A framework to determine the CO_2 impact of land use change to support municipal planning

– a case study in SE Uppsala

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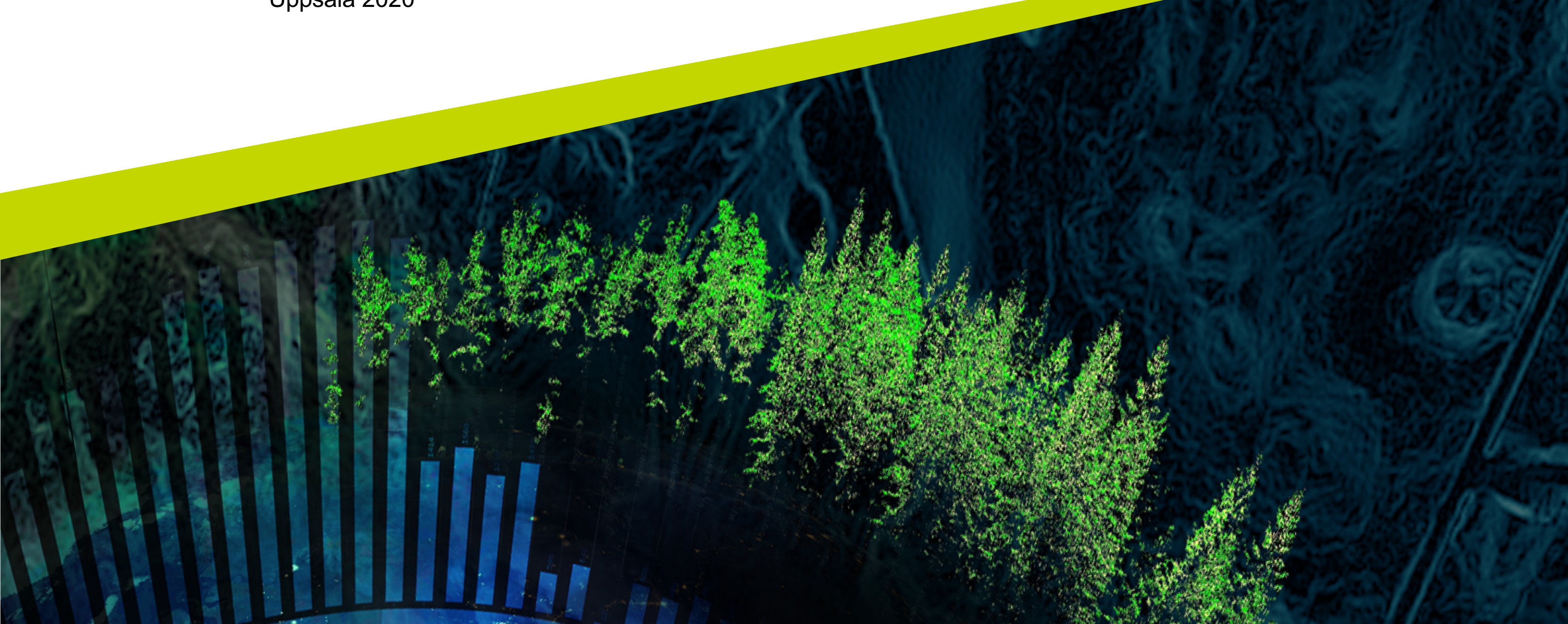

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Abstract

Growing populations and urban sprawl are among the main reasons for land use changes across the world, which often occur hand in hand with deforestation, one of the largest global causes for greenhouse gas emissions and climate change. Many global regions are affected by these dynamics that occur with a rising population, one of them is Uppsala in central Sweden. However, the interest and awareness of municipalities to define their environmental impact is starting to grow. The aim of this study was to develop a framework that enables municipalities across Sweden to determine carbon stocks and CO_2 emissions occurring during land use changes into settlement land. Two levels of precision were included that are based on either regional climate zone data published by the IPCC in their National Greenhouse Gas Inventory program (Level 1) or national inventory data (Level 2). In order to support decision-making, the emissions were determined in space and time. The developed framework was applied to a case study area in Uppsala, where 224 ha of mostly forest land is proposed to be converted to settlements. The results showed that the Level 1 CO_2 emissions were generally higher than in the national Level 2, with the rate of biomass growth in forests being the main source of variation. This indicates that due to Uppsala's location in the northernmost part of the temperate climate zone, the lower growth rate of the bordering boreal zone may have an impact on the site, raising questions on the applicability of the Level 1 approach to areas in central regions of Sweden. Concerning the case study area, the most effective strategy to reduce emissions is to avoid land use change from wetlands and the biomass-rich forest land depicted in a CO_2 emission potential map.

Popular Science Summary

An increasing global population and growing urban areas are among the main reasons for changing landscapes worldwide. The demand for land is growing rapidly and most often, nature and especially forests are the main land uses that are converted into settlements. This situation is reflected in Uppsala, which is growing by an estimated 100,000 people until 2050. Therefore, an overview plan to convert 224 ha of various land uses in Uppsala's south-east into settlement land has been published.

The aim of this study was to provide a framework to determine relevant C stocks and potential CO_2 emissions that occur during the land use change and in the decades following it. A CO_2 balance was calculated that included current and future C stocks as well as potential C sinks and compensation measures

The plan in Uppsala served as a case study area. Additionally, the potential emissions were allocated and displayed on a map. This was carried out by using two levels of precision that each use different data sources. Level 1 was based on the Tier 1 approach used in the National Greenhouse Gas Inventory program by the Intergovernmental Panel on Climate Change (IPCC), while Level 2 used Swedish national inventory data. Two different scenarios were applied to each level, these describe the rate at which land use is converted and the present C stocks removed.

The results showed generally higher CO_2 emissions in Level 1 compared to Level 2, mainly due to a difference of the C content in forest soils and the expected growth rate of forest biomass. The latter was explained by the location of Uppsala within the temperate climate zone but in close proximity to the boreal zone, where lower growth rates are present. The application of the Level 1 approach may therefore lead to large overestimations in central regions of Sweden.

The majority of the emissions occurred within the building period and after around 50 years, the annual CO_2 fluxes turned negative, indicating sequestration instead of emission.

Concerning the case study area, the most effective strategy to reduce emissions is to avoid the conversion of forest parts with high biomass and wetlands into settlement land. Decision-making can be supported by a CO_2 emission potential map that provides an overview over potential hotspots that should be avoided.

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Abbreviations

AGB	above-ground biomass
BGB	below-ground biomass
C	carbon
CL	cropland
CO_2	carbon dioxide
DOM	dead organic matter
FL	forest land
GIS	geographic information system
GL	grassland
HWP	harvested wood products
NGGI	2006 IPCC Guidelines for National Greenhouse Gas Inventories
OL	other land
WL	wetland

1. Introduction

1.1 Urbanization and land use changes

Urbanization and the resulting land use change are two of the major challenges of today's global reality across the planet. Advances in information technology since the 1980s have created a new wave of urbanization, which takes place not only in a demographic sense, but also in an economic, social and cultural way (Andersson, 1985). Farrell (2017) goes on to point out that the most rapid current increase in urban populations occurs in the developing world, although this development is just as apparent in the rest of the world. Naturally, the ever-increasing size of city areas pushes agriculture and nature further and further away from the city cores. According to Westlund (2018), in Sweden, a disconnection between the urban and rural world is taking place with changing land use patterns most prominently in the Stockholm region. However, urban expansion in the Stockholm area is reaching a ceiling, causing a more rapid increase in nearby areas such as Uppsala. The main factor driving this development is the rapid increase of land prices in proximity to cities, leading to a large land use change from agricultural land to settlements (Westlund & Nilsson, 2019).

These land use changes lead to an increasing food demand from a growing urban population. Therefore, agricultural land is increasingly valued, causing a shift towards forest land and other natural land as the preferred source of urban expansion. This shift takes place not only in rapidly growing developing countries worldwide but also in Sweden. Additionally to ecosystems and their services, carbon stored in vegetational biomass and soils is impacted. These pools play an important role as carbon sinks in the global carbon cycle (Pan et al., 2011). Deforestation has been occurring on a large scale globally, especially in tropic regions where land use is changed from rainforests to agricultural and grazing land at a rapid pace. According to Barker et al. (2007), emissions resulting land use changes were estimated to around 17 % of all anthropogenic greenhouse gas emissions in 2004.

1.2 Climate impact of the land use sector

Anthropogenic greenhouse gas emissions are among the main drivers of the global climate change contributing to the rise of the global carbon dioxide levels in the atmosphere since the beginning of the industrial age (Prentice et al., 2001). The reduction of greenhouse gas emissions is a goal on the agenda of most countries around the world and measures are taken at an increasing rate. While certain sectors like industry and transportation have received a lot of public attention, the “Land use, Land Use Change and Forestry” sector has often been overlooked. However, the interest is starting to grow on a national and regional level, especially because the above- and below-ground pools are two large and very sensitive global carbon sinks (Lal, 2008).

While the process of changing the land use of an area may only take a few years, the subsequent impact on the greenhouse gas balance and hence the climate can remain for decades. Therefore, it is important to quantify the climate impact over time. Main regulating factors in these processes are the adjustment of carbon levels in soils to the new land use and the different uses of wood products, as well as their longevity. The latter are usually assessed in life-cycle analyses, where their impact on carbon balances can last for many years even after their production.

Sweden has set its national climate target to reach net-zero emissions by the year 2045 (Swedish Climate Policy Council, 2019). With many Swedish municipalities starting to set their own climate goals for a reduction of emissions, the interest in the effects of land use is growing rapidly and in connection to the urbanization, areas are turned into settlement land more frequently. However, there is very little information available on how these conversions can be accounted for in annual carbon balances on a municipal scale.

1.3 Case study area: land use change in Uppsala

Uppsala, Sweden’s fourth-largest city, is a municipality with very ambitious climate goals. Having won the World Wildlife Fund’s award as Swedish Climate City of the year in 2020, Uppsala aims to reduce their greenhouse gas constantly and to be climate positive by the year 2050 (Uppsala klimatprotokoll, n.d.). However, these challenges become increasingly difficult, as Uppsala is also among the fastest growing cities in Sweden. Its population has risen from around 190,000 in 2008 to 225,000 in 2018, equaling an increase of almost 20 %. The municipality expects a further growth to 318,600 inhabitants by the year 2050, an additional increase of over 40 % (Uppsala municipality, 2017). This population growth rate surpasses the national average of around 1 million or 10 % during the last 10 years, which is predicted to increase further to roughly 12 million by 2050 (Statistics Sweden, 2020).

In order to handle the expected population growth, an expansion of Uppsala's city borders is inevitable to provide sufficient housing opportunities. In 2016, the municipality council thus decided to work out an overview plan which will provide 21,500 new households in close proximity to the south-eastern city districts Sävja and Bergsbrunna by the year 2050. The preliminary overview plan ("Fördjupad översiktsplan") was published in February 2020 and establishes ecological sustainability as one of the main cornerstones of the project (Uppsala municipality, 2020). The plan includes not only the construction of buildings used for housing, but also an infrastructural network (i.e. tram and the required railway system) and commercial buildings creating between 10,000 and 20,000 new jobs for the community.

1.4 Aim

The purpose of this thesis is to develop a framework which enables the inclusion of carbon stocks, sinks and overall CO_2 balances in the planning process for areas in Sweden, whose current land uses are consequently converted into settlements. Both long-term and short-term climate impacts and developments on the land during and after a land use change of this scale are considered. The area close to Bergsbrunna in south-eastern Uppsala serves as a case study area for the application of this framework due to the municipalities interest to determine the environmental impact and its effects from a climatic point of view. The aim is to provide methods at two levels of precision that can be applied depending on data availability and to ensure comparability between them.

Many of the methods are based on guidelines provided by the Intergovernmental Panel on Climate Change (IPCC), implemented by the European Union to enable their member countries to provide annual national greenhouse gas reports which covers the environmental impact of various sectors. Other materials used include maps and datasets that are publicly available from Swedish governmental organizations or the Swedish University of Agricultural Sciences.

To develop a framework which can be applied to sites across Sweden, the initial carbon stocks and sinks of the site area were determined (including living biomass, dead organic matter, and soil) based on available land use, forest and soil data. Additionally, the future development of C sinks during and after the building period were taken into account. The different uses of the harvested wood and the lifecycle of the harvested wood products was considered, as well as compensation measures that can be taken, like the introduction of urban trees and biochar. The included compensation measures were limited to architectural landscape measures, while emissions associated directly with the building process (e.g. fuel and used materials) were not included. By combining all of these factors, the annual CO_2 balance from the site and the products originating from it were calculated for a time period of 100 years after the initial building process was started.

1.5 Site description

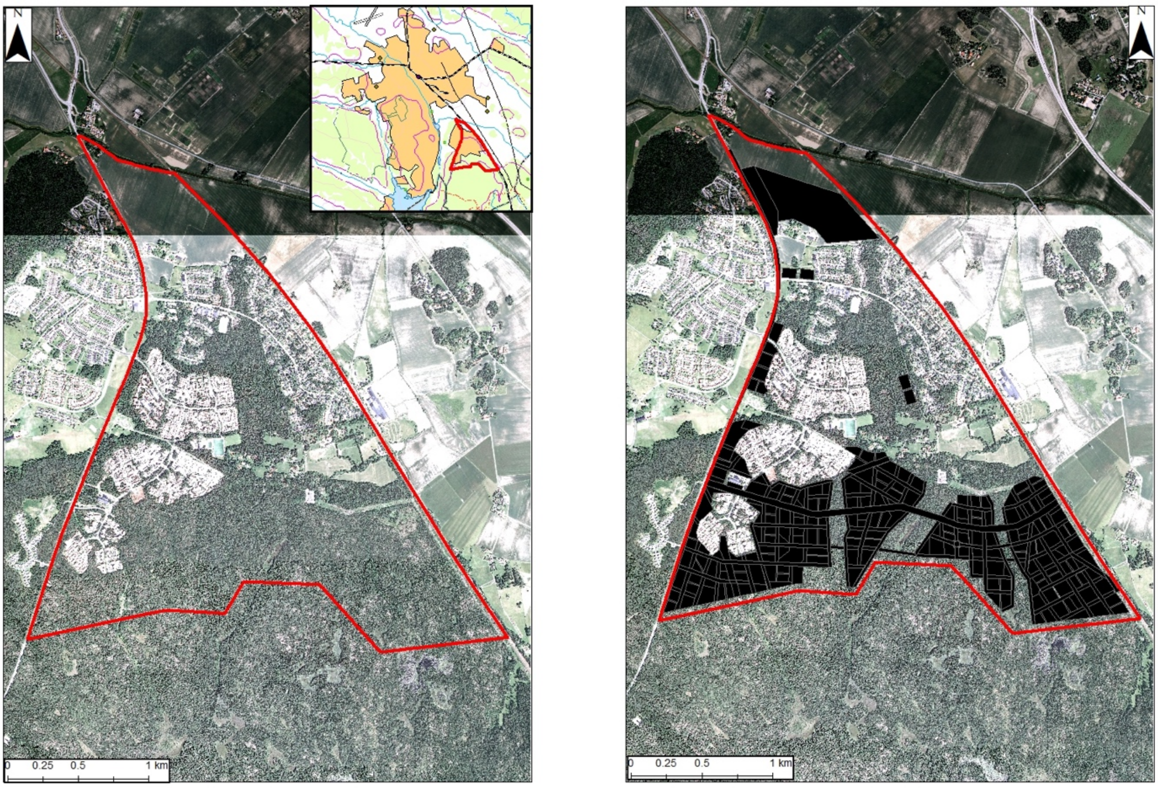

Figure 1: Left: Location of the case study area (surrounded by the red line) in Uppsala (top right) and aerial overview; Right: location of the area whose land use will be changed (marked black) (© Lantmäteriet)

The case study area is located near Uppsala’s south-eastern city parts of Bergsbrunna and Sävja (Figure 1). It is bordered by the Sävjaån stream in the north, the railway connecting Uppsala and Stockholm in the east, the Lunsen nature reserve in the south, and road 255 connecting Uppsala and Märsta in the west. The total area of the project site is 558 ha, of which around 40 % will be converted into settlement land according to the current plan published by Uppsala municipality. The height above sea level varies between 8 m close to the stream at the northern border to around 65 m close to the southern nature reserve border.

There are two main croplands in the area, the major one is located in the north and some smaller patches are located in the east. The current settlement area can be found mostly in the center of the area with grassland located close to the present infrastructure, mostly as lawns and parks. However, there are also grasslands that include meadows and grazing land used by livestock. The main forest land is located in the southern part and reaching into the central areas where it divides the urban parts of Sävja in the west from Bergsbrunna in the east. It consists mostly of coniferous forest, which continues into the Lunsen nature reserve that borders the area in the south. The trees grow on young and thin soils that are fragmented with smoothly shaped bedrock outcrops on the surface. The Stordammen, a small forest lake, is located in the central southern part of the area. Throughout the forest land, small forest mires of varying areas can be located that often are not bigger than a few hundred m^2 in size.

2. Materials and methodology

2.1 Materials

2.1.1 ArcGIS 10.7

ArcGIS 10.7, a general-purpose GIS software system (Maguire, 2008), was used for the GIS analysis, mainly to extract data from attribute tables contained in maps and to edit and transform between raster and vector formats of specific maps to be able to compare them. With the help of shape files provided by Uppsala municipality outlining the areas undergoing a land use change within the case study area, the steps to adapt to the case specific requirements were taken. In order to combine data and features from multiple maps, the map algebra features were used.

2.1.2 2006 IPCC Guidelines for National Greenhouse Gas Inventories (NGGI)

The Guidelines for National Greenhouse Gas Inventories (NGGI) were published by the Intergovernmental Panel on Climate Change (IPCC) in 2006. In order to gain a better understanding of the impact that humans have on the global climate change, the IPCC was founded in 1988 by the World Meteorological Organization and the United Nations Environment Programme. The goal of their National Greenhouse Gas Inventory Programme is to develop an internationally applicable methodology that enables national reporting of greenhouse gas emissions and removals (Eggleston et al., 2006). Volume 4 of the NGGI introduces guidelines on how emissions from agriculture, forestry and other land uses should be reported on a national level.

A structure with three different “Tiers” is used to provide multiple levels of precision to calculate carbon stocks depending on the nationally available data density and frequency. Tier 1 is the most basic one and requires only regional estimates based on climate zones that can be obtained from tables within the guidelines. Tiers 2 and 3 go more into detail and require national average values or models to account for national circumstances, respectively. The additional publications “2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands” (IPCC, 2014) and “Good Practice Guidance for Land Use, Land-Use Change and

Forestry" (IPCC, 2003) were used to gain further insight and information regarding the use of the NGGI.

2.1.3 National Land Cover Data (Nationella Marktäckedata)

The National Land Cover Data is a collection of data and maps which assigns different land use classes to all of Sweden's area published by the Swedish Environmental Protection Agency (Naturvårdsverket). It was developed within the CadasterENV Sweden project, which was conducted by the European Space Agency. It defines land cover mapping and land cover change monitoring as the two main objectives of the program in order to fulfill the national reporting standards set by the European Union. It is based on Earth observation data that has been cross-referenced and validated by other data sources like topographical maps, digital elevation models and light detection and ranging (LIDAR) data. A classification system with 24 different thematic classes is used to distinguish between the different land covers (Ahlkrona et al., 2019).

2.1.4 Swedish National Forest Inventory (NFI) and Swedish Forest Soil Inventory (SFSI)

The NFI and SFSI aim to evaluate the current state and changes within Swedish forest land. The inventory is based on sample plots that are able to estimate both areas and volumes of different forest components. Therefore, around 30,000 (20,000 in case of the SFSI) circular sample plots, grouped into clusters, are monitored. While one third of the sampling sites are used only once, two thirds are classified as "permanent" and are re-sampled every fifth year for the NFI (Fridman et al., 2014). For the annual greenhouse gas reporting of Sweden, only the permanent sites are used. As changes in soil are expected to be slower, the SFSI is re-inventoried every tenth year. Topsoil cores are only taken at every second sampling plot while deeper soil cores are analysed at every fourth sampling plot (Lundblad et al., 2019). The stock changes gained from these repeated measurements of the same permanent sites were interpolated in order to obtain the annual C stock changes in the sampled pools, which include above-ground biomass, litter and soil.

2.1.5 SLU Forest Map (Skogskarta)

The SLU Forest Map is based on SPOT satellite images from the Saccess program by the Swedish National Land Survey (Lantmäteriet) and data from the NFI, where tree diameters are measured and the biomass-expansion factors by Petersson & Ståhl (2006) are applied. During the map's creation, the kNN (k Nearest Neighbours) method was developed for Sweden, which combines the inventory data with satellite images and calibration data (Swedish University of Agricultural Sciences, n.d.). Among other things, data on age, height, species distribution, biomass and standing volume of forests can be obtained.

2.1.6 Parent Material Map (Jordartskarta)

The Parent Material Map is supplied by the Geological Survey of Sweden in a scale of 1:25,000 to 1:100,000. Its purpose is to provide a background for studies carried out in groundwater analysis, soil stability, erosion and other soil related questions. Most of the data used for the map are based on mapping that began in the 1960s and is continued until today, combined with an analysis of aerial photographs including field verifications. However, the soils that are determined in the map do not reflect the topsoil or a World Reference Base classified soil type but the parent material that is present at around 50 cm depth (Geological Survey of Sweden, n.d., a). They are subject to spatial errors of up to 50-70 m depending on the location in Sweden in the older datasets, as well as errors because it commonly combines few small patches of a soil type into a larger object on the map. In the present study this is especially relevant for wetland patches within the site, whose area may be subject to overestimation by combining a few smaller peatlands into larger ones (Geological Survey of Sweden, 2014).

2.1.7 Stadsträd (stadstrad.se)

Stadsträd is a project which was started in 2019. It uses laser scanning, tree databases and individual measurements to provide a web application showing urban trees and some of their properties. The project was developed by the Swedish consulting companies Calluna and GiB (Geografiska Informationsbyrån) and financed by the Swedish Environmental Agency (Naturvårdsverket) and a group of eleven municipalities, including Uppsala. It currently covers cities across Sweden including Uppsala, northern Stockholm, Östersund and Helsingborg with the aim to engage with the app users and allow them to add tree properties like species or height to the database (Stadsträd, 2020). In this study, the data was used to get an insight into the number of urban trees to estimate a potential amount of urban trees in the case study area.

2.2 Methodology

The methodology was designed to provide a framework for the estimation of different C stocks and fluxes to determine CO_2 emissions over a timescale of up to 100 years in an area in Sweden undergoing a land use change from a variety of current land uses into settlement land. The site in Uppsala serves as an example of the application of this framework.

In order to provide comparability between the results, two different calculation approaches were used, whenever possible. In the following, these will be referred to as "Level 1" and "Level 2". The Level 1 approach is based on data for the regional climate zone, similar to the Tier 1 approach in the NGGI, whereas the Level 2 approach utilizes data from at least a national scale with more detail that require more intensive work.

Nine main steps were taken in the process of determining a CO_2 balance:

1. establishing a site database, using and including maps and background data and material
2. estimation of the current C stocks in the different pools that are present before any kind of land use change takes place
3. using the calculated C stocks within the case study area to define spatial emission potentials
4. calculation of the C stocks that are developing during the building period on the land that is not converted yet but will be eventually
5. estimation of the C stocks that are not added as a C sink in the future due to the land use change and the removal of the sequestration potential

6. analysis of the emission potential of the C stocks that estimates the amounts of C that will remain or be removed from the site respectively during the process of the land use change
7. analysis of the influence of different wood uses on the time scale in which emissions take place
8. analysis of compensation measures through architectural landscape that function as a C sink during and/or after the land use change
9. calculation of an overall CO_2 balance that takes all the previous steps into account and assigns a point in time or time period to emissions in order to provide annual emissions over a time period of 100 years after the building was started.

In the following, the loss of a C sink is denoted as an “emission”, while C sequestration in a sink is considered as an “uptake”. In the context of land use changes, these C stock net-changes are assumed to also represent a net-change within the CO_2 balance, resulting in CO_2 uptakes or emissions.

2.2.1 Map analysis and site data collection

ArcGIS 10.7 was used to create maps containing relevant information and to extract data from the materials which were compiled into site databases for the climate impact analysis. Data sources include National Land Cover Data, SLU Forest Map and Parent Material Map.

2.2.2 Current C stocks

Firstly, the present carbon stocks were defined and calculated according to the NGGI, which categorizes the three main C sinks as living biomass, dead organic matter (DOM) and soil. A variety of land use types is introduced to classify surface areas into six land uses: forest land (FL), cropland (CL), grassland (GL), wetland (WL), settlement land (SL) and other land (OL). For the present case of land which is converted into settlement land, the C pools of each land use except for settlement land were determined. When taking into account that the three described C sinks are present in each land use, this resulted in a total of 15 pools. It was assumed that the pools for already declared settlement land will remain constant throughout the land use change. Additionally, the other land was treated similar to the settlement land and was considered to remain constant as well. Most of this land, which makes up roughly 0.1 % of the area that will be converted, is currently used for schoolyards, playgrounds or areas immediately surrounding sport facilities and there are no significant C stock changes to be expected.

The Level 1 approach was carried out following the Tier 1 approach of the NGGI. The IPCC provides tables (sheet 3B5b), that allow the user to calculate the present C stocks in an area. Although the NGGI and sheet 3B5b were mainly designed to support the reporting of annual stock changes, they can be used to calculate initial C stocks by excluding parts of equations that concern the annual changes.

First, the different areas which will undergo a conversion were determined in the Land Cover Map, compiled from the National Land Cover Data. The areas obtained were subsequently reclassified and adjusted to fit the six classes introduced by the NGGI.

2.2.2.1 Biomass stocks

To calculate the biomasses of the different land uses, equation 2.16 from the NGGI was used. For forest land, regional values for the above-ground biomass of the different land uses were added. In order to use tables given in the NGGI, the site area needed to be allocated to one of the generic climate zones provided in the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003). For Uppsala, the "Cold Temperate Wet" zone was applicable, whereas the "Polar/Boreal Wet" zone may be used preferably for regions further north in Sweden. The "Temperate continental forest" ecological zone for Asia/Europe with an average tree age of over 20 years was used. The ratio of below-ground and above-ground biomass was taken from the NGGI which resulted in a root-to-shoot ratio of 0.29. Additionally, the given C fractions for forests dominated by coniferous tree species were inserted into the equation.

To calculate the cropland sinks, the recommended value of 4.7 t C/ha for cropland containing annual crops was used.

For grassland sinks, the total above-ground and below-ground non-woody biomass was obtained from the NGGI and for the temperate climate zone, 13.6 t dry matter/ha was chosen. As the C fraction is not further specified for grasslands, the calculations were carried out using the recommended default value of 0.5.

For wetland sinks, no regional values are given in the NGGI which could be used to determine the current pools of the wetland areas. The calculation is split into on-site (equation 7.4) and off-site (equation 7.5) C emissions, which are added to gain the total C pool. While the on-site C emissions were derived from the provided values, the off-site emissions required more information than just the area of the wetlands. As there is no known data from on-site measurements, the Swedish national averages for peat depth (1.7 m), bulk density (0.094 g dry matter/cm^3) and C fraction (0.445) were used to calculate the peat stocks (Olsson, 2015).

The forest land areas gained from the Land Cover Map are classified as forest types “on wetland” or “not on wetland”. In order to ensure that these areas are considered appropriately, they were classified differently for the determination of the area of the biomass, DOM and soil pools. For biomass and DOM calculations, the areas of the forest types “on wetland” were added both to the forest land pool and the wetland pool, while for the soil calculations these areas were only added to the wetland pool. Areas that were classified as “temporary not forest”, which is forest land that has undergone a recent clear-cut, have been assumed to have no biomass stocks, while the DOM and soil stocks are continuously a part of the forest land use due to their unchanged properties.

For Level 2 calculations, the SLU Forest Map was used to gather data on forest above-ground biomass in the site area. The steps taken to extract data with the help of ArcGIS 10.7 were similar to the process that had been used to extract data from the Land Cover Map. The gained data was used to calculate the forested area, total biomass, average biomass density, total carbon stocks and distribution of tree species in the total site as well as the areas that will be undergoing a land use change.

To calculate the below-ground biomass from the extracted above-ground biomass, root-to-shoot ratios (R) were used. According to Petersson (1999), stump and roots make up 22 % of the present coniferous tree species on average in Sweden, resulting in a value of 0.28 for R. Additionally, Smith et al. (2012) estimated that for the present birch species 29.2 % of the total biomass is below-ground, resulting in an R-value of 0.41. The abundance of various tree species within the site was obtained by extracting the relevant information from the SLU Forest Map and a distribution of 90 % coniferous trees and 10 % deciduous trees was obtained. Due to the fact that birches constitute the largest portion of the present deciduous tree species, an R-value of 0.41 was used for all deciduous trees.

2.2.2.2 DOM stocks

The DOM pools, which consist of deadwood, litter and the humus layer of the soil, were calculated for Level 1 using the NGGI. According to the Tier 1 guidelines, the DOM pools for all non-forest land uses were assumed to be 0 consistently and not be affected by a land use change into settlement area. Therefore, the only calculation applied was the multiplication of the forest area (including forest land “on wetland”) with the dead wood/litter C stocks given in the NGGI. As there are mostly coniferous tree species present, the “Needleleaf evergreen” forest type was chosen. Due to a lack of available values for dead wood carbon stocks in the table, only the litter C stocks were taken into account.

The Level 2 method used to calculate the DOM pools was to utilize the national average values derived from the annual Swedish greenhouse gas reporting according to the NGGI standards (Lundblad et al., 2020). These values represent average dead wood and litter C stocks per hectare for every land use (Table 1).

Table 1: Average dead wood and litter C stocks in Swedish forest land for various land uses according to Lundblad et al. (2019)

Land use	Dead wood [ton C/ha]	Litter and humic layer [ton C/ha]
Forest land	0.35	24.63
Cropland	0.00134	-
Grassland	0.0516	1.019
Wetland	0.0082	-

2.2.2.3 Soils

The Level 1 approach to estimate the C stocks in soils was to follow the NGGI, which supplies reference soil organic C stocks for various climate zones up to a soil depth of 30 cm. However, there are various soil types present in the site area. Thus, assigning one soil type to one land use may work in some cases, while in other cases a land use area may consist of various soil types and assigning only a single soil type would simplify the reality too much. Therefore, site specific assumptions were made that simplify reality while being more accurate than assigning one soil type to the whole area:

- The forest land that will undergo a land use change is estimated to consist of roughly one half of soils based on glacial till (Podzol) and one half on bedrock (Leptosol) according to the Parent Material Map. However, this map does not reflect soil types but the parent material underlying the soil, which needs to be applied carefully for soil estimations (Geological Survey of Sweden, 2014). Therefore, the assumption was made that podzols cover 100 % of the area classified as glacial till, as well as 50 % of the area classified as bedrock to account for thin forest soils covering bedrocks. The other 50 % of bedrock are assumed to be rock outcrops on the surface that do not function as a C sink. The NGGI suggests a value of 115 t C/ha in the uppermost 30 cm of spodic soils, to which category podzols belong. This value was adjusted to 86.25 t C/ha considering the described bedrock outcrop assumptions.
- Most of the cropland within the site was present on soils with glacial or post-glacial clay as parent material. As these soils were formed in connection with the last ice age, they are relatively young and not strongly weathered yet. Thus, the value of 95 t C/ha for “high activity clay” soils in the present climate region was chosen.
- Many different types of grassland, mostly lawn, grazing land and meadows, make up this land use. As they are spread over many of the present soil parent materials within the case study area, the assumption was made that, in accordance with the Soil Map of Sweden (Troedsson & Wiberg, 1986), Cambisols are mostly present and the “high activity clay” soil category with a carbon content of 95 t C/ha is to be used.

- Wetlands were calculated with the value of 128 t C/ha given for cold temperate, moist wetland soils in the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC, 2014). The area of wetlands was assumed to include all the land uses of forest land classified as "on wetlands" for the purpose of calculating the soil C pools.

To calculate Level 2 estimates of the C stocks in soils, the national average values derived from the annual Swedish greenhouse gas reporting according to the NGGI standards were utilized (Table 2). The same approach was used earlier for the calculation of the DOM pools. As there were no values available for wetland soils, the value used in the Level 1 approach was also applied for Level 2.

Table 2: Average soil C stocks in Swedish forest land for various land uses according to Lundblad et al. (2019) and the NGGI (Wetland)

Land use	Mineral soil [ton C/ha]
Forest land	53.9
Cropland	80.6
Grassland	81.5
Wetland	128.0

2.2.3 Spatial CO_2 emission potential

In order to display the spatial distribution of potential CO_2 emissions within the case study area, these were calculated and depicted in a map. The present C stocks calculated with the Level 2 approach were converted into CO_2 stocks, and for each land use, an average t CO_2/ha value of the accumulated biomass, DOM and 20 % of the soil pool (the NGGI suggest potential emissions of 20 % of the soil C stocks in areas that are surface sealed during the land use change, the C stock removal scenarios are described more detailed in section 2.2.6) was calculated that describes the possible CO_2 emission potential in the case study area. These values were assigned to the different land uses in the Land Cover Map. An exception is forest land, to which only DOM and soil were assigned. Instead of using an average for the forest land biomass, the SLU Forest Map was utilized, in which the above-ground biomass t/ha value is provided for every pixel. For below-ground biomass, the assumptions described in section 2.2.2.1 were used. Areas that were classified as “Forest on wetland” by the Land Cover Map were assumed to feature both forest land and wetland biomasses, if there was biomass present according to the SLU Forest Map.

2.2.4 C stocks developing during the building period

Adding onto the amount of present C stocks within the case study area are C stocks developed during the building period of the project, as presumably not the whole area will undergo a land use change at the same time and there will be changes in the biomass, DOM and soil pools during this time. Instead it is more likely that each year or every few years a part of the study area will be converted.

In accordance with the overview plan published by Uppsala municipality, a building period of 30 years was assumed. Two different scenarios were used for the calculations, these are referred to as Scenario I and Scenario II in the following. Scenario I assumes that 1/30 of the area will be converted annually and after this conversion no further C is taken up. In Scenario II, 5/30 of the area is converted every five years. Both scenarios start with the first land use change at time point zero, hence after 29 and 25 years respectively, the land use change is completed.

The assumption was made that only the forest land pools and the biomass of wetlands are relevant C sinks during this building period, whereas the C stocks in the grassland and cropland pools are expected to remain steady at a comparably low level.

2.2.4.1 Forest land

The NGGI Tier 1 approach was used to calculate the forest land carbon pools for Level 1. The approach takes only the above- and below-ground biomasses into account, while a potential change of the DOM and soil pool C content is not assumed. The annual above-ground net biomass growth in natural forests is provided by the NGGI.

To calculate the below-ground biomass growth rate, the provided root-to-shoot ratios were used. Finally, after applying the given C fraction, the annual C stock changes within the building period were determined. To calculate the forest land pools of Level 2, the average annual CO_2 storage changes (Table 3) for all of Sweden from the National Forest Inventory were used.

Table 3: Average annual C stock changes in the forest land pools. A negative value represents an uptake of CO_2 or C, hence an annual increase of the sink, while a positive value represents an emission of CO_2 or C

C pool	C storage changes [t/ha/a]
Biomass	-0.37521
Litter	0.10637
Soil	-0.17544
Litter/soil combined	-0.06082

The C pools for litter and soil are strongly interrelated, as the humus layer of the soil can be difficult to designate to either the soil or the litter pool. Therefore, a weighted average of the two values was calculated (Table 3) and used for the calculations in order to get a value that includes both pools and represents the interchangeability between them.

The gained annual uptakes or emissions during the building period were accumulated over time to obtain a total amount of C that is stored during the building period in the different pools.

2.2.4.2 Wetlands

The second C sink expected to grow during the building period is the biomass of wetlands. In order to define the C stock increase during the building period, various studies were analysed and the resulting annual growth rates used for calculations. As the present site is located in the temperate wet climate zone with close proximity to the boreal zone, studies from both of these climate zones were taken into account. If required, the DOM stocks were converted to annual C stocks changes by applying a C fraction value of 0.445 (Olsson, 2015).

Table 4: Annual wetland accumulations according to various studies across Sweden and Finland

	Annual dry matter accumulation [g/m^2/a]	Annual C stock change [t C/ha/a]
Wallen et al. (1988)	55 (25-75)	0.245
Franzen (2006)	39.8	0.177
Tolonen & Turunen (1996)	-	0.261
Nilsson et al. (2008)	-	0.235

The studies by Wallén et al. (1988) and Franzén (2006) were carried out in wetlands across southern Sweden, which is part of the temperate climate zone, whereas Tolonen & Turunen (1996) and Nilsson et al. (2008) conducted their research in a boreal climate setting, across Finland and in a wetland in northern Sweden respectively. As each of these studies uses a different methodology to gather the values in Table 4, it is important to distinguish between them. Wallén et al. looked at the accumulation of *Sphagnum spp.*, a moss genus typically present on rainfed and low-nutrient wetlands and regularly making up a big part of them, on peat and determined their dry matter. Franzén and Tolonen & Turunen considered the long-term accumulation of organic matter and C respectively to determine stock changes over time. Nilsson et al. determined the accumulation of C in a peatland over a range of two years.

In order to choose a value that is used to determine the annually stored C in the wetland areas of the site, an average of the values obtained from Wallén et al., Tolonen & Turunen and Nilsson et al. was assumed to be the best fit for this case. The value gained from Franzén's study was disregarded, as it reflects a time scale of more than 6000 years. If an average of only the last 500 years was to be considered, its value would be in the range of 55 to 60 g dry matter/m^2/a, indicating a similar growth rate as the other three studies. Calculating the average growth rate of the three evaluated studies led to an annual C stock growth of 0.247 t C/ha/a. In order to estimate the amount of C that will accumulate in the wetlands of the site area during the building period of 30 years, the described two removal scenarios were applied.

2.2.5 Lost C sequestration potential

To be able to consider the environmental impact of a large-scale land use change, not only the near future but also the long-term effects should be considered. Due to the removal of the potential C sinks, a large quantity of C cannot be sequestrated that would be taken up by the current land uses, mainly forest land, otherwise. However, these C losses do not reflect actual C emissions that end up in the atmosphere, they provide an overview of potential C sequestration that is not happening due to the changed land use.

To calculate these stocks, the same approach as in section 2.2.3 was chosen and the annual growth rates from Table 3 and 4 were used. Using this method, the two different scenarios were applied over time periods of up to 100 years to determine the C sequestration potential.

2.2.6 Removal of C stocks

An estimation was made of how much carbon from each of the calculated pools remains on-site after the land use change is completed.

The Level 1 approach chosen to determine the amount of C remaining on site, was the Tier 1 approach on land that is converted to settlements in section 8.3 of the NGGI. According to the guidelines, the complete amount of the present biomass (including below-ground) and DOM pools will be extracted, and their C pools will be considered to be depleted completely. For C stored in soils, the following assumptions were made in order to simplify the calculations:

- A weighted average value for soil carbon content of the whole converted area was calculated using the areas and soil carbon contents per land use type used in section 3.2.2.3. For the purpose of the case study area, an average value of 77.53 t C/ha was gained.

- The area converted into settlement land was divided into parts that will be either paved over or converted into turfgrass and lawn spaces between houses and in parks. The area was divided into three parts according to the planned architectural landscape design in the overview plan published by Uppsala municipality, where a total of 95 % of the site area will be paved over and 5 % will function as grassland areas. The paved over area was further divided into buildings and various surface sealed areas (85 %) and roads of various sizes including pavement (10 %).
- According to the NGGI Tier 1 assumptions, there will be an adaption of the C soil content within 20 years after the land use change has been completed. Furthermore, it was expected that 80 % of the soil C stocks will remain in the areas that are paved over or build on, whereas the areas that will be converted into grassland will go on to level off at a soil C content of 95 t C/ha, the same average value used for the land use type before the conversion.

Additionally, the C pools that will grow during the building period that were determined in section 2.2.3 were added to the current C pools and taken into consideration.

The Level 2 calculations follow the same approach as Level 1 with a complete removal of the biomass and DOM pools and the assumptions described above for the soil pools.

2.2.7 Above-ground biomass utilization

The removed C pools were analysed to get a better understanding of how and over which time period the carbon will be released to the atmosphere or how long it will be stored in harvested wood products (HWP). While most of the C pools that are extracted are estimated to release their C as CO_2 within the year of the removal, the above-ground biomass of forest land is an exception. Due to the longevity of some wooden products, it is important to take into account the pace, in which the extracted C will decay. Firstly, the different C sinks within the HWP were defined and estimated. This was carried out by using the gross felling statistics of the year 2017 according to the Swedish Forest Agency (2019) and converting the absolute numbers into relative percentages (Figure 2) which could then be applied to the much smaller scale site.

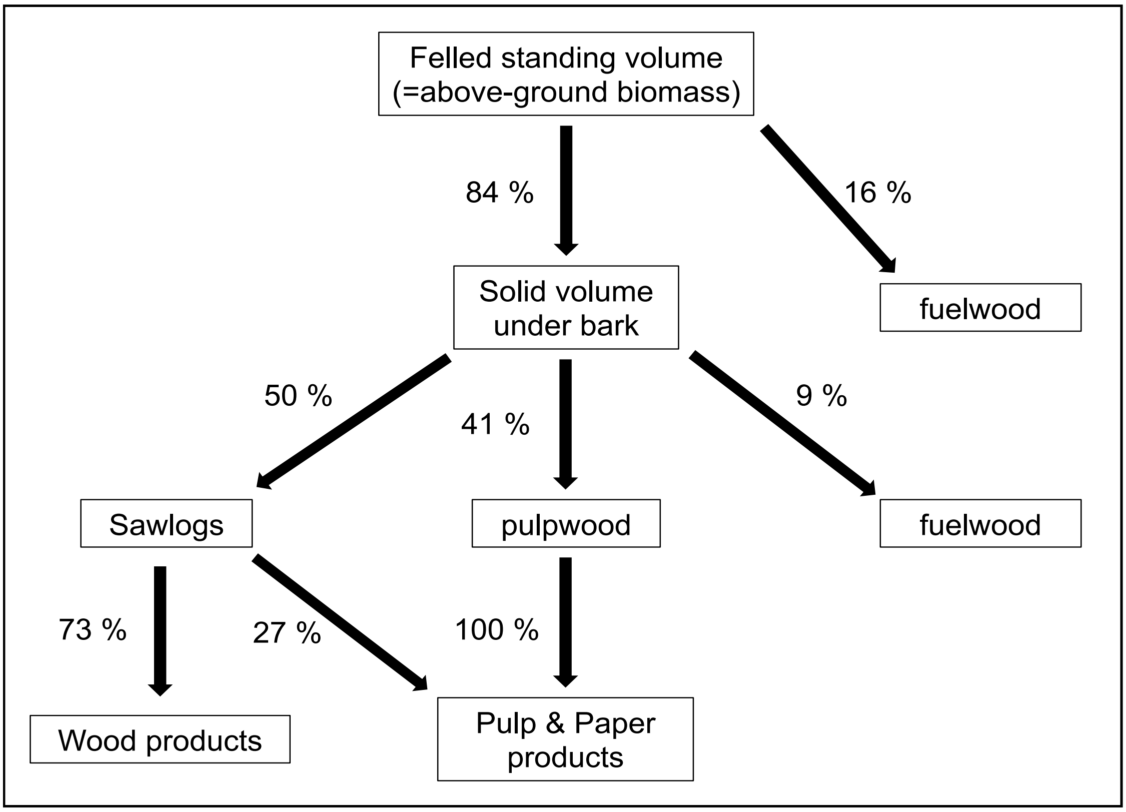

Figure 2: Use of felled tree biomass for HWP in Sweden according to the Swedish Forest Agency (2019) for the year 2017. The percentages of the continued use of sawlogs as wood products and via wood chips as Pulp & Paper products were gained from the Swedish Forest Industries Federation (n.d.)

The information about the utilization of the extracted wood was used to estimate the rate of depletion of the C from these newly shaped HWP pools. By defining a half-life of each of the HWP, a decay rate is defined. The half-life represents a number of years until half of the initial amount has reached an end of life and thus not functions as a C sink any longer. Values for the half-lives of Pulp & Paper and solidwood products (2 and 30 years respectively) were gained from the NGGI. The equation used to calculate the decay rates was:

$$A = A_0 \cdot e^{-\lambda \cdot t}$$

where: λ = decay rate; A_0 = initial amount of the respective HWP

Additionally, it was expected that all the fuelwood will be used for the purpose of energy and heat generation within the year of its felling, hence no half-life was applied and the C stocks were added as CO_2 emissions in the year of their production.

During the inclusion of the values and timescales gained from this section into the overall C balance, the two scenarios with annual removal or removal every fifth year were applied. Therefore, the beginning of the half-life time of different HWP was adjusted to the time it was extracted from the site.

2.2.8 Compensation measures through landscape architecture

A way to compensate for the C emissions is to create new C sinks within the new settlement land. There is a variety of different methods and possibilities available and in the following, two different ones (urban trees and biochar in pavement construction) were used to gain an understanding of how effective these C sequestration strategies can mitigate the C emissions. These strategies were applied in a similar way on both Level 1 and Level 2.

The first method was the introduction of urban trees. To assess the quantity of how much C will be stored in these trees, the approximate number of trees that will be planted within the site area was estimated with the help of the web application stadsträd.se. It allows the user to see how many trees are currently present in urban areas. Uppsala's southern city part Sunnersta was used as a reference area to gather information on tree stocks, because it is a rather green part of the city and more similar to what the case study area is projected to look like after the land use change compared to the strongly urbanized city core. A selected, representative area without any forest patches and a size of seven hectares in Sunnersta resulted in an average of 22.6 trees/ ha. This value was scaled up to the total area that will be converted to get an estimation of how many trees could be planted.

The total number of trees was combined with the average annual C accumulation per tree ratios, given in the NGGI. As most urban trees in Uppsala currently are deciduous species, the "mixed hardwood" tree species was chosen. Consequently, the annual C storage capacity of urban trees was determined and the two scenarios during the building period were applied.

The second applied method was the use of biochar underneath pavements, a method to create a C storage in the soils that were partly paved over. According to Gaunt and Cowie (2009), biochar created during the process of pyrolysis can have a significant impact on mitigating C emissions. Pyrolysis is a burning process that uses biomass and releases a part of the C contained in it immediately for the production of bioenergy and the resulting product of this process is biochar, whose remaining C content is stable for hundreds of years (Lehmann et al., 2009).

According to the Swedish landscape architectural consulting agency edges (n.d.), between 200 and 300 tons of CO_2 can be applied and sequestrated per hectare of street. The average value of 250 t CO_2 was scaled up to the area converted into roads and pavements, which was 10 % of the converted site area, as assumed in section 2.2.5. Due to the long stability of biochar, it was assumed that there will be no half-life or decay impacting the time scale that is used in this case study. The two scenarios during the building period were applied to assign a time to the C sequestration.

2.2.9 Annual and total CO_2 balance

In order to gain an overall CO_2 balance, the previously determined C stocks and processes were combined, converted into CO_2 and a time period was assigned to them. Thus, a balance could be created that displays annual emissions and uptakes for up to 100 years, as well as adding up the annual values to gain insight on the total CO_2 balance after certain time periods. This was done for Level 1 and Level 2 with Scenario I and II applied to each of the levels, hence four different balances were obtained in total. The process described below was used for both Level 1 and 2.

First, all biomass and DOM pools, except for the forest land above-ground biomass, were assumed to be emitted within the year of the removal according to the scenarios. The same goes for the C pools that will grow during the building period. However, for these pools it was assumed that the emitted CO_2 will rise linearly throughout the building period, because on the areas that are converted later, more time has passed which equals more carbon that has been stored in these pools over time.

For the soil carbon pools, various assumptions were made in section 2.2.5 that lead to a decrease in soil carbon due to the land use change. One of the assumptions states that it takes the soil 20 years to adapt and reach the new carbon content before a new constant state is reached. Therefore, CO_2 will be emitted until 20 years after the final part of the area has been converted.

The next step taken was the determination of the time periods over which the above-ground biomass, both initially existing and developing during the building period, is emitted. Therefore, the different HWP's and their decay rates described in section 2.2.6 were taken into account to get information of how much CO_2 is emitted annually while considering the constant new input of material according to the two scenarios for the building period.

The compensation measures described in section 2.2.7 were deducted to outline the CO_2 uptake which takes place by their introduction. While biochar creates a sink during the building period by its inclusion in the pavement structures, urban trees provide a sink that lasts for as long as the trees are present. Their annual uptake is expected to rise according to the two scenarios during the building phase. With an increased converted area, more and more urban trees are introduced, until the CO_2 sequestration comes to a constant rate after the land use change is completed.

In addition to the net CO_2 fluxes, the lost sequestration potential was added as a CO_2 source. Since these emissions are not physically taking place, they were not included as a net flux within the CO_2 balances but added as an external source.

3. Results

3.1 Map analysis

According to the Land Cover Map, the total case study area has a size of 558 ha. Out of the total size, 223.7 ha will undergo a land use change to settlement land. Figure 3 shows that around 80 % of the area that will be converted is forest land, 10 % cropland and 10% a combination of grassland, wetland and settlement land. Appendix Figure 1 provides an overview of the spatial distribution of the different land uses.

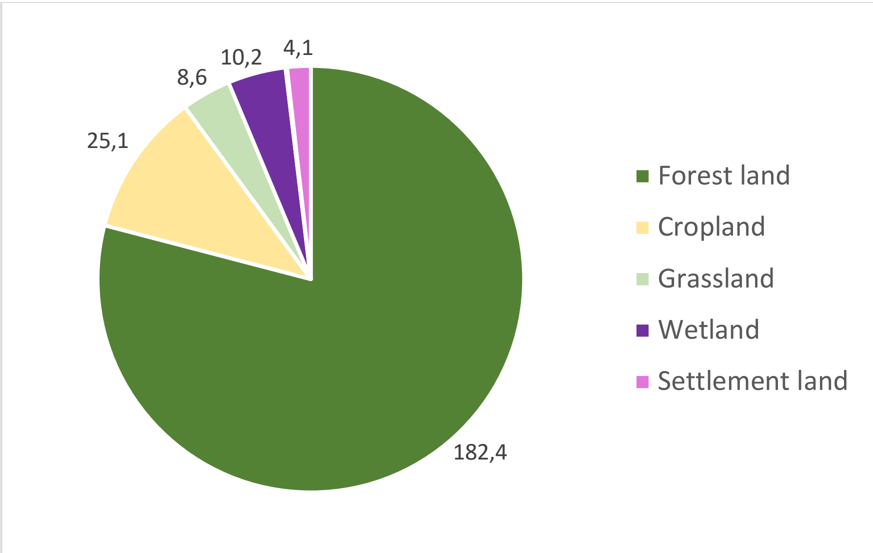

Figure 3: Distribution of land use sizes [ha] currently present within the area that will undergo a land use change; the areas of forest land "on wetland" have been added to both forest land and wetland, the sum of the areas thus resulting in a slightly larger number than 223.7 ha; other land has been excluded due to its small size of less than 0.3 ha

3.1.1 Vegetation

The vegetation in the forest land is strongly dominated by coniferous tree species. The dominant species is the Scots Pine (*Pinus sylvestris*). However, there are smaller forest parts that are predominated by other species like Norway spruce (*Picea abies*), Birch (*Betula pubescens* and *Betula pendula*), Oak (*Quercus robur*) or a mix of deciduous trees.

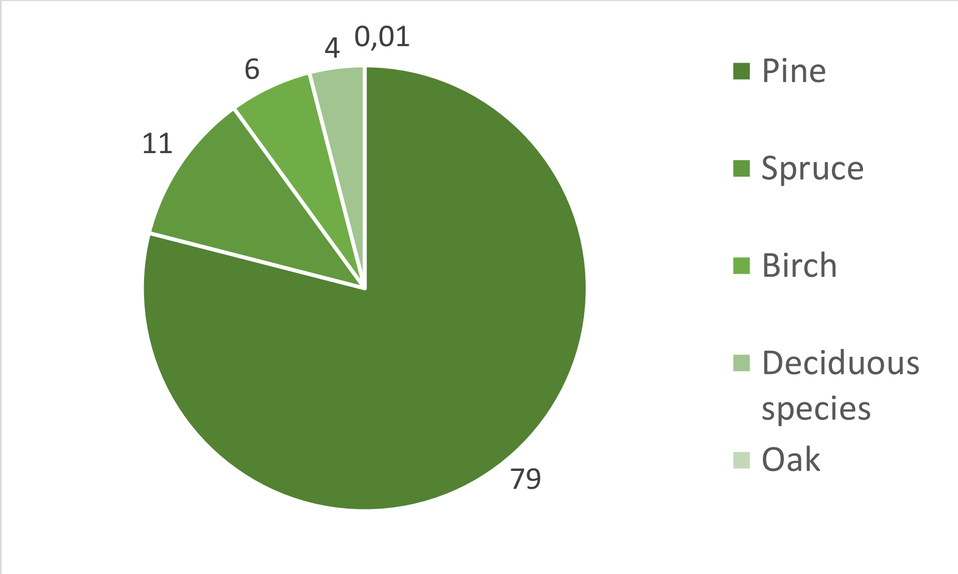

Figure 4: Tree species distribution [%] in forest land according to the SLU Forest Map

The total standing tree volume in the forest area was 55,512 m^3 with an average of 181 m^3/ha. The average tree age across species is 91.9 years. The total biomass adds up to 34,656 t, which leaves an average biomass density of 113 t/ha. The highest biomass density in the subject area can be observed in the central parts between the already developed settlement areas and in the south around the Stordammen lake (Appendix Figure 2). The biomass density decreases with distance from the lake and proximity to the infrastructural borders (railway in the east, road 255 in the west).

3.1.2 Soils and geology

Uppland and the Uppsala area are one of the regions in Sweden that were, and still are, affected the most by land rising due to the glacial rebound after the disappearance of the ice sheets from the underlying landmass during the deglaciation process of the inland ice sheet which began in Sweden around 11,500 years ago (Ekman, 2007).

In the largest part of the area, a high percentage of glacial till as parent material (Table 5) but also smoothly shaped bedrock outcrops (mostly granitoids) are present with coniferous forest growing on top (Appendix Figure 3). It has been influenced not only by deglaciation and the linked processes but also wave-washing of the shores during an age of regionally receding sea levels and land masses rising above the water level (Geological Survey of Sweden, n.d., b). Therefore, most soils are very young and have only had a short time period to develop, resulting in a high acidity. Materials finer than sand have been washed out in high quantities with the regression of the shoreline, leading the till to consist mainly of rather coarse-grained deposits (Bergström, 2001). These finer materials may have been moved along the slope within the site to the northern parts close to the Sävjaån, where postglacial and glacial clay soil parent material dominates the area. The soils on top of these deposits may therefore be higher in clay content than the forest soils, a reason why they are more productive and used for agriculture.

Additionally, a small percentage of the area is covered by wetlands. Their formation benefits strongly from the concavity and shallowness between the smoothly shaped rock outcrops, as relief is one of the key factors influencing the formation of peatlands (Jeglum et al., 2011).

Table 5: Soil parent material distribution within the case study area

Soil parent material	Area [ha]	%
Sandy till	271	49
Crystalline rock	122	22
Glacial clay	97	17
Postglacial clay	34	6
Fen peat	21	4
Artificial fill	7	1
Bog peat	6	1
Postglacial sand	1	0.2

3.2 Current C stocks

The current C stocks in the different land use types before the land use change are shown in Table 6 for Level 1 and in Table 7 for Level 2.

Table 6: C stock [t] per land use according to the Level 1 methodology; the forest land biomass pool was divided into above-ground biomass (AGB) and below-ground biomass (BGB)

	Biomass	DOM	Soil
FL AGB	11,161	4,807	15,123
FL BGB	3,237	-	-
CL	118	-	2,385
GL	59	-	821
WL	7,228	-	1,300
Sum	21,803	4,807	19,629

The total sum of present C stocks is 46,239 t for Level 1. The largest amount, 74.2 %, is present in forest land pools. Another 18.4 % are stored in wetland pools which are mostly forest mires located within the forested area, equaling a total of 92.6 % of C present in pools connected to forests. When taking only the biomass and DOM pools into account, the importance of forests as a C sink is even higher with percentages of 99.2 % and 100 % respectively.

Table 7: C stock [t] per land use according to the Level 2 methodology

	Biomass	DOM	Soil
FL AGB	10,737	4,619	9,456
FL BGB	3,168	-	-
CL	118	0.03	2,022
GL	59	9.3	705
WL	7,228	0.005	1,300
Sum	21,310	4,628	13,483

According to the Level 2 calculations, the sum of all C stocks is 39,424 t, meaning that there is 9.5 % less C than in Level 1. Mainly responsible for the majority of this difference is a smaller forest land soil C pool in Level 2, thus further increasing the importance of the biomass and DOM pools.

3.3 Spatial CO_2 emission potential

Figure 5 shows the CO_2 emission potential in each pixel within the case study area. While areas covered with cropland, grassland or settlement land have very low emission potential, the forest land areas vary depending on the present biomass. Areas that are covered with wetland have an emission potential that is more than three times higher than the forest land with the most biomass.

This map can be used to support decision-making as it provides an indication to where some of the CO_2 emission hotspots area located within the case study area and which areas should be avoided from a climate aspect in urban planning.

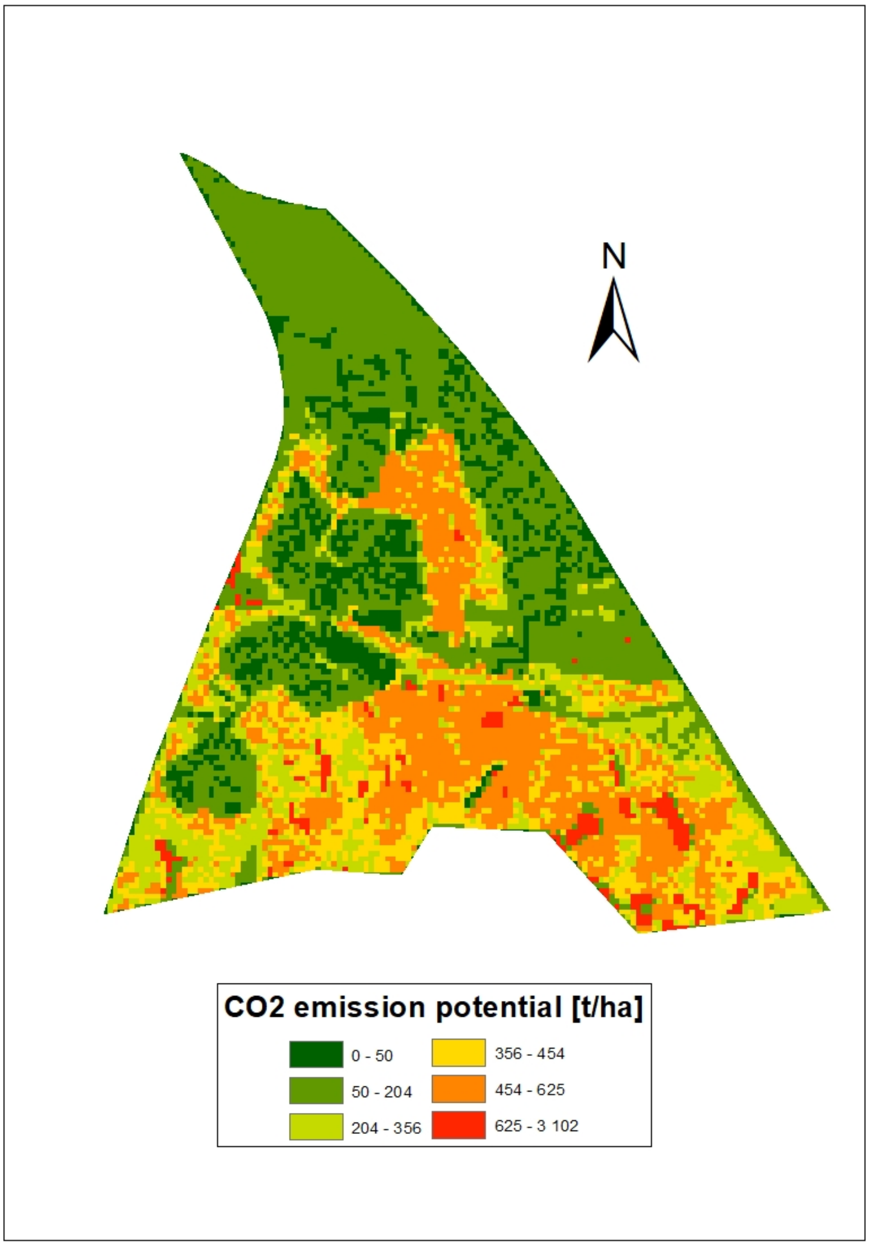

Figure 5: CO_2 emission potential map of the case study area (© Lantmäteriet/SLU)

3.4 C stocks developing during the building period

Table 8 shows that the C pool stored in Scenario I with its longer building period is larger than in Scenario II for both levels. The C stored according to the Level 1 methodology exceeds the Level 2 results by almost six times for each scenario. Generally, the impact of the forest land is much larger compared to the wetland additions during the building period, especially in Level 1. The contribution of wetland biomass to the total additions is around 0.5 % (compared to 3 % for Level 2).

Table 8: C stock additions [t] during the building period for Level 1 and 2 with Scenario I and II applied each

	Level 1		Level 2	
	Scenario I	Scenario II	Scenario I	Scenario II
FL AGB	5,395	4,651	766	660
FL BGB	1,564	1,349	226	195
FL DOM/Soil	-	-	159	137
WL Biomass	36	31	36	31
Sum	6,995	6,031	1,187	1,023

3.5 Lost C sequestration potential

The amount of annual C stocks which are not developed due to the land use change increases with the duration of the building period according to the applied scenario. Once all the land has been converted, the annual C growth rates in Table 9 are reached and continue to have an impact for as long as time is considered.

Table 9: Annual C stocks [t] not saved due to loss of the C sequestration potential of the original land uses

	Level 1	Level 2
FL AGB	372	53
FL BGB	108	16
FL DOM/Soil	-	11
WL Biomass	2.5	2.5
Sum	482.5	82.5

The same data was utilized to gain these values as in section 3.3. Therefore, the observations used to describe Table 8 are applicable here as well. However, an exception are the two applied scenarios. While more C is developed during the building period for Scenario I than Scenario II, this is reversed for C stocks that are not developed, resulting in higher values for Scenario II than I in Table 10.

Table 10: Total C stocks [t] not saved due to loss of the C sequestration potential of the original land uses during the 30 (50, 100) years after the building was initially started

	Level 1		Level 2	
	Scenario I	Scenario II	Scenario I	Scenario II
Year 30	7,479	8,444	1,279	1,444
Year 50	17,129	18,094	2,929	3,094
Year 100	41,254	42,219	7,054	7,219

3.6 Removal of C stocks

All of the current and during the building period developed C stocks from the biomass and DOM pools are removed. Additionally, the assumptions that were made in section 2.2.5 concerning the removal of C stocks from the soil were considered. Therefore, the only remaining C pools in both scenarios are located within the soil and are shown in Table 11.

Table 11: Removed and remaining C stocks [t] in the study area that is converted

	Level 1		Level 2	
	Scenario I	Scenario II	Scenario I	Scenario II
Removed C stocks	37,239	36,279	29,483	29,319
Remaining C stocks	15,960	15,960	10,949	10,949

3.7 Above-ground biomass utilization

The current above-ground biomass C stocks and the ones developed during the building period are used for a variety of purposes after their removal from the case study area. These are wood products (30.7 %), pulp & paper (45.8 %) and fuelwood (23.5 %).

Table 12: C stocks [t] used as different HWP after their removal

	Level 1		Level 2	
	Scenario I	Scenario II	Scenario I	Scenario II
Wood products	5,076	4,848	3,527	3,494
Pulp & Paper	7,579	7,239	5,266	5,218
Fuelwood	3,901	3,725	2,710	2,685

3.8 Compensation measures through landscape architecture

The total C stocks which are stored by the use of biochar are 1,495 t C. This pool is created during the building period and does not have an effect on the carbon balance after the land use change is completed.

Contrary to this, the second used compensation measure, the introduction of urban trees, creates a lasting C sink. Its annual C sequestration rate is 50.5 t, once the land use change is completed.

Table 13: C stocks [t] sequestrated by urban trees after different time periods

	Scenario I	Scenario II
Year 30	783	883
Year 50	1,792	1,893
Year 100	4,317	4,418

3.9 Annual and total CO_2 balance

The previous results were compiled and the C stocks converted into CO_2 stocks. By assigning a time scale, these CO_2 stocks were considered as annual fluxes, which provide either an annual net uptake (negative values) or net emission (positive values) that is reflected in the CO_2 balances below (Figure 5 to 8).

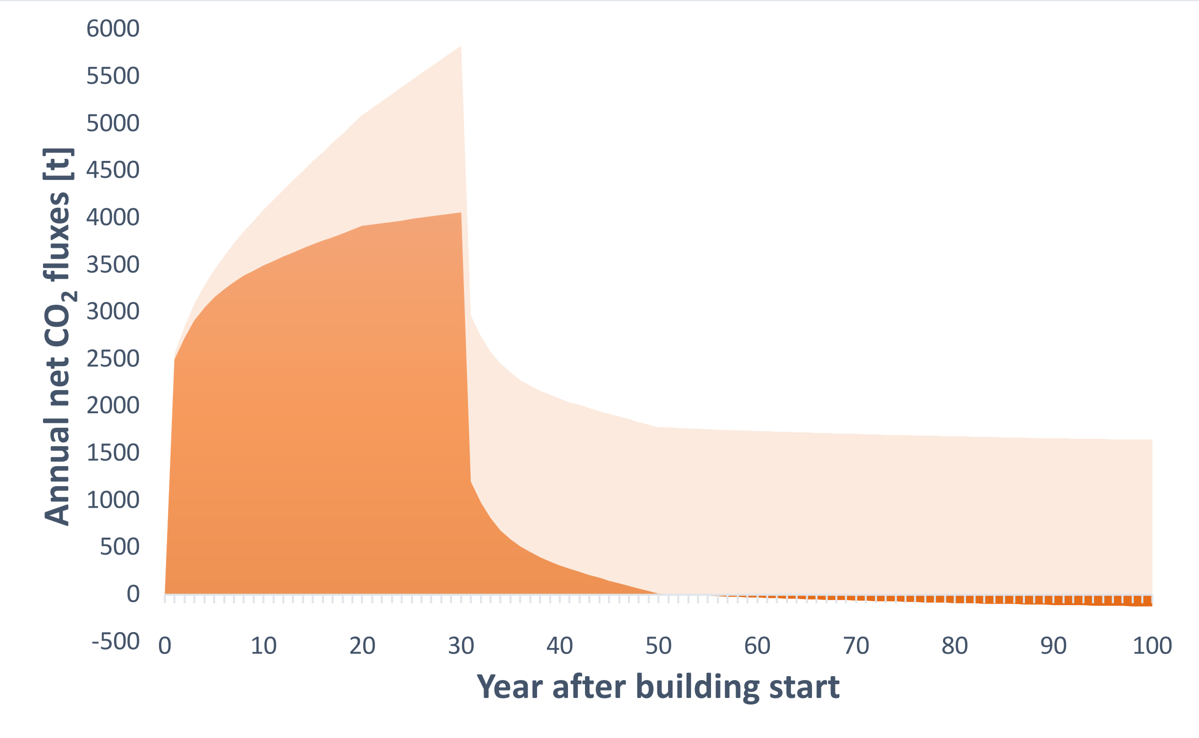

Figure 6: Annual net CO_2 fluxes during the first 100 years after the building start of the case study area according to the Level 1, Scenario I assumptions; the lighter color includes the lost C sequestration potential due to the land use change

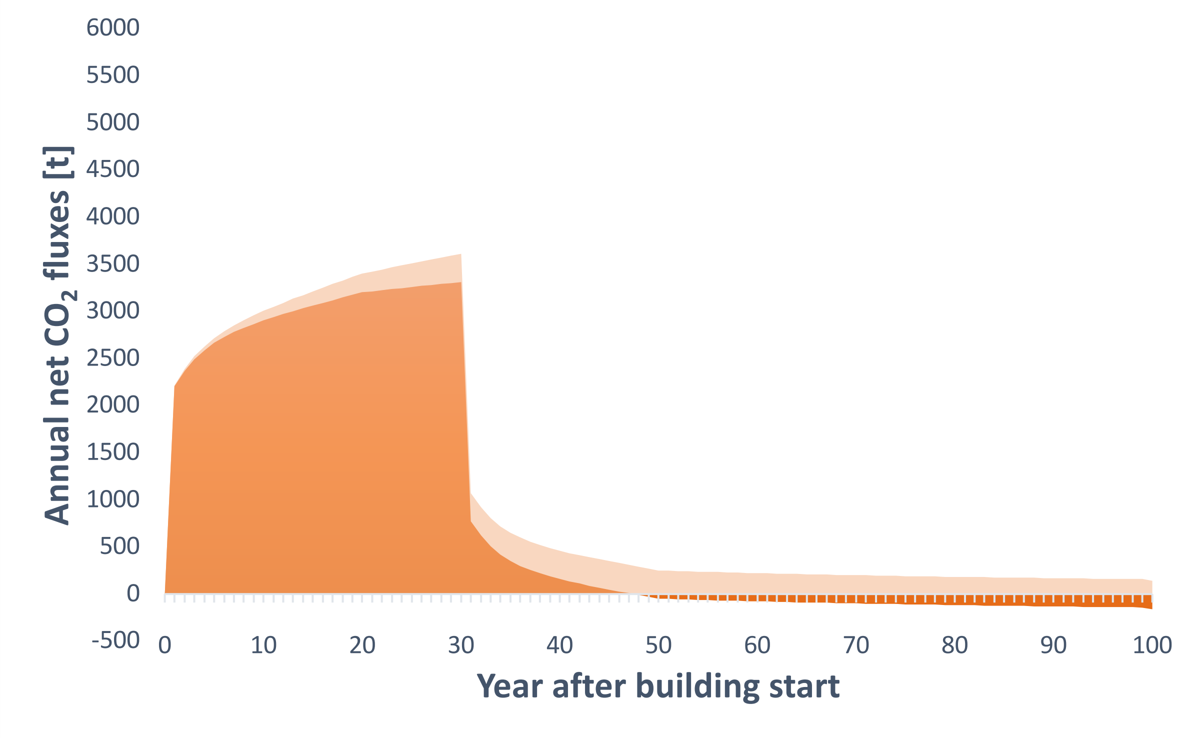

Figure 7: Annual net CO_2 fluxes during the first 100 years after the building start of the case study area according to the Level 2, Scenario I assumptions; the lighter color includes the lost C sequestration potential due to the land use change

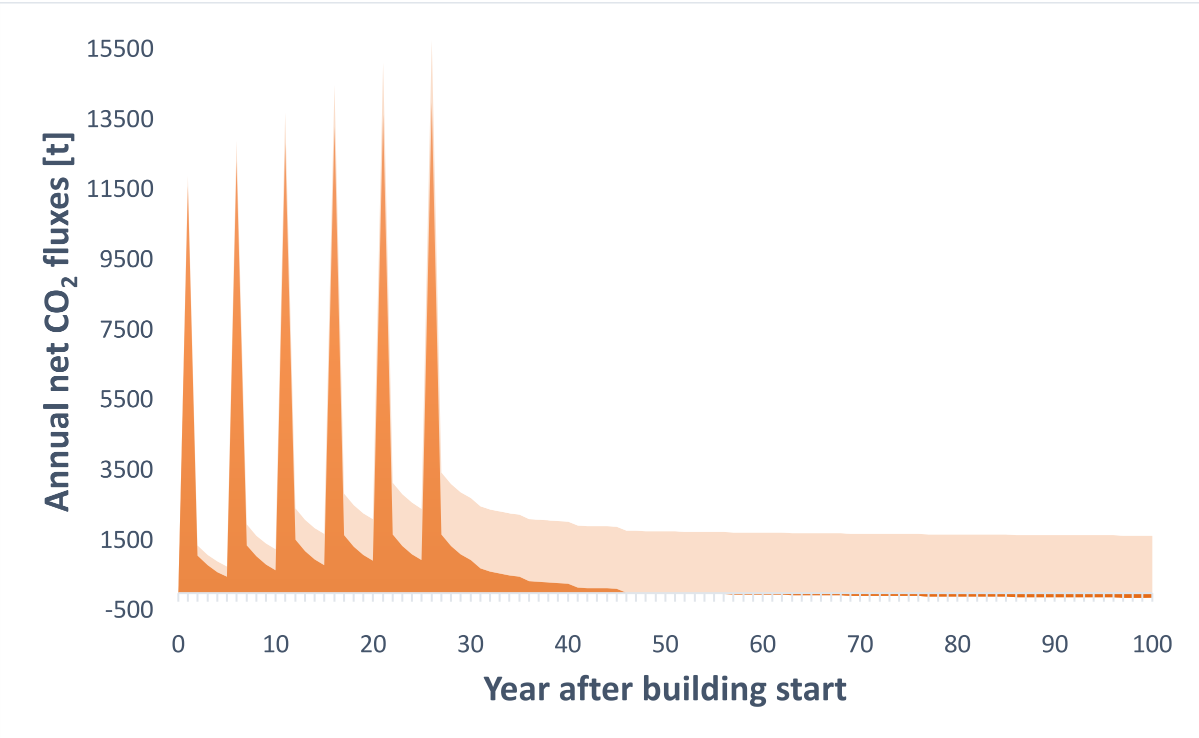

Figure 8: Annual net CO_2 fluxes during the first 100 years after the building start of the case study area according to the Level 1, Scenario II assumptions; the lighter color includes the lost C sequestration potential due to the land use change

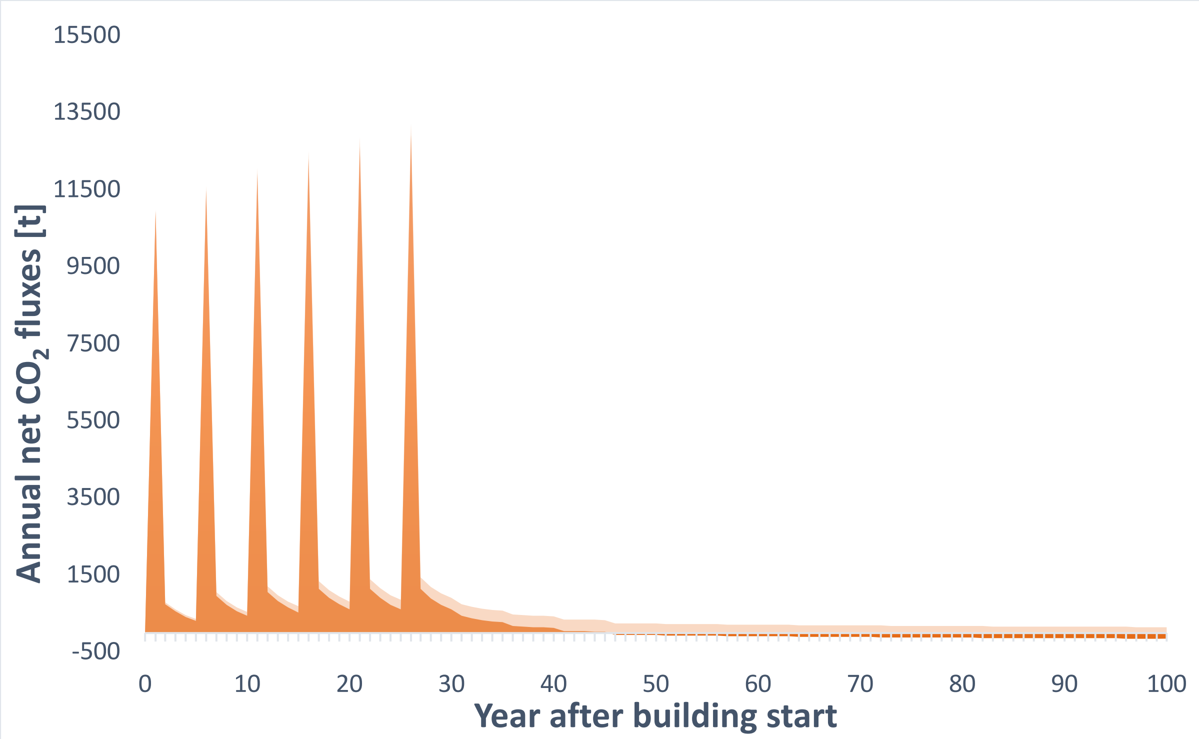

Figure 9: Annual net CO_2 fluxes during the first 100 years after the building start of the case study area according to the Level 2, Scenario II assumptions; the lighter color includes the lost C sequestration potential due to the land use change

Figures 6 to 9, as well as Table 14, allow a comparison within the two applied levels and scenarios. The Level 1 approach displays generally higher emissions than Level 2, roughly 25 % for Scenario I and 18 % for Scenario II. Both Levels emit the largest part during the land conversion and building period. After around 50 years, slightly earlier for Level 2, there are no further net emissions and the balances shift towards CO_2 sequestration (negative values). Table 14 confirms this by showing a lower CO_2 emission value after 100 years compared to 50 years in all four scenarios.

When comparing the two scenarios, Scenario I generally emits more CO_2 than Scenario II, with an exception in the first 30 years of Level 2 (Table 14).

With the inclusion of the lost sequestration potential in the balances, the emissions rise significantly. There is no more net CO_2 uptake at any time in Figures 6 to 9. The difference between the Level 1 and Level 2 methodology is very large. While an additional 25,673 t CO_2 are added after 100 years for Scenario I of Level 2, there are an additional 151,249 t CO_2 impacting Level 1.

Table 14: Total CO_2 emissions [t] after various time periods for the applied Levels and Scenarios; the values in brackets include the lost C sequestration potential due to the removal

Emission time period	Level 1		Level 2	
	Scenario I	Scenario II	Scenario I	Scenario II
30 years (incl. not seq.)	108,541 (135,960)	104,176 (135,133)	89,788 (94,442)	90,287 (95,542)
50 years (incl. not seq.)	116,231 (179,030)	109,251 (175,589)	93,982 (104,642)	92,810 (104,070)
100 years (incl. not seq.)	112,711 (263,960)	105,223 (260,010)	88,693 (114,366)	87,322 (113,596)

4. Discussion

4.1 Evaluation of the chosen methodology

The Level approach was chosen to provide different ways to calculate C stocks in a case study area based on the availability and quality of data sources. It is inspired by the "Tier" approach used in the NGGI, where three different Tiers are used. According to Houghton et al. (2012), three approaches are commonly used for the estimation of C density and their changes as a result of a land use change: inventory-based estimates, satellite-based estimates and process-based vegetation models. While the NGGI follows this structure with their three Tiers, only the first two were used in the methodology chosen for this thesis. The first Level is based on inventory-based estimates corresponding to the NGGI. However, the second level is not purely based on satellite-based estimates but rather a combination that also includes inventory-based estimates, for example from the NFI and SFSI.

The levels chosen for this project can also be looked at from a spatial perspective. While Level 1 uses climate zones as references, Level 2 is set on a national scale. Due to time and budget restrictions, only two levels were chosen for the purpose of this thesis. A further refinement, the introduction of a possible third level, could take place from two different angles in the future: the use of a process-based vegetation model following the methodology suggested by Houghton et al. (2012) or narrowing down the spatial scale to values from the site itself or at least similar conditions as present within the study area.

The two chosen scenarios reflect two different ways of how the C stocks are removed from the case study area. While Scenario I assumes annual removals, Scenario II is supposedly closer to reality with a larger area whose land use is changed every few years. However, the main concern about this methodology is that an equal removal from each land use takes place annually (every five years respectively). It is rather unlikely that the land use change takes place in such a linear way and more likely that a spatial approach will be chosen, for example the area will be converted from north to south regardless of which land uses are present and in which quantity. By directing the exploitation towards areas with the least climate impact, short-term climate benefits could be gained. However, due to the early stage of the planning by the municipality, no time or spatial schedule for the potential land use change has been released yet. Therefore, the methodology based on equal removal of the different land uses was applied as a baseline.

One major challenge was the determination of the present wetland biomass. The NGGI does not recommend any reference values to calculate the C stocks per area. Therefore, average Swedish national values were used for both levels. The accuracy of these values, especially the average depth of 1.7 m, is uncertain. Presumably, the small forest mires present within the case study area between the many bedrock outcrops are not as deep as this average suggests, as it includes the large boreal wetlands in northern Sweden. It would have been possible to use average values for C stocks of northern peatlands on an international level for the Level 1 calculations, for example as suggested by Loisel et al. (2017) or Yu (2012). However, these values tended to be even larger as they included Russian or North American peatlands. For a potential third level refinement that utilizes site-specific data, one approach could be to carry out basic peat depth measurements that would improve the assumptions significantly.

The biomass of the grassland and cropland pools was estimated according to the NGGI and used for both levels, due to their small impact on the overall balance and comparably small areas that are affected.

The determination of the soil pools of Level 1 also posed challenges. Due to the variety of present parent materials, the assumption that only one soil type covers the complete case study area, including all of its bedrock outcrops, would have been too much of a simplification. Instead, the assumption was made that Swedish forest soils located in the present latitude are typically podzols. Now, the values given in the NGGI still vary greatly from the values obtained from the NFI used for the Level 2 calculations. One possible explanation may be the large stone and boulder content in Swedish forests (Stendahl et al., 2009) due to their young age and glacial origin which could potentially lead to much less C stocks compared to other regions within the temperate climate zone used in the NGGI approach. The chosen methodology which uses the podzol C stocks given in the NGGI while assuming that a certain part of the area is covered with bedrock outcrops and does not contain any C stocks, is a compromise that aims to keep the method as simple as possible for Level 1.

For wetland soils, it was assumed that the forest mires within the case study area are mostly present on mineral soils instead of organic soils (according to the

NGGI descriptions). According to the Parent Material Map (Table 5), around 75 % of the present mires are fen peats and thus influenced by water from soils, which originate mostly from bedrock and glacial till in this area.

The C stock growth rates for the stocks which are both created and not sequestrated during the building period are assumed to remain constant throughout the applied time periods and for the whole case study area. This is unlikely for two reasons: firstly, some of the trees, especially in the central parts of the area, are already quite old and will grow significantly slower than other parts; secondly, the rate will slow down after a while if no clear cuts or other forest management practices (e.g. thinning of older trees) are applied. Irregular environmental events (e.g. storms) could pose an additional reason for variance within the linear growth rates.

The main assumption used for the removal of biomass and DOM was that no C stocks from these pools will remain in the soil after the land use change. There are few studies available concerning this topic, but it seems unlikely that the full amount of the below-ground biomass and DOM pools will be removed. Especially during the building process, some of the C containing materials may be mixed into the soil where they are slowly decomposed, potentially leading to C emissions that are happening over time after the land use change. This concerns especially the wetland pools. A complete removal of its biomass, which requires a prior draining, is highly unlikely and a different scenario with assumptions which are more practically applicable should be potentially used.

The applied compensation measures are only examples of strategies which can be used to reduce the climatic impact of the land use change. While urban trees are commonly used across the world not only for environmental, but also aesthetic reasons, the application of biochar is a comparably new practice with much less studies yet completed. However, most of the research so far is leaning towards a potentially suppressing effect which biochar may have on long-term greenhouse gas emissions (for example Mukherjee & Lal (2013)), additionally to the C sequestrating effect of the biochar itself. It was chosen as one of the two compensation measures, because it has already been applied successfully in another recent building project in Uppsala.

Finally, it should be stated that most of the used values from maps and guidelines, as well as assumptions within the calculations are prone to a certain degree of inaccuracy. While the NGGI provides ranges for some of the used values, the map data processing and the information used from field inventories are all subject to certain imprecisions. It is important to keep in mind that the values are an indication of the reality but should be considered as more of an indication of the dimension that emissions will take place.

4.2 Evaluation of the results and level approach

The major conclusion drawn from the gained results is the difference between the Level 1 and Level 2 total CO_2 emissions, which indicate that the regional NGGI approach used for Level 1 results in considerably larger values than the Level 2 approach with national values. The two main components creating this difference between the two levels are higher values for forest land soils and the assumed C growth rates of the future C sinks. The assumptions for forest soils in Level 1 were challenging to come up with due to the amount of bedrock outcrops which are present in the area, making it more likely that the Swedish national averages used in Level 2 are a better representation of the reality than the climate zone approach from the NGGI. The big difference between the C growth rates of the two methods can potentially be explained by the location of the case study area in the northernmost part of the temperate continental forest climate zone assigned by the NGGI, in close proximity to the boreal coniferous forest climate zone which makes up the largest part of northern Sweden. The NGGI suggests a value of 4.0 (t dry matter/ha/a) with a range of 0.5 to 8.0 in their guidelines for the temperate continental climate zone, which covers large parts of eastern Europe to the Black Sea and big parts of western and central Russia. Uppsala is located in the far north of the climate zone, making it reasonable to assume that it would be on the lower side of the provided range. For the boreal zone, whose southernmost town in Sweden is located around Gävle (Appendix Figure 4), a range between 0.1 and 2.1 is provided. The national average used for Level 2 provides a value of roughly 0.6, which may be strongly influenced by the northern, boreal part of Sweden that makes up the larger part of Sweden's area compared to the southern, temperate part. Considering all of these factors, the conclusion can be drawn that the value of 4.0 used in for Level 1 is likely a strong overestimation that does not reflect the situation of the case study area very well. On the other hand, Level 2 may be influenced heavily by the boreal part of Sweden.

Generally, the size of the climate zones shows that the Tier 1 data is hard to apply for such a small area as the case study area and is meant for countries as a whole.

Contrary to this observation, the biomass and DOM C stocks in the two levels are relatively similar, with Level 2 having slightly smaller values. However, this suggests, that the case study area does have properties of the temperate continental forest climate zone concerning the current C stocks, but it takes longer to build them up compared to other, more southern areas within the climate zone.

Following a similar reasoning, the biomass produced by the urban trees as a compensation measure is very high compared to the current C stocks using the annual C accumulation values provided by the NGGI. As the provided values are not climate zone but tree species specific, the conclusion can be drawn that the calculated values are overestimating the reality and growth rates are not as high as suggested by the NGGI, due to the northern location of the case study area.

When it comes to the two used scenarios, the overall CO_2 balances suggested that Scenario I, which used an annual removal, generates slightly higher emissions than Scenario II, which assumed a removal every fifth year. An early removal scenario may therefore have a positive impact on the CO_2 balance. However, less C is sequestrated during the building period that can be used for HWP's while the loss of the C sequestration potential is higher. To conclude, Scenario II was beneficial for the CO_2 emissions over time, but to a very small degree, especially in Level 2.

A comparison of the importance of the emissions and their timing shows significant differences between the two levels. When looking at the values in table 14 from a 100-year perspective, the lost CO_2 sequestration potentials exceed the actual CO_2 emissions in both scenarios. Thus, the conclusion could be drawn that the older areas of the forest with higher biomass should be used for the land use change instead of the younger parts with less present biomass, because their C sequestration potential is much larger and could compensate for the removal in the long run. However, when looking at the values from Level 2, the current C stocks are much larger than the potential C sink of the growing forest in a time period of 100 years. This indicates that the importance of the standing tree biomass and their potential emissions exceeds the sequestration potential, meaning that the current C stocks are a much larger emission source which should be preserved where possible from a climate perspective.

To be able to predict the potential C sink in the future even better, the age of the forest and its relation to productivity or growth rate is important to consider. Older forests with an average age of over 100 years tend to be in equilibrium and are not considered to function as a significant C sink (Jarvis, 1989), thus having very low growth rates that are similar to the tree mortality. On the other hand, younger forests are able to accumulate biomass much faster with higher growth rates. Using a function which provides a relationship between forest age and growth rate could support the argument that in the present case with slower growth rates in a northern climate, the standing biomass of the older forest is more valuable from a climate point of view compared to the removal of the C sequestration potential from the younger forest over the applied time period.

4.3 Summary of the results for the case study area

The vast majority of the present C stocks are located in the forest land and wetland pools. The CO_2 emission potential map provides an overview of potential hotspots that are higher concentrated in potential emission. Information about these hotspots can be used to support decision-making and avoid high C stock areas. One possibility to adjust the current plan could be the adjustment of the natural strips, which are planned in between housing areas within the southern case study area, to exclude wetlands and some of the biomass-rich forests parts surrounding them.

Decision-making should not only be based upon an NGGI approach like in Level 1, as some flaws concerning its application in Sweden, especially the central region, have become apparent. The validation of some of the values by using a second Level and evaluating the obtained results carefully provides a much better basis to decide, which areas should be considered for a building project of this size.

For the consideration of a complete greenhouse gas emission balance, the CH_4 and N_2O pools of the wetlands may have to be taken into account additionally to the calculated CO_2 pools. Due to the limitation of this thesis to CO_2, additional greenhouse gases were not considered but they might still have an influence on the balancing done within the municipality, especially in areas with organic soils which emit mostly N_2O. At these locations, a land use change may even reduce long-term greenhouse gas emissions largely.

4.4 Additional carbon mitigation strategies

Biochar and urban trees were the two measures for carbon mitigation which were used in this thesis. However, also other strategies can be used to further create C sinks which have a positive impact during or after the land use change is completed which may be relevant for Uppsala municipality and their ambitious climate goals. By using only the current two measures, the difference between net CO_2 sequestration and emission is tremendous (Appendix Figure 5). Adding supplementary C sinks could be a strategy to account for the emissions. The potential of some additional measures will be discussed below.

The design of "urban courtyards" as C sinks could have a positive impact on climate balances (edges, n.d.). These courtyards consist of added biochar, plants and green roofs among other things. Their total sequestration potential is between 30 and 46 kg CO_2/m^2, while the introduction of green roofs on property area by itself can result in a total of 13 to 20 kg CO_2/m^2 reduced emissions. This strategy can help to create C sinks on sealed areas that cannot benefit from soil or biomass strategies.

One major factor that determines the climate impact of a land use change to settlement land are the housing materials used within a building project. Using wooden frames instead of concrete can have a large impact on the total CO_2 emissions. According to Sathre & O'Connor (2010), for each ton of wood products which is used instead of non-wood products, a greenhouse gas emission reduction of roughly 3.9 t CO_2 was observed. This "substitution" effect can also be specified for certain materials. Petersen & Solberg (2005) claim that per m^3 input of wood instead of steel, between 36 and 530 kg CO_2 emissions can be avoided, depending on factors like discount rate and waste management. For the replacement of concrete by timber, the avoided emissions are potentially even higher, ranging between 93 and 1062 kg CO_2 per m^3.

The concrete industry is one of the worldwide largest contributors to CO_2 emissions, accounting for approximately five percent of all anthropogenic sources (Hasanbiegi et al., 2012). Therefore, various efforts are taken to develop concrete products that produce fewer emissions during their production, thus reducing their carbon footprint. According to Calkins (2017), various methods that include sequestering carbon in concrete or the production of energetically modified cement instead of traditional commercial concrete can have a positive impact. Although numbers for potential savings vary, companies claim a reduction of the carbon footprint of up to 80 % from portland cement, the most frequently used market leader.

4.5 Further research questions

This thesis introduces different methods and evaluates them to develop a CO_2 balance, while considering temporal and spatial features. However, the subject is much larger than the presented features and there are many possibilities to widen the scale of this project.

By introducing a third, local or even site-specific level of precision, an evaluation of not only the site, but the accuracy and usability of the other two levels on a multitude of projects could be improved substantially. Using local data like a forest management plan and detailed remote sensing data, could provide valuable information about the productivity and growth rate of C stocks or by adding field measurements for the biomass of wetlands could provide much more precise assumptions.

While the used scenarios are useful to get an initial understanding of the removal of C stocks which goes hand in hand with the land use change, they are not very applicable in reality. Designing new scenarios, which are based not only on temporal, but also spatial approaches, could create far more realistic scenarios which improve the CO_2 balances significantly. Additionally, a different approach or scenario for the C stocks that remain after the land use change on the site could be developed. There seems to be little information available of how many C stocks remain after a land use change and how they behave over time, especially below a surface that has been sealed.

Adding the elements of substitution and life-cycle analysis of the used wood products to the CO_2 balances could substantially improve the temporal aspect of when emissions take place and how large these are. Generally, the introduction of further remediation measures into the balances as C sequesters and the evaluation of their effect on the carbon footprint, as well as their financial feasibility, can be interesting additions to the developed framework.

5. Conclusions

When comparing the two chosen levels, Level 1 based on regional climate zone data resulted in much higher CO_2 emissions than Level 2 based on the national data. This may be due to the impact of the size of the climate zone and the location of the case study area close to the border between the temperate and boreal zone. Therefore, the outcome of Level 1 is likely an overestimation of the present pools and efforts to improve the methodology should not be based on an improvement of Level 1 but rather to go more into a local level to use the national data and potentially developing regions within Sweden with similar properties which can be used as references. This could be achieved by adding a third, site-specific level to the structure of the methodology.

According to Level 2 calculations, the standing tree biomass and its CO_2 emission potential of the older forest exceeds the sequestration potential of the younger forest in the analysed time period. Therefore, the younger forest parts with less accumulated biomass should be converted preferably.

The biomass of wetlands is the largest unknown in the methodology and local measurements or data from previous building projects or local forest authorities could be provide much-needed additional information to assess this pool better. In addition to the calculated results, creating a CO_2 emission potential map can be an important tool to support decision-making and to review which areas are most suitable for building projects from a climatic point of view.

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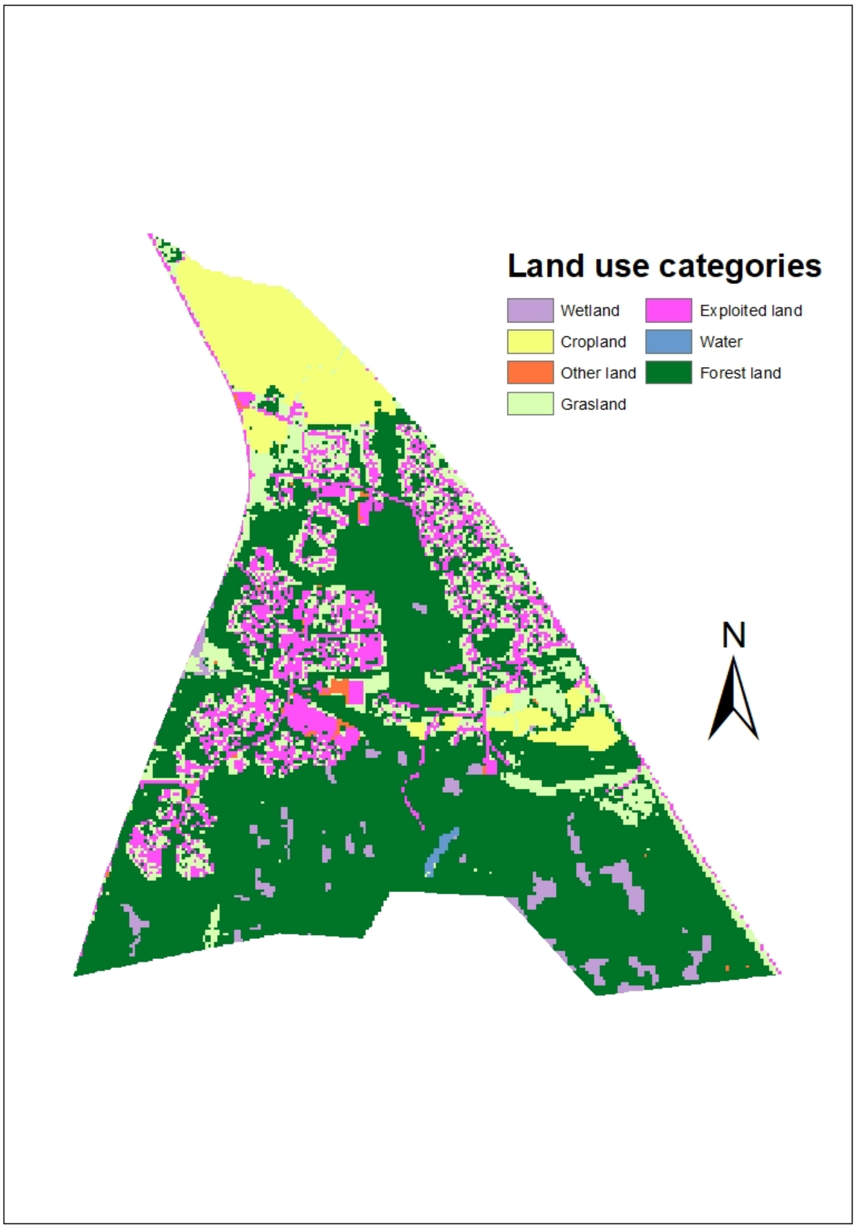
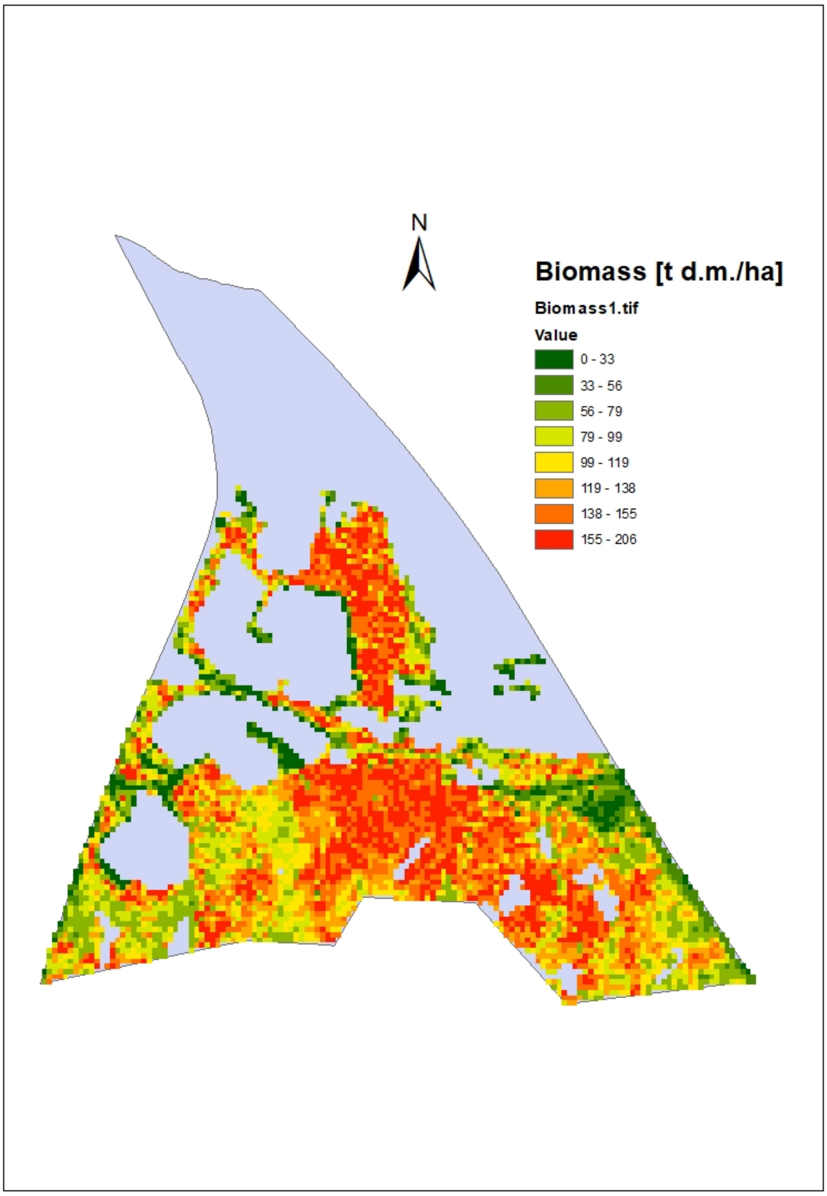
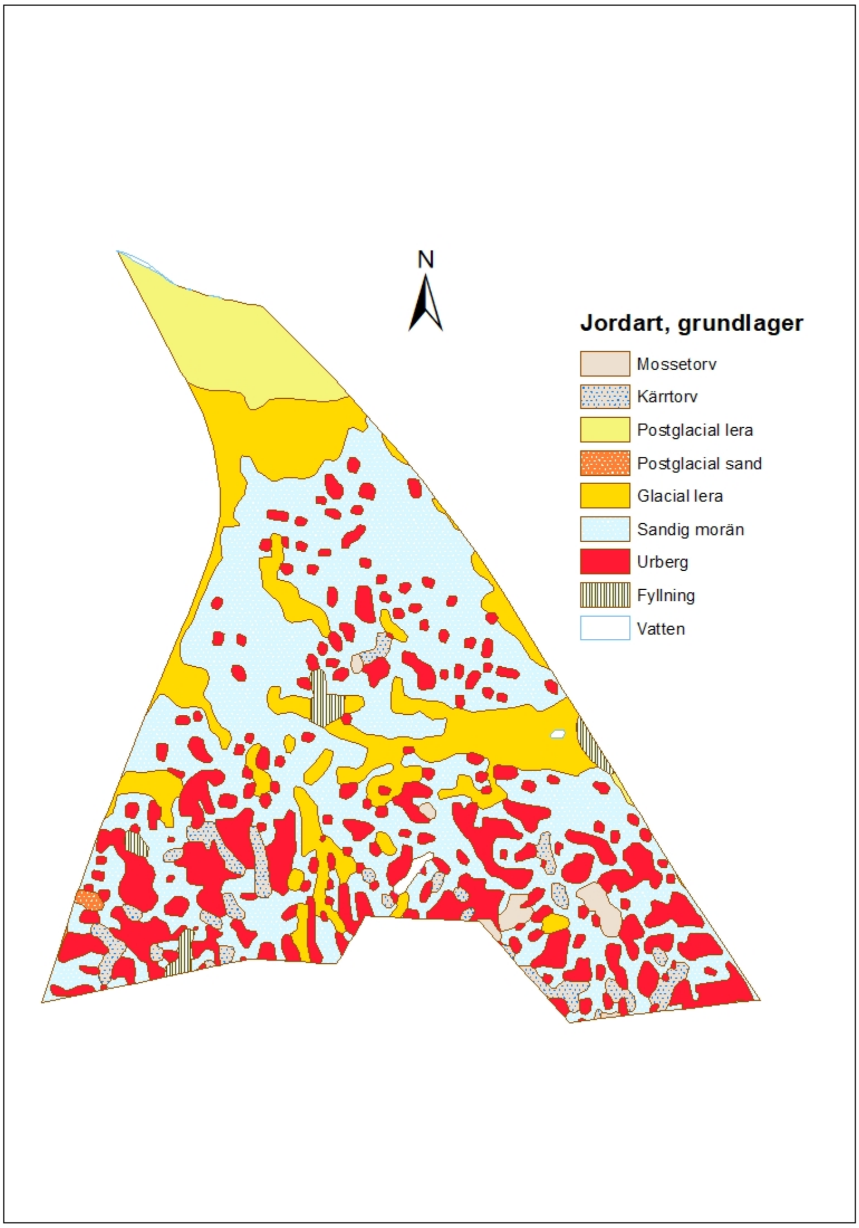
8. Appendix



Appendix Figure 1: Land Cover Map showing the different land uses within the case study area; forest land areas described as “on wetland” were added to the purple wetland category (© Lantmäteriet)

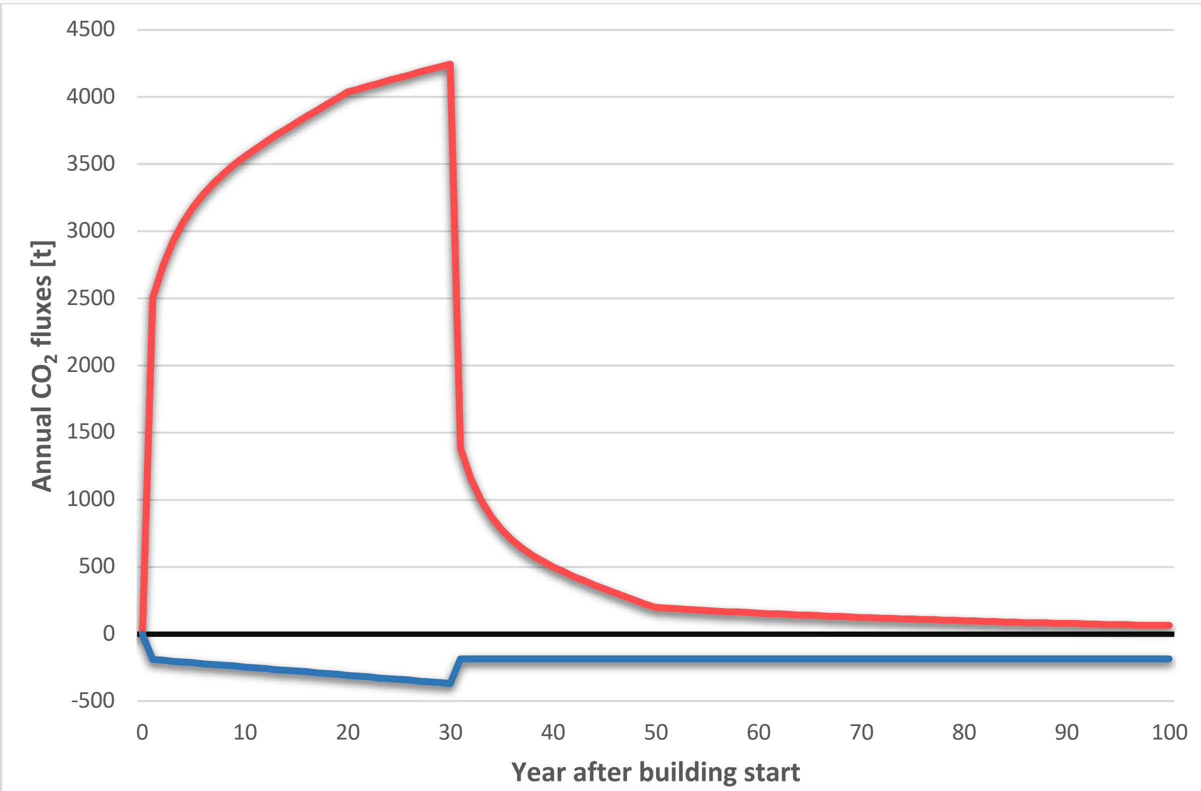


Appendix Figure 2: SLU Forest Map showing the spatial distribution of biomass within the case study area (© SLU)



Appendix Figure 3: Parent Material Map showing the different parent materials within the case study area (© Lantmäteriet/SGU)

Appendix Figure 4: Location of the case study area (red cross) in the light green "Temperate continental forest" climate zone (TeDc); the "Boreal coniferous forest" climate zone (Ba) is dark green (IPCC, 2003)



Appendix Figure 5: Annual CO_2 fluxes during the first 100 years after the building start of the case study area according to the Level 1, Scenario I assumptions; the red line indicates CO_2 emissions, the blue line indicates CO_2 sequestration