UPPSALA UNIVERSITET

Master thesis in Sustainable Development 2021/18

Examensarbete i Hållbar utveckling

Climate mitigation potential of the Swedish forest under different forest management regimes and levels of substitution effect

Kristian Tufvesson

DEPARTMENT OF
EARTH SCIENCES

INSTITUTIONEN FÖR
GEOVETENSKAPER

Master thesis in Sustainable Development 2021/18

Examensarbete i Hållbar utveckling

Climate mitigation potential of the Swedish forest under different forest management regimes and levels of substitution effect

Kristian Tufvesson

Supervisor: Camilla Widmark

Subject Reviewer: Eva-Maria Nordström

Contents

Climate mitigation potential of the Swedish forest under different forest management regimes and levels of substitution effect

Kristian Tufvesson

Tufvesson, K., 2021: Climate mitigation potential of the Swedish forest under different forest management regimes and levels of substitution effect. *Master thesis in Sustainable Development at Uppsala University,* No. 2021/18, 54 pp, 30 ECTS/hp

Abstract:

The Swedish forest is currently being debated as to how it should be managed to provide climate mitigation. Forest management can contribute to climate mitigation in mainly two ways. Either through increased sequestration and storage of carbon in the forest or as a consequence of the substitution effect, through which emissions can be avoided by utilizing harvested wood products to replace other emission-intensive products. However, these two climate benefits are at odds with each other, as efforts to increase the sequestration of carbon in the forest by increased conservation will decrease the amount of harvested biomass available for substitution. This fact has led to a disagreement between scholars regarding the climate benefits of increased forest conservation versus the climate benefits of maintaining a high harvest level. The climate benefit of increased forest conservation is influenced by how much additional carbon the growing forest can sequester over time. The climate benefit of forest harvest is instead directly related to the level of achieved substitution effect. As the substitution level is dynamic, it may change in the future due to various technological, economic, and societal developments, which would influence the potential climate benefit of forest harvest. In addition, intensifying forest management as a means to increase forest growth is also commonly suggested as a possible measure for enhancing the climate mitigation potential of the Swedish forest.

This study aimed to investigate how the climate mitigation potential of different forest management regimes develops over time based on different potential levels of achieved substitution effect. Based on input data from the National Forest Inventory, the Heureka RegWise system was used to simulate the impact on sequestration of carbon dioxide and the available harvested biomass to be used for substitution for the different forest management regimes over a 150-year period. The results indicate that increased forest conservation provides a higher climate mitigation potential throughout a majority of the 150-year period. However, the climate benefit of increased conservation does diminish over time due to the set-aside forests' declining ability to sequester additional carbon. The rate at which the forest management regimes without increased conservation can catch up is influenced on which level of substitution that is applied. The results also indicate that increased utilization of growth-enhancing practices increases the climate mitigation potential of forest management.

Keywords: Sustainable Development, forest management, scenario analysis, climate mitigation, sequestration, substitution

Kristian Tufvesson, Department of Earth Sciences, Uppsala University, Villavägen 16, SE- 752 36 Uppsala, Sweden

Climate mitigation potential of the Swedish forest under different forest management regimes and levels of substitution effect

Kristian Tufvesson

Tufvesson, K., 2021: Climate mitigation potential of the Swedish forest under different forest management regimes and levels of substitution effect. *Master thesis in Sustainable Development at Uppsala University,* No. 2021/18, 54 pp, 30 ECTS/hp

Summary:

Humanity faces an existential threat from climate change and decisive actions are needed to prevent the worst effects. Forests will be an essential tool in our effort to curb the accumulation of greenhouse gases in the atmosphere. Forests reduces the accumulation of greenhouse gases in the atmosphere in mainly two ways. When the forest grows it converts atmospheric carbon dioxide into organic compounds which can be stored in the vegetation and soil. Forests also provide a climate benefit by offering renewable raw material which can be used to substitute other emission-intensive materials such as steel and concrete. This is known as the substitution effect. The magnitude of the substitution effect is determined by which products and materials the forest raw material replaces and can, therefore, change in the future.

However, these two climate benefits are unfortunately in conflict with each other, as efforts to increase the significance of one consequentially reduces the significance of the other. Increased forest conservation to enhance the uptake and storage of carbon in the forest will reduce the amount of harvested biomass available for substitution. While increased forest harvest to substitute more material with forest raw material will reduce the uptake and storage of carbon in the forest. This conundrum has sparked a debate concerning how the Swedish forest should be managed to provide an increased climate mitigation potential in the future. With some arguing for an increased forest conservation to allow for a larger uptake and storage of carbon in the standing forest. While others argue for maintaining or increasing the level of forest harvest to allow for more emission-intensive materials to be replaced with renewable forest raw material. In addition, the prospect of increasing forest growth by intensifying forest management with growth-enhancing practices such as fertilization, increased utilization of genetically improved plant material, and fast-growing exotic tree species, is often raised as a potential measure to boost the climate mitigation potential of the Swedish forest.

The purpose of this study was, therefore, to explore how the climate mitigation potential of different forest management regimes develops over time based on different potential magnitudes of substitution effect. This was done by simulating the effects on both the uptake and storage of carbon as well as how much harvested biomass that can be used for substitution for the different forest management regimes. The simulations were performed with the forest modelling software RegWise and the simulations were run over a 150-year period. By developing three potential future levels of substitution, it was possible to examine how the dynamics between the different forest management regimes in terms of climate mitigation potential varies depending on which level of substitution that was applied. The results indicate that increasing the uptake and storage of carbon through increased forest conservation can be an effective measure to increase the climate mitigation potential of the Swedish forest in the short- to medium term. The effect does, however, diminish over time as a result of the forests declining ability to store additional carbon. How fast the forest management regimes without increased conservation are able to catch depends on how large the substitution effect may be in the future. The results also showed intensified forest management with increased utilization of growth-enhancing practices increased the climate mitigation potential of the Swedish forest.

Keywords: Sustainable Development, forest management, scenario analysis, climate mitigation, sequestration, substitution

Kristian Tufvesson, Department of Earth Sciences, Uppsala University, Villavägen 16, SE- 752 36 Uppsala, Sweden

1. Introduction

Climate change is considered to be one of the defining issues of our time. Climate change is driven by the increased accumulation of greenhouse gases (GHGs) in the atmosphere, mainly brought on by human-induced emissions from excessive utilization of fossil fuels (Friedlingstein et al., 2019). However, other factors such as Land-Use, Land-Use Change, and Forestry (LULUCF) also influence the concentration of GHGs in the atmosphere. To curb future emissions, decisive actions are required, and forests are considered critical in the transition towards a sustainable society (IPCC, 2019). Sweden is a forest-rich country, with approximately 70 % of the land area being forested (Skogsdata, 2020). Sweden, therefore, has a unique opportunity to contribute to this collective effort. Forests can provide climate change mitigation in different ways. When the forest grows, it converts atmospheric carbon dioxide through photosynthesis to organic compounds, which are then stored in the vegetation and soil (Bergh et al., 2020). A growing forest, thereby, transfers carbon from the atmosphere to the biosphere, consequently reducing the concentration of GHGs in the atmosphere. The other way the forest can provide climate mitigation is through the so-called substitution effect, which refers to the process of substituting products associated with high fossil fuel emissions with Harvested Wood Products (HWPs) from renewable forest biomass (Bergh et al., 2020). Thus, reducing the influx of GHGs, which has been excluded from the natural carbon cycle for hundreds of millions of years. Long-lived HWPs also store biogenic carbon for varying lengths of time, keeping it out of the atmosphere.

As climate change has become an increasingly pressing issue, a division in opinion regarding how the Swedish forest may best provide climate mitigation has become evident (Röstlund, 2021). On the one side, there are those who argue that more forests should be set aside for conservation to allow for maximum uptake and sequestration of carbon dioxide from the atmosphere. In contrast, others argue for a continuation of intensified management of forests for harvest to replace more products associated with heavy fossil fuel emissions with HWPs. Those who advocate that forest should be left for conservation often emphasizes that a clear-cut forest stand emits GHGs 10-15 years after a harvest and that it takes several decades for the harvested stand to reabsorb the same amount of carbon dioxide that was previously stored in the stand (Lindroth et al., 2009). They refer to the urgency of limiting the concentration of GHGs in the atmosphere if we are to avoid setting of irreversible and self-reinforcing warming by passing certain tipping points in the biophysical subsystems that regulate the earth's climate (Lenton, 2011; Lontzek et al., 2015). They also point out that most harvested biomass is used to produce short-lived products such as paper, hygiene items, and bioenergy (Swedish Statistical Yearbook of Forestry, 2014). Those who promote the continuation of managing forests for production instead maintain that forest raw material allows us to reduce our dependency on fossil fuels, which is crucial if we are to move towards a sustainable bioeconomy. They emphasize that HWPs provide a substantial substitution effect when replacing products associated with heavy fossil fuel emissions such as concrete, steel, plastics, and aluminum. They also highlight that an unmanaged forest can only provide additional climate mitigation as long as it grows. Eventually, the forest reaches an equilibrium where the uptake of carbon dioxide is more or less equal to the emissions from respiration, and the forest thereby becomes carbon neutral. The substitution effect is instead cumulative as avoided fossil fuel emissions can be accounted as being avoided forever. The significance of substitution, therefore, increases over time (Bergh et al., 2020). The possibility of increasing forest growth by intensifying the forest management is also often raised as a potential measure to enhance the climate mitigation potential of the Swedish forest.

The climate mitigation potential of forest harvest is directly linked to the magnitude of substitution achieved from the various HWPs, as well as the amount and longevity of the carbon stored in the different HWPs. However, quantifying the substitution effect of HWPs is highly complex and requires a holistic systems perspective. Different variables need to be considered, e.g., the type of HWP, which fossil fuel product it substitutes, the product's lifespan, and the end-of-life management of the product. The analyses are further complicated by the fact that wood production systems often are integrated. Residues from the sawmill industry are, for example, often used to produce paper or energy. A study conducted on the Swedish forest market have estimated the current average substitution effect of HWPs to be somewhere around 500 kg of avoided CO_2 emission per cubic meter of harvested forest biomass (Lundmark et al., 2014). How substantial the substitution effect of HWPs will be in the future is, however, uncertain as it will depend on larger societal, technological, and economic trends. Emerging HWPs such as textiles and Cross-Laminated Timber (CLT) may, for example, increase the average substitution effect (Lehmann, 2013; Leskinen, 2018). While low-emission technological breakthroughs in steel and concrete production could potentially lower the average substitution effect (Karakaya et al., 2018; Sathanandam et al., 2017).

The conflict between actively managing the forest for harvest and setting it aside for nature conservation has a long history in Sweden. While the debate historically mainly has been centered around questions of biodiversity, as well as recreational and cultural values, the current debate is increasingly concerned with the climate mitigation potential of the two options (Berndes et al., 2018; Röstlund, 2021). The climate mitigation potential offered by setting aside forests to act as carbon sinks can be equated with the amount of carbon dioxide that the forest can sequester over time. The magnitude of sequestration is influenced by the level of carbon uptake achieved through photosynthesis and how much carbon is transferred back to the atmosphere through respiration processes. If the forest is affected by a disturbance, e.g., a fire, windthrow, or pest outbreak, the respiration processes may outweigh the uptake of carbon achieved through photosynthesis, and the forest goes from a carbon sink to a carbon source. The climate mitigation potential of forest harvest instead depends on the rather uncertain future level of substitution effect offered by HWPs, as well as how much biomass that can sustainably be harvested.

1.1. Study aim

How the Swedish forest should be managed to provide climate mitigation is currently under debate. The aim of this study was, therefore, to investigate how the dynamics of climate mitigation potential changes over time depending on forest management regime and potential future substitution level. This was done by developing four different forest management regimes, together with three potential future levels of substitution. The three following research objectives were established:

- To examine how an increased forest conservation would influence the climate mitigation potential of the Swedish forest.
- To examine how an increased application of growth enhancing practices would influence the climate mitigation potential of the Swedish forest.
- To examine how the level of substitution effect influence the dynamics between different forest management regimes over time in terms of climate mitigation potential.

2. Theoretical background

2.1. The Carbon cycles

The biogeochemical cycle through which carbon flows between the biosphere, geosphere, hydrosphere, and atmosphere is known as the carbon cycle. These four spheres act as carbon reservoirs. The absolute majority of carbon on earth is found in the geosphere, stored deep in the earth's core and mantle or as different sedimentary rock formations in the earth's crust (Ciais et al., 2013). The second-largest carbon pool is located in the oceans, which contains roughly 40 000 gigatons of carbon (GtC), mainly as inorganic dissolved carbon dioxide. Depending on how the biosphere is defined, it contains around 650 GtC in the vegetation together with another 2000 GtC in the soil. The atmosphere currently contains around 750 GtC (Ciais et al., 2013). A substantial amount of carbon is also stored as hydrocarbons in the form of oil, coal, and gas, also known as fossil fuels. These fossil fuels are formed when organic matter is excluded from decomposition and put under high pressure and heat for millions of years.

The way carbon fluxes between these reservoirs can be described in terms of sources and sinks, where sources denote the influx of carbon and sinks denote the outflux. A distinction is made between the fast and slow carbon cycle. The slow carbon cycle refers to the geochemical processes where oceanic carbon deposits on the ocean floor where it forms sedimentary rock. Carbon is released back to the atmosphere either through weathering of rocks or through volcanic eruptions. The slow carbon cycle operates on the timescale of millions of years, with a yearly turnover rate of between 10 and 100 million tonnes of carbon (Berner and Lasaga, 1989). The fast carbon cycle mainly constitutes the movement of carbon between the atmosphere, oceans, and biosphere. Photosynthesizing organisms such as plants, algae, and cyanobacteria utilize solar energy to convert atmospheric carbon in the form of carbon dioxide into different organic compounds. Carbon is then transferred back to the atmosphere when other organisms consume the organic compounds through the process of cellular respiration. The fast carbon cycle operates on timescales between a few years up to millenniums and has a yearly turnover rate of between 1000 and 100 000 million tonnes of carbon (Ciais et al., 2013). The sources and sinks of carbon in the main reservoirs have for millenniums existed in a state of dynamic equilibrium. But as humans started to utilize the energy stored in fossil fuels to power our growing economies, this equilibrium has been disrupted.

2.2. Climate change

The gases in the atmosphere which have properties that allow them to absorb and reemit some of the heat radiation that would otherwise have been reflected from earth to outer space are known as GHGs (Ledley et al., 1999). The concentration of GHGs in the atmosphere thereby influences the earth's climate by affecting how much heat is trapped. The main GHGs in the atmosphere are water vapor, carbon dioxide, methane, and nitrous oxide. Thanks to a stable concentration of GHGs in the atmosphere, the earth's climate has been relatively stable for the last 12 000 years. Scholars argue that it is thanks to this stable climate that humans have been able to flourish to the extent that we have. However, as humans, with the onset of the industrial revolution, started utilizing fossil fuels on a large scale and thereby releasing large amounts of carbon dioxide, the concentration of GHG in the atmosphere has increased dramatically. Prior to the industrial revolution, the concentration of CO_2 in the atmosphere remained fairly stable at around 280 parts per million (Joos and Spahni, 2008). But as of the year 2021, the concentration of CO_2 in the atmosphere has reached 415 ppm and the rate of emissions has accelerated drastically over time (NOAA, 2021). Before the 1950's the global emissions were still relatively low, with an annual emission of 5 billion tons of CO_2 by the year 1950 (Friedlingstein et al., 2019). From the 1950's to 1990's, the annual CO_2 emissions more than quadrupled to reach 22 billion tons. Furethermore, the annual emissions have continued to rise, reaching 36.5 billion tons in 2019 (Friedlingstein et al., 2019). As a result, more than 50 % of all emissions since the 1750's have occurred in the last 30 years. However, not all emitted CO_2 ends up in the atmosphere. Terrestrial ecosystems are currently absorbing roughly 30 % of annual emissions, and the oceans are absorbing an additional 25 %, while the remaining 45 % are concentrating in the atmosphere (Friedlingstein et al., 2019). Though there are worrying signs that some important carbon sinks may experience a declining ability to absorb CO_2 in the future (Brown et al., 2019; Hubau et al., 2020)

As a result of the increased concentration of GHGs in the atmosphere, the global average temperature has increased by roughly 1 degree Celsius compared to pre-industrial levels (Hawkins et al., 2017).

There are however large variations in how the warming is distributed over the planet. For example, the arctic region is warming more than twice as fast as the global average (IPCC, 2019). Climate change is and will continue to have an increasingly large impact on our planet, with consequences for human livelihoods. Increased temperatures are causing ice caps to melt, which leads to rising sea levels. According to IPCC, an estimated 680 million people currently live in low-lying coastal areas, and this number is expected to reach 1 billion by the year 2050 (IPCC, 2019). These communities will experience an increased risk for flooding. Climate change will also have a major impact on our ability to grow food. Increased temperature, changes in precipitation patterns, more extreme weather, and reduced water availability will all affect agricultural output (Smith et al, 2014). Extreme weather events such as heatwaves, drought, storms, and heavy precipitation will all increase due to climate change (Stott, 2016). Climate change is also profoundly affecting biodiversity and ecosystems by altering habitats and living conditions (Pecl et al., 2017). The speed of climate change makes it difficult or impossible for many species to adapt. As the oceans have and continue to absorb much of the emitted carbon dioxide, the oceans are becoming increasingly acidic (Hoegh-Guldberg et al., 2007). This is already having severe consequences for vital marine ecosystems such as corals and reefs.

To avoid the worst impacts of climate change, most countries worldwide have agreed to work towards limiting global warming to well-below 2 ° while striving for 1.5 ° Celsius compared to pre-industrial levels (UN). This agreement is known as the Paris Agreement and was adopted in 2015. To achieve this, the member states formulate how they aim to reduce their emissions and present it in the form of Nationally Determined Contributions (NDCs). However, given the current development, scholars deem it unlikely that we will be able to limit global warming to below 2 degrees (Rogelj et al., 2016; Raftery et al., 2017; Brown et al., 2019). Instead, indicators suggest that we are moving towards roughly 3 degrees of warming by the end of the century (Rogelj et al., 2016; Raftery et al., 2017). This involves risks as it increases the threat of passing so-called tipping points in the biophysical subsystems that regulate the earth's climate (Lenton, 2011). A climate tipping point can be described as a threshold that, when passed, triggers self-reinforcing warming, thereby pushing the whole system towards a new equilibrium. Several systems have in recent years been identified as being vulnerable to tipping over (Lenton et al., 2019). One example is the melting of the arctic sea ice. As snow and ice are replaced with dark seawater, the albedo level is reduced, and more heat is added to the system (Lenton, 2012). Thawing of permafrost as temperature increases may release increasingly large quantities of carbon dioxide as well as the more potent GHG methane (Turetsky et al., 2020). Increased frequency of droughts and heatwaves cause large forest fires and dieback, leading to the release of carbon stored in the vegetation (Jump et al., 2017; Stevens-Rumann et al., 2018). There is an increased concern that reaching a tipping point in one of these climate subsystems may cause a cascading effect on other subsystems (Dekker et al., 2018). To avoid setting of such a chain reaction, both scholars and citizens are calling for more ambitious measures to curb climate change than what is currently in place.

2.3. Forests and climate change mitigation

The definition of forest land developed by the Food and Agricultural Organization (FAO) defines forests as*; "Lands of more than 0,5 hectares, with a minimum tree height of 5 meters and a tree canopy cover of more than 10 percent. Areas under reforestation which have yet to reach a tree canopy cover of 10 percent or tree height of 5 m are included, as are temporarily unstocked areas, resulting from human intervention or natural causes, that is expected to regenerate"* (FAO, 2010). By this definition, it is estimated that roughly 30 % of the earth's land surface is covered with forest (FAO and UNEP, 2020). Forests are fundamental to human flourishing as they provide essential ecosystem services. Ecosystem services can be divided into four categories: *provisioning*, *supporting*, *cultural*, and *regulating* services (Millennium Ecosystem Assessment, 2005). *Provisioning* services include the products that can be extracted from the forest, such as timber, berries, mushrooms, and freshwater. *Supporting* services are the processes and qualities necessary for the production of other ecosystem services. These can be water and nutrient cycling, photosynthesis, and maintaining high biodiversity. *Cultural* services include the cultural and recreational benefits we derive from interacting with forests. *Regulating* services are the benefits obtained from the forest's ability to serve as erosion and flood control, carbon storage, and climate regulator.

The world's forests have been identified as a critical resource in the effort to curb climate change (IPCC, 2019). It is, therefore, worrying that deforestation and forest degradation have been and continue to be widespread (FAO and UNEP, 2020). The FAO defines deforestation as *"the conversion of forest to other land use or the long-term reduction of tree canopy cover below the minimum 10 percent threshold"* (FAO, 2001). Since the 1990's approximately 420 million hectares of forest land have been lost due to deforestation. However, due to forest expansion in other areas the net forest loss for the same period has been roughly 180 million hectares (FAO and UNEP, 2020). Although the annual rate of deforestation has declined, from 16 million hectares in the 1990s to 10 million hectares between 2015 and 2020, the rate of deforestation remains high. The main driver for deforestation is agricultural expansion, accounting for around 80 % of global deforestation. Approximately 95 % of deforestation occurs in the tropics, where the expansion of soybean and oil palm cultivation and the expansion of pastureland for cattle ranching are the primary drivers (FAO and UNEP, 2020). Deforestation not only poses a great threat to global biodiversity as forests provide habitat for around 80 % of terrestrial plants and animals. Deforestation also emits huge amounts of carbon dioxide when the carbon stored in the vegetation is released. After fossil fuel combustion, deforestation is currently the second-largest source of anthropogenic carbon emissions

(Friedlingstein et al., 2019). Before the 1950s, deforestation and other land-use change activities was the primary driver of anthropogenic carbon emissions. However, as the utilization of fossil fuels has increased sharply from the mid-1900s up until today, while the rate of deforestation has remained fairly stable, the share of total annual emissions from deforestation and other land-use changes is currently around 13 % (Friedlingstein et al., 2019). Nevertheless, due to the CO_2 fertilization effect, longer growing seasons, and increased nitrogen deposition, forests and other terrestrial ecosystems are able to absorb approximately 30 % of the total annual emissions. This demonstrates the huge potential forests have to act as carbon sinks.

Forests can also provide climate benefits in other ways than just as carbon sinks. HWPs from sustainably managed forests can be utilized to replace products associated with heavy GHG emissions from fossil fuels. This is known as the substitution effect. HWPs are all the different wood-based products that can be derived from forest biomass. The harvested biomass is processed into different wood-use subcategories such as sawn wood, wood-based panels, pulp, and bioenergy. Downstream manufacturers then use these materials to produce products for various applications (*Fig 1*).

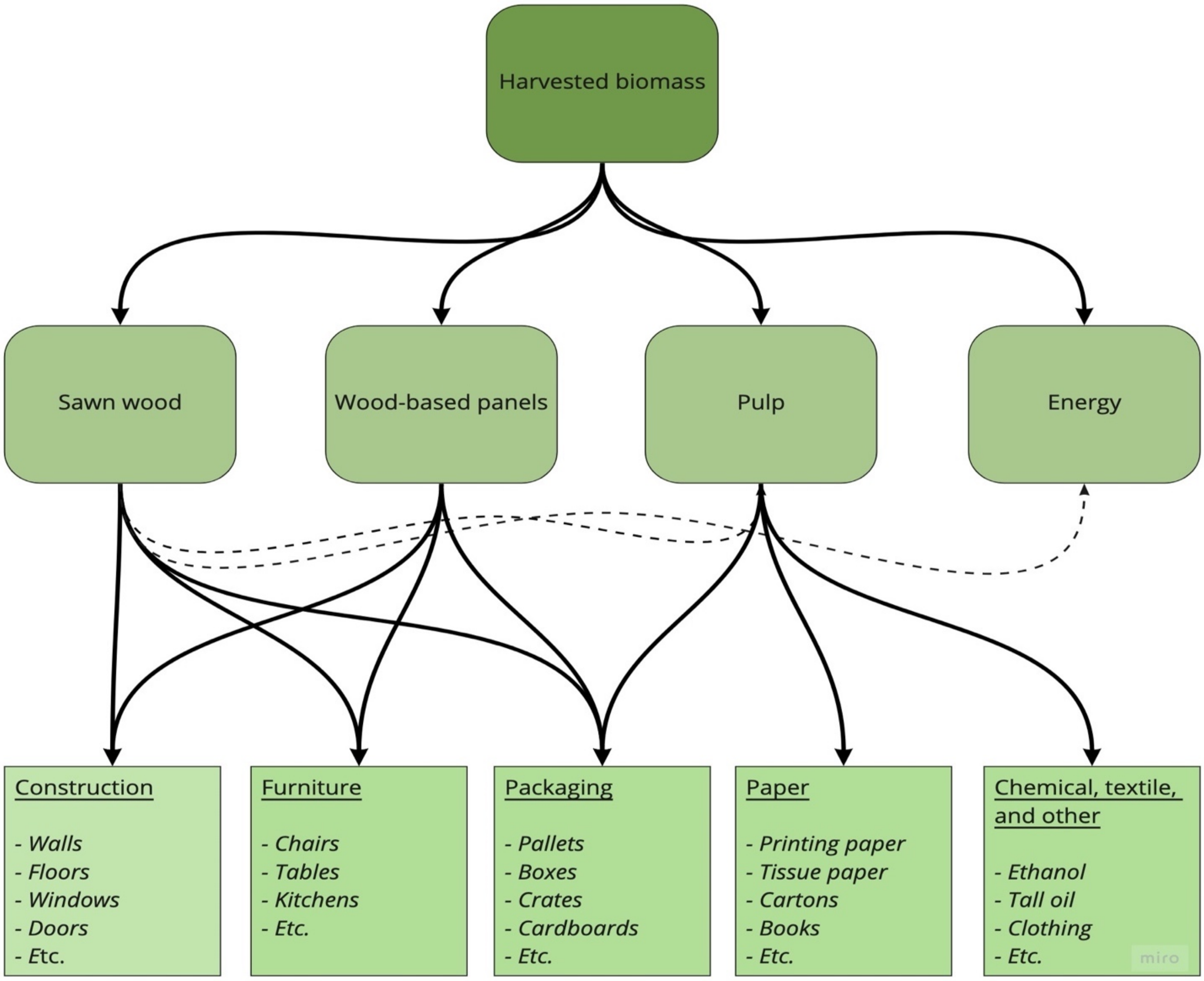


Fig 1: *Typical utilization pathways for harvested forest biomass (modified from Leskinen et al., 2018).*

The amount of avoided GHG emissions achieved from using a HWP instead of a non-wood product is often denoted as a Substitution Factor (SF). The SF for any HWP can be expressed as an equation (Sathre and O'Connor, 2010):

$$SF = \frac{\mathrm{GHG(non-wood)} - GHG\mathrm{(HWP)}}{WU\mathrm{(HWP)}}$$

The GHG emissions associated with non-wood products are subtracted with GHG emissions associated with the HWP, which is then divided with the amount of Wood Use (WU) for the HWP. Both the GHG emissions and WU are expressed as units of Carbon equivalents. The resulting SF is expressed as the amount of avoided atmospheric carbon per unit of carbon in the HWP. A positive SF-value indicates that using a HWP causes less GHG emissions than the non-wood alternative. While the equation is rather simple, the process of estimating the SF for different HWPs is highly complex and often includes many uncertainties. There are, for example, two approaches to quantifying WU for products. One where only the wood contained in the end-use product is considered, and one where also the harvest and wood processing residues are included. The different approaches often lead to considerable differences in terms of estimated SF. Estimating the GHG emission from HWPs and non-wood products is also difficult as it needs to include all associated emissions from the product's whole life cycle. This includes emissions from raw material extraction, processing, transportation, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal. Standards are continuously being formulated to guide life cycle assessments and the associated emissions for different products. This is important as it facilitates the process of calculating the substitution effect offered by HWPs.

The substitution effect can occur either as material or energy substitution. Material substitution occurs when emission-intensive materials are replaced with HWPs. The production of materials such as concrete, steel, plastics, and aluminum all generate enormous amounts of GHG emissions. For example, the steel and concrete industries are together estimated to account for roughly 15 % of all annual GHG emissions (Nidheesh & Kumar, 2019). By substituting these materials with HWPs, large amounts of GHG emissions can be avoided (Braun, 2016.; Hurmekoski et al., 2020; Leskinen et al., 2018; Lundmark et al., 2014). Energy substitution instead occurs when forest biomass is used to replace fossil fuel energy sources. The substitution achieved varies depending on what fossil energy sources are being replaced and under which circumstance the forest biomass is collected. The most notable substitution is achieved when coal is replaced with biomass from harvest and processing residues (Leskinen et al., 2018). The burning of forest biomass actually releases more CO_2 per unit of energy than coal and other fossil fuels (Creutzig et al., 2015). It is, therefore, vital that the use of forest biomass for energy does not cause an overall reduction of the carbon stored in vegetation and soil.

Leskinen et al. (2018) reviewed 51 studies concerning the SF of different HWPs. Most available studies have focused on North America and the Nordic countries, such as Sweden and Finland. Based on the reviewed studies, Leskinen et al. (2018) found an average SF of 1.2 kg C / kg C for all the analyzed HWPs. This means that for every kg of C in HWPs used to substitute non-wood products, an average emission reduction of 1.2 kg C was achieved. Leskinen et al. (2018) divided the studied HWPs into broad product categories (Table 1).

Table 1: *Average substitution effect across different product categories (modified from Leskinen et al., 2018)*

Product categories	**Average substitution effect (kg C / kg C in HWP)**
Structural construction *(e.g., internal or external wall, wood frame, beam etc.)*	1.3
Non-structural construction *(Windows, doors, ceiling, floor etc.)*	1.6
Textiles	2.8
Other products (e.g., f*urniture, packaging, chemicals)*	1-1.5
Average substitution across all HWPs	**1.2**

There were, however, significant variations in estimated SF between different studies and the HWPs considered. This was explained by the different approaches and assumptions made in the studies. The estimated SF for *textiles* and *other products* is based on only a few studies and should be considered with care. It is important to bear in mind that the SF value is a dynamic measurement. It may change in the future due to various technological and societal developments.

To estimate the climate mitigation potential of HWPs, it is also important to consider the carbon stock of HWPs. The HWP's lifespan highly influences the size of the carbon stock, as long lifespans allow for more carbon to be stored over time. However, the average lifespan of different HWPs varies greatly. For example, HWPs used for building construction have an average lifespan of 80 years, and interior constructions such as furniture have an average lifespan of 30 years, while bioenergy and packaging products instead have a very short average lifespan of just a few years (Werner et al., 2010). To achieve the highest climate mitigation from forest harvest, the biomass should consequently be directed towards producing the HWPs with high SFs and long lifespans.

In summary, the climatic impact in terms of carbon flows related to forest management is influenced by the combined effect of changes in the forest carbon stock, changes in the carbon stock of HWPs, and the avoided emissions achieved through substitution *(Fig 2)*.

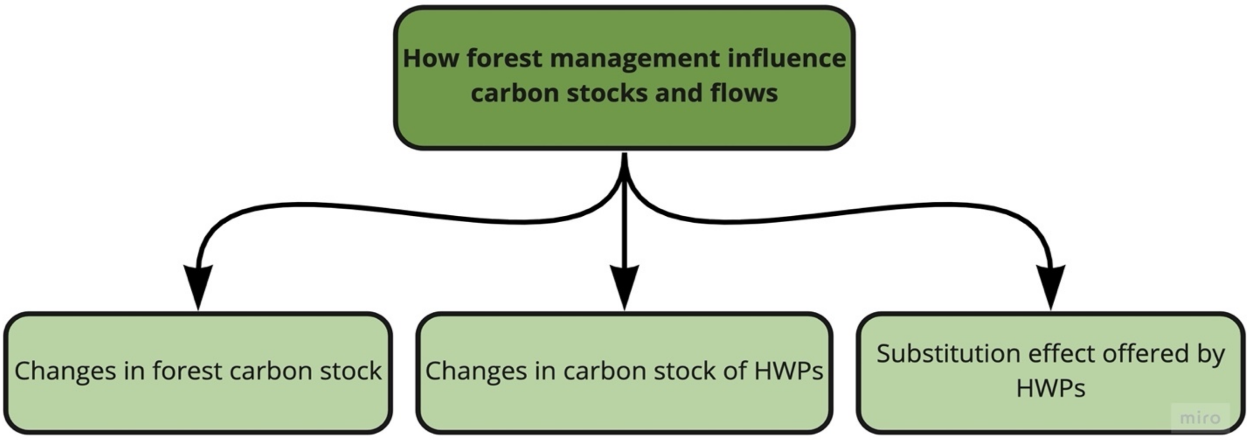


Fig 2*: How forest management influence carbon stocks and flows.*

This relationship can be expressed as an equation:

$$Net\ carbon\ balance = \Delta CS(Forest) + \Delta CS(HWPs) + \overline{X}SF \times HW$$

With $\Delta CS(Forest)$ denoting changes in forest carbon stock, $\Delta CS(HWPs)$ denoting the changes in the carbon stock of HWPs, and $\overline{X}SF \times HW$ denoting the average substitution factor multiplied with the harvested wood expressed as carbon equivalents.

3. Swedish context

Sweden has approximately 28 million hectares of forest area (Skogsdata, 2020). With a total land area of 40,8 million hectares, nearly 70 % is thereby classified as forest land. However, if the low-productive forest area (< 1 m3 per hectare and year) is excluded, the area of productive forest land is estimated to be 23,6 million hectares. Most forested area in Sweden belongs to the boreal ecosystem dominated by coniferous tree species with a mixture of deciduous tree species such as birch and aspen. In terms of forest volume, Norway spruce and Scots pine account for roughly 40 % each, birch accounts for approximately 12 %, and the remaining 8 % mainly consists of other deciduous tree species (Skogsdata, 2020).

While having less than 1 % of global forest cover, Sweden produces roughly 5 % of all forestry products used worldwide (KSLA, 2015). The primary forest products from the Swedish forest industry are pulp, paper, and sawn timber. The Swedish forest industry is highly oriented towards export, as approximately 80 % of all forest products are exported (KSLA, 2015). The forest industry has historically been vital for Sweden's economic prosperity. The Swedish forest industry directly employs around 60 000 people, and an additional 200 000 people are indirectly employed through various subcontractors (KSLA, 2015). The forestry sector handles, by far, the largest carbon flows in the Swedish economy. Forest management is, therefore, an essential tool in terms of climate mitigation potential.

At the beginning of the 20th century, the forests in Sweden were highly degraded (KSLA, 2015). Slash-and-burn agriculture, forest grazing, and the mining industry's great demand for charcoal had for centuries put a strain on Sweden's forests. When the forest industry emerged in the latter half of the 19th century with the subsequent large-scale harvest of older mature trees, the standing forest volume fell dramatically. With the realization of Sweden's poor forest condition, in combination with the increased economic value of timber, voices demanding regulatory measures to prevent deforestation and securing the future supply of timber were raised. As a result, the first Forestry Act in Sweden was passed in 1903 (KSLA, 2015). The Swedish Forestry Act (SFA) states that a forest owner is required to ensure sufficient forest regeneration after a harvest. Over time, the SFA was strengthened and focused on maintaining a high level of forest production. Selection forestry of uneven-aged forests was increasingly replaced in favor of even-aged clear-cutting forestry as it was deemed to be more productive (Holmberg, 2005). With the rapid technological development that followed after the Second World War, forestry became increasingly mechanized and rationalized. Large clear-cuts without environmental considerations were not uncommon. Deciduous trees were unwanted, and herbicides were therefore used on a large scale to suppress them. Public criticism towards the practices within Swedish forestry grew in the '60s and '70s, particularly regarding the harmful effect herbicides posed to human health (Holmberg, 2005). As a response, chemical herbicides were prohibited within forestry in 1977. This led to a temporary reduction in public criticism towards Swedish forestry, but the debate gained new momentum a few years later. This time the critique was centered around biodiversity and the adverse effects caused by forestry. This resulted in the 1993 revision of the SFA, stating that production and environmental goals are equally important (Holmberg, 2005). Forest owners were thereby expected to maintain a high level of wood production while simultaneously preserving and improving the environmental conditions in the forest. This forest policy is often described as the Swedish forestry model and is characterized by the notion of "freedom with responsibility" (Appelstrand, 2007). However, many environmental organizations remain critical and point to the forests sector's inability to meet environmental goals due to a continued prioritization of wood production (Lindahl et al., 2017). In recent times, the conflict between wood production and environmental conservation has increasingly become centered around the issue of climate change (Berndes et al., 2018).

The Swedish forests currently accounts for a net uptake of almost 40 million tons of CO_2 annually, while simultaneously providing roughly 75 million cubic meters of harvested biomass (Naturvårdsverket, 2020; Skogsdata, 2020). The Swedish forestry model has, therefore, been described as a success story in terms of climate mitigation, in which forest management has enabled both an increased carbon sequestration in the standing forest stock as well as an increased harvest level (Swedish Forest Industries, n.d.). However, scholars and proponents of environmental movements have started to question this narrative. They instead maintain that the level of carbon sequestration in the standing forest stock could be substantially larger if the level of forest harvest would be reduced, and that this should be justified based on the urgency posed by climate change (Röstlund, 2021). This standpoint reflects a shift in perception of climate change as something that can be solved in the future to an issue that needs to be addressed immediately (Lindahl et al., 2017). This perspective also makes no distinction between biogenic carbon emissions and fossil emissions. While increasing the carbon stock in the standing forest by reducing the level of harvest can be an efficient strategy in the short term, it has limitations in the longer term as forests does not store additional carbon indefinitely (Bergh et al., 2020). Eventually, the forest reaches an equilibrium where the uptake of carbon dioxide is more or less equal to the emissions from the decaying vegetation, and the forest thereby becomes carbon neutral. Others therefore instead advocate for maintaining a high harvest level to ensure the availability of forest raw material to be used for substitution. Nevertheless, in the short term it would be better from a climate perspective to leave more forests to act as carbon sinks as long as the uptake of carbon dioxide from the growing forest is greater than what forest harvest can offer in terms of substitution effect. However, due to the cumulative effect offered by substitution, in combination with the forests declining ability to sequester additional carbon over time, a scenario with maintained harvest level would eventually catch up and pass a scenario with reduced harvest level in terms of climate mitigation potential. After how long time this transition occurs depends on how much additional carbon the forest can sequester, and the magnitude of substitution effect offered by HWPs. The question of which alternative is best from a climate perspective therefore depends on which time horizon that is applied. The possibility of an increased utilization of practices that enhances forest growth are also often raised as a potential measure to boost the climate mitigation potential offered by forests. These practices include increased fertilization, increased utilization of genetically improved plant material, and increased plantation of fast-growing exotic tree species, such as the lodgepole pine (Nilsson et al., 2011).

Harvested biomass is commonly measured in volume of stem wood under bark (m^3sub). Lundmark et al. (2014) analyzed the current climate mitigation potential of forest harvest in Sweden, considering both domestic and international consumption. When taking into account the emissions from forest management, logistics, and wood product processing, the average amount of avoided carbon dioxide emissions from substitution and changes in the carbon stock of HWPs, was found to be in the magnitude of 500 kg of carbon dioxide per m^3sub of harvested biomass. But as stated previously, the level of substitution is a dynamic measurement. It will likely change as new technological and societal developments alter the emissions connected to different products. Whether or not the average level of substitution increases or decreases in the future becomes a question of how the harvested biomass is utilized and how the emissions connected to non-wood alternatives progress. The average level of substitution may increase if the harvested biomass is directed towards producing HWPs with long lifespans and high SFs. But the average level of substitution could also potentially decrease if no such efforts are made, while emissions from non-wood alternatives are decreased.

The climate mitigation potential of forest management is influenced by how much CO_2 the forest can sequester and store over time, as well as how much CO_2 emission that can be avoided as a result of the substitution effect offered by HWPs. These two climate benefits are, however, in conflict with each other, as efforts to increase the carbon stock in the forest by increased conservation consequentially results in a reduced harvest level. Increased forest conservation will offer a greater climate mitigation potential as long as the sequestration of CO_2 is greater than the amount of avoided CO_2 emissions offered by substitution. A more intensive forest management with increased utilization of growth enhancing practices can boost the forests climate mitigation potential by increasing the volume of forest biomass that can be sustainably harvested. Increased knowledge in how the dynamics of climate mitigation potential changes over time depending on forest management and achieved substitution is crucial if we are to make sensible decisions concerning future forest management. The purpose of this study was to compare the future climate mitigation potential of the Swedish forest under different forest management regimes and different potential levels of achieved substitution.

4. Material and methods

4.1. Forestry modelling

Forest growth and biomass harvest were simulated with the Heureka Forestry Decision Support System (DSS) developed by SLU (Wikström et al., 2011). The Heureka DSS contains a number of software aiming to facilitate forestry planning and analysis. This study was conducted with the Heureka RegWise application, which is suitable for large-scale forestry scenario analysis. RegWise contains a number of deterministic models that describe the development of the tree-layer over time for different tree species and forest management regimes (Wikström et al., 2011). By assigning forest area to different "domains" in which a given share of the area can be coupled with different "control categories" containing settings for how the forest should be managed, the user may ascribe different forest management for separate forest areas. RegWise can simulate several different forest management practices, such as cleaning, thinning, fertilization, final felling, and different forms of regeneration. It can also simulate forest growth based on different climate scenarios. In addition, RegWise contains models to describe the development of carbon sequestration in the forest, both above and below ground. RegWise estimates changes in soil carbon with the so-called Q model. The Q model describes the amount of carbon entering the soil over time based on variables such as microbial efficiency, the buildup of litter, and the type of litter (Ågren et al., 2008). Input data on current forest conditions in Sweden was collected from the National Forest Inventory (NFI) (Fridman et al., 2014). The NFI has since 1923 continuously carried out inventories of the Swedish forest to measure conditions and changes in the forest landscape. The inventory is performed on systematically laid out sample plots all over Sweden, where various tree and stand data is collected. Some sample plots are permanent, where inventory is performed repeatedly, while other plots are temporary, where inventory is performed only once. The inventory is repeatedly carried out in 5-year intervals. Within these 5-year intervals, inventory is performed on roughly 55 000 sample plots (Fridman et al., 2014). This study was conducted on forest data collected between 2014 and 2018. Only productive forest land (growth > 1 m3 yr-1) was included in the analysis. The RCP 4.5 climate scenario was used for all simulations and all simulations were run for 150 years. This resulted in an increased forest growth over time, mainly due to longer growing seasons (Eriksson et al., 2015). It would, however, also likely result in a higher risk for both biotic and abiotic disturbances (Eriksson et al., 2015). The aspect of a modified disturbance regime was not considered in this study.

4.2. Forest management regimes

The forest management regimes used in this study were based on previous work by Andersson et al. (2008) and Claesson et al. (2015), in which impact assessments of different forest management regimes was conducted. Claesson et al. (2015) formulated a Business As Usual management regime *("Dagens skogsbruk")* which aimed to reflect how the Swedish forest currently is managed. Claesson et al. (2015) also formulated a regime with increased forest conservation *("Dubbla naturvårdsarealer).* Andersson et al. (2008) formulated a forest management regime with increased efforts to enhance forest growth *("Production").* On the basis of these forest management regimes, the following four regimes were developed:

1. A Business As Usual (BAU) regime, aimed to reflect the current forest management in Sweden.

2. An Intensive Forest Management (IFM) regime, with increased utilization of forest practices that enhances forest growth.

3. A regime with increased conservation where the remaining forest area was managed according to a BAU regime (Conservation + BAU).

4. A scenario with increased conservation where the remaining forest area was managed according to an IFM regime (Conservation + IFM).

4.2.1. Business As Usual (BAU)

The BAU regime aimed to reflect the current forest management regime in Sweden and is based on the scenario *"Dagens skogsbruk"* from the 2015 forest impact assessment (Claesson et al., 2015). Sweden has roughly 23,6 million hectares of productive forest land. This land is divided into four different land-use categories. Namely, formally protected nature reserves, voluntary set-aside forest area, retention patches, and production forests. The areal distribution between these land-use categories is currently 3,9 % nature reserves, 5,5 % voluntary set-aside, 7,0 % retention patches, and 83,6 % production forest (Claesson et al., 2015). The same distribution was consequently used under the BAU regime. RegWise allows for the division of forest land into domains where different forest management practices can be applied. As forest conditions largely vary based on a latitudinal gradient, the forest landscape was divided between four domains: *Northern*, *South-Northern*, *Mid*, and *Southern* Sweden (*Fig 3)*. This was done to better reflect how the forest is managed differently in different regions of Sweden.

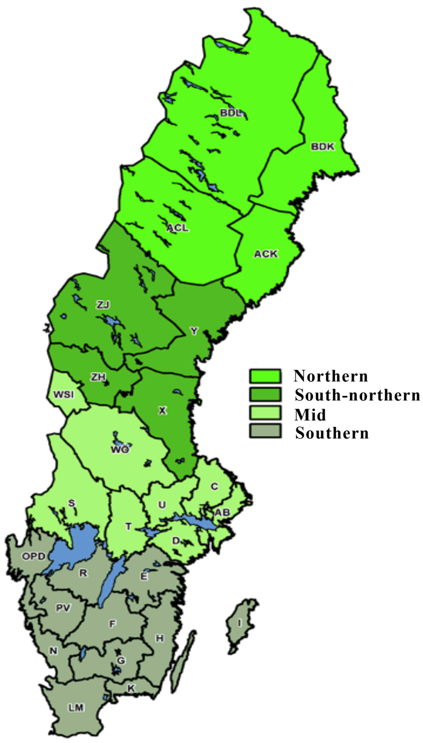


Fig 3: *Division of the Swedish forest landscape into different forest domains (Claesson et al., 2015).*

The forest was then further divided based on land-use category. Data from the NFI contains information regarding which specific geographical area belongs to the formally protected nature reserves. This land-use category could therefore easily be coupled with a control category without active forest management. A majority of the area found in voluntary set-asides and retention patches are also unmanaged. Although, a small portion of this area is managed to maintain different environmental and cultural values. This management often includes the felling of trees that threatens to lower the cultural and environmental values. However, information regarding the specific area that belongs to voluntary set-asides or saved as retention patches was not readily available. This was imperfectly solved by letting RegWise randomly select an area corresponding to the areal extent of the unmanaged and managed share of these two land-use categories, which was either coupled with a control category without active forest management or one with conservation management. To reflect conservation management, this area was managed with recurring thinnings. The remaining forest area was assumed as production forest and was coupled with control categories with active forest management (Table 2).

Table 2*: Distribution of forest between land-use categories in the different forest domains under a BAU regime. Expressed in 1000s of hectares and as share of total area within each domain.*

Forest domain	**Nature reserves**	**Unmanaged voluntary set-asides + retention patches**	**Conservation management**	**Production forest**
Northern	433 ha (6 %)	840 ha (12%)	152 ha (2%)	5790 ha (80 %)
South-Northern	121 ha (2 %)	722 ha (12,5 %)	135 ha (2%)	4862 ha (83,5 %)
Mid	249 ha (4,5 %)	463 ha (8,5 %)	142 ha (2,5 %)	4589 ha (84,5 %)
Southern	112 ha (2 %)	357 ha (7 %)	143 ha (3 %)	4413 ha (88 %)
<u>All of Sweden</u>	**915 ha** **(3,9 %)**	**2382 ha** **(10, %)**	**572 ha** **(2,4%)**	**19 654 ha** **(83,6%)**

Production forest can be managed either through practices adapted for an even-aged or uneven-aged forest. However, Claesson et al. (2015) deemed the models describing the forest development under uneven-aged management to be too uncertain. In addition, uneven-aged forest management is currently used to only a small extent in Sweden. All production forest in these regimes is therefore managed according to practices for even-aged forestry. The management of even-aged production forests is divided into four phases, the *regeneration phase*, the *young forest phase*, the *thinning* *phase*, and the *felling phase*. In RegWise, regeneration is mainly controlled by settings concerning soil scarification, regeneration methods, and regeneration species. The regeneration phase in Sweden today is characterized by high utilization of soil scarification and plantation (Claesson et al., 2015). Soil scarification is performed on roughly 85 % of all regenerated land, with a slight south to north gradient. Plantation is performed on approximately 79 % of regenerated land, while natural regeneration is practiced on 18 %, and the remaining 3 % is regenerated by sowing. During plantation and sowing, genetically improved plant material is commonly used. The choice of regeneration species during plantation and sowing is dominated by Norway spruce and Scots pine. There is, however, a very clear latitudinal gradient with Norway spruce dominating in the south of Sweden while Scots pine being more common in the north. Regeneration with deciduous trees occurs only to a small extent and mainly in southern Sweden. Regeneration with lodgepole pine also occurs to a small extent and only in northern and south-northern Sweden (Table 3).

***Table 3**: Soil scarification, regeneration method, and regeneration species as share of total regenerated area within each domain under the BAU regime.*

Regeneration Practice	Northern	South-Northern	Mid	Southern
Soil scarification	94 %	91 %	81 %	75 %
Plantation	75 %	80 %	76 %	88 %
Sowing	7 %	3 %	2 %	0 %
Natural regeneration	18 %	17 %	22 %	12 %
Norway spruce	36 %	50 %	75 %	86 %
Scots pine	60 %	40 %	22 %	5 %
Lodgepole pine	2 %	6 %	0 %	0 %
Deciduous species	2 %	4 %	3 %	9 %

Management during the young forest phase is primarily influenced by cleaning. In RegWise, cleaning is controlled by stating the share of cleaning objects that are set to be cleaned and the desired tree density after cleaning. Whether or not a forest stand is categorized as a cleaning object is determined by its average height and tree density. The share of cleaning objects being cleaned is currently following a clear latitudinal gradient, with a larger share being cleaned in southern Sweden (Claesson et al., 2015). After cleaning, the average stem density varies between 2200-3400 stems/ha, without showing a clear latitudinal gradient (Table 4).

Table 4: *Cleaned area as share of available cleaning objects, and average stem density after cleaning within each forest domain under the BAU regime.*

	Northern	South-Northern	Mid	Southern
Cleaned area	52 %	58 %	62 %	80 %
Stem density after cleaning	2200 stems/ha	3200 stems/ha	2600 stems/ha	3400 stems/ha

The thinning configuration was set to promote the regeneration species as well as the larger trees. This was done by setting the tree species distribution after thinning to be at least 80 % regeneration species and setting the thinning quota to 0,8. This was done for all forest domains. Conventional fertilization is typically performed approximately ten years before final felling. It, therefore, occurs between the thinning and harvest phase. In RegWise, conventional fertilization is controlled by stating how much of the suitable area should be fertilized every year. Whether or not a forest stand is deemed suitable for fertilization is constrained by variables concerning site index, soil moisture, and proportion of conifer trees. At present, roughly 50 000 hectares of forest are fertilized annually (Claesson et al., 2015). Due to legal constraints, the fertilized area in southern Sweden is substantially lower than in the other domains (Table 5).

Table 5*: Annually fertilized area within each forest domain under the BAU regime.*

	Northern	South-Northern	Mid	Southern
Fertilized area	17 100 ha/year	22 900 ha/year	11 300 ha/year	700 ha/year

The felling phase is mainly controlled by setting how much of the forest growth should be harvested. The harvest level was set to 100 % for all forest regimes. Meaning that the harvested volume is equal to the volume of forest growth. The harvested volume can, however, be lower than the volume growth if not enough forest stands fulfill the age requirements. The extraction of slash to be used for biofuel is controlled by setting the share of final felled area where extraction should be carried out, as well as the share of different tree parts (tops, branches, stumps, etc.) to extract. Whether or not a final felled area is deemed suitable for slash extraction is constrained by variables concerning soil moisture and proportion of spruce trees. The extraction of slash currently amounts to roughly 8 terawatt-hours (TWh) a year (De Jong et al., 2018). This level is met by setting the share of final felled area on where slash extraction should be carried out to 50 % for all forest domains. Slash can also be extracted from thinnings, but due to the lower amount of available slash it is usually not financially profitable and was therefore not included in this study.

4.2.2. Intensive Forest Management (IFM)

The IFM regime aimed to reflect a forest management that is more directed towards achieving increased forest growth. It is based on the "*Produktion*"- scenario formulated in the 2008 forest impact assessment (Andersson et al., 2008). The areal distribution between the regions and land-use categories is assumed to be the same as in the BAU regime (Table 2). Changes in the regeneration phase compared with the BAU regime include increased soil scarification, increased plantation, and increased utilization of lodgepole pine (Table 6). Andersson et al. (2008) also include the afforestation of roughly 400 000 ha of unused farmland. Due to time constraints, this measure was not included in this study.

Table 6: *Soil scarification, regeneration method, and regeneration species as share of total regenerated area within each domain under the IFM regime.*

Regeneration practice	Northern	South-Northern	Mid	Southern
Soil scarification	94 %	95 %	91 %	85 %
Plantation	85 %	90 %	85 %	95 %
Sowing	5 %	3 %	2 %	0 %
Natural regeneration	10 %	7 %	13 %	5 %
Norway spruce	40 %	50 %	70 %	86 %
Scots pine	50 %	36 %	22 %	5 %
Lodgepole pine	8 %	10 %	4 %	0 %
Deciduous	2 %	4 %	3 %	9 %

Cleaning and thinning are typically performed to increase the share of timber in future harvests, but it occurs at the expense of overall forest growth. To avoid this impacting the result of this study, the same cleaning and thinning configuration as in the BAU regime was applied in the IFM regime (Table

4).

The annual fertilized area was substantially increased compared to the BAU regime. From roughly 50 000 ha/year to 200 000 ha/year. RegWise can also simulate a practice known as intensive fertilization. This includes repeated fertilization of spruce plantations throughout the rotation period and continuing in the next rotation period (Andersson et al., 2008). This practice is utilized on roughly one million hectares of forest. The area is built up during the first 50 years and then kept stable for the remaining period (Table 7).

Table 7: *Annually fertilized area and total area under intensive fertilization after 50 years within each forest domain under the IFM regime.*

	Northern	**South-Northern**	**Mid**	**Southern**
Fertilized area	54 000 ha/yr	74 000 ha/yr	58 000 ha/yr	14 000 ha/yr
Area under intensive fertilization	79 000 ha	345 000 ha	360 000 ha	331 000 ha

The harvest level was set to 100 % of volume growth. The extraction of slash was substantially increased compared to the BAU regime as it was set to be carried out on 100 % of the suitable final felled area. No slash was extracted from thinnings.

4.2.3. Increased conservation + BAU

This regime aimed to reflect a forest management with a larger share of the forest area set aside for conservation, while the remaining production forest are managed according to a BAU regime. It was based on the *"Dubbla naturvårdsarealer"*- scenario formulated in Claesson et al. (2015). In this regime the total area set aside for conservation was doubled. The additional area excluded from active forest management is distributed in such a way that the share of production forest area excluded from active forest management is equal in all forest domains, roughly 33 % (Claesson et al., 2015) (Table 8).

Table 8: *Distribution of forest between land-use categories in the different forest domains under a regime with increased conservation. Expressed in 1000s of hectares and as share of total area within each domain.*

Forest domain	Nature reserves	Unmanaged voluntary set-asides + retention patches	Conservation management	New set-aside area	Production forest
Northern	433 6 %	840 12 %	152 2 %	956 13 %	4834 67 %
South-Northern	121 2 %	722 13 %	135 2 %	950 16 %	3912 67 %
Mid	249 4,6 %	463 8,5 %	142 2,6 %	942 17 %	3647 67 %
Southern	112 2 %	357 7 %	143 3 %	1046 21 %	3367 67 %
All of Sweden	**915** **3,9 %**	**2382** **10,1 %**	**572** **2,5 %**	**3894** **16,5 %**	**15 760** **67 %**

All other settings regarding forest management of the production forest were set according to the BAU regime (see pages 23-27).

4.2.4. Increased conservation + IFM

This regime aims to reflect what would happen if a larger share of the forest area was set aside for conservation, while the remaining production forest would be managed according to a IFM regime. The same areal distribution between land-use categories as can be seen in table 8 was used also for this regime. All other settings regarding forest management of the production forest were set according to the IFM regime (see pages 28-29).

4.3. Level of substitution

The future level of substitution is uncertain as it will be influenced by larger societal, technological, and economic trends. Three different levels of substitution were, therefore, developed to reflect scenarios in which the future substitution level is either kept at the current level, is increased, or is decreased. The current level of substitution was based on findings from Lundmark et al. (2014) in which the amount of avoided emissions per harvested m^3sub was estimated to 466 kg CO_2. For the sake of simplicity, this number was rounded to 500 kg CO_2/m^3sub. The magnitude of an increased level of substitution was also based on Lundmark et al. (2014) in which the marginal substitution effect of harvested biomass if it was directed towards products with a higher substitution effect was estimated to 719 kg CO_2/m^3sub. This number was rounded to 750 kg CO_2/m^3sub. The magnitude of a decreased level of substitution was set to 350 kg CO_2/m^3sub. This figure was not based on any study but was instead chosen to reflect a potential scenario where different developments cause a reduction in the achieved substitution from harvested biomass. The following three levels of substitution were consequently considered in this study:

1. 500 kg CO_2/m^3sub: Aimed to reflect a scenario where the current average substitution effect remains.

2. 750 kg CO_2/m^3sub: Aimed to reflect a scenario where the average substitution effect is increased.

3. 350 kg CO_2/m^3sub: Aimed to reflect a scenario where the average substitution effect is decreased.

4.3.1. Current level: *500 kg CO_2/m^3sub*

This substitution level aims to reflect a scenario where the current level of approximately 500 kg CO_2 per harvested m^3sub in avoided emissions is maintained in the future. This figure is based on findings from Lundmark et al (2014) in which the climate mitigation potential of forest harvest in Sweden was analyzed.

4.3.2. High level: *750 kg CO_2/m^3sub*

This substitution level aims to reflect a scenario where various societal and technological developments lead to an increased level of avoided CO_2 emissions per harvested m^3sub. This could be achieved in different ways, for example, by directing the flow of harvested biomass towards producing HWPs with both a high SF and long lifespans. New and emerging HWPs with high SFs such as textiles and cross-laminated timber could also increase the average substitution effect in the future (Leskinen et al., 2018). Improved resource efficiency and recyclability of HWPs would also increase the substitution effect of forest harvest. Another important aspect lies in the prospect of increased utilization of Bioenergy with Carbon Capture and Storage (BECCS). BECCS refers to the process of extracting energy from biomass, capturing the resulting CO_2 emissions, and storing it below ground. Thereby keeping it out of the atmosphere. This is known as a negative emission technology and has been highlighted by the IPCC as necessary to reduce the atmospheric concentration of GHGs in the future (IPCC, 2019). The BECCS technology is currently constrained by costs as well as the availability of land and biomass (Hanssen et al.,2020). This may, however, change in the future as increased climate mitigation ambitions are likely.

4.3.3. Low level: *350 kg CO_2/m^3sub*

This substitution level aims to reflect a scenario where various societal and technological developments instead decrease the average amount of avoided CO_2 emissions per m^3sub. A large share of the substitution effect from using HWPs instead of non-wood alternatives occurs in the construction sector as the production of steel and concrete are currently associated with very high emissions. Substituting these materials with HWPs, therefore, offers a substantial substitution effect. However, several ongoing projects are currently operating to drastically reduce the emissions associated with steel and concrete production. One such project is the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) (Pei et al., 2020). HYBRIT is a joint venture by the steel-producing company SSAB, the mining company LKAB, and the energy company Vattenfall, with the aim to produce fossil-free steel. The conventional steel-making process relies heavily on coal in the form of coke to transform iron ore into steel in a blast furnace. The HYBRIT project instead aims to use a process known as direct reduction, where coke is replaced with hydrogen from renewable energy. This would drastically reduce the emissions associated with steel production. There are also ongoing efforts to reduce the emissions related to concrete production (Naqi & Jang, 2019). Conventional concrete is made by mixing and heating Portland cement with air, water, sand, and gravel. Portland cement is, in turn, made by mixing and heating limestone and clay. Limestone is a sedimentary carbonate rock which when heated, releases large amounts of CO_2. Therefore, the production of concrete and cement generates emissions both through the utilization of limestone and the utilization of fossil fuel for heating. Cementa AB is the largest cement producer in Sweden. They aim to provide carbon-neutral concrete by 2030 by utilizing alternative materials such as fly ash and slag instead of limestone in their cement production and by increasing the uptake of CO_2 in demolished concrete structures through the carbonation process, as well as by adopting Carbon Capture and Storage technologies (Cementa AB, 2018). If the emissions associated with steel and concrete production are substantially lowered in the future, the average substitution effect from HWPs could be reduced.

4.4. Calculations

RegWise calculates the amount of carbon present in the tree layer, dead wood, and the soil for each five-year interval (Wikström et al., (2011). The carbon found in these three layers represents the total carbon stock in the forest. Changes in carbon stock are influenced by harvest level, decomposition, and uptake through growth. Based on the changes in the total carbon stock over time, it is possible to estimate how much carbon has been sequestrated or emitted over a given period. To convert the amount of carbon to the equivalent amount of carbon dioxide, the molecular weight of carbon dioxide is divided by the molecular weight of carbon. This gives a factor of 44/12 = 3,67, which means that each ton of carbon sequestrated is the equivalent of 3,67 tons of carbon dioxide.

The harvested biomass can be divided between three categories: timber, pulpwood, and biofuel. As the calculations are based on the average amount of avoided emissions per m^3 for all harvested biomass, no distinction was made between these different categories. Harvested biomass is expressed as cubic meters of solid wood under bark (m^3sub) for both timber and pulpwood. Biofuel, however, is expressed in watt-hours or tons of dry matter. The harvested biofuel, therefore, had to be converted into m^3sub. This was done with WeCalc, a conversion tool for biofuel provided by Skogforsk (Skogforsk, n.d.).

5. Results

5.1. Sequestration of carbon dioxide

The accumulated sequestration of CO_2 for each forest management regime was compared over a 150-year period (Fig 4). The accumulated amount of sequestrated CO_2 was significantly higher in the two regimes with increased forest conservation. There was also a clear difference between the regimes depending on whether the production forest was managed according to IFM or BAU, with the regimes managed according to IFM providing a slightly higher CO_2 sequestration. By the year 2175, the four different forest management regimes have achieved the following amount of CO_2 sequestration: *BAU* ≈ 6000 Mt CO_2, *IFM* ≈ 6350 Mt CO_2, *Conservation + BAU* ≈ 8200 Mt CO_2, *Conservation + IFM* ≈ 8500 Mt CO_2.

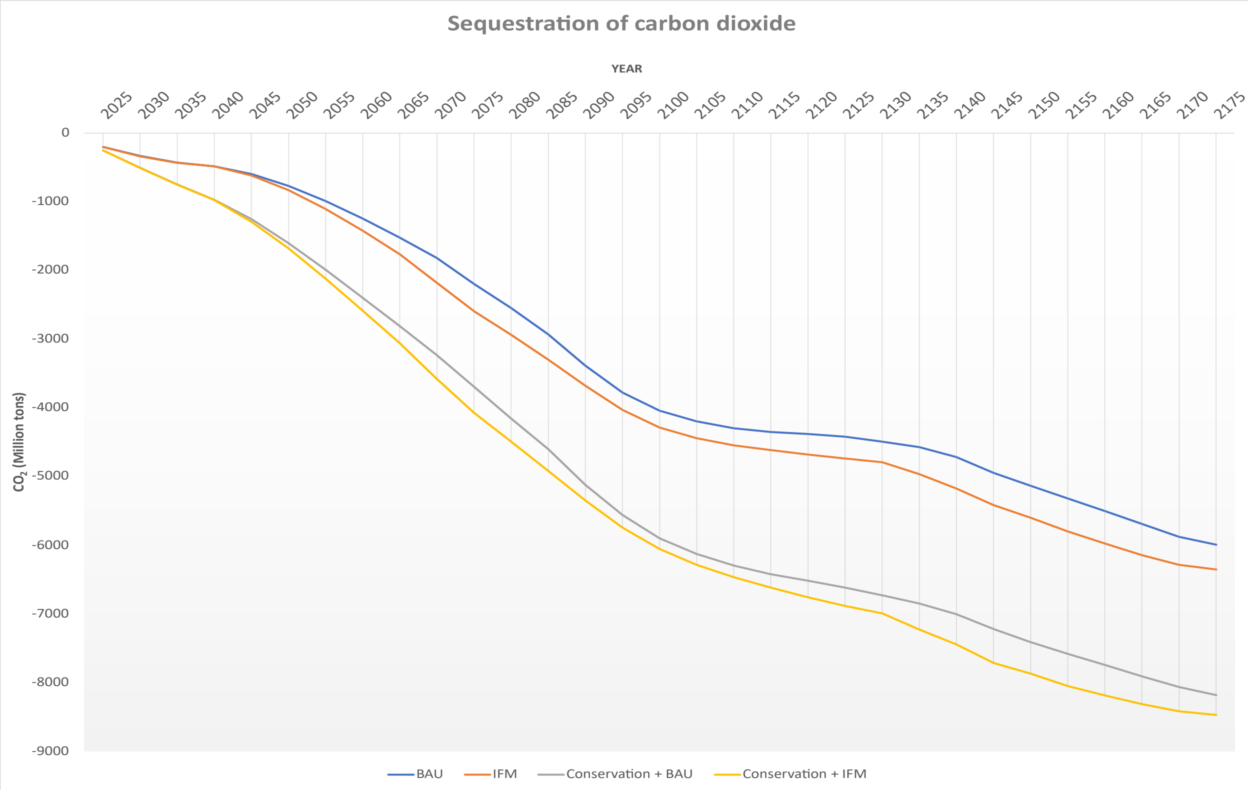


Fig 4: The accumulated amount of sequestrated CO_2, expressed in million tons, over a 150-year period for the different forest management regimes.

5.2. Avoided emissions through substitution

The amount of avoided CO_2 emissions achieved from forest harvest is influenced by the volume of harvested biomass, as well as the achieved level of substitution. The volume of harvested biomass is in turn influenced by which forest management regime that is applied. Increased forest conservation will naturally lead to a lower volume of harvested biomass, as a smaller share of the forest area is available for harvest. More intensive forest management will instead lead to a higher volume of harvested biomass as growth enhancing practices are utilized. These relationships can be observed in figure 5, where the harvested biomass, expressed as million m^3sub/year, is compared between the different forest management regimes. The level of harvest varies considerably over time for all forest management regimes. This can be explained by an uneven age distribution, causing temporarily limitations for forest harvest as not enough forest stands fulfill the age requirements.

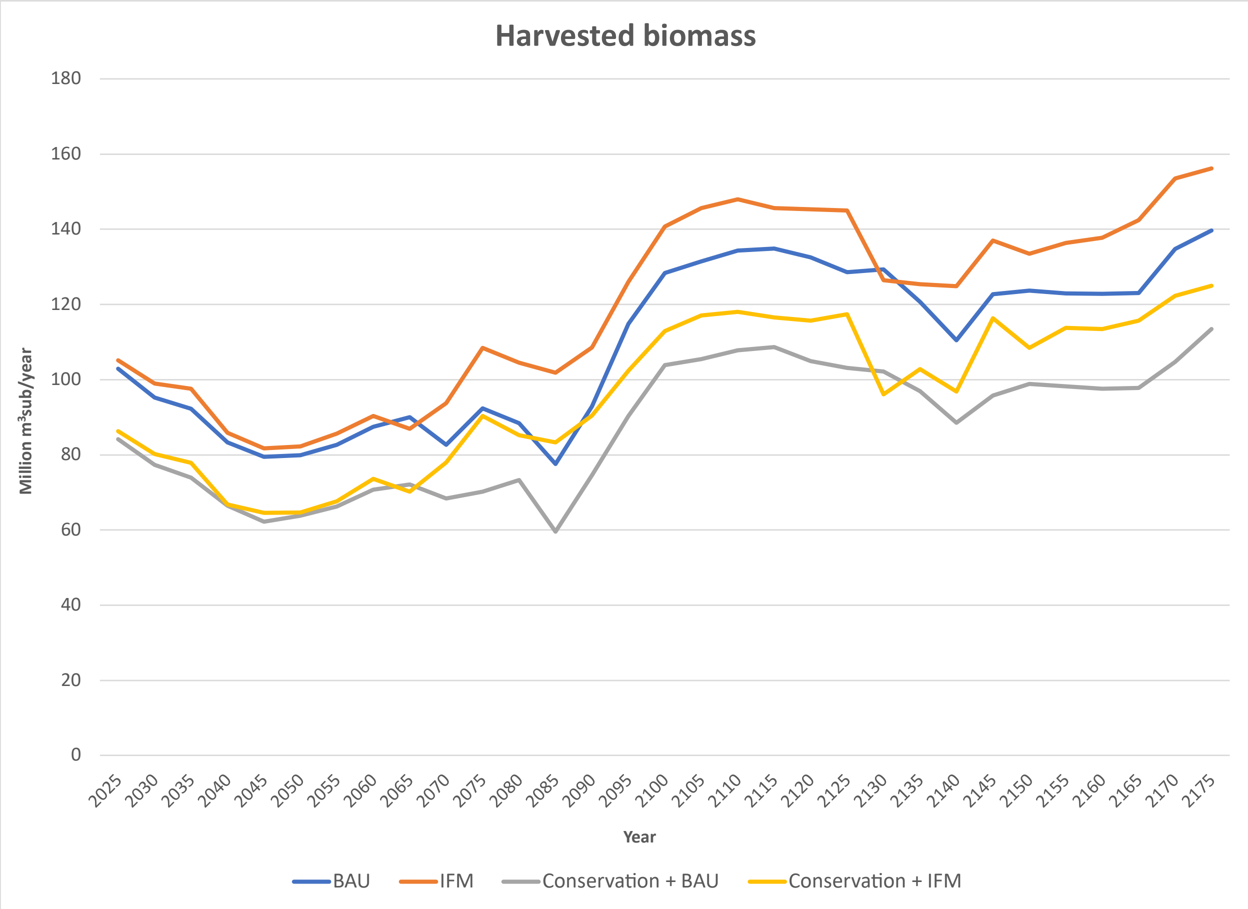


Fig 5: *The harvested biomass, expressed in million m³sub/year, over a 150-year period for the different forest management regimes.*

Regarding the amount of avoided CO_2 emissions achieved through substitution, this study applied three potential future levels. Namely, 500 kg CO_2/m^3sub, 750 kg CO_2/m^3sub, and 350 kg CO_2/m^3sub. While the total amount of avoided emissions varies depending on which substitution level that is applied, the relationship between the different forest management regimes is identical for all levels of substitution. The relationship between the regimes is visualized in figure 6. The regimes with increased conservation provided a considerably lower amount of avoided CO_2 emissions compared to the regimes without increased conservation. A clear difference can also be observed between the regimes depending on whether the production forest was managed according to IFM or BAU, with the regimes managed according to IFM providing a significantly greater amount of avoided emissions.

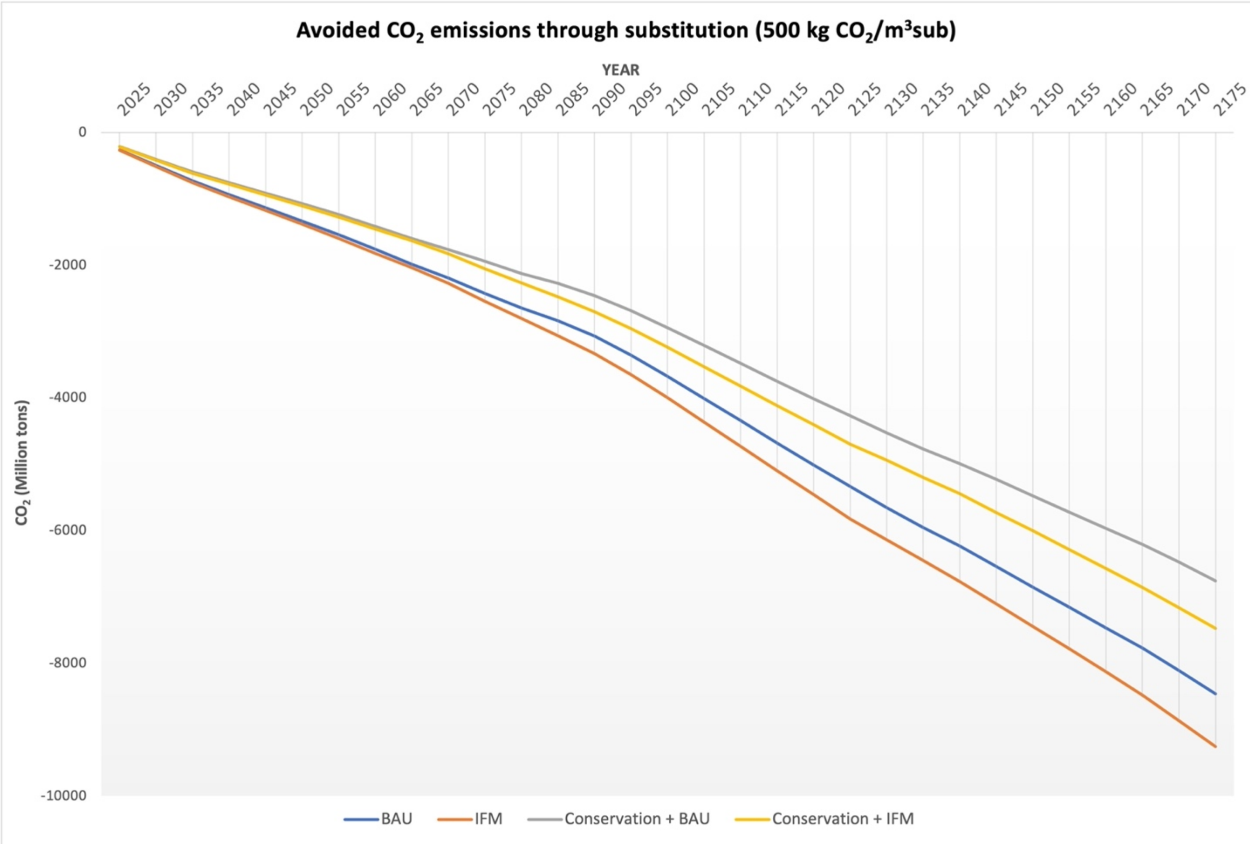


Fig 6: *Avoided CO_2 emissions achieved through substitution, expressed in million tons, over a 150-year period for the different forest management regimes.*

5.3. Total climate mitigation

By adding the amount of sequestrated CO_2 with the amount of avoided CO_2 emissions achieved through substitution, the total climate mitigation potential in the form CO_2 reduction offered by the different forest management regimes under different levels of substitution was estimated.

5.3.1. Current substitution level: 500 kg CO_2/m^3sub

Under a scenario where the current substitution level of 500 kg CO_2/m^3sub remains in the future, the *Conservation + IFM* regime provides the highest total climate mitigation potential throughout the whole 150-year period (Fig 7). The *Conservation + BAU* regime achieves the second highest climate mitigation potential up until approximately year 2140, when it is passed by the *IFM* regime. The *BAU* regime provides the lowest climate mitigation potential throughout the whole 150-year period. By the year 2175, the four different forest management regimes have achieved the following amount of CO_2 reduction: *BAU* ≈ -14 450 Mt CO_2, *IFM* ≈ -15 600 Mt CO_2, *Conservation + BAU* ≈ -14 950 Mt CO_2, *Conservation + IFM* ≈ -15 950 Mt CO_2.

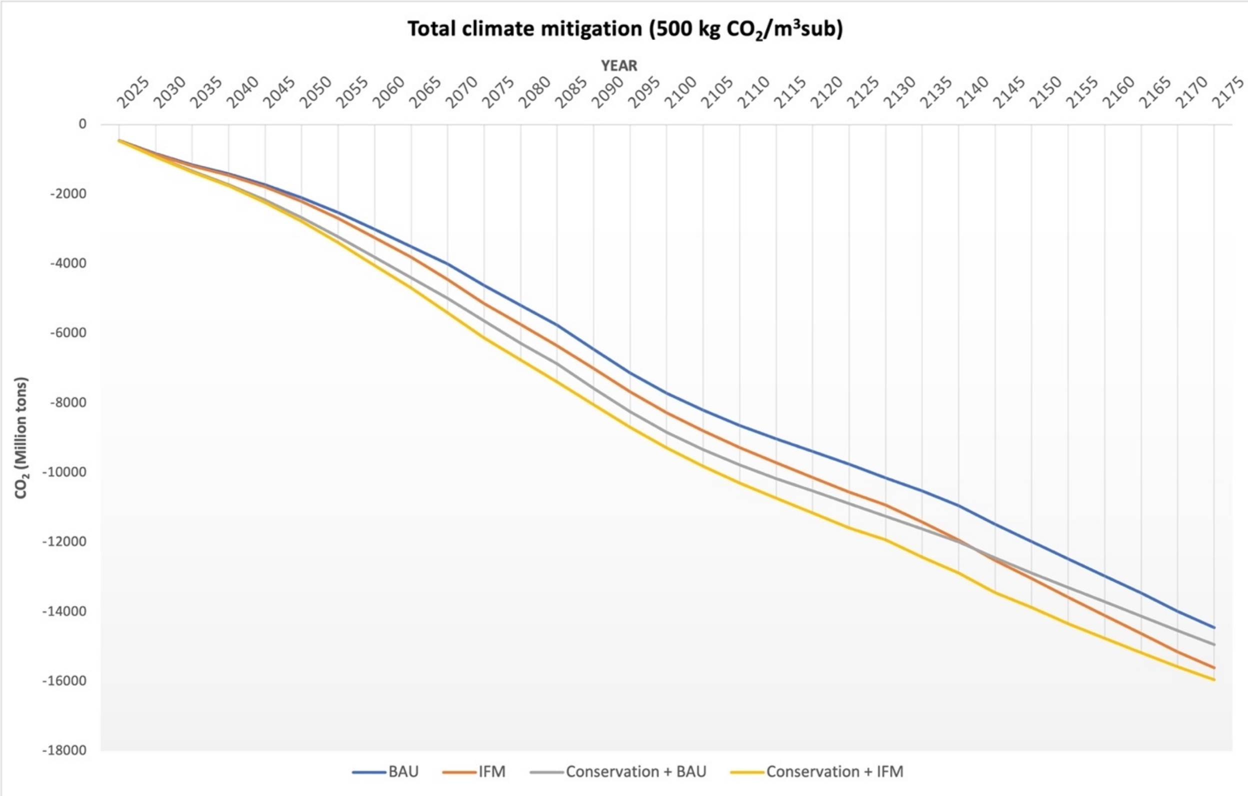


Figure 7: *The total climate mitigation potential over a 150-year period for the different forest management regimes under a substitution level of 500 CO_2/m^3sub. Expressed in million tons of CO_2 reduction,*

The distribution between the sequestration of CO_2 and the avoided emissions achieved though substitution for the different forest management regimes is visualized in figure 8. There is a clear difference between the regimes with increased conservation and those without in terms of whether the weight of climate mitigation is placed on sequestration or substitution. A more intensive management of the production forest mainly increases the significance of substitution but also slightly increases the level of sequestration.

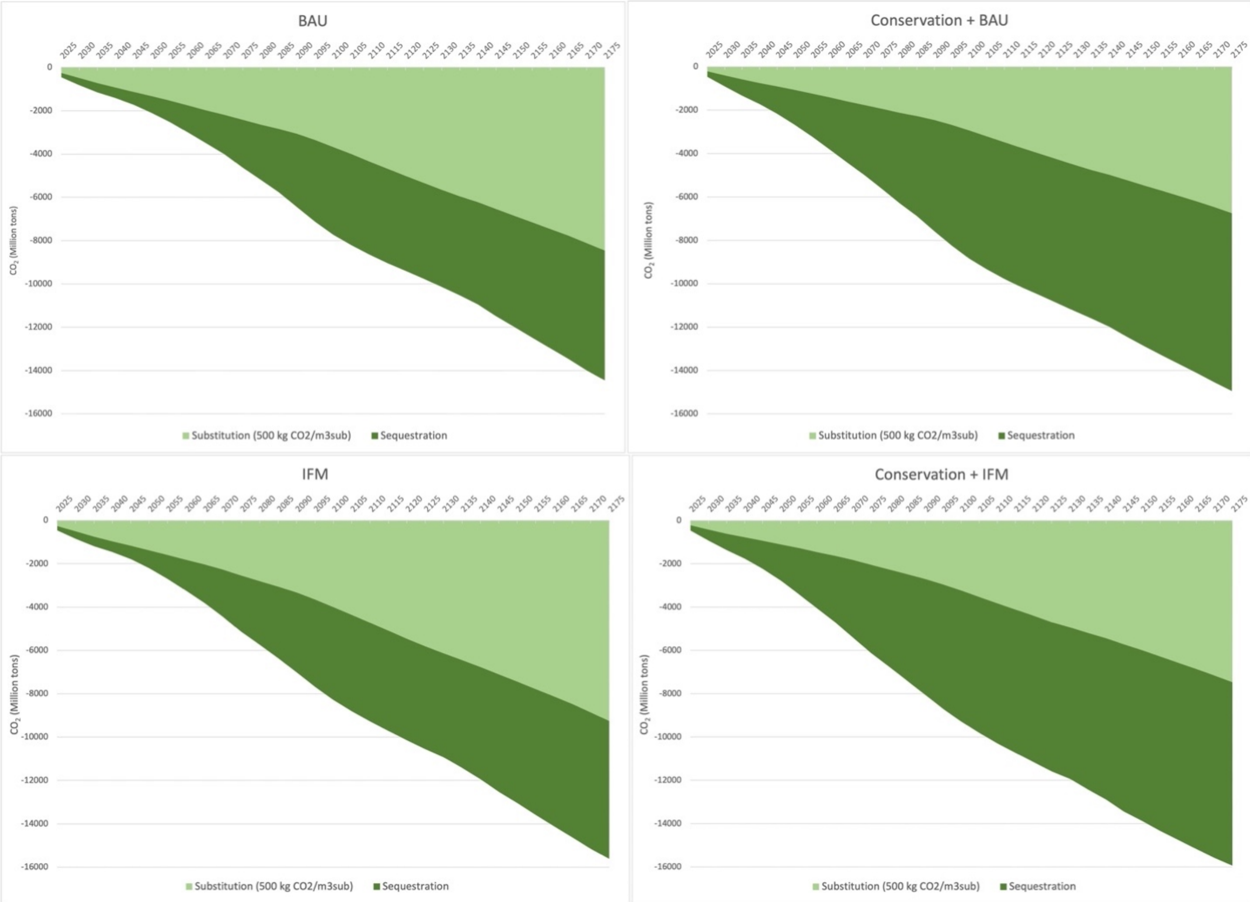


***Fig 8**: The distribution of sequestration of CO_2 and the avoided emissions achieved through substitution for the different forest management regimes under a substitution level of 500 kg CO_2/m^3sub.*

5.3.2. High substitution level: 750 kg CO_2/m^3sub

Under a scenario where the level of substitution is increased to 750 kg CO_2/m^3sub, the *Conservation + IFM* provides the highest total climate mitigation potential up until around year 2155, when it is passed by the *IFM* regime (Fig 9). The *Conservation + BAU* regime is passed by both the *IFM* regime, around year 2100, and by the *BAU* regime, around year 2160, and ends up providing the lowest climate mitigation potential at the end of the 150-year period. By the year 2175, the four different forest management regimes have achieved the following amount of CO_2 reduction: *BAU* ≈ -18 700 Mt CO_2, *IFM* ≈ -20 250 Mt CO_2, *Conservation + BAU* ≈ -18 300 Mt CO_2, *Conservation + IFM* ≈ -19 700 Mt CO_2.

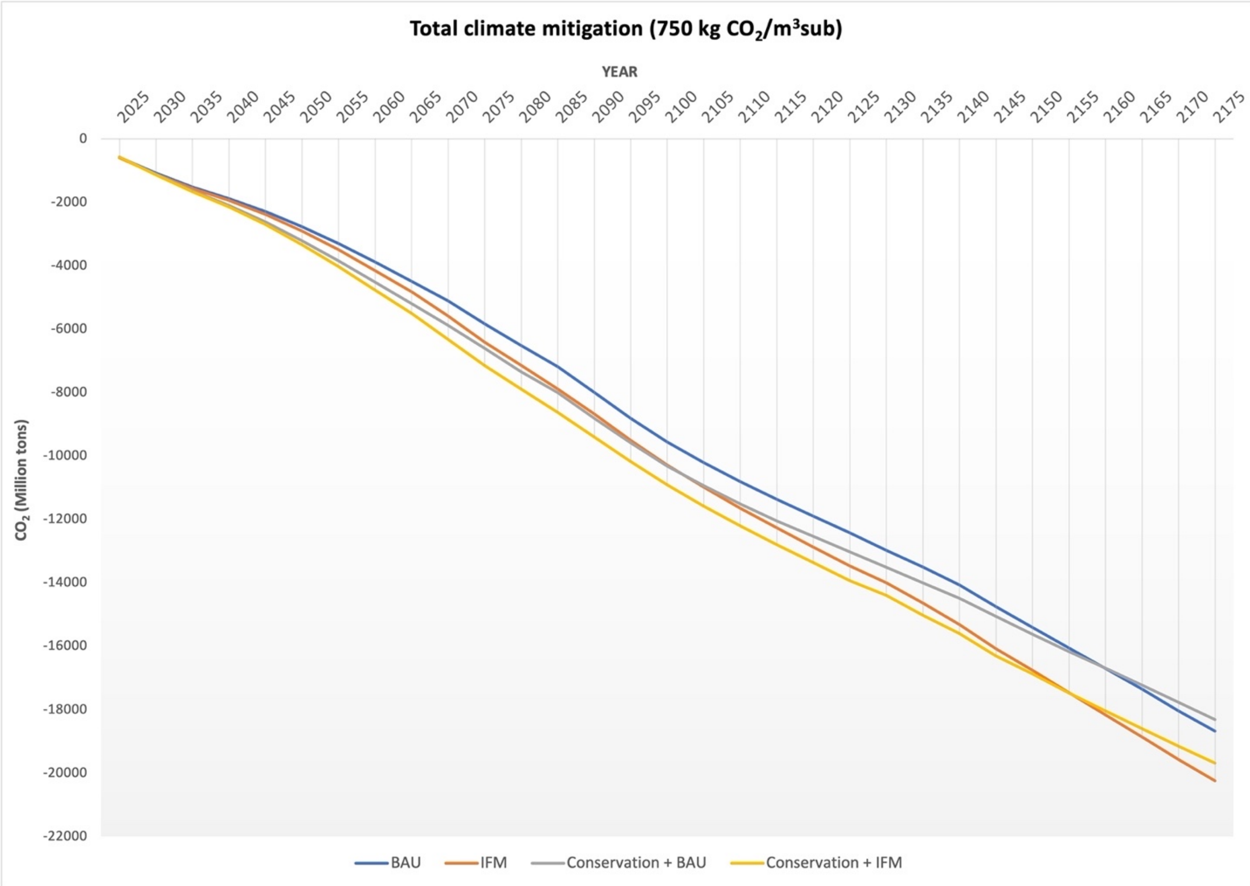


Fig 9: *The total climate mitigation potential over a 150-year period for the different forest management regimes under a substitution level of 750 CO_2/m³sub. Expressed in million tons of CO_2 reduction,*

The significance of substitution compared to sequestration increases substantially under a scenario with an increased substitution level (Fig 10). An increased significance of substitution favors the regimes without increased conservation more than the regimes with increased conservation, as they are able to provide a higher level of harvested biomass. The influence of a more intensive forest management of the production forest also increases for the same reason.

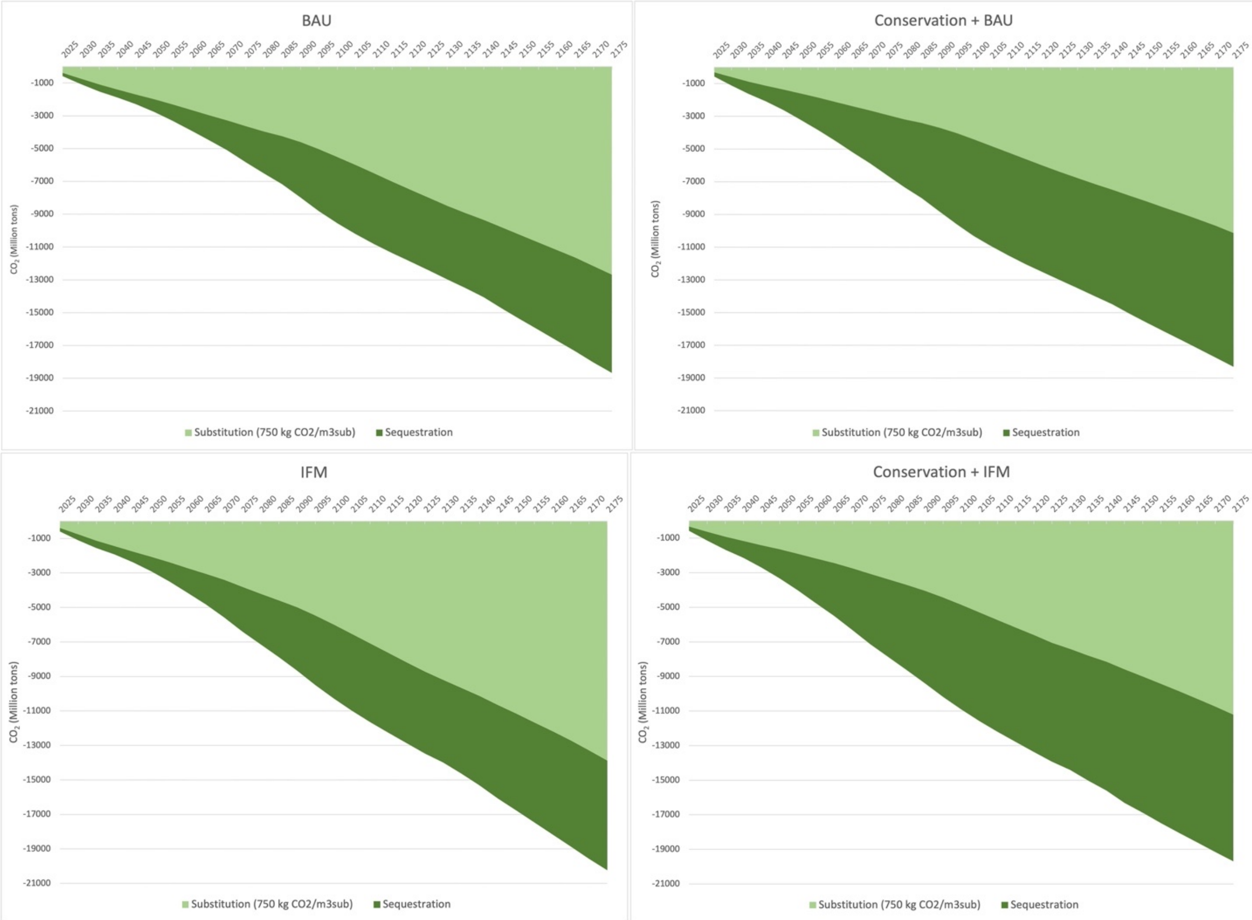


Fig 10*: The distribution of sequestration of CO_2 and the avoided emissions achieved through substitution for the different forest management regimes under a substitution level of 750 kg CO_2/m^3sub.*

5.3.3. Low substitution level: 350 kg CO_2/m^3sub

Under a scenario where the level of substitution is decreased to 350 kg CO_2/m^3sub, the *Conservation + IFM* regime provides the highest climate mitigation potential throughout the whole 150-year period (Fig 11). The *Conservation + BAU* regime provides the second highest climate mitigation potential throughout the whole period, although, it has a similar CO_2 reduction as the *IFM* regime by the year 2175. The *BAU* regime provides the lowest climate mitigation potential throughout the whole 150-year period. By the year 2175, the four different forest management regimes achieved the following amount of CO_2 reduction: *BAU* ≈ -11 900 Mt CO_2, *IFM* ≈ -12 850 Mt CO_2, *Conservation + BAU* ≈ -12 900 Mt CO_2, *Conservation + IFM* ≈ -13 700 Mt CO_2.

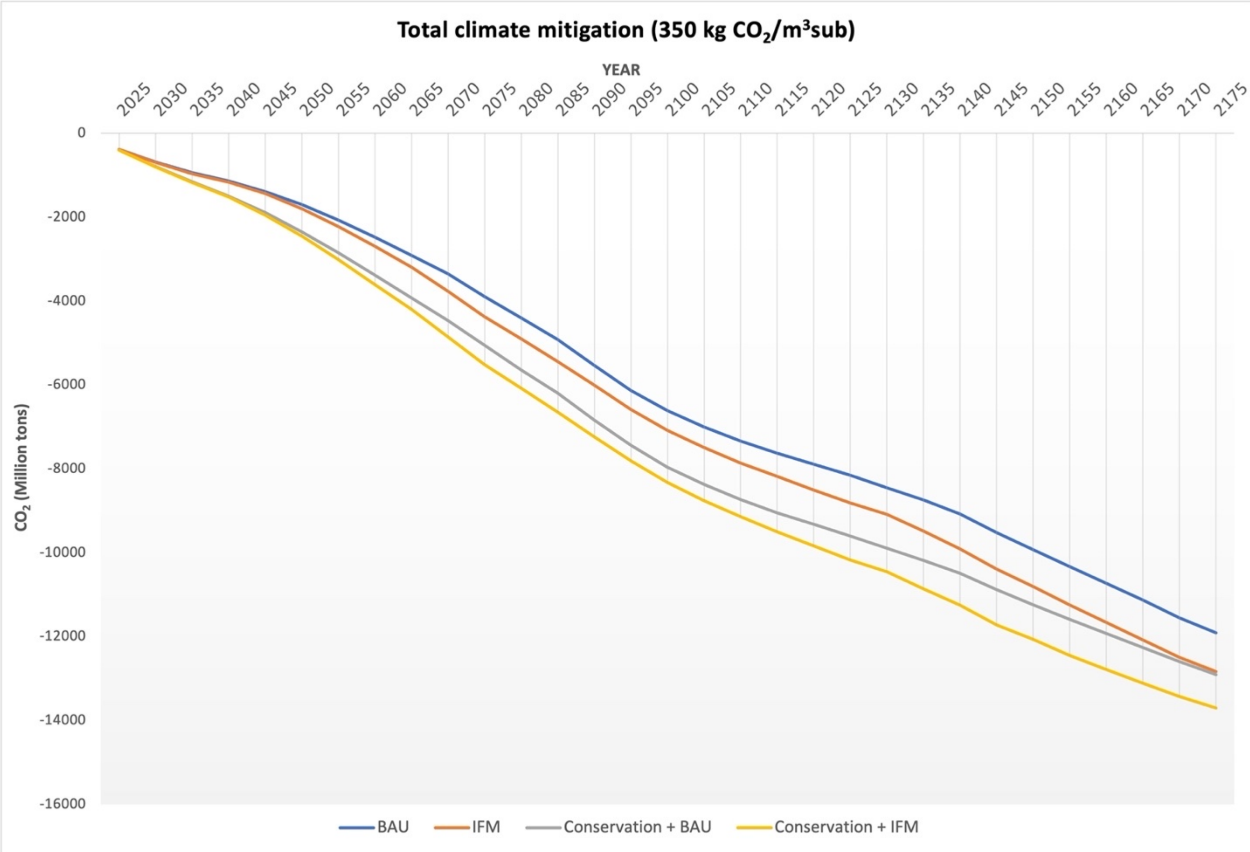


Fig 11: *The total climate mitigation potential over a 150-year period for the different forest management regimes under a substitution level of 350 CO_2/m^3sub. Expressed in million tons of CO_2 reduction,*

Under a scenario with a decreased substitution level, the significance of substitution relative to sequestration decreases (Fig 12). This disfavors the regimes without increased conservation more than the regimes with increased conservation. The influence of a more intensive forest management is also slightly decreased.

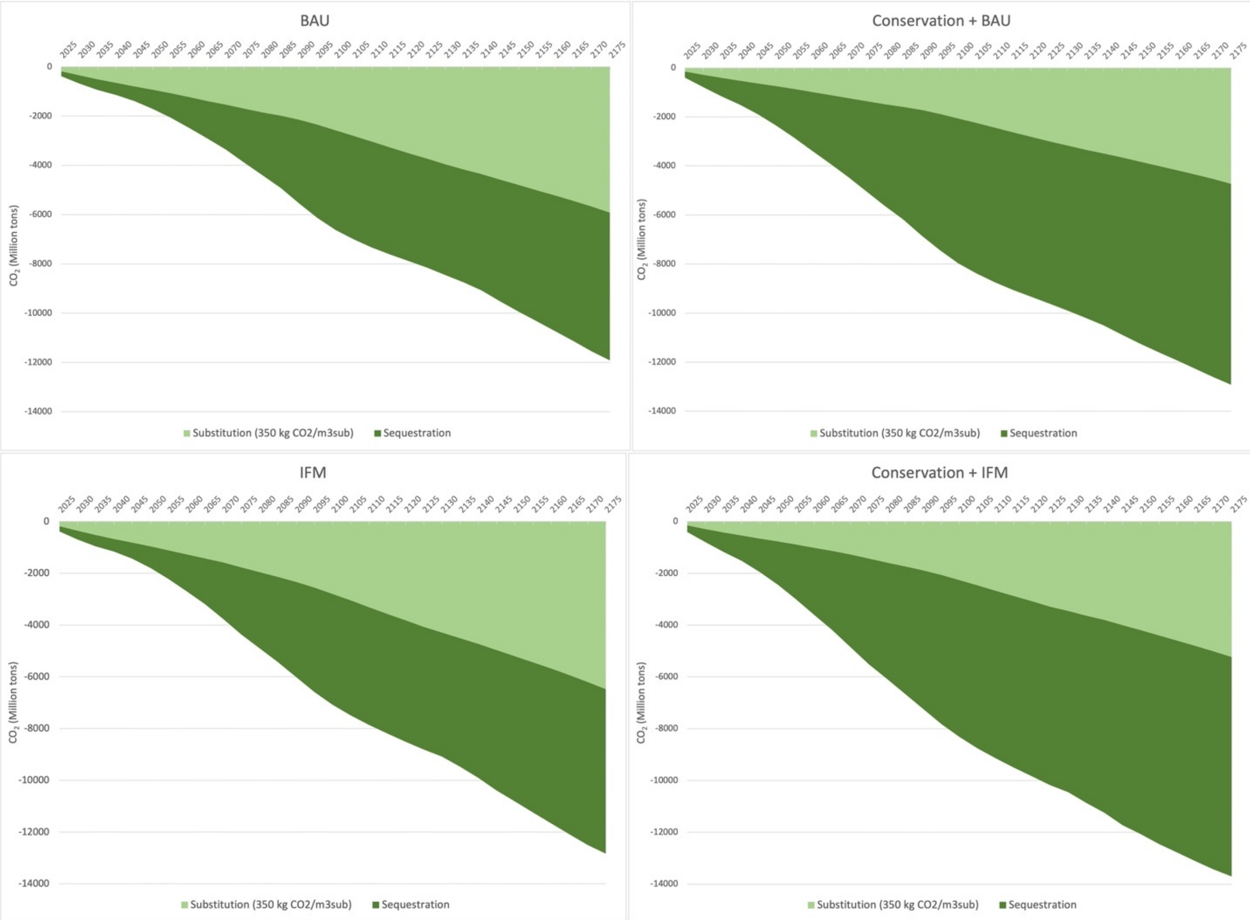


Fig 12*: The distribution of sequestration of CO_2 and the avoided emissions achieved through substitution for the different forest management regimes under a substitution level of 350 kg CO_2/m^3sub*

6. Discussion

This study investigated the climate mitigation potential of four different forest management regimes under three potential future levels of substitution. The different forest management regimes considered were, Business As Usual (*BAU)*, Intensive Forest Management (*IFM)*, increased conservation in combination with Business As Usual (*Conservation + BAU)*, and increased conservation in combination with Intensive Forest Management (*Conservation + IFM)*. The three levels of potential future substitution effect aimed to reflect scenarios in which the level of avoided emissions per m^3sub is either kept at the current level of approximately 500 kg CO_2/m^3sub*,* is increased to 750 kg CO_2/m^3sub, or is decreased to 350 kg CO_2/m^3sub. The simulations of the different forest management regimes were performed with the Heureka RegWise simulator (Wikström et al., 2011). Based on the resulting data regarding forest carbon stock changes, harvest of timber and pulpwood, and biofuel extraction, the accumulated climate mitigation potential was calculated for each level of potential future substitution effect. The impact on climate mitigation can be divided between the sequestration of CO_2 and the avoided emissions achieved through substitution.

The results showed that the regimes with increased conservation achieved a significantly higher sequestration of CO_2 throughout the whole period (Fig 4). While the vice versa was true in terms of avoided CO_2 emissions achieved through substitution (Fig 6). This is well in line with what can be expected, as increased conservation naturally results in a larger share of the forest acting as a carbon sink while consequently offering less biomass to be used for substitution. The results also showed that the regimes with a more intensive forest management achieved a higher amount of avoided CO_2 emissions achieved through substitution, but also a slightly higher sequestration of CO_2. Enhanced forest growth in the production forest will increase the volume of forest biomass to be harvested, and thereby increase the amount of avoided CO_2 emissions that can be achieved through substitution. However, it also seems to increase the overall carbon stock in the production forest.

The total climate mitigation potential was in this study equated with the sum of sequestrated CO_2 and the avoided CO_2 emissions achieved through substitution. The relationship between the different forest management regimes regarding climate mitigation potential varies over time depending on which substitution level that was applied. Under a substitution level of 500 kg CO_2/m^3sub the regimes with increased conservation provides a higher climate mitigation potential during a majority of the 150-year period (Fig 7). The difference does, however, diminish over time. This relationship can be explained by the set-aside forest's diminishing ability to sequester additional CO_2 over time, while the ability to avoid emissions through substitution remains. How rapidly the regimes without increased conservation are able to catch up is influenced by the level of substitution achieved. Under a substitution level of 750 kg CO_2/m^3sub the difference between the regimes with increased conservation and those without becomes less distinct as the significance of substitution increases. The regimes without increased conservation are, therefore, able to catch up before the end of the simulation (Fig 9). Whereas under a substitution level of 350 kg CO_2/m^3sub the difference between the regimes with increased conservation and those without instead becomes more distinct and the regimes without increased conservation are not able to catch up before the end of the simulation (Fig 11).

With increasing concern about the forest's role as a climate regulator, the number of studies analyzing the trade-offs and synergies between different forest management regimes and their implications for climate mitigation has grown rapidly in recent years (Braun et al., 2016; Gustavsson et al., 2017; Hurmekoski et al., 2020; Lundmark et al., 2014; Seppälä et al., 2019; Soimakallio et al., 2021; Werner et al., 2010). There seems to exist a consensus that increased conservation provides a greater climate mitigation potential in the short to medium term, while a maintained or increased harvest may provide a greater climate mitigation potential in the long term. This study's results further support this notion while also offering a wider perspective in which the prospect of either an increased or decreased substitution effect is considered. Increased utilization of growth enhancing practices have in previous studies been identified as an effective tool to boost the climate mitigation potential of forest management (Gustavsson et al., 2017; Lundmark et al., 2014). This notion is also supported by the results in this study.

Estimating the climate mitigation potential of different forest management regimes includes many uncertainties. The forest's ability to sequester CO_2 over time and the impact forest management have on soil carbon is still a subject for debate (Jandl et al., 2007; Luyssaert et al., 2008; Mayer et al., 2020). Other variables, such as changes in albedo and the forest's natural release of cooling aerosols, will also impact the overall climate mitigation potential of forest management (Kalliokoski et al., 2020; Kulmala et al., 2014). It was, however, beyond the scope of this study to include the impact of these effects. The simulations in this study adopted a climate scenario in accordance with RCP 4.5 (Thomson et al., 2011). This results in a significant growth-enhancing effect over time due to more favorable growth conditions. It will, however, also result in an increased risk for both biotic and abiotic disturbances (Seidl et al., 2017). The impact a modified disturbance regime could have on forest growth was not taken into account in this study. It is, therefore, possible that this study has overestimated the overall forest growth. A modified disturbance regime would likely influence the climate mitigation potential of the different forest management regimes considered in this study. Active forest management could facilitate a more rapid adaptation to climate change (Keenan, 2015). While it is at the same time well established that unmanaged forests with high biodiversity are more resistant to disturbances (Jandl et al., 2019). The fact that the market for forest products and forest raw material is highly globalized adds an additional degree of complexity. A reduced harvest level in Sweden may not necessarily reduce the total global consumption as it is possible that this reduction is compensated by increased harvest outside of Sweden. Since climate change is a global issue, reduced harvest in Sweden may, therefore, not necessarily lead to increased climate mitigation if it isn't coupled with a decrease in overall wood consumption. To complicate things even further, some scholars argue that the concept of a substitution effect is misleading if the use of HWPs is not matched with a verifiable global reduction in the use of non-wood products (Leturcq, 2020; Howard et al., 2021). In other words, it is disputed whether or not HWPs reduces the use of non-wood products or if they simply add to the total global material consumption.

The use of forest biomass for bioenergy has been promoted as a climate-neutral energy source. However, the climate neutrality of using forest biomass for energy has become increasingly questioned in recent years (Booth, 2018; Searchinger et al., 2018; Norton et al., 2019). Emissions from forest harvest are accounted to the LULUCF sector. Soo to avoid double counting, the emissions from the combustion of forest biomass are counted as zero. Although, in reality the combustion of biomass naturally results in CO_2 emissions. This fact has led scholars to challenge the use of forest biomass for energy. To assess the climatic impact of bioenergy different aspects needs to be considered. The main aspect that needs to be considered is how the use of forest biomass for energy affects the forest carbon balance. If the biomass is sourced from a sustainably managed forest landscape in which the forest volume is maintained or increased, the use of forest biomass for energy does not increase the concentration CO_2 in the atmosphere. It is, thereby, a fundamental difference between biogenic and fossil fuel emissions as the biogenic emissions is part of a natural carbon cycle and does not add additional CO_2 to the atmosphere if the forest biomass is sourced from sustainably managed forests, while the combustion of fossil fuels always increases the concentration of CO_2 in the atmosphere. However, if the forest biomass is sourced from an un-sustainably managed forest landscape where the forest volume is allowed to decline, it would lead to an increased concentration of CO_2 in the atmosphere. Another important aspect is whether or not the forest biomass is sourced from by-products and residues from other forestry operations in which the carbon stored in the biomass due to decay would have been emitted to the atmosphere regardless, albeit at a lower rate, or if it is sourced from high-quality timber in which the forest biomass could have been utilized to produce HWPs with a substantially higher substitution effect.

It should be noted that this study adopted a highly simplified approach in terms of estimating the avoided emissions offered by substitution. No distinction was made between different categories of harvested biomass, as the same average substitution effect was assumed for all categories. A more in-depth analysis is needed to examine how different forest management regimes would affect the distribution between these categories, and how this in turn would influence the overall substitution effect. Furthermore, while a more intensive forest management would increase forest growth, there are concerns about the negative impact they could have on other environmental and social values (Brännlund et al., 2012; Lindkvist et al., 2012). The current Swedish Forestry Act stipulates a land-sharing approach where different economic, environmental, and social values are to coexist on the same forest area. A forest management regime with increased conservation combined with a more intensive management in the production forest can instead be regarded as a land-sparing approach in which some forest area is managed more intensively while a larger share of the forest is left unmanaged. The two different approaches have been widely discussed and both come with distinct trade-offs and synergies between different forest values (Eggers et al., 2019).

The answer to the burning question of how the forest should be managed to provide optimal climate mitigation largely depends on what time and system perspective that is applied, and how large the substitution effect may be in the future. Increased conservation will likely provide a greater climate mitigation in the short to medium term. While maintained and increased harvest is likely to provide greater climate mitigation in the long term, assuming that the substitution effect is kept at a high level. It is, therefore, possible to argue for either increased conservation or a maintained harvest level depending on which time horizon that is applied. However, given the urgency of reducing the concentration of GHGs in the atmosphere if we are to avoid setting of irreversible and self-reinforcing warming, it is reasonable to question the climate benefit of a high harvest level. Especially if the harvested biomass is used to produce short-lived products with a low substitution effect. Furthermore, an answer to how the forest should be managed must also consider other values associated with the forest, such as social, cultural, environmental, and economic values.

7. Conclusion

The purpose of this study was to compare the climate mitigation potential of four different forest management regimes under three potential future levels of substitution effect. The climate mitigation potential offered by forest management is influenced by the level of CO_2 sequestration in the growing forest as well as the substitution effect offered by harvested biomass. The results from this study showed a greater initial climate mitigation potential for the forest management regimes with a larger forest area set aside for conservation. This divergence, however, tends to diminish over time due to the set-aside forest's declining ability to sequester CO_2. How rapidly the regimes without increased conservation are able to catch up is influenced by the substitution level. The results also showed a higher climate mitigation potential for the forest management regimes with increased utilization of growth enhancing practices. Which forest management regime that provide the highest climate mitigation potential therefore varies depending on the time horizon, level of substitution, and how intensively the forest is managed.

Long-term simulations of forest management include many uncertainties. The models may overestimate certain parameters while underestimating others. The potential influence of a modified disturbance regime in the future was not included in this study. Neither was the impact from an altered albedo and the release of cooling aerosols. These limitations should be taken into consideration when interpretating the results from this study.

Forest management will have an essential role to play in the effort to tackle climate change. The findings from this study may provide policymakers with valuable insights on how different forest management regimes coupled with different potential future substitution levels may influence the climate mitigation potential of the Swedish forest over time. However, further research is needed to evaluate different trade-offs and synergies concerning other social, environmental, and economic values connected to the forest.

8. Acknowledgement

I would like to thank the following people who have guided and supported me through this interesting topic. Firstly, I would like to thank my supervisor, Associate Professor Camilla Widmark, for providing me with valuable feedback throughout this project. I would also like to thank my subject reviewer, Eva-Maria Nordström, for her helpful insights on my work. And last but not least, I would like to thank Jeannette Eggers, for guiding me through the realm of RegWise.

9. References

Andersson, B., Bergh, J., Claesson, S., Duvemo, K., Fridh, M., Lundström, A., Nilsson, U., Nordfjell, T., Svensson, S. A. & Sollander, E. (2008). Skogliga konsekvensanalyser 2008 – SKA-VB 08. Jönköping: Skogsstyrelsen

Appelstrand, M., 2007. Miljömålet i skogsbruket: Styrning och frivillighet. Lund Studies in Sociology of Law 26. Lund University, Lund (Doctoral Thesis).

Appelstrand, M., 2012. Developments in Swedish forest policy and administration – from a "policy of restriction" toward a "policy of cooperation." Scandinavian Journal of Forest Research 27, 186–199. https://doi.org/10.1080/02827581.2011.635069

Bergh, J., Egnell, G., Lundmark, T, 2020. Skogsskötselserien kapitel 21, Skogens kolbalans och klimatet. Skogsstyrelsen.

Berndes, G., Goldmann, M., Johnsson, F., Lindroth, A., Wijkman, A., & Abt, B. et al. (2018). Manage for maximum wood production or leave the forest as a carbon sink?. Retrieved 5 May 2021, from https://cfs.nrcan.gc.ca/publications?id=39466

Berner, R.A. & Lasaga, A.C. 1989, "Modeling the Geochemical Carbon Cycle", *Scientific American,* [Online], vol. 260, no. 3, pp. 74-81

Booth, M.S. 2018; "Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy", *Environmental research letters,* vol. 13, no. 3, pp. 35001.

Braun, M., Fritz, D., Weiss, P., Braschel, N., Büchsenmeister, R., Freudenschuß, A., Gschwantner, T., Jandl, R., Ledermann, T., Neumann, M., Pölz, W., Schadauer, K., Schmid, C., Schwarzbauer, P., Stern, T., 2016. A holistic assessment of greenhouse gas dynamics from forests to the effects of wood products use in Austria. Carbon Management 7, 271–283. https://doi.org/10.1080/17583004.2016.1230990

Brännlund, R., Carlén, O., Lundgren, T., Marklund, P.-O., 2012. The Costs and Benefits of Intensive Forest Management. J. Benefit Cost Anal. 3, 1–23. https://doi.org/10.1515/2152-2812.1105

Brown, C., Alexander, P., Arneth, A., Holman, I. & Rounsevell, M. 2019, "Achievement of Paris climate goals unlikely due to time lags in the land system", *Nature climate change,* vol. 9, no. 3, pp. 203-208.

Brown, M.S., Munro, D.R., Feehan, C.J., Sweeney, C., Ducklow, H.W. & Schofield, O.M. 2019, "Enhanced oceanic CO2 uptake along the rapidly changing West Antarctic Peninsula", *Nature climate change,* vol. 9, no. 9, pp. 678-683.

Cementa AB. (2018). *Färdplan cement för ett klimatneutralt betongbyggande*. Cementa AB. Retrieved from: https://www.cementa.se/sv/system/files_force/assets/document/fardplan_cement-for_klimatneutralt_betongbyggande-20180424.pdf?download=1

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., ... & Thornton, P. (2013). Carbon and other biogeochemical cycles. In *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 465-570). Cambridge University Press.

Claesson, S., Duvemo, K., Lundström, A., & Wikberg, P.-E. (2015). Skogliga konsekvensanalyser 2015 - SKA 15. Skogsstyrelsen, SLU. Jönköping: Skogsstyrelsens böcker och broschyrer.

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., ... & Masera, O. (2015). Bioenergy and climate change mitigation: an assessment. *Gcb Bioenergy*, *7*(5), 916-944.

De Jong, J, Akselsson, C, Egnell, G, Löfgren, S & Olsson, BA 2018, *Miljöpåverkan av skogsbränsleuttag: En syntes av forskningsläget baserat på Bränsleprogrammet hållbarhet 2011-2016*. ER, no. 2, vol. 2018, vol. 2018:02, Energimyndigheten. <https://energimyndigheten.a-w2m.se/FolderContents.mvc/Download?ResourceId=5723>

Dekker, M.M., Von Der Heydt, Anna S & Dijkstra, H.A. 2018, "Cascading transitions in the climate system", *Earth system dynamics,* vol. 9, no. 4, pp. 1243-1260.

Eggers, J., Holmgren, S., Nordström, E. M., Lämås, T., Lind, T., & Öhman, K. (2019). Balancing different forest values: Evaluation of forest management scenarios in a multi-criteria decision analysis framework. *Forest Policy and Economics*, *103*, 55-69.

Eriksson, H., Fahlvik, N., Freeman, M., Fries, C., Jönsson, A. M., Lundström, A., ... & Wikberg, P. E. (2015). *Effekter av ett förändrat klimat-SKA 15*. Skogsstyrelsen.

FAO and UNEP. 2020. The State of the World's Forests 2020. Forests, biodiversity and people. Rome. https://doi.org/10.4060/ca8642en

FAO, 2001: Global Forest Resources Assessment 2000, Rome, Italy.

FAO. (2010). Global forest resource assessment 2010. Terms and definitions. Retrieved 3 March 2021, from http://www.fao.org/3/am665e/am665e00.pdf

Fridman, J., Holm, S., Nilsson, M., Nilsson, P., Ringvall, A., Ståhl, G., 2014. Adapting National Forest Inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century. Silva Fenn. 48. https://doi.org/10.14214/sf.1095

Friedlingstein, P., Jones, M. W., O'sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., ... & Zaehle, S. (2019). Global carbon budget 2019. *Earth System Science Data*, *11*(4), 1783-1838.

Gustavsson, L., Haus, S., Lundblad, M., Lundström, A., Ortiz, C.A., Sathre, R., Truong, N.L., Wikberg, P.-E., 2017. Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels. Renewable and Sustainable Energy Reviews 67, 612–624. https://doi.org/10.1016/j.rser.2016.09.056

Hanssen, S.V., Daioglou, V., Steinmann, Z.J.N., Doelman, J.C., Vuuren, V., D.P & Huijbregts, M.A.J. 2020, "The climate change mitigation potential of bioenergy with carbon capture and storage", *Nature climate change,* vol. 10, pp. 1023-1029.

Hawkins, E., Ortega, P., Suckling, E., Schurer, A., Hegerl, G., Jones, P., ... & van Oldenborgh, G. J. (2017). Estimating changes in global temperature since the preindustrial period. *Bulletin of the American Meteorological Society*, *98*(9), 1841-1856.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A. & Hatziolos, M.E. 2007, "Coral Reefs under Rapid Climate Change and Ocean Acidification", *Science (American Association for the Advancement of Science),* vol. 318, no. 5857, pp. 1737-1742.

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., ... & Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, *579*(7797), 80-87.

Hurmekoski, E., Myllyviita, T., Seppälä, J., Heinonen, T., Kilpeläinen, A., Pukkala, T., Mattila, T., Hetemäki, L., Asikainen, A., Peltola, H., 2020. Impact of structural changes in wood-using industries on net carbon emissions in Finland. Journal of Industrial Ecology 24, 899–912. https://doi.org/10.1111/jiec.12981

IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253–268. https://doi.org/10.1016/j.geoderma.2006.09.003

Joos, F. & Spahni, R. 2008, "Rates of Change in Natural and Anthropogenic Radiative Forcing over the Past 20,000 Years", *Proceedings of the National Academy of Sciences - PNAS,* vol. 105, no. 5, pp. 1425-1430.

Kalliokoski, T., Bäck, J., Boy, M., Kulmala, M., Kuusinen, N., Mäkelä, A., Minkkinen, K., Minunno, F., Paasonen, P., Peltoniemi, M., Taipale, D., Valsta, L., Vanhatalo, A., Zhou, L., Zhou, P. & Berninger, F. 2020, "Mitigation Impact of Different Harvest Scenarios of Finnish Forests That Account for Albedo, Aerosols, and Trade-Offs of Carbon Sequestration and Avoided Emissions", *Frontiers in Forests and Global Change,* vol. 3.

Karakaya, E., Nuur, C., & Assbring, L. (2018). Potential transitions in the iron and steel industry in Sweden: towards a hydrogen-based future?. *Journal of cleaner production*, *195*, 651-663.

Keenan, R.J. 2015, "Climate change impacts and adaptation in forest management: a review", *Annals of forest science.,* vol. 72, no. 2, pp. 145-167.

Kulmala, M., Nieminen, T., Nikandrova, A., Lehtipalo, K., Manninen, H.E., Kajos, M.K., Kolari, P., Lauri, A., Petäjä, T., Krejci, R., Hansson, H.-C., Swietlicki, E., Lindroth, A., Christensen, T.R., Arneth, A., Hari, P., Bäck, J., Vesala, T., Kerminen, V.-M., 2014. CO2-induced terrestrial climate feedback mechanism: From carbon sink to aerosol source and back 19, 10.

Kungliga Skogs- och Lantbruksakademien (KSLA). (2015). Forests and Forestry in Sweden. Retrieved 4 May 2021, from https://www.skogsstyrelsen.se/globalassets/in-english/forests-and-forestry-in-sweden_2015.pdf

Ledley, T. S., Sundquist, E. T., Schwartz, S. E., Hall, D. K., Fellows, J. D., & Killeen, T. L. (1999). Climate change and greenhouse gases. *Eos, Transactions American Geophysical Union*, *80*(39), 453-458.

Lehmann, S. (2013). Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions. *Sustainable Cities and Society*, *6*, 57-67.

Lenton, T.M. 2011, "Early warning of climate tipping points", *Nature climate change,* vol. 1, no. 4, pp. 201-209.

Lenton, T.M. 2012, "Arctic Climate Tipping Points", *Ambio,* vol. 41, no. 1, pp. 10-22.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. & Schellnhuber, H.J. 2019, "Climate tipping points - too risky to bet against", *Nature (London),* vol. 575, no. 7784, pp. 592-595.

Leskinen, P., Cardellini, G., González-García, S., Hurmekoski, E., Sathre, R., Seppälä, J., Smyth, C., Stern, T., Verkerk, P. J., & European Forest Institute. (2018). *Substitution effects of wood-based products in climate change mitigation* (From Science to Policy) [From Science to Policy]. European Forest Institute. https://doi.org/10.36333/fs07

Leturcq, P. 2020, "GHG displacement factors of harvested wood products: the myth of substitution", *Scientific reports,* vol. 10, no. 1, pp. 20752.

Lindahl, K.B., Sténs, A., Sandström, C., Johansson, J., Lidskog, R., Ranius, T., Roberge, J.-M., 2017. The Swedish forestry model: More of everything? Forest Policy and Economics 77, 44–55. https://doi.org/10.1016/j.forpol.2015.10.012

Lindkvist , A., Mineur, E., Nordlund, A., Nordlund, C., Olsson, O., Sandström, C, Westin, K., Keskitalo, E. C. H. (2012). Attitudes to intensive forestry: An investigation of perceptions of increased production requirements in Swedish forestry. Scandinavian Journal of Forest Research. 1-11.

Lindroth, A., Lagergren, F., Grelle, A., Klemedtsson, L., Langvall, O. L. A., Weslien, P. E. R., & Tuulik, J. (2009). Storms can cause Europe-wide reduction in forest carbon sink. *Global change biology*, *15*(2), 346-355.

Lontzek, T.S., Cai, Y., Judd, K.L. & Lenton, T.M. 2015, "Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy", *Nature climate change,* vol. 5, no. 5, pp. 441-444.

Lundmark, T., Bergh, J., Hofer, P., Lundström, A., Nordin, A., Poudel, B., Sathre, R., Taverna, R., Werner, F., 2014. Potential Roles of Swedish Forestry in the Context of Climate Change Mitigation. Forests 5, 557–578. https://doi.org/10.3390/f5040557

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215. https://doi.org/10.1038/nature07276

Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.-P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020. Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. Forest Ecology and Management 466, 118127. https://doi.org/10.1016/j.foreco.2020.118127

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Naqi, A. & Jang, J.G. 2019, "Recent Progress in Green Cement Technology Utilizing Low-Carbon Emission Fuels and Raw Materials: A Review", *Sustainability (Basel, Switzerland),* vol. 11, no. 2, pp. 537.

National Oceanic and Atmospheric Administration (NOAA). (2021). Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases. Retrieved 2 March 2021, from https://www.esrl.noaa.gov/gmd/ccgg/trends/

Naturvårdsverket, 2020. Utsläpp och upptag av växthusgaser från markanvändning. (LULUCF). Retrieved 6 May 2021, from http://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-utslapp-och-upptag-fran-markanvandning/?visuallyDisabledSeries=bcfbd5485e7f5819

Nidheesh, P. V., & Kumar, M. S. (2019). An overview of environmental sustainability in cement and steel production. *Journal of Cleaner Production, 231*, 856-871. https://doi.org/10.1016/j.jclepro.2019.05.251

Nilsson, U., Fahlvik, N., Johansson, U., Lundström, A. & Rosvall, O. 2011, "Simulation of the Effect of Intensive Forest Management on Forest Production in Sweden", *Forests,* vol. 2, no. 1, pp. 373-393.

Norton, M., Baldi, A., Buda, V., Carli, B., Cudlin, P., Jones, M. B., ... & Wijkman, A. (2019). Serious mismatches continue between science and policy in forest bioenergy. *GCB Bioenergy*, *11*(11), 1256-1263.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., ... & Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, *355*(6332).

Pei, M., Petäjäniemi, M., Regnell, A. & Wijk, O. 2020, "Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland", *Metals (Basel),* vol. 10, no. 7, pp. 972.

Raftery, A.E., Zimmer, A., Frierson, D.M.W., Startz, R. & Liu, P. 2017, "Less Than 2 °C Warming by 2100 Unlikely", *Nature climate change,* vol. 7, no. 9, pp. 637-641.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., ... & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature*, *534*(7609), 631-639.

Röstlund, L. (2021). Klimatet – frågan som splittrar den svenska skogsforskningen - DN.SE. Retrieved 15 March 2021, from https://www.dn.se/sverige/klimatet-fragan-som-splittrar-den-svenska-skogsforskningen/

Sathanandam, T., Awoyera, P. O., Vijayan, V., & Sathishkumar, K. (2017). Low carbon building: Experimental insight on the use of fly ash and glass fibre for making geopolymer concrete. *Sustainable Environment Research*, *27*(3), 146-153.

Searchinger, T. D., Beringer, T., Holtsmark, B., Kammen, D. M., Lambin, E. F., Lucht, W., ... & van Ypersele, J. P. (2018). Europe's renewable energy directive poised to harm global forests. *Nature communications*, *9*(1), 1-4.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O., 2017. Forest disturbances under climate change. Nature Clim Change 7, 395–402. https://doi.org/10.1038/nclimate3303

Seppälä, J., Heinonen, T., Pukkala, T., Kilpeläinen, A., Mattila, T., Myllyviita, T., Asikainen, A., Peltola, H., 2019. Effect of increased wood harvesting and utilization on required greenhouse gas displacement factors of wood-based products and fuels. Journal of Environmental Management 247, 580–587. https://doi.org/10.1016/j.jenvman.2019.06.031

Skogforsk. WeCalc – räkna på skogsbränsle - Skogforsk. Retrieved 6 May 2021, from https://www.skogforsk.se/produkter-och-evenemang/verktyg/wecalc/

Skogsdata 2020. SLU, inst. för skoglig resurshushållning. Tillgänglig på: https://www.slu.se/globalassets/ew/org/centrb/rt/dokument/skogsdata/skogsdata_2020_webb.pdf.

Smith, K., Woodward, A., Campbell-Lendrum, D., Chadee, D., Honda, Y., Liu, Q., ... & BUTLER, C. (2014). Human health: impacts, adaptation, and co-benefits. In *Climate Change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of*

Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change (pp. 709-754). Cambridge University Press.

Soimakallio, S., Kalliokoski, T., Lehtonen, A., Salminen, O., 2021. On the trade-offs and synergies between forest carbon sequestration and substitution. Mitig Adapt Strateg Glob Change 26, 4. https://doi.org/10.1007/s11027-021-09942-9

Stott, P. 2016, "How climate change affects extreme weather events", *Science (American Association for the Advancement of Science),* vol. 352, no. 6293, pp. 1517-1518.

Swedish Forest Industries. The Swedish model of forestry. Retrieved 7 May 2021, from https://www.forestindustries.se/bioeconomylife/how-we-manage-the-forest/the-swedish-model-of-forestry/

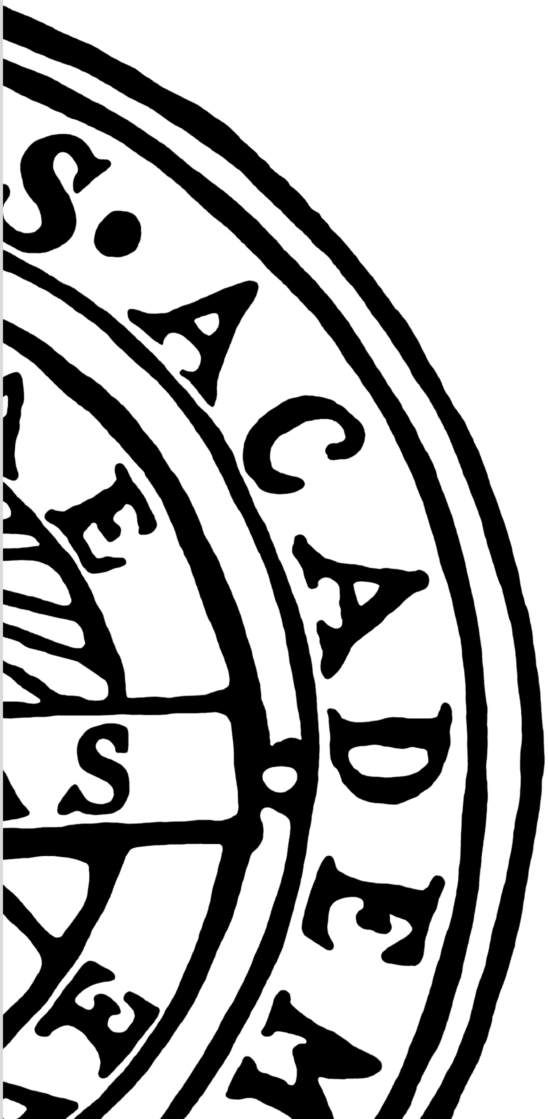
Thomson, A.M., Calvin, K.V., Smith, S.J., Kyle, G.P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M.A., Clarke, L.E., Edmonds, J.A., 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change 109, 77–94. https://doi.org/10.1007/s10584-01101514

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A., ... & McGuire, A. D. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*, *13*(2), 138-143.

Werner, F., Taverna, R., Hofer, P., Thürig, E., Kaufmann, E., 2010. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environmental Science & Policy 13, 72–85. https://doi.org/10.1016/j.envsci.2009.10.004

Wikström, P., Edenius, L., Elfving, B., Eriksson, L.O., Lämås, T., Sonesson, J., Öhman, K., Wallerman, J., Waller, C., Klintebäck, F., 2011. The Heureka forestry decision support system: An overview. Mathematical and Computational Forestry and Natural-Resource Sciences 3, 87-95.

Ågren, G.I., Hyvönen, R., Nilsson, T., 2008. Are Swedish forest soils sinks or sources for CO2—model analyses based on forest inventory data. Biogeochemistry 89, 139–149. https://doi.org/10.1007/s10533-007-9151-x


S·ACADEM