

ReCiPe calculates biodiversity impact through six different midpoint impact categories which to some degree covers the pollution, global warming, and land use aspects of biodiversity decline. Table 24 presents the impact from the two buildings, calculated using the ReCiPe method of impact assessment. The biodiversity damage is shown for the whole building and is presented for each impact category in the unit potentially disappeared fraction of species.

Table 24: ReCiPe results per impact category and total.

Impact category	Timber [PDF]	Concrete [PDF]
GWP	-7,65E-04	3,07E-04
POCP	3,09E-06	1,24E-05
AP	2,41E-07	2,54E-06
EP	1,79E-06	3,58E-06
WDP	2,99E-04	5,58E-02
LU	1,77E-03	4,04E-06
Total	**1,31E-03**	**5,61E-02**

For the timber building, GWP has a net negative impact resulting in a potential increase of number of species. The reason for this is due to biogenic carbon having a significant negative impact, which can be explained by the forest acting as a natural carbon sink and as such would decrease the CO_2-levels in the ecosystem, which is consistent with that concept that trees will sequester carbon through photosynthesis storing it in the biomass (Cole, 2012).

It is worth noting that the negative impacts due to biogenic carbon will exit the system at later stages of the lifecycle, after which they should be accounted for as positive impacts. Hence, in a cradle-to-grave assessment looking at the entire lifecycle of the building, the sum of the impacts due to biogenic carbon would be zero (Larsson et al., 2016). Table 25 presents the GWP impact for the timber building in CO_2 equivalents, both excluding and including the effects of biogenic carbon. Notably, the inclusion of biogenic carbon severely alters the results turning the impact from positive to negative.

Table 25: Results for the impact category 'global warming' for the timber building including and excluding biogenic carbon

Global Warming	**[PDF]**
Excluding biogenic	6.55E-05
Including biogenic	-7,65E-04

Figure 10 is a visualisation of the contribution from each impact category for the timber building. To make comparison possible the impacts has been normalised to the largest one, which was ‘Land use’. The second largest positive impact was ‘Water deprivation potential’ while the remaining positive impacts equals less than a half percent. Finally, it can be seen as mentioned earlier that the impact of ‘Global warming’ contributes with a significant negative impact. The positive impacts can be explained as potential loss of species while the opposite is true for the negative impact.

Figure 10: Timber building midpoint impact contribution shares, normalised.

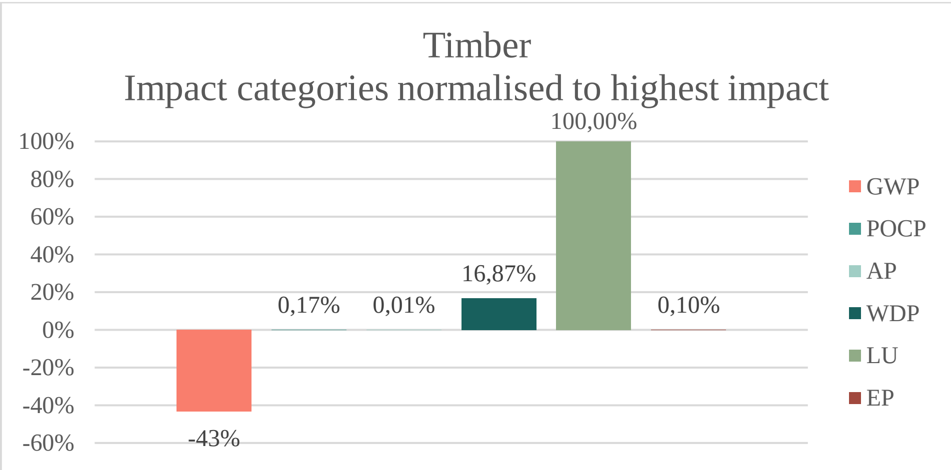
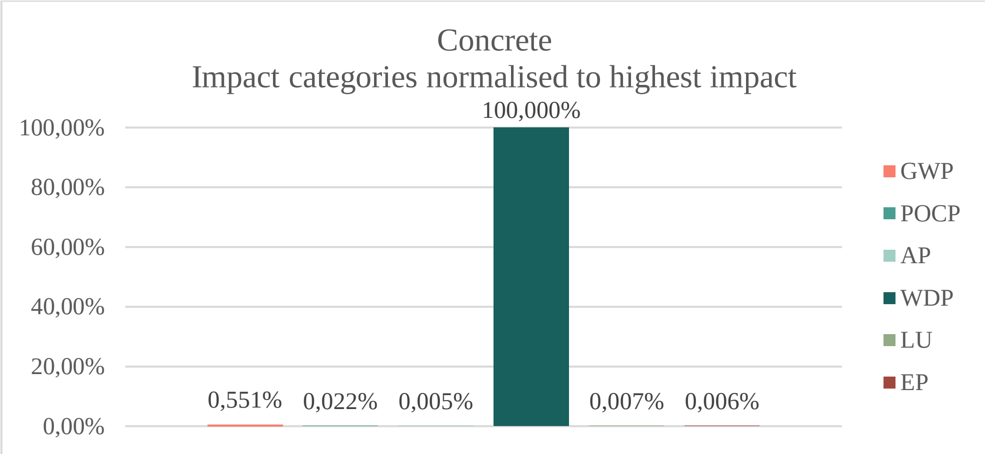


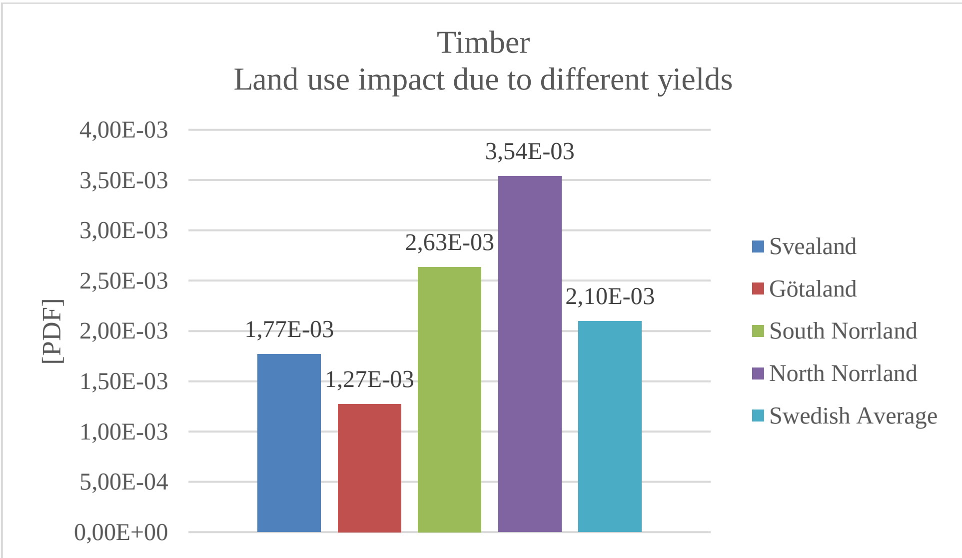
Figure 11 follows a similar structure, presenting the shares of the positive impacts for the concrete building. Here, ‘Water consumption’ is by far the most dominant impact category, contributing more than 99% of the total impact. This can be explained by the fact that concrete production requires large amount of water, which in turn would have considerable effects on the ecosystems where the water is taken from and thus the species in those ecosystems.

Figure 11: Concrete building midpoint impact category shares, normalised.



In order to assess how the impact of land use changes depending on where the materials where extracted, yields for different regions of Sweden was applied to the land use calculations of the two buildings. Figure 12 presents a comparison between different geographical regions in Sweden and illustrates how the impacts could differ if timber would be extracted from these regions instead of Svealand. The impact is based on the land use needed to meet the wood demand and is calculated based on the yields of forests in each of the geographical regions.

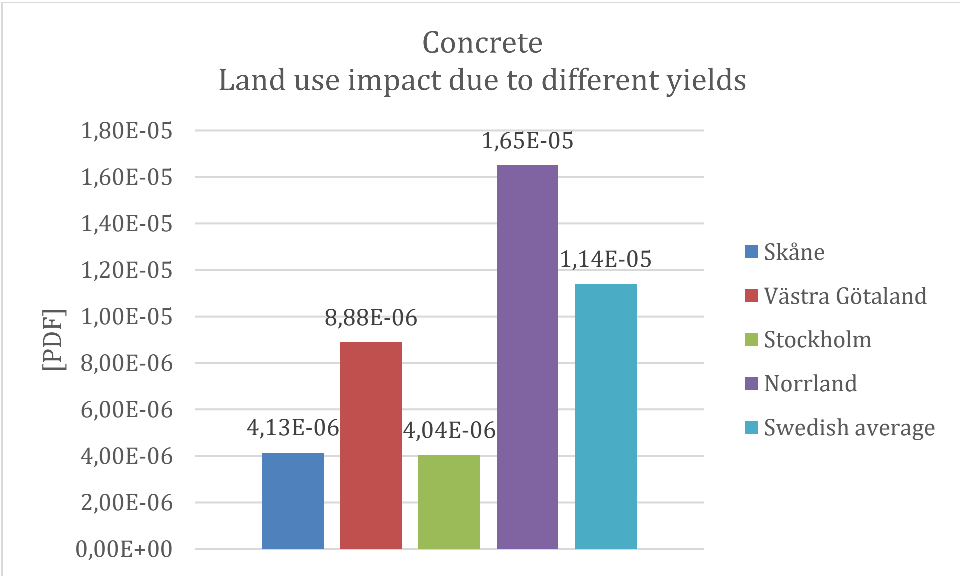
Figure 12: Comparison of total land use impact due to different yields in different geographical regions, timber.



Forestry in Götaland would result in the lowest total impact, approximately 30% lower than the studied region of Svealand, which has the second lowest impact. Using average Swedish yields would result in impacts approximately 19% higher than in Svealand. Southern and Northern Norrland shows the highest impacts, with Southern Norrland being roughly 50% higher than Svealand and Northern Norrland approximately double the impact compared to Svealand. Notably, the impact increases the further north the forest is located. Furthermore, the impact is connected to the area efficiency of each of the different regions, where less efficient areas requires more land use to produce the same amount of material, thus having a larger impact on species lost.

Figure 13 presents a comparison of the impacts due to land use when using gravel yields from different geographic areas in Sweden, as well as Swedish average yields. The land use calculations are based on the amount of land required to produce one ton of gravel and the impacts are presented for the entire building. Limestone yield and land use are kept the same due to Slite limestone quarry being by far the largest supplier of limestone and cement in Sweden.

Figure 13: Comparison of total land use impact due to different yields in different geographical regions, concrete.



Notably, the original yield based on the Stockholm area results in the smallest overall impact while yields from quarries in Norrland results in the largest impact, approximately four times larger compared to Stockholm. Yields based on the Skåne region result in roughly the same impact as Stockholm, Västra Götaland yields result in roughly double the impact compared to Stockholm, and using the Swedish average results in impacts almost three times the size compared to Stockholm. A possible explanation for the results is that Stockholm and Skåne quarries are among the more area efficient when it comes to extraction, while Norrland quarries are less area efficient leading to a higher amount of land required to produce the same amounts of gravel as the other areas. Thus, the results show that land use impacts calculated using the ReCiPe method of impact assessment depend on the yield and efficiency of the quarries investigated, rather than geographical location.

4.2. Biodiversity impact due to land use

The C&B and HF methods cover the land use aspect of biodiversity decline. The methods use variations of species-area relationships to factor in how different aspects of land use transformation and occupation affect biodiversity.

4.2.1. Land use effects using the C&B method

Table 26 presents the total taxa aggregated impacts for each building in the four different ecoregions found in Sweden. Notably, the impact caused by the timber building is consistently larger than the impact caused by the concrete building for each ecoregion.

Table 26: Taxa aggregated results per ecoregion, C&B method.

Ecoregion	**Timber taxa aggregated [PDF]**	**Concrete taxa aggregated [PDF]**
Baltic mixed forests	7,10E-08	1,60E-10
Sarmatic mixed forest	6,64E-08	1,39E-10
Scandinavian and Russian taiga	6,19E-08	1,32E-10
Scandinavian Montane Birch forests and grassland	3,85E-08	8,15E-11

Figure 14 presents the taxa specific impacts of the timber building in the unit PDF for the ecoregion 'Sarmatic mixed forest'. The highest disappeared fraction of species can be found in amphibians, followed by mammals, birds, reptiles, and plants.

Figure 14: Taxa specific impact, timber building.

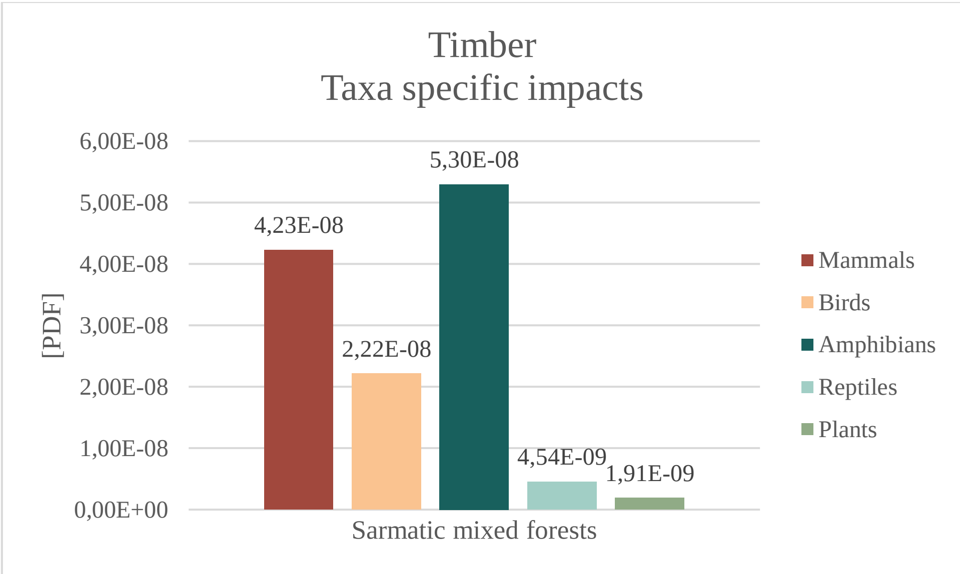
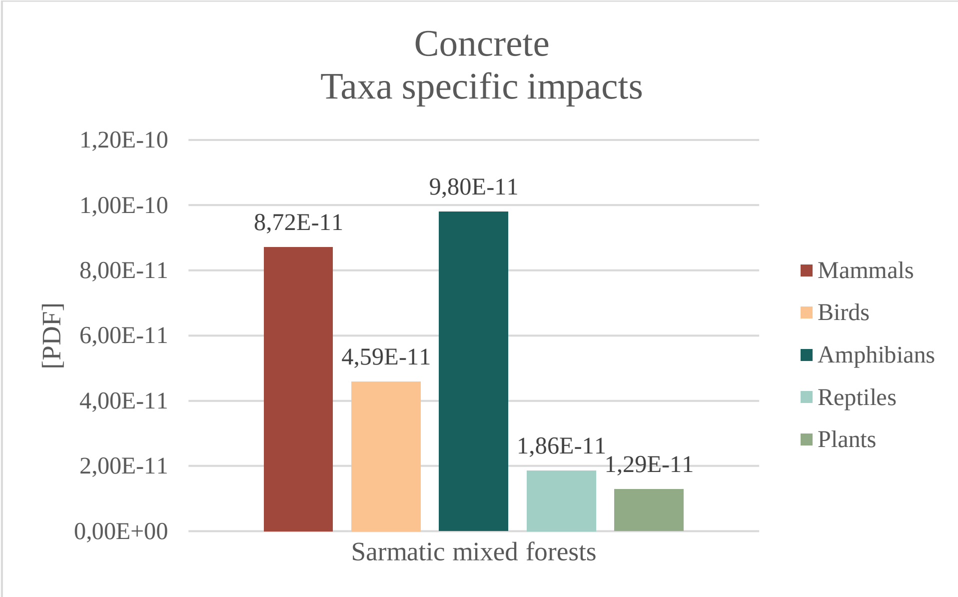


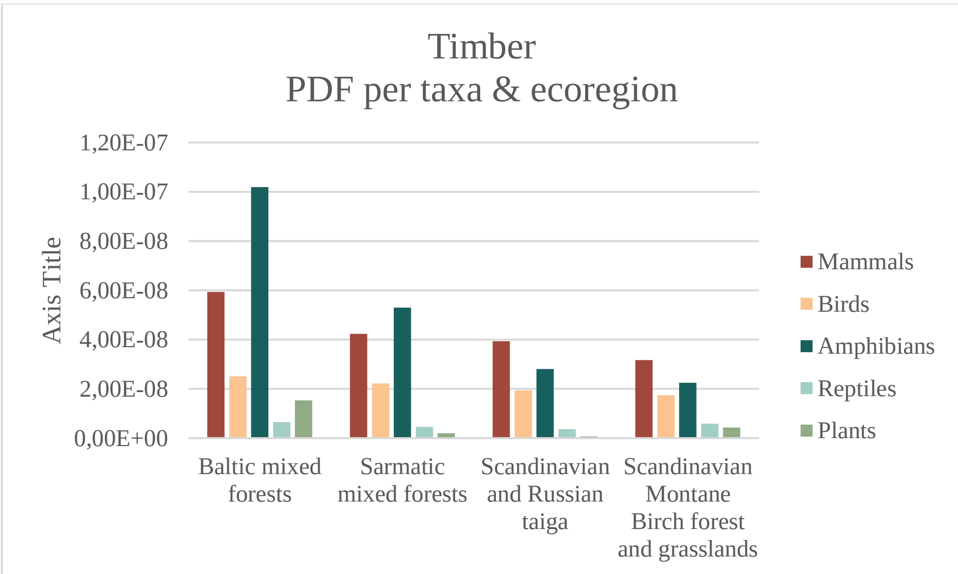
Figure 15 presents the taxa specific impact of the concrete building in the unit PDF for the ecoregion 'Sarmatic mixed forest'. The highest disappeared fraction of species can be found in amphibians, followed by mammals, birds, reptiles, and plants. Notably, the relationship of PDF among the different taxa follows the same structure for both the timber and concrete building.

Figure 15: Taxa specific impact, concrete building.



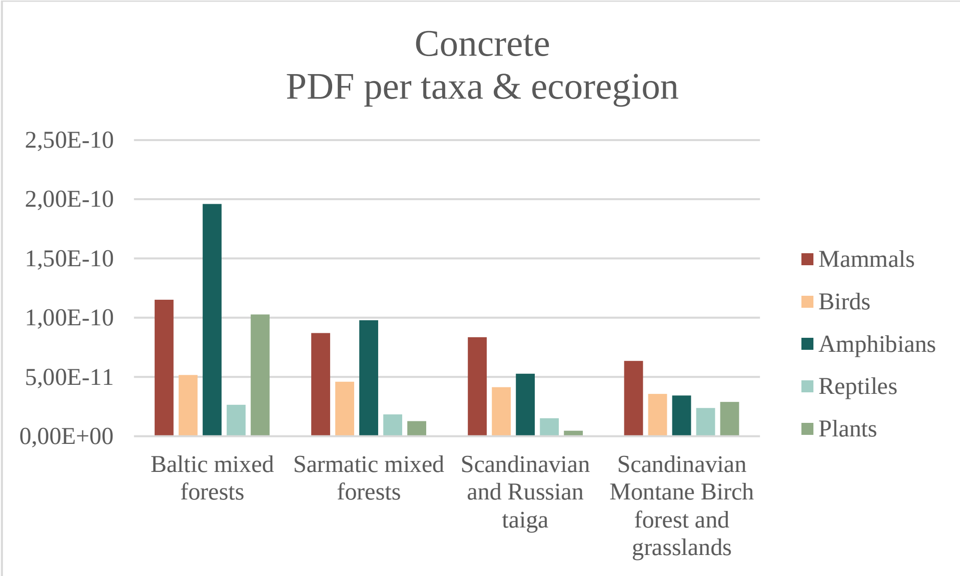
In order to assess how geographic location affects the results, Figures 16 and 17 presents the taxa specific impacts in PDF for all ecoregions of Sweden. The ecoregions are presented from south to north, 'Baltic mixed forest' being the southernmost ecoregion and 'Scandinavian Montane Birch forest and grasslands' being the northernmost ecoregion.

Figure 16: Taxa specific impact per ecoregion, timber building.



For the timber building, the effect on mammals, birds, and amphibians seem to decrease the further north the land use takes place. The effect on reptiles and plants seems to have a lower correlation to geographical location. Overall, land use in the ecoregion 'Baltic mixed forests' has the largest impacts among all taxa while land use in 'Scandinavian Montane Birch forest and grasslands' seem to have the lowest impacts. The taxon where the land use impact varies the most is amphibians, while the land use impact on birds and reptiles seems to be the most stable.

Figure 17: Taxa specific impact per ecoregion, concrete building.



Similar to the timber building, land use in the ecoregion 'Baltic mixed forests' seem to have the highest impact across all taxa, while land use in 'Scandinavian Montane Birch forest and grasslands' seems to have the lowest impact across the taxa. The land use impacts on amphibians sees the largest variation between the different ecoregions, while land use impacts on birds and reptiles seems to be more consistent through all ecoregions.

4.2.2. Land use effects using the HF method

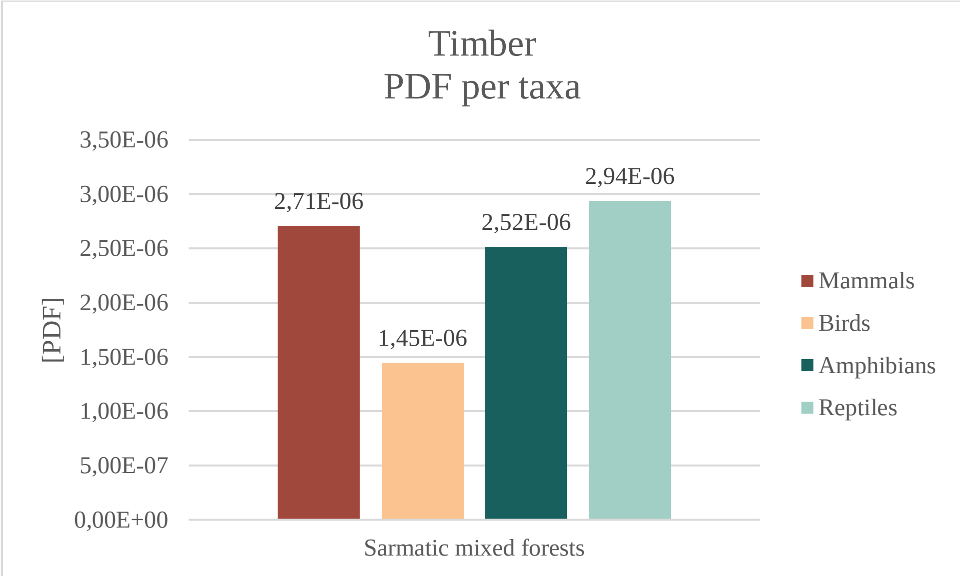
Table 27 presents taxa aggregated results for each building per ecoregion. Similar to the results from the C&B method, the timber building has the highest impact across all ecoregions.

Table 27: Taxa aggregated results per ecoregion, HF method.

Ecoregion	Timber Taxa aggregated [PDF]	Concrete Taxa aggregated [PDF]
Baltic mixed forests	1,50E-05	3,11E-08
Sarmatic mixed forest	2,40E-06	4,66E-09
Scandinavian and Russian taiga	2,15E-06	4,29E-09
Scandinavian Montane Birch forests and grassland	1,11E-05	2,24E-08

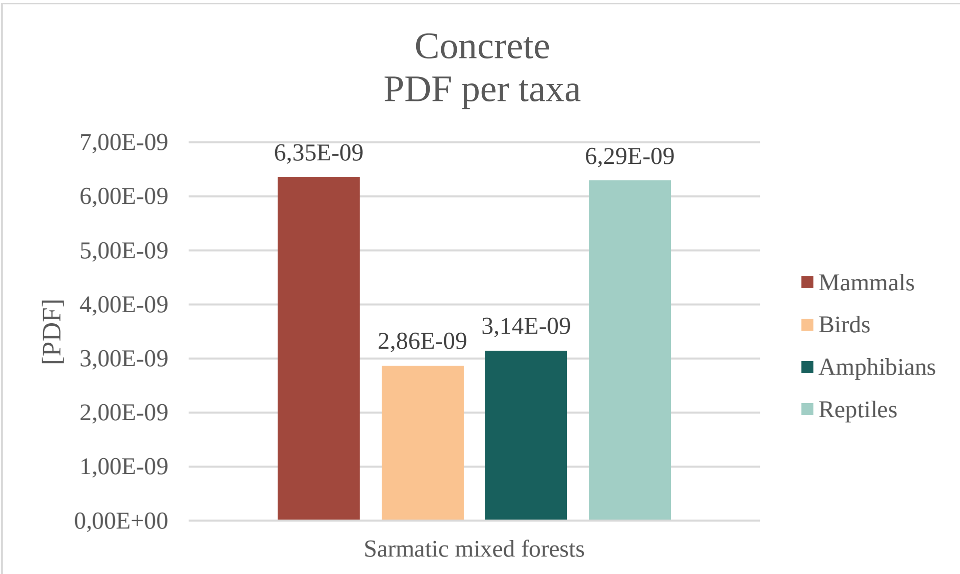
Figure 18 presents the taxa specific impacts for the ecoregion 'Sarmatic mixed forests'. The highest disappeared fraction of species can be found in reptiles, followed by mammals and amphibians, while the impact on birds saw the lowest impact at approximately half of the impact found for reptiles.

Figure 18: PDF per impact, timber building.



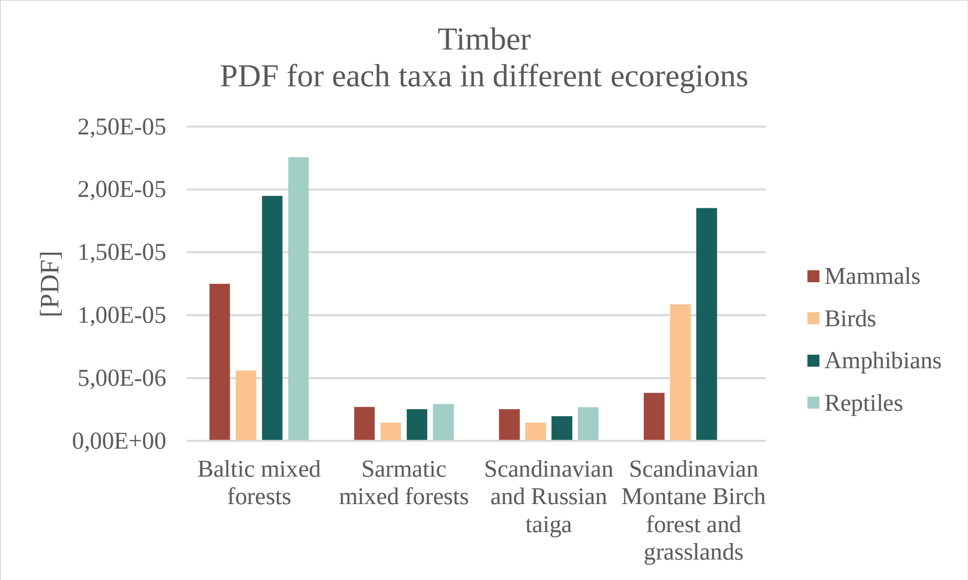
The taxa specific impacts due to the materials used in the concrete building is presented in Figure 19. Here the highest impact was found in mammals closely followed by reptiles, while the two lowest impacts were found in amphibians and birds.

Figure 19: PDF per taxa, concrete building.



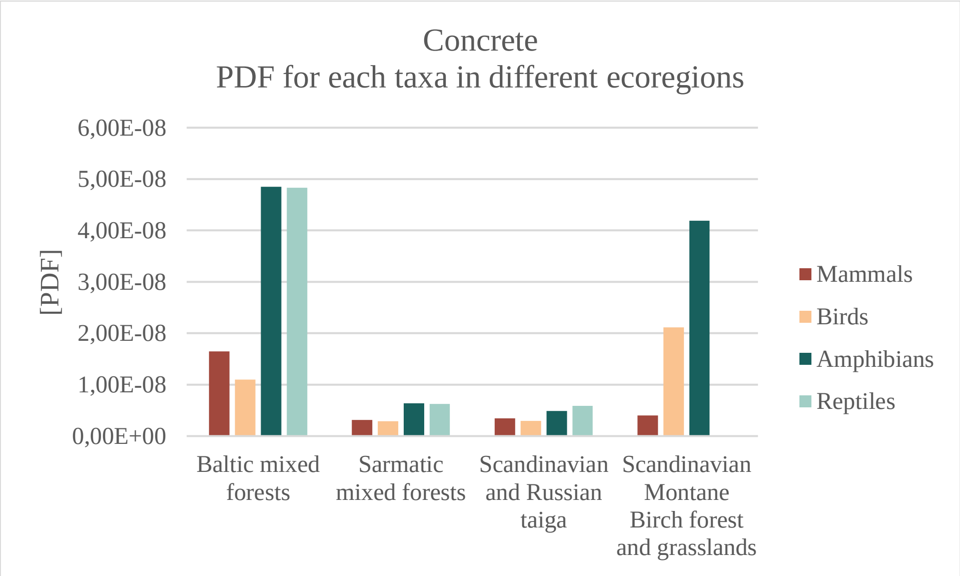
To assess how the impact for each taxa differ depending on the geographical location, the taxa specific impact in PDF for the four ecoregions found in Sweden is presented in Figure 20 and 21, respectively. The highest impacts in mammals, amphibians and reptiles can be found in the ecoregion 'Baltic mixed forests', while 'Scandinavian Montane Birch forest and grasslands' shows the highest impact in birds. 'Sarmatic mixed forests' and 'Scandinavian and Russian taiga' shows similar results across all taxa. Notably, no conclusion can be drawn for reptiles in 'Scandinavian Montane Birch forest and grasslands' as no CF was available.

Figure 20: PDF per taxa and ecoregion, timber building.



Similarly, a comparison of how the geographical location would affect the taxa specific impact for the concrete building is presented in Figure 21. The results show the impacts in mammals, amphibians, and reptiles are largest in the ecoregion ‘Baltic mixed forests’, while the impact in birds is highest for the ecoregion ‘Scandinavian Montane Birch forest and grasslands’. Again, the ecoregions ‘Sarmatic mixed forests’ and ‘Scandinavian and Russian taiga’ shows similar results across the taxa. No conclusion can be drawn for reptiles in ‘Scandinavian Montane Birch forest and grasslands’ as no CF was available.

Figure 21: PDF per taxa and ecoregion, concrete building.



While the impacts differ between the ecoregions, no clear connection between impacts and latitude can be drawn as ‘Scandinavian and Russian taiga’ and ‘Scandinavian montane Birch forest and grasslands’ cover the same geographical latitude in Sweden but differ wildly in results.

4.3. Comparison between methods

All three methods used in the thesis covers biodiversity impact due to land use to some degree. Table 28 presents the total taxa aggregated impact due to the materials needed for both buildings according to the three different methods of impact assessment.

Table 28: Land use impacts, all methods.

Method of impact assessment	Timber Taxa aggregated [PDF]	Concrete Taxa aggregated [PDF]
ReCiPe	1,77E-03	4,04E-06
C&B	6,64E-08	1,39E-10
HF	2,40E-06	4,66E-09

The timber building has the unanimously highest impact across the three methods, ranging from approximately 440 times larger using ReCiPe to approximately 515 times larger using the HF method. It is worth noting that the difference between the two buildings impacts increases as the complexity of the land use calculation increases, ReCiPe being the least complex and HF being the most complex.

Table 29 presents the impact per taxa and ecoregion in PDF due to the materials used in the timber building calculated using the two methods C&B and HF. ReCiPe does not include a way to differentiate between taxa and is thus not included.

Table 29: Impacts per taxa and ecoregion using C&B and HF method in the unit PDF, timber.

	Ecoregion\Taxa	Mammals	Birds	Amphibians	Reptiles	Plants
C&B	Baltic mixed forest	5.93E-08	2.51E-08	1.02E-07	6.49E-09	1.53E-08
	Sarmatic mixed forest	4.23E-08	2.22E-08	5.30E-08	4.54E-09	1.91E-09
	Scandinavian and Russian Taiga	3.93E-08	1.94E-08	2.81E-08	3.64E-09	6.72E-10
	Scandinavian Montane Birch forest and grassland	3.17E-08	1.74E-08	2.25E-08	5.88E-09	4.37E-09
HF	Baltic mixed forest	1.95E-05	5.61E-06	1.25E-05	2.26E-05	NA
	Sarmatic mixed forest	2.71E-06	1.45E-06	2.52E-06	2.94E-06	NA
	Scandinavian and Russian Taiga	1.97E-06	1.46E-06	2.52E-06	2.67E-06	NA
	Scandinavian Montane Birch forest and grassland	1.85E-05	1.09E-05	3.81E-06	NA	NA

Notably, the impacts calculated using the HF method is consistently higher compared to the C&B method for each taxon and ecoregion. The highest impact for the C&B method was found in amphibians in the ecoregion 'Baltic mixed forests' while the results using the HF method instead attributed highest PDF to reptiles in the same ecoregion. The lowest impact was found in plants in the ecoregion 'Scandinavian and Russian taiga' using C&B, and in birds in the ecoregion 'Sarmatic mixed forests'. The same comparison between taxa in different ecoregion was performed for the concrete building, presented in Table 30.

Table 30: Impacts per taxa and ecoregion for C&B and HF method in the unit PDF, concrete.

	Ecoregion\Taxa	Mammals	Birds	Amphibians	Reptiles	Plants
C&B	Baltic mixed forest	1,15E-10	5,18E-11	1,96E-10	2,66E-11	1,03E-10
	Sarmatic mixed forest	8,72E-11	4,59E-11	9,80E-11	1,86E-11	1,29E-11
	Scandinavian and Russian Taiga	8,36E-11	4,13E-11	5,27E-11	1,53E-11	4,62E-12
	Scandinavian Montane Birch forest and grassland	6,37E-11	3,58E-11	3,43E-11	2,39E-11	2,90E-11
HF	Baltic mixed forest	4,85E-08	1,10E-08	1,65E-08	4,83E-08	NA
	Sarmatic mixed forest	6,35E-09	2,86E-09	3,14E-09	6,29E-09	NA
	Scandinavian and Russian Taiga	4,88E-09	2,98E-09	3,45E-09	5,86E-09	NA
	Scandinavian Montane Birch forest and grassland	4,19E-08	2,11E-08	4,01E-09	NA	NA

Here, the HF method again present consistently higher impacts across all taxa and ecoregions compared to the C&B method. The largest impact using C&B was found in amphibians in the ecoregion 'Baltic mixed forests' while the highest impacts using HF was found in mammals in the ecoregion 'Baltic mixed forests'. The lowest impacts using C&B was found in plants in 'Scandinavian and Russian taiga', while the lowest impacts using HF was found in birds in 'Sarmatic mixed forests'. It is worth mentioning that the HF method does not contain CFs for reptiles in the 'Scandinavian Montane Birch forest and grasslands' ecoregion and that plants are not considered at all.

5. Discussion

The impacts due to the two buildings were assessed using three different methods of impact assessment. The results can be interpreted in numerous ways and this section includes discussion on the methods used, the results, and potential uncertainties due to the methodological choices made.

5.1. Assessing the methods of impact assessment

The three methods of impact assessment used in this thesis differ in what categories as well as approaches used when assessing biodiversity damage. Thus, the results vary widely. ReCiPe follows general guidelines when assessing biodiversity impact through ‘standard’ LCA calculations. It currently allows quantification of impacts caused by drivers such as ‘climate change’, ‘pollution’ and ‘land use’. While ‘land use’ is a midpoint impact category included in ReCiPe, it is flawed when it comes to measuring impact on biodiversity. There are only five general land use types accounted for and there is no differentiation between land use intensities. In ReCiPe, this means that all types of forestry or quarrying will be attributed the same characteristics regardless of how they are actually conducted. Furthermore, the method does not differentiate between different geographical preconditions or taxa-specific impacts. While using ReCiPe is a flawed way to measure biodiversity loss, it still results in an impact score for each material and when considering that the flaws of the method applies to the calculations regarding both materials, the results could still be used as a very basic, general way of looking at the biodiversity damage on species level.

Chaudhary and Brooks method of impact assessment is a better representation of biodiversity impact than ReCiPe when it comes to the land use aspect. Impacts are calculated based on a wider range of variables, looking at different taxa in different ecoregions and the impact from different land use types of varying intensities. As such, when measuring biodiversity loss due to land use, C&B is more preferrable than ReCiPe. However, C&B only look at the impact due to land use transformation and occupation whereas ReCiPe takes into account ‘Pollution’ and ‘Global warming’ when calculating the biodiversity impact. While the impact from ‘Land use’ is the most pressing of the five direct drivers behind biodiversity, it alone does not show the entire picture.

The case for the HF method is similar the C&B method in the sense that it only accounts for biodiversity impact due to ‘Land use’. The HF method builds on the cSAR model, as used in C&B, and incorporates habitat fragmentation in the CFs to widen the scope of biodiversity damage due to land use. Hence, this method is likely more precise in its calculations compared to both ReCiPe and C&B. However, while C&B factors in the intensity of different land use types in its calculations, the HF method has no such distinction and thus all land use types of the same category are calculated the same. An example of where this could be less favourable is the case of forestry, where clear-cutting and selective logging would be attributed different intensities according to the C&B method, are seen as similar in the HF method.

Based on the known strength and weaknesses of the C&B and HF method, it can be argued that they each fulfil different niches when assessing biodiversity impacts. With the earlier example illustrating the strength of the C&B method, by differentiating the impact caused by intensities in land use types, it also shows the weakness of the HF method. The C&B method as such could be a good choice in method to use when assessing different land uses of the same category, e.g. by comparing impacts between different forest management options. On the other hand, the HF method is more suitable for assessing impacts caused by different land uses, e.g. between urban and agricultural land uses or between forestry and agricultural land, as land use intensity is not included in the method thus making it more suitable for comparing general land use types.

While the used methods have their benefits and drawbacks, none of them covers all aspects of biodiversity. The impacts due to overexploitation of species and invasive species are not covered at all. Furthermore, all of the methods used investigate biodiversity loss at the species level looking at absolute numbers, thus missing out on possible effects on the landscape, ecosystem, or genetic level.

5.2. Assessing the results

Results assessing the impact caused by ‘Land use’ are consistent throughout all three methods, showing that the biodiversity impact is higher for the timber building compared the concrete building. However, the overall results using the ReCiPe method shows a larger impact associated with the concrete building compared to the timber building, showing the importance of including multiple aspects of biodiversity loss. The two dominating impact categories when using ReCiPe was ‘Land use’ for the timber building and ‘Water deprivation potential’ for the concrete building showing that different materials having separate properties will result in different impacts. Thus, no individual impact category can be ascribed as the most impactful across different materials which further adds to the argument that more methods capturing the full scope of biodiversity are needed.

Results gained for the timber building by using the ReCiPe method resulted in negative impacts for impact category ‘Global warming’ which would lead to an increase in biodiversity. This negative impact is due to biogenic CO_2, which is accounted for in connection to the extraction of raw material. In the full lifecycle of wood, biogenic CO_2 exits the system in the later stages which means that it should be counted again, this time as a positive impact, effectively making the impact of biogenic CO_2 neutral over the entire lifecycle. Since the assessment was conducted as cradle-to-gate, it only factors in the negative impact of biogenic CO_2 and thus the results for the timber building can be seen as misleading.

When comparing the results gained for the C&B and HF method for each taxon and ecoregion, trends as well as outliers could be found. The C&B method was more consistent with its’ results than the HF method, visualised by that the highest impacts from the C&B method for both timber and concrete resulted in higher impacts in amphibians found in the ‘Baltic mixed forests’, while the lowest impacts were found in plants in the ‘Scandinavian and Russian taiga’. For the HF method the results instead changed depending on building material. Highest impact for the timber building was found in reptiles in the ‘Baltic mixed forests’ while the highest for the concrete building was found in mammals in the same ecoregion. When looking at taxa aggregated impacts, the ecoregions with the lowest impact differ between the methods, with the C&B method resulting in a lower potential disappeared fraction of species in the ecoregion ‘Scandinavian Montane Birch forest and grassland’. For the HF method the result instead showed that the lower potential disappeared fraction of species could be found in the ecoregion ‘Scandinavian and Russian taiga’. This tells us that geographical location matters when it comes to material extraction, however, there seems to be less correlation between impact and latitude.

5.3. Possible uncertainties

Land use calculations are based on average data regarding yields, which means that the following results are applicable in a general sense. However, if the origin of materials used in the buildings are known, using specific data would lead to more accurate results. In the case of quarrying of gravel, the size of an average quarry was assumed based on measurements of quarries used by a larger construction company. Similar to yields, using specific data for the sizes of quarries would result in more precise calculations of yield per hectare and by extension more accurate impacts due to a specific building.

EPDs were chosen on the basis that they had been submitted, reviewed, and accepted for publication, thus indicating that they follow the rules and regulations put in place by the publisher and as such contains reliable data. The chosen EPDs represent products for use in the Swedish construction market. However, there is a degree of variation in the materials used and the environmental impacts between products. As such, the following results are applicable in a general sense and knowing exactly which product will be used would allow for the usage of more specific data leading to more accurate results. Furthermore, EPDs presents a set of predetermined impact categories according to the rules and regulations set out by the publisher. A couple of notable impact categories that were not included in the EPDs, and thus left out of the assessment, and are assumed to have an impact on biodiversity are terrestrial eutrophication and ecotoxicity.

Land use transformation impacts were calculated by assuming that forests are operational for 75 years, whereas quarries are operational for 30 years. In reality the operational years for each land type varies and using data specific to a certain forest or quarry would yield more accurate results.

Only looking at biodiversity at the species level disregards a large fraction of biodiversity. How different drivers affect biodiversity at landscape, ecosystem, or genetic level are not included in the assessments. Thus, the results show a fraction of the total biodiversity damage and in order to get the full picture, alternative methods including ways to measure biodiversity damage at several levels are required.

5.4. Recommendations for future research

Considering the scope of the thesis and after assessing the results, there are opportunities for further research regarding the impacts of the two materials. Some of the more interesting areas of research include:

- How different land use intensities would affect the results, especially when assessing and comparing different forestry types using LCA.
- How the environmental impacts of the materials would affect different levels of biodiversity, e.g. landscape, ecosystem and genetic levels.
- How the impact on biodiversity would change when including additional methods of impact assessment looking at ‘overexploitation of species ‘ and ‘invasive species’.
- How the results of a cradle-to-grave approach differs from a cradle-to-gate, by including environmental impacts during the use phase and end-of-life phase.

Apart from the listed suggestions, it would be interesting to assess the possibility of presenting biodiversity damage of the building materials as a single score, by employing a different approach than LCA. One such approach could include the utilisation of indicators to present biodiversity damage due to the five direct drivers behind biodiversity decline. Possibly by including expert opinions on each driver due to each material, using a weighting system, and presenting aggregated results.

6. Conclusion

The aim of the thesis was to evaluate the impact on biodiversity at the species level due to the building materials wood and concrete. Three methods were utilised, a more classical LCA approach in using ReCiPe to assess impacts due to 'Global warming', 'Pollution' and 'Land use', and two separate methods to assess 'Land use' in more depth, one developed by Chaudhary and Brooks utilising the countryside species-area relationship together with land use intensities, and a method developed by Kuipers et al. that expanded on the countryside species-area relationship by including habitat fragmentation.

Using ReCiPe as a method of impact assessment includes looking at midpoint impact categories commonly used in LCA, such as global warming potential, acidification potential, eutrophication potential or water deprivation potential. The inclusion of such categories is relevant in the assessment of biodiversity impact due to the fact that they all affect biodiversity in different ways. The results showed that land use is the most contributing impact category for wood, and that water deprivation is the most contributing for concrete. This tells us that different materials affect biodiversity in different ways.

The land use category was included in all methods used and measured biodiversity impact on different levels of complexity. Land use is presented as the most pressing issue when it comes to biodiversity and is thus an important factor to consider. Different types, intensities, and geographical locations of land use practices all affect biodiversity in different ways. Furthermore, individual taxa have different affinities to ecoregions and land use types and are thus affected differently depending on which type, how intense, and where the land use is located.

All three methods showed that the land use connected to the timber building led to a higher potential disappeared fraction of species compared to the land use connected to the concrete building. However, when factoring in the effects of pollution and global warming via the ReCiPe method, the results showed that the concrete building led to a higher potential disappeared fraction of species. Thus, using timber as the construction material would be the overall preferred material. However, the study only covers three out of five direct drivers behind biodiversity decline and only look at biodiversity damage at the species level. In light of this, it would be recommended to utilise several additional methods to capture the entire impact of the two materials.

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Appendix A

Tables A1-A6 presents the material compositions of the elements as well as the total weight of each material included in the elements of the building.

Table A 1: Material compositions and weights, Load bearing interior wall, Timber.

Material composition: Load bearing interior wall, Timber		
Material	Weight-%	Weight [ton]
Timber	98,62%	23,21
Polyurethane adhesive	1,29%	0,30

Table A 2: Material compositions and weights, Load bearing outer wall, Timber.

Material composition: Load bearing outer wall, Timber		
Material	Weight-%	Weight [ton]
Timber	98,62%	32,41
Polyurethane adhesive	1,29%	0,42

Table A 3: Material compositions and weights, Timber beams.

Material composition: Timber beams, Timber		
Material	Weight-%	Weight [ton]
Timber	98,62%	95,21
Polyurethane adhesive	1,29%	1,25

Table A 4: Material compositions and weights, Load bearing interior wall, Concrete.

Material composition: Load bearing interior wall, Concrete		
Material	Weight-%	Weight [ton]
Aggregates (Gravel)	73,70%	142,87
Cement	15,60%	30,24
Water	4,15%	8,05
GGBS	3,20%	6,20
Reinforcing steel	3,00%	5,82
Additives	0,22%	0,43
Steel	0,07%	0,14
Plastic	0,05%	0,10

Table A 5: Material compositions and weights, Load bearing outer wall, Concrete.

Material composition: Load bearing outer wall, Concrete		
Material	Weight-%	Weight [ton]
Aggregates (Gravel)	66,30%	136,45
Cement	20,10%	41,37
Water	5,00%	10,29
Additives	4,00%	8,23
Reinforcing steel	3,23%	6,65
Insulation	0,64%	1,32
Steel	0,39%	0,80
Rock wool	0,29%	0,60
Plastic	0,02%	0,04

Table A 6: Material compositions and weights, Hollow concrete beams.

Material composition: Hollow concrete beam, Concrete		
Material	Weight-%	Weight [ton]
Aggregates (Gravel)	81,50%	214,96
Cement	10,72%	28,27
Water	5,10%	13,45
Metal - Steel	1,30%	3,43
SCM	1,27%	3,35
Chemicals	0,10%	0,26

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