Rapport 2023/10

Effect of some forestry measures on the carbon sink in Sweden

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Ver 221130

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Preface

Forest as a carbon sink play an important role for climate action. Therefore, there is a need to increase knowledge and understanding on how different forestry measures can influence carbon sequestration and release of carbon dioxide in the forest.

This report illustrates the estimated effects of forestry measures for increased carbon sink based on analyses carried out within the project Forest Impact Assessment 2022 (Skogliga Konsekvensanalyser - SKA22). The measures that are included in this report should not be interpreted as suggestions by the Swedish Forest Agency on what should be implemented. The report rather constitutes a basis for knowledge.

The report was developed by the Swedish Forest Agency in connection to the government's assignment to strategically plan for increased carbon sinks. The main report for that assignment was presented in December 2022 together with the interim report "Overview of forestry measures for increased carbon sinks", which provides additional knowledge base.

We warmly thank all employees at the Agency and others that contributed with valuable comments and inputs. We especially want to thank the researchers from SLU for a constructive and valuable collaboration.

Jönköping, 2023-08-17

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Summary

This report aims to describe the effect of selected forestry measures on the forest carbon balance, compared to current forest management. The results are based on model simulations done by SLU in the decision support system Heureka RegWise within the project “Forest Impact Assessment – SKA 22”. The analysed measures in this report are among the measures included in the forest management scenarios in SKA 22 and that were identified as measures that have a potential to affect the forest carbon sink. The report includes a quantitative analysis of the effects of the measures on forest growth, growing stock, felling and natural mortality as well as on carbon stocks and fluxes in different carbon pools, including harvested wood products. The effect of the measures on soil carbon was excluded in the report because of uncertainties in model simulations of soil carbon.

The results are confined to the effects on the carbon sink in Swedish forests and do not include leakage or substitution effects. Only a qualitative discussion on those effects is included.

The measures which were separately analysed are:

- Reduce browsing damage in young forests from 12 to 5 percent (DAM-)
- Longer rotation periods by increasing the youngest age for final felling by 30 percent (ROT+)
- Three-fold increase of area which is regenerated with birch compared to current practice (BRD+)
- A quarter of production[1] forest area is managed with continuous cover forestry (patch cutting and selective cutting) compared with 4 percent today (CCF+)
- Forest area fertilized with nitrogen is 4.5 times larger than today (FERT+)
- Set-aside forest area is twice as large as today (CONS+)
- Felling is reduced by 10 percent compared to today’s level (FELL90%)

Except for model simulations in FELL90%, the volume of felling was constrained to the same level as reported in recent statistics, i.e., to the same felling intensity as in the business-as-usual scenario. This implies that if a measure leads to less intensive forest management in some forest areas, felling increases in other parts of the country to maintain the same felled volume as today.

According to model results, the measure FELL90% can potentially increase the carbon sink both in the short (30 years) and long term (80-100 years) (-9.6 Mton

[1] Production forest area is the area of forest suitable for wood production that is not protected and where management is not restricted; productive forest is forest suitable for wood production but that can also be protected or set aside.

CO_2/y until 2100). ROT+ can also contribute to an increased carbon sink (-7.5 Mton CO_2/y until 2100), according to simulations. This effect is mainly linked to a temporary reduced felling och partially to a change in age-class distribution in model projections. ROT+ indicates that the felling only can be maintained in Götaland (southern Sweden), while it needs to be temporary reduced in other parts of the country. According to model results, CONS+ will not contribute to an increased carbon sink when the remaining production forestland is managed more intensively to maintain the current felled volume. CONS+ reduces the simulated carbon sink by 1.3 Mton CO_2/y until 2100 when the felled volume remains unchanged.

A reduced felling in Sweden leads to a reduced supply of wood products. This can reduce the possibility of substitution, i.e., that forest products substitute other materials and fuels with a higher climate impact. It can also lead to leakage which implies increased felling och lower carbon sink in other countries. Neither leakage effects nor substitution are included in the results of this report because the report focuses on carbon sink in Swedish forests. A reduced felling also leads to Swedish forests being on average older which can imply a higher risk for damage from natural disturbances and thereby release of greenhouse gases. Climate adaptation will play an important role to reduce the risk for damage, but its effect is not included in the analysis.

Other measures that can have a more long-term positive effect on the carbon sink according to model results is DAM- and, to a lesser extent, FERT+ (-5.3 and -2.1 Mton CO_2/y until 2100, respectively). Further analysis would be needed to investigate in which way browsing damage can be reduced in practice in different part of the country and how the implemented measures would affect the forest carbon sink.

Nitrogen fertilization has a limited effect on the carbon sink according to model results and it can be expected to lead to conflicts with other ecosystem services (for ex. water quality and pasture for reindeer) which can constrain the possibility to implement this measure and thereby its potential to increase the carbon sink.

The model analysis indicates that BRD+ can reduce the carbon sink by 6.2 Mton CO_2/y until 2100 due to a lower tree growth in birch forests. However, further analysis should be carried out on the positive effect that more broadleaves could have on the risk for damage from natural disturbances and on the effect that other broadleaves species than birch could have on the carbon sink.

Model results suggest that CCF+ does not significantly affect the carbon sink in the forest and harvested wood products as compared to current forest management. The simulation of CCF+ is uncertain regarding the modelling of ingrowth and the choice of forest areas for this type of management in the simulations. The results om CCF+ should therefore be interpreted with caution and further method development and analysis are required concerning this measure.

The results indicates that different measures can be more or less effective in different parts of the country. To identify strategies that combine different measures can therefore be crucial to increase the carbon sink in an effective way.

The simulations suggest that Swedish forests and harvested wood products will continue to be carbon sinks in the coming one hundred years, but the carbon sink will decrease over time regardless of which measure is implemented. A general uncertainty is how forest growth will be affected by a changing climate. Data from the Swedish National Forest Inventory indicates that growth has decreased in the past years, presumably because of summer drought. If droughts become more frequent due to climate change, there is a risk that model results in this report overestimate the carbon sink over time. That is, the carbon sink in Swedish forests can decrease faster than indicated by the results in this report. Therefore, it becomes even more important to identify measures that can preserve or increase the carbon sink in the forest and wood products to achieve current climate goals.

Concerning the comparison between different measures in this report, the climate effect and the frequency of natural disturbances is the same for all measures. In practice, the frequency of damage from natural disturbances is likely to be affected by management actions that are implemented, but this effect is not included here.

1 Introduction

1.1 Aim

The aim of this report is to describe the effect of selected forestry measures for increased carbon sink on the forest carbon balance as compared to current forest management. The results are expected to contribute to an increased understanding and knowledge on how different forestry measures affect carbon sequestration and release of carbon dioxide in the forest.

To reach this aim, the report includes a quantitative analysis of the effects on forest growth, growing stock, felling and natural mortality as well as on the carbon stocks and flows in different pools, including harvested wood products[2]. The analysis is carried out at the national and regional levels to identify which measures can lead to an increased carbon sequestration as compared to the current forest management in different parts of the country. In addition, the effects of the measures are considered in different time perspectives and synergies and conflicts with other environmental goals are discussed. The report also includes a description of risks for leakage when a measure implies a lower wood production and a qualitative description of the effects on substitution.

The results are discussed in comparison with results from published scientific studies to illustrate the uncertainty around the effects of different measures as well as knowledge gaps.

The results are based on analyses that were developed within the project Forest Impact Assessment 2022 (SKA 22) to assess the effects of individual measures on the forest ecosystem, including effects on carbon sequestration. The measures were selected among those that were included in the SKA 22 scenarios.

The analyses include the following measures:

- Reduce browsing damage
- Longer rotation periods
- Reduced felling
- Increased proportion of birch
- Increased use of continuous cover forestry (patch cutting och selective cutting)
- Increased nitrogen fertilization
- Increased set-aside areas

[2] According to the IPCC guidelines, chapter 12, harvest wood products – HWP includes all wood material (including bark) that leaves harvest sites.

1.2 Limitations of the study

The results are based on model simulations developed by SLU in the forestry decision support system Heureka RegWise within the project SKA 22. The measures are analysed individually, and it is not taken into consideration if they are partially implemented on the same forest areas. The aim of the report was to analyse the potential effect of measures for increased carbon sink in the forest, but these measures should not be interpreted as a suggestion by the Swedish Forest Agency on what should be done. A correct interpretation of results should consider that some measures are implemented to a lesser extent than others, which can influence the size of the effect that the measure has on the carbon sink.

The model simulations include an assessment of the carbon stock changes in HWP but does not include an assessment of the effects of the climate benefit via substitution of fossil-based products or displacement of logging in other countries (leakage).

Measures on organic soils, such as rewetting which can lead to great climate benefits is not included in the analysis because the model Heureka RegWise has a limited capability to simulate the soil carbon balance, especially in organic soils.

Because of uncertainties around the model results on soil carbon the effects of the measures on this carbon pool are excluded from the report. Heureka RegWise has a functionality to simulate a starting value for the soil carbon pool and soil carbon stock changes over time. However, tests showed that this starting value is overestimated by the model (Eggers et al., 2022), which leads to uncertainties around changes over time and thereby on the validity of the results on soil carbon. The overestimate was confirmed by further test analyses for this report. In SKA 22 the estimates of soil carbon stock and stock changes are based on the historical soil carbon sink from inventory data in alternative to the simulated starting value. This approach implies though that the carbon sink remains unchanged regardless of the scenario chosen. Therefore, the effects of different measures as compared with the current forest management cannot be assessed by using the approach used in SKA 22. That is, the approach is not suitable for the analyses in this report that aims to compare effects of different measures. However, the report includes a discussion on the effects of the measures on soil carbon based on previous studies.

A further shortcoming regards results on the increased use of continuous cover forestry that in Heureka RegWise is simulated as selective cutting and patch cutting. Test analyses indicates that the simulated tree growth under selective cutting sharply decreases after reiterated thinning from above and this decrease is not comparable with the tree growth which is expected in reality under similar conditions (Eggers et al., 2022). The effects of different continuous cover forestry methods could not be separated and therefore the results on the effect of increased use of continuous cover forestry in the long-term should be considered uncertain.

The results on unproductive forest land are also excluded from the analyses because forest growth and other analysed variables remain unchanged on unproductive forest land when different measures are implemented.

The discussion on synergies and conflicts with other ecosystem services and biodiversity refer to selected ecosystem services and excludes the effects on cultural environments and cultural heritage.

This report does not discuss either which instrument of control could promote the implementation of the analysed measures. However, proposals for policy instruments to deal with barriers for implementing measures for increased carbon sink in the forestry and agricultural sectors were presented in a previous report produced by the Swedish Environmental Protection Agency, the Swedish Forestry Agency and the Swedish Board of Agriculture (NV et al., 2022).

1.3 Climate goals

The UN climate convention was adopted in 1992 and aims to stabilize "the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". With the Paris agreement which entered into force in 2016, countries committed themselves to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels". In 2017, Sweden adopted a Climate Policy Framework and the European Union adopted a new Climate Law in April 2021.

With the Climate Law, the EU has committed itself to achieve carbon neutrality by 2050 and reduce the net greenhouse gas emissions by at least 55% by 2030 compared to levels in 1990. In March 2023, the regulation of the EU Parliament and the Council to set a target to be achieved by 2030 within the Land Use, Land-Use Change and Forestry sector (LULUCF sector) was adopted. This sets a target for 310 million tons carbon dioxide equivalents (Mton CO_2e) of net removals within the LULUCF sector at the EU level, which is about 15% higher than today. For Sweden it means that the removals shall increase with 4 Mton CO_2e by 2030 compared with the average removals in 2016-2018.

Sweden's goal is to have zero net emissions of greenhouse gases to the atmosphere by 2045 and reach negative emissions after that. The emissions from the Swedish territory shall be 85% lower in 2045 compared to 1990. The remaining 15% emissions can be achieved through supplementary measures which also include removals of CO2 within the LULUCF-sector. Compared to the EU target, the Swedish goal does not imply a specific quantitative target within the LULUCF-sector. Further measures are needed to achieve the new EU target by 2030 and to compensate for the emissions that will remain by 2045.

1.4 Interplay with other environmental goals

Forest delivers multiple ecosystem services (Hassan et al., 2005) and therefore it can contribute to achieve several environmental and sustainability goals such as the Sustainable Development Goals "Life on land", "Climate action" and "Good health and well-being". The forest's ability to fulfill several functions at the same time constitutes a key resource for a society that strives to reduce its environmental impact and to promote welfare for all.

However, the relationships between different ecosystem services and biodiversity are not always positive or linear (Biber et al., 2020; Jopke et al., 2015). Therefore, measures that are optimal to achieve a single goal are most likely not optimal to achieve multiple goals at the same time. To achieve greater benefits and reduce costs for the society, it is important to consider synergies and conflicts which selected measures can lead to and promote solutions that can reach a balance between different goals.

In this section, effects of selected forest management practices on some ecosystem services are discussed based on the Swedish Forest Agency's report 2022/15 "Overview of measures for increased carbon sink in the forest" and a selection of scientific studies. Table 1 provides an overview of these effects. The analysis should be considered as an attempt to discuss which strategies for an increased carbon sink can imply a lower risk for negative effects on other ecosystem services and therefore a knowledge base to identify effective measures to achieve climate goals as well as other environmental goals.

Table 1 – Overview of the effects of forest management practices on different ecosystem services. Red: negative effect; orange: likely negative effect; blue: no effect; light green: likely positive effect; dark green: positive effect; grey: unknown/uncertain effect.

Measure	Ecosystem services					Biodiversity
	Wood raw materials	Carbon sink in the forest	Recreation	Grazing for reindeer	Water quality	
Reduced browsing damage	dark green	dark green	light green	grey	light green	light green
Longer rotation periods	orange	dark green	light green	light green	dark green	light green
Increased proportion of broadleaves	grey	grey	dark green	dark green	dark green	dark green
Continuous cover forestry	orange	grey	dark green	light green	dark green	dark green
Nitrogen fertilization	light green	light green	grey	red	red	orange
Increased set-aside	red	light green	dark green	dark green	dark green	dark green
Reduced felling	red	dark green	light green	light green	dark green	light green

A review study shows that browsing damage can have a negative effect on forest growth (Gill, 1992) which can lead to negative effects on the production of wood raw materials and the carbon sink in the forest. On the contrary, positive effects on forest growth, on the production of wood raw materials and on the carbon sink can be expected if browsing damage is reduced. Browsing damage can also affect other ecosystem services and biodiversity. High browsing pressure can lead to forests that are less species-rich (Reed et al., 2022) and therefore reduced browsing damage can have positive effects on biodiversity. However, game browsing can also have positive effects on biodiversity because it can lead to increased heterogeneity at the forest stand level (Edenius et al., 2002). Conflicts with hunting and thus recreation may possibly arise when the population of ungulates is reduced to reduce browsing damage (Sjölander-Lindqvist och Sandström 2019). On the other hand, reduced browsing damage can benefit deciduous trees, which can have positive effects on recreation, water quality and biological diversity. An increased proportion of deciduous trees near watercourses, for example, can have a positive effect on water quality and the aquatic fauna (Maher Hasselquist et al., 2021) and thereby on fishing and recreation. In addition, reduced browsing damage can indirectly affect ecosystem services by increasing the proportion of pine in the forest, which can have positive effects on biodiversity, recreation and resilience to forest disturbances, which in turn can positively affect the production of wood raw materials and the carbon sink in the forest (Felton et al., 2020). Comprehensive analyses on the effects of browsing damage on lichen abundance and thereby grazing for reindeer are lacking.

Longer rotation periods can lead to increased carbon sink in the forest, but also to reduced production of wood raw materials depending on the extent to which the rotation period is extended (Kaipainen et al., 2004; T. Lundmark et al., 2018; Roberge et al., 2016) (Box 1). When the production of wood raw materials is reduced, substitution can be reduced, but the overall climate benefit still appears to be positive (T. Lundmark et al., 2018). Longer rotation periods can have a positive effect on biodiversity due to the fact that habitats important for several species, such as the number of older and large trees increases (Roberge et al., 2016). However, the relationship between biodiversity and stand age appears to vary between studies depending on which indicator and thereby species is chosen to investigate this relationship (Coote et al., 2013; Saraev et al., 2019). Roberge et al. (2016) also summarizes the effects on indicators for recreation, grazing for reindeer and water quality. Longer rotation periods can lead to an increased area of mature forest and less clear-cutting areas at the landscape level, which can have a positive effect on recreation. Positive effects on lichen occurrence and thus grazing for reindeer can only be expected when the rotation period is extended significantly, and forest thinning is adjusted accordingly. Negative effects on water quality linked to clear-cutting, including effects on runoff and erosion, decrease as the rotation period increases (Shah et al., 2022) and therefore positive effects on water quality can be expected.

The effects of an increased proportion of deciduous trees can vary significantly depending on several factors, such as tree species and region, and whether there is increased mixing with other tree species or whether a pure deciduous forest is established. Growth varies greatly among different deciduous trees (Rytter, 2019) and thus the production of wood raw materials and carbon storage. Mixing birch in spruce forests has a positive effect on recreation, water quality and biological diversity, but effects on production and carbon sink are uncertain (Felton m.fl. 2016; Pukkala 2018). A Finnish study based on model simulation over 150 years indicates that forestry that aims to increase the proportion of birch in the forest leads to higher natural beauty and higher biodiversity but lower production of wood raw materials and carbon storage than forestry that promotes coniferous forests (Pukkala, 2018). At the same time, an increased proportion of deciduous trees can contribute to increased variation in the forest landscape and thereby reduce the risk of biomass loss and emissions linked to damage from natural disturbances (Jactel et al., 2017).

Box 1 – Rotation period in Swedish forests

In rotation forestry, the rotation period is of great importance for the production of standing volume, but also for other forest values. To maximize standing volume production, the stocks must be felled when the mean annual increment peaks. The final felling is regulated in the Swedish Forestry Act (1979:429) which specifies the minimum age for final felling (MAF) depending on the fertility of the forest (site index). The MAF is regulated to provide protection to young forests and at the same time give freedom of action to landowners to determine the time of felling based on their management goals. The mean annual increment at MAF is 80–90% of maximum average production and is 10–40 years earlier than the time of maximum average production. This means that if forest stands are usually felled at MAF, the production of standing volume could increase even more if rotation periods are extended. The general effect that a longer rotation period can have at the regional and national level depends also on the age distribution of the forest, i.e., if there are large areas of forest that are older than the set final felling age the felling will not be affected. If, on the other hand, MAF would be increased in the Forestry Act and at the same time no or few forest stands would be available for final felling, the felling would be constrained.

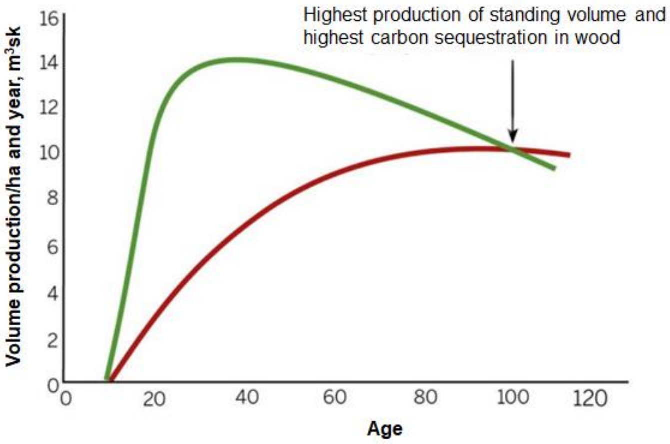

Figure 1- The figure illustrates an example of the development over time of current annual increment (green line) and mean annul increment (red line) in a spruce forest with site index G 32. The site index indicates the maximum height in a forest stand at a reference age, here 100 years. Source: (Lundqvist, Lindroos, et al., 2014)

Continuous cover forestry is a collective term for multiple forest management methods that can affect forest ecosystems in different ways. According to the definition drawn up by the Swedish Forestry Agency, continuous cover forestry means that the forest is managed to maintain a tree cover without implementing clear-cut areas larger than 0.25 hectares and it includes practices such as selective cutting, patch cutting and shelterwood uniform system (Appelqvist et al., 2021). Therefore, effects of continuous cover forestry on different ecosystem services and biodiversity can vary because it can be implemented in different ways in practice. Most published scientific studies that analyse the effects of continuous cover forestry on various ecosystem services and biodiversity focus on methods that involve repeated thinnings aimed at creating uneven-aged forests, i.e., different forms of selective cutting, while knowledge of the effects of other continuous cover forestry methods appears to be very limited. Therefore, in this section only the effects of selective cutting on various ecosystem services and biodiversity are discussed. Scientific studies based on model simulation indicate that an increased use of selective cutting can contribute to increase the multifunctionality of forests in Nordic countries (Eyvindson et al., 2021; Peura et al., 2018; Zanchi & Brady, 2019). Several studies indicate that selective cutting can contribute to diversifying the forest landscape and thus have positive effects on biological diversity (Ekholm et al., 2022; Sténs et al., 2019). It can also lead to forests becoming less dense and thus have a positive effect on lichen flora and grazing for reindeer (Korosuo et al., 2014). Selective cutting can increase the recreational value of the forest and is considered a good alternative for managing forests close to urban areas (Hertog et al., 2022; Vitkova & Ní Dhubháin, 2013). It reduces negative effects on water quality that are linked to clear-cutting, including a reduced risk of landslides and erosion, and can help regulate the groundwater level in peatlands as an alternative to ditch cleaning (Laudon & Maher Hasselquist, 2023; Reynolds, 2004). Whether selective cutting has a positive or negative effect on the carbon balance compared to rotation forestry is uncertain because different effects need to be taken into account at the same time. Selective cutting seems to lead to a reduced tree growth by 10-20 percent than the potential growth in rotation forestry and thus to a lower carbon storage, but the effect can be influenced by local conditions (Lundqvist, Cedergren, et al., 2014). At the same time, research studies suggest that selective cutting has the potential to avoid emissions of greenhouse gases from the soil linked to clear-cutting (Lindroth et al., 2018) and to reduce the risk of damage from natural disturbances and emissions linked to them by creating more diverse forest stands and forest landscapes (Potterf et al., 2022). However, knowledge on the effect of selective cutting on forest resilience to disturbances at the stand level is lacking (Mason et al., 2022) The effect on the carbon stock in harvested wood products is also uncertain because selective cutting can lead to lower production of wood raw materials but also to different types of assortment, which can affect the lifespan of the wood products (Pukkala, 2014).

Nitrogen fertilization is a measure that can increase forest growth where the forest is nitrogen limited (Aber et al., 1989). The positive effect on growth in nitrogen-limited forests can lead to positive effects on the production of wood raw materials and on the carbon storage in the forest ecosystem. At the same time, nitrogen fertilization can have negative effects on other ecosystem services. In Sweden, there is a strong geographical gradient of nitrogen deposition that increases from north-east to south-west (Karlsson et al., 2022). This gradient affects nitrogen availability and can lead to a limited effect of nitrogen fertilization on forest growth and a higher risk for nitrogen leakage in southern Sweden (Akselsson et al., 2010; Hedwall et al., 2013). The Swedish Forestry Agency's General Guidance to the provisions in chapter 7, Section 26 of the Forestry Act indicates that fertilization should not be carried out in Götaland [3] to prevent or limit negative effects that nitrogen fertilization can lead to. Nitrogen fertilization leads to increased nitrogen leakage and thereby deteriorated water quality (Shah m.fl. 2022) and can lead to vegetation changes towards more nitrophilic species, which means that, among other things,

[3] Excepted spruce forests where branches and tops, including bark, have extracted or are planned to be extracted in Area 2 (North Götaland).

lichens and mosses, and thereby grazing for reindeer, are negatively affected (Sandström m.fl. 2016). Therefore, the Swedish Forestry Agency's General Guidance states that fertilization should not take place in lichen-rich forests. Background studies about the effect of fertilization on recreation is lacking. However, it can be expected that dense ground vegetation in fertilized stands can negatively affect the recreational value of forests (Larsson et al., 2009). A review of studies on the effect of nitrogen fertilization on biodiversity concludes that fertilization can lead to changes in flora and fauna and can negatively affect some species, but the effect can vary depending on species groups (Sullivan och Sullivan 2018).

An increase of protected forest areas primarily aims to preserve or increase biodiversity, but at the same time can lead to synergies and conflicts with different ecosystem services (Biber et al., 2020; Eggers et al., 2020; Mazziotta et al., 2022). When production forest land is set aside, the production of wood raw materials can decrease or logging can be moved to other parts of the country or to other countries (R. Lundmark, 2022; Schier et al., 2022). Several studies suggest that increased protection of forests leads to increased carbon storage in the forest ecosystem in the short and medium term, but at the same time increased protection of forests can affect substitution of carbon storage in harvested wood products and thereby the total climate benefits in the long term (Gustavsson et al., 2017; Petersson et al., 2022; Taeroe et al., 2017). Protected forests also have high recreational value (Balmford et al., 2015) and an important role in preserving resources for reindeer husbandry (Kivinen, 2015). However, planning of formally protected forest should take into account stakeholders' perspectives to avoid conflicts linked to restrictions or increased tourism that may affect reindeer husbandry (Hovik et al., 2010). The preservation of forests also leads to positive effects on water quality. This is especially true close to lakes and watercourses that act as chemical and physical filters for nutrients and sediments (Kuglerová et al., 2020; Sweeney & Newbold, 2014) and can prevent landslides and mudflows close to watercourses.

Various forestry measures can be used to reduce felling at landscape level. A reduced felling can be achieved by setting aside forest land from production, by extending rotation periods or using less intensive forestry methods such as various forms of continuous cover forestry. A negative consequence of reduced felling can be that the national production of wood raw materials decreases, which can lead to part of the felling being moved to other countries and to a reduced possibility for substitution (R. Lundmark, 2022). At the same time, reduced felling leads to a higher biomass stock and thus a higher carbon stock in the forest. Therefore, the total climate benefit may vary depending on assumptions about the substitution effect, leakage and in which time perspective the climate benefit is estimated (Schulte et al., 2022; Soimakallio et al., 2021). As reduced felling can be implemented in different ways at the landscape level, the measure can likely lead to positive effects on other ecosystem services if forest management strategies that promote these positive effects are prioritised. For example, by setting aside forests with high natural value, old forests, riparian forests or forests close to urban areas and by implementing continuous cover forestry on lichen-rich forests, riparian forests or forests with high recreational value, reduced felling can lead to positive effects on biodiversity, recreation, grazing for reindeer and water quality. Depending on which forest is set aside and where it is located, the forest can also provide protection against the climate change effects (e.g., protection against erosion and landslides, fire protection).

2 Methods

2.1 Selected measures

The effects of different forest management scenarios on the forest ecosystem were assessed within the project SKA 22. Each scenario consisted of a combination of different measures. This report presents the analysis of the effects of each single measure as compared to the scenario “current management” in SKA 22. A selection of specific measures which can be simulated in Heureka RegWise was made to increase the understanding and knowledge on how the different measures affect carbon sequestration and release in the forest. The measures were selected among those for which the simulation was already set in the SKA scenarios and that had a potential to affect the carbon sink in the forest. A short description of the selected measures in comparison to current management (BAU) is given in Table 2. A more detailed description of the measures is presented in section 2.2.1 as well as in Eggers et al. (2022).

Table 2 – Description of measures analysed in the report.

Measure	Acronym	Description
1. Reduced browsing damage	DAM-	Halving of browsing damage in young forests: 5% compared to 12% in BAU
2. Longer rotation period	ROT+	The minimum age for final felling is 30% higher than in the existing legislation
3. Reduced felling	FELL90%	10% less felling than in BAU
4. Increased proportion of birch	BRD+	30% of area is rejuvenated with birch compared to 10% in BAU
5. Increased use of continuous cover forestry	CCF+	About a quarter of production forest land is managed with continuous cover forestry methods (patch cutting and selective cutting) compared to 4% in BAU
6. Increased nitrogen fertilization	FERT+	150 000 ha/y forest land is fertilized compared to 33 000 ha/y in BAU
7. Increased set-aside areas	CONS+	Area of set-aside forest areas is doubled: 22% of production forest land compared to 11% in BAU

2.2 Model simulations

The methods used to simulate the effects of different measures on the forest ecosystem in Sweden are described in detailed in Eggers et al. (2022). In that report a detailed description of shortcomings and need for further development of background data on current forest management, of models and functionalities in Heureka RegWise is given. A summary of these methods is presented in this section.

2.2.1 Simulated forest management

The current forest management and the different selected measures imply different settings in model simulations regarding land management and use. Except for in the measure “reduced felling”, all forestry alternatives seek to maintain a felled volume on production forest land that corresponds to the felling intensity in the current forest management scenario. Temporary reductions of felled volume compared to current management depend on the fact that the forest area that has reached the lower age for final felling according to the Swedish law is not enough to maintain the desired felling volume. On the contrary, temporary increases of the simulated felling in the measure “patch cutting” included in continuous cover forestry depends on the fact that only half of the forest area is felled in a first step and the other part is felled some years later. This leads to a delayed felling as compared to the current forest management.

Current forest management (BAU)

In the BAU scenario the forest is managed with current methods and intensity, including current felling intensity (in relation to forest growth on production forest land) (Eggers et al., 2022). The settings for forestry activities in BAU is based on statistics from the Swedish Forest Agency and the National Forest Inventory. The data used are the latest available information from 2020. The data include information on areas of forest divided in different categories (production forests, formally protected, voluntary set-aside, retained, unproductive forest area), areas of rotation and continuous cover forestry, felled, rejuvenated and fertilized areas.

Reduced browsing damage (DAM-)

In Heureka RegWise the level of browsing damage can be adjusted by giving a degree of damage which correspond to a certain percent of damage of seedlings. A degree of damage of 1 correspond to a situation equal to when data was collected in 1970’s and 1980’s. In BAU the degree of damage is set to 5 which correspond to a level of 12% fresh damage on the seedlings and in DAM- the degree of damage is halved to 2.2 which correspond to 5% fresh damage (Bergquist et al., 2019; U. Nilsson et al., 2016).

Longer rotation periods (ROT+)

In ROT+ the minimum allowed age for final felling is increased by 30% compared to BAU. In BAU the minimum age for final felling regulated by the Swedish Forestry Act is the limit for when final felling can be implemented.

Reduced felling (FELL90%)

In FELL90%, felling is reduced by 10% compared to BAU. In BAU, the target is to try to maintain the same felling intensity per calculation area as shown in the latest available statistics. These are based on the period 2016–2020 and corresponds to 79% of the net annual increment (gross increment minus natural mortality) on production forest land. Felling concern living trees but exclude pre-commercial thinnings. The corresponding regional felling intensities in BAU are: Mountain area 39%, North Norrland 62%, South Norrland 66%, Svealand 92%, Götaland 89%.

Increased proportion of birch (BRD+)

Rejuvenation methods are changed in BRD+ to increase the proportion of forest land which is planted with birch. In BRD+, the aim is that broadleaves (mainly birch) constitute at least 30% of the basal area in the forest compared to 10% in BAU.

More continuous cover forestry (CCF+)

Continuous cover forestry is simulated by selective cutting and patch cutting but does not include the option shelterwood uniform system. Therefore, two of the options included in the definition of continuous cover forestry of the Swedish Forest Agency are included in the simulations (Appelqvist et al., 2021) (Figure 2). Patch cutting is implemented in Heureka RegWise in pine dominated forests and by dividing the stand in two parts. Felling in the first part can occur if the forest is older than the minimum age for felling. The other part can be felled only when the new forest in the first part has reached at least 2.5 m of height. Selection cutting is implemented in spruce forests, and it is simulated as a series of thinning's from above with at least 20 years in between. There is no restriction regarding the age when the first thinning can be carried out. The areal of continuous cover forestry is equally divided between the two methods selective and patch cutting. In CCF+ about a quarter of the production forest land (5 Mha) is managed with continuous cover forestry compared to 4% (0.67 Mha) in BAU.

Figure 2 – Simulated options of continuous cover forestry: patch cutting (left) that implies to actively create gaps of 20-50 meters of diameter in the stand; selective cutting which implies that the forest is managed with reiterated thinnings from-above that aims to create an uneven-aged forest (right) (Photos: Leif Milling, Johan Nitare).

Increased fertilization (FERT+)

The measure FERT+ implies that the area of forest land fertilized with nitrogen increases as compared to BAU. The fertilized area increases from 33 100 ha/y in BAU to 150 000 ha/y in FERT+. The size of the area in BAU is based on the average value in the period 2016-2020 reported in the Swedish Forest Agency's survey on implemented forestry measures (*åtgärdsundersökning*[4]). The allocation of the area by region is the same as in Claesson et al. (2015), since statistical data at the regional level were not available. In North Norrland the fertilized area is increased from 7 100 to 53 600 ha/y, in South Norrland from 15 300 to 69 400 ha/y, in Svealand from10 100 to 23 000 ha/y och in Götaland from 600 to 2 700 ha/y. The allocation per region is changed in FERT+ by mainly increasing the fertilized area in Norrland (83% of fertilized area) because fertilization in the south of Sweden should be avoided according to the General Guidance to the provisions in chapter 7, § 26 in the Swedish Forestry Act. In Heureka RegWise the effect of fertilization is simulated as an increase of tree growth through projection functions based on a large amount of data from fertilized study areas (Pettersson, 1994a, 1994b). The projection functions assess the fertilizing effect based on variables such as site index, slope, height above sea level, current annual increment, dominating tree species, type of fertilizer (urea, ammonium nitrate) and dose of fertilizer. In the simulations in this report there is no restriction regarding fertilization on lichen-rich forest. This implies that the analysis does not follow the Swedish Forest Agency's General Guidance which indicates that lichen-rich soils should not be fertilized.

<u>Increased set-aside areas (CONS+)</u>

In CONS+ the area of set-aside in production forest land is increased to 5.2 million hectares compared to 2.6 million hectares in BAU which reduces the area of production forest land to the same amount. These increased set-aside areas are selected by a model used in SKA 22 that sets both a target area and the prioritization of certain forest features. In this model Sweden is divided in 5 natural-geographical regions: alpine, north-western boreal, south-eastern boreal, southern boreal and continental. In each region, except the alpine region, the total area of set-aside is increased to 20% of the total production forest area. The new set-aside areas are chosen based on a series of ground principles aiming to choose areas of forest with existing or presumed high natural value. These principles are applied to add up to 80% of the set-aside area inside each region. The remaining 20% is assigned by randomly selecting forest stands of production forest land to reflect the fact that forest land close to set-aside areas or areas with potential to develop high natural value are usually included in practice to define the total set-aside area.

2.2.2 Heureka RegWise

Forest development was simulated with the application Heureka RegWise (Wikström et al., 2011) which is primarily built for the analysis of different forest management strategies at the regional level. The system is constituted of a series of simulating models to project the status of forests as well as models that describe forestry activities and felling.

The individual plots in the National Forest Inventory 2016–2020 are used in Heureka RegWise as management unit. A combination of stand- and tree-based models are used to simulate forest status (growth, height, age, diameter, etc.). The units that are used in the system for simulation and management enables the production of detailed results. The information at stand-level is aggregated in

[4] https://www.skogsstyrelsen.se/statistik/statistik-efter-amne/atgarder-i-skogsbruket/

assessment areas and ownership categories or further aggregated to produce model results.

The simulations in SKA 22 and this analysis start in 2020 and stop after 100 years. The results for each 5 year-period consist of detailed information on the forest status, forest growth, cuttings and other performed activities.

2.2.3 Climate change and risk for damage

Climate change is simulated in Heureka RegWise mainly through its effect on forest growth. The system is originally based on empirical models at the tree and stand level. Since these models are based on historical data, they are not fully applicable to project forest development in a changing climate. Therefore, a growth effect assessed with the process-based model BIOMASS is added to the simulations (Bergh et al., 2003; McMurtrie et al., 1990). This growth effect is assessed for different conditions and is determined by the selected climate scenario and climate model. The model simulations in BIOMASS use results based on:

1) the RCP4.5 scenario by IPCC (Thomson et al., 2011) which is used as a basis to all the management measures. RCPs are “Representative Concentration Pathways” which are a way to describe the expected future radiative forcing dependent on a possible development of emissions and land use. The RCP4.5 scenario depends on ambitious climate policies that leads to an increase of carbon dioxide up to 2040 and a decrease afterwards and is expected to maintain the global temperature rise within 2 degrees.

2) the results from the climate model MPI-ESM-LR when using the climate scenario RCP4.5. These results are used in the simulations with BIOMASS (Eriksson et al., 2015). The climate model MPI-ESM-LR (Giorgetta et al., 2013) is one of the nine climate models that SMHI uses in their ensembles of climate scenarios.

The natural mortality is simulated in Heureka RegWise through mortality functions. It is simulated at the stand level and occurs in two steps. In the first step, the forest stands where mortality occurs are identified. In the second step, the proportion of basal area of surviving trees is calculated in the stands identified in the first step.

The effect of storms is assessed by a storm-module that reiterates an historical time series of storms adjusted to climate change. The historical data series for storms is based on statistical data from 1953 to 2021. Information on volumes of wind-thrown at the provincial level are used together with data from the Swedish Forest Inventory on the condition of the forest in the current year to adapt a wind model for that particular storm. The wind model includes variables that are related to the stand (tree composition, height, performed thinning, height of the surrounding stand, frozen ground, etc.) (Lagergren et al., 2012). A calibrating factor is also included (wind factor) which is adjusted to simulate the same number of cubic meters of wind-throw as in historical data. Within SKA 22, the time series was adjusted to include the effect of climate change which is expected to reduce the number of days with frozen soil and thereby the risk for wind-throw. The relative decrease of frost days over time in the climate scenario RCP4.5 was calculated, and the storm risk was increased accordingly. This implies that the number of storms increases over time in BAU as well as in other scenarios. However, the volume affected by the storm varies according to the implemented measure as compared to BAU because the forest status differs.

The risk for spruce beetle outbreak is assessed through a risk index that describes the relative susceptibility of a stand to be attacked by bark beetle which depends on the type of stand and climate variables (Nordkvist et al., 2023). The index is based on empirical studies, models observations and expert judgement. The variables influencing the index are: the temperature sum, soil humidity, storm damage, volume of spruce, volume of birch, stand density, the spruce diameter and the age structure of the stand. Since the soil humidity in the model is not influenced by the climate scenarios, precipitation changes have no effect on the risk for bark beetle included in the projections in this report.

The risk for root rot is calculated as a number if spruce trees that are expected to be affected by root rot based on different variables (age of the stand, site index, temperature sum, diameter at breast height, soil moisture, soil texture, heigh above sea level, longitude and proportion of spruce) (Thor et al., 2005). The risk is calculated in Heureka RegWise also as total basal area and tree volume that are affected by root rot.

Other risks for damage are not included in the simulations, for example the risk to damage from forest fires.

2.2.4 Carbon balance

Heureka RegWise simulates the carbon stock in tree biomass, dead wood, soil and in harvested wood products (HWPs). Carbon stock changes over a period depend on the removals by felling, emissions from decomposition and uptake by growth. The carbon stock in tree biomass is calculated with the help of biomass functions to assess tree biomass for individual trees (Claesson et al., 2001; Marklund, 1988; Petersson, 1999; Petersson & Ståhl, 2006) and a default factor to convert biomass (dry matter) to amount of carbon (Thuresson, 2000).

Carbon accumulation in dead wood depends on the incoming amount – inputs through natural mortality, felled trees left in the forest, felling residues (for ex. stumps) – and decomposition. The initial amount of dead wood in the beginning of the simulating period are based on National Forest Inventory data. The estimate of carbon stock in HWPs is based on the method in the IPCC Guidelines (Pingoud et al., 2006; Wikberg, 2011). The carbon stock changes in HWPs are calculated as the difference between the annul inflow and outflow from HWP. The inflow is given by the production of three categories of semi-finished products (sawn wood, panels and paper products) from the simulated felling. The outflow is the decomposition of the existing carbon pool and of the inflow of HWP and it is calculated based on half-life default values per category of product (35 years for sawn wood, 25 years for panels and 2 for paper products). The results for soil carbon are excluded from this report (see section 1.2).

3 Results

3.1 Growth and mortality

Recent results from the National Forest Inventory showed a declining tree growth in the past 10 year, mainly in southern Sweden and in spruce forests (P. Nilsson et al., 2022). The cause of the decreasing growth is unclear, but drought seems to be the most important factor (Fridman et al., 2022). To understand how tree growth is going to develop in the future, further results from the National Forest Inventory and research are needed. Felling in Swedish forests has significantly increased since the 1950's, approaching forest growth in recent years. Recently, felling is about 90 million m^3sk per year[5] which corresponds to about 86% of the net annual increment on forest land (104 million m^3sk per year). The natural mortality has increased in the past decades from 4-5 million m^3sk per year in the 1980s' to 16 million m^3sk per year today (Kempe et al., 2000; P. Nilsson et al., 2022).

The model results indicate that DAM- leads to an increase of the gross annual increment[6] by 7% compared to BAU in 2100 (Figure 3). The measures BRD+ and CONS+ leads to an opposite effect on the gross annual increment which decreases by 7% and 3%, respectively. ROT+ and to a lesser extent FELL90% lead to a positive effect on the gross annual increment in the short and medium term (+6% and +3% in 2050) but the positive effect decreases over time (+1% in 2100). FERT+ leads to a limited increase both in the short and long term (+2%). CCF+ leads to a temporary increase of the gross annual increment in the short term (+1% in 2050) but to a decrease in the medium to the long term (-2% in 2070 and -7% in 2100).

A changed management has marginal effects on natural mortality, but these effects can increase in the long term (Figure 4), especially in FELL% where natural mortality shows a 19% increase in 2100. The mortality increases also in the long term in DAM- and ROT+ (+14% and +11% in 2100, respectively) and to a lesser extent in FERT+ (4%). Mortality increases in all measures except for BRD+ which significantly reduces growth and therefore natural mortality (-11% in 2100). CCF+ leads to a certain decrease of natural mortality in the long term (-2% in 2100).

[5] m^3sk is a forest cubic meter and includes the stem volume including bark but excluding branches and roots.

[6] The gross annual increment is the potential tree growth under local conditions and current management. The net annual increment is the difference between the gross annual increment and natural mortality. The difference between net annual increment and felling determines the change of growing stock in the forest.

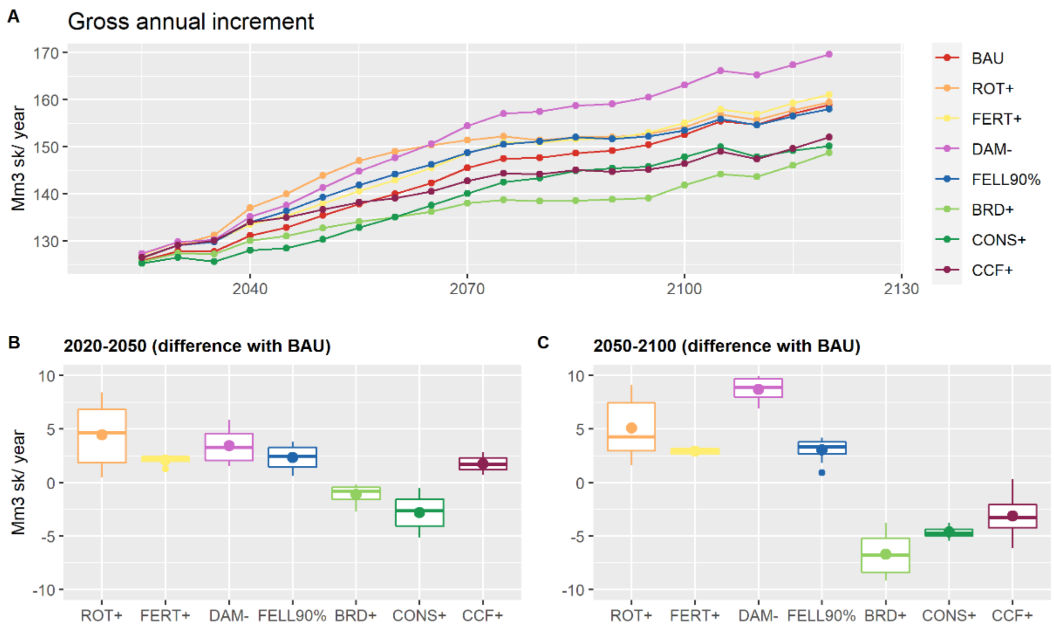

Figure 3 – Effect of different measures on the gross annual increment on productive forest land. A: development of gross annual increment over time; B: gross annual increment in the period 2020-2050 as a difference between the measure and BAU; C: gross annual increment in the period 2050-2100 as a difference between the measure and BAU. The box plot shows the results as the median value (dash through the box), lower and upper quartile (lower and upper line of the box) and minimum and maximum values (lower and upper vertical lines). A description of acronyms for the measures is reported in Table 2.

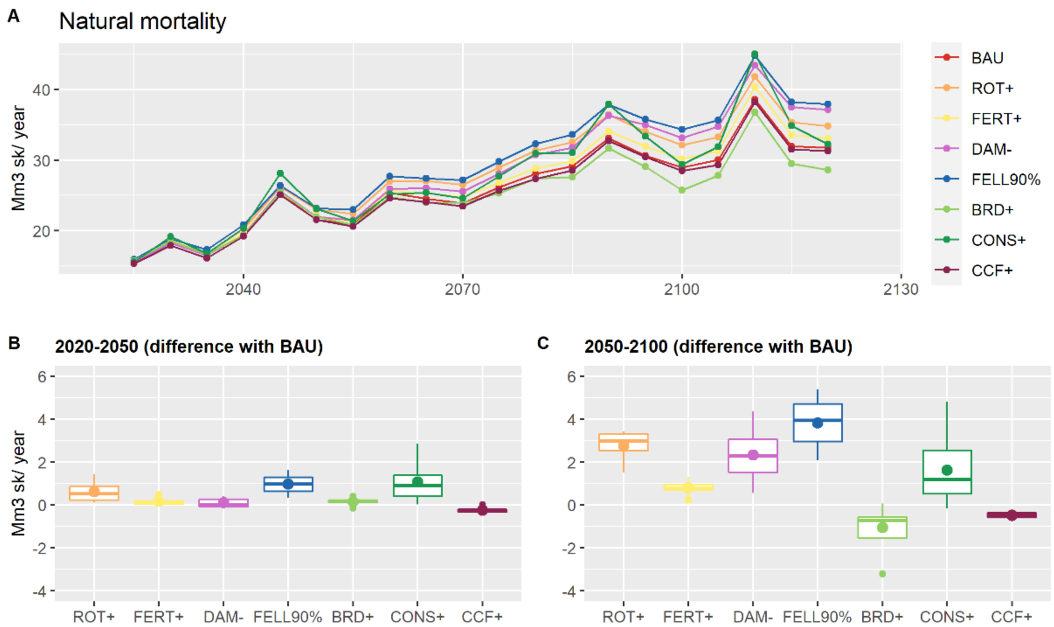

Figure 4 – Effect of different measures on natural mortality on productive forest land. A: development of natural mortality over time; B: natural mortality in the period 2020-2050 as a difference between the measure and BAU; C: natural mortality in the period 2050-2100 as a difference between the measure and BAU.

The combination of the effects on gross annual increment and natural mortality determines the changes in net annual increment (Figure 5). Because of the lower gross annual increment and higher natural mortality, the net annual increment is lower in CONS+ in the short and long term (-6% in 2050 and -4% in 2100). BRD+ leads also to a lower net annual increment over the entire simulation period because the gross annual increment is significantly lower (-3% in 2050 and -6% in 2100). The net annual increment is also lower in FELL90% because of the higher natural mortality, but only in the long term (-4%). DAM- leads to higher net annual increment both in the short and long term (+5% in 2050 and 2100), while ROT+ had positive effects on the net annual increment only in the short and medium term (+6% in 2050 and +3% in 2070) but leads to a marginal decrease of the net annual increment in the long term (-1% in 2100). FERT+ has also a certain positive effect on net annual increment (+2% in 2050 and +1% in 2100), while CCF+ leads to a marginal positive effect in the short term (+1% in 2050) but a negative effect in the long term (-5% in 2100). In the long term, a higher variability in net annual increment is simulated in all scenarios because of more frequent natural disturbances.

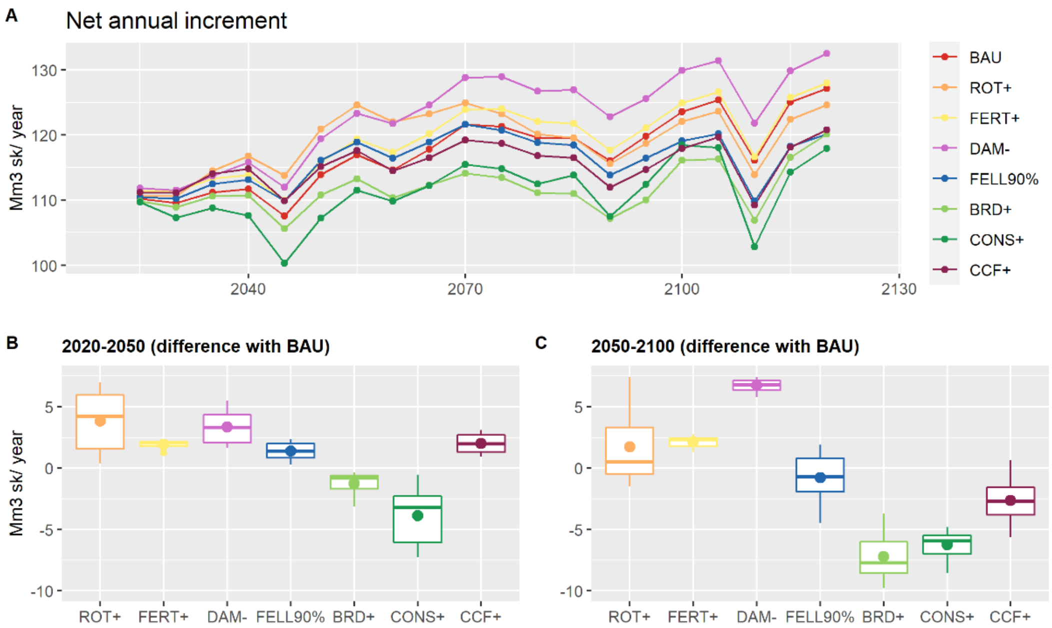

Figure 5 – Effect of different measures on net annual increment on productive forest land. A: development of net annual increment over time; B: net annual increment in the period 2020-2050 as a difference between the measure and BAU; C: net annual increment in the period 2050-2100 as a difference between the measure and BAU.

In the simulations, the aim is to fell a volume of wood that correspond to the volume felled in BAU, except for in FELL90%. Temporary reductions of felling compared to BAU in ROT+, BRD+, CONS+ and CCF+ depend on the fact that the forest area that has reached the minimum age for final felling is not enough to maintain the felling. For this reason, the felling is lower in ROT+ in the short term (-11% in 2050) and in CCF+ in the long term (-5% in 2100) while in CONS+ felling is reduced mainly in the medium term but also in the long term (-13% in 2070 and -7% in 2100). A temporary increase of felling is simulated in CCF+ in the period 2030-2050 probably because of patch cutting which is implemented in the model by dividing the felled stand in two parts which are felled in two different periods. This leads to a delayed felling on the second part of the felled area.

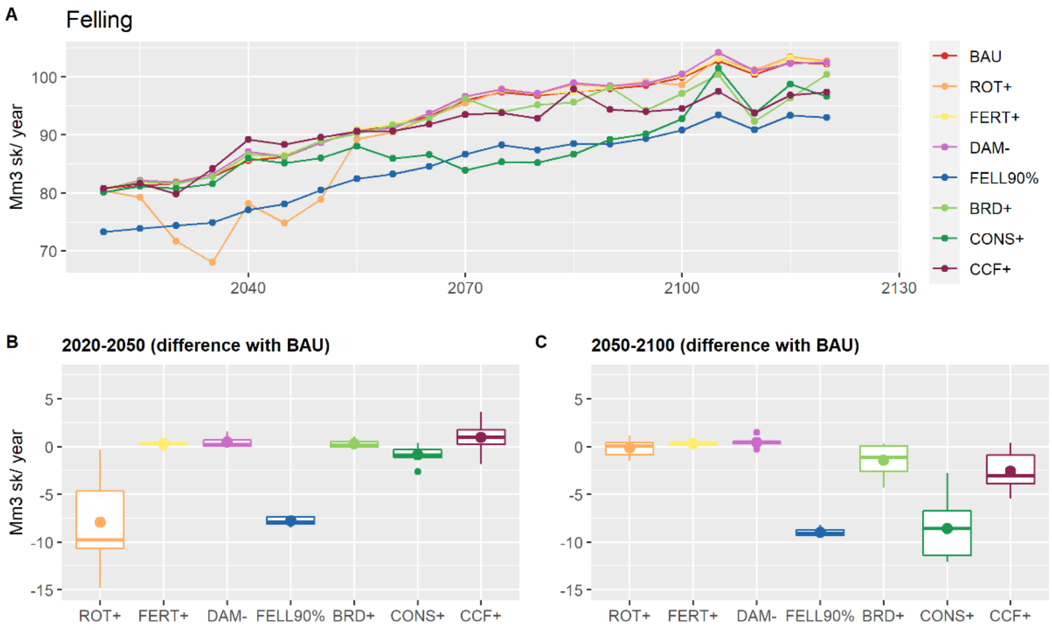

Figure 6 – Effect of different measures on felling on productive forest land. A: development of felling over time; B: felling in the period 2020-2050 as a difference between the measure and BAU; C: felling in the period 2050-2100 as a difference between the measure and BAU.

The analysis of the effects of measures at the regional level indicates the CONS+ can have more negative effects on the net annual increment in Svealand and North Norrland (Figure 7). In Götaland, CONS+ can lead to a higher variability of natural mortality and therefore to temporary changes in net annual increment. ROT+ has positive effects on the net annual increment mainly in southern Sweden where a higher net annual increment than BAU occurs over a longer period that in other regions. BRD+ leads to a reduced net annual increment especially in Svealand, but also in Norrland. This measure has lower negative effect on tree growth in Götaland. Since FERT+ is mainly carried out in Norrland, the measure has positive effects only in that region. FELL90% and DAM- have the same effect in the entire country, that is, a reduced net annual increment in the long term in FELL90% and a higher net annual increment in DAM-.

In CONS+ the felling cannot be maintained at the same level as in BAU in most regions (Figure 8). In Svealand where the felling intensity is highest, CONS+ has a long-term effect on felling that is like the effect of FELL90%. Only in South Norrland the felling can be maintained in CONS+. ROT+ have the largest negative effect on felling in Svealand where the area of production forest land older than the minimum felling age is probably small. The limited area of mature forest can be explained by the current felling intensity. However, ROT+ has a little effect on the felling in Götaland. Effects on montane forests are excluded from the analysis.

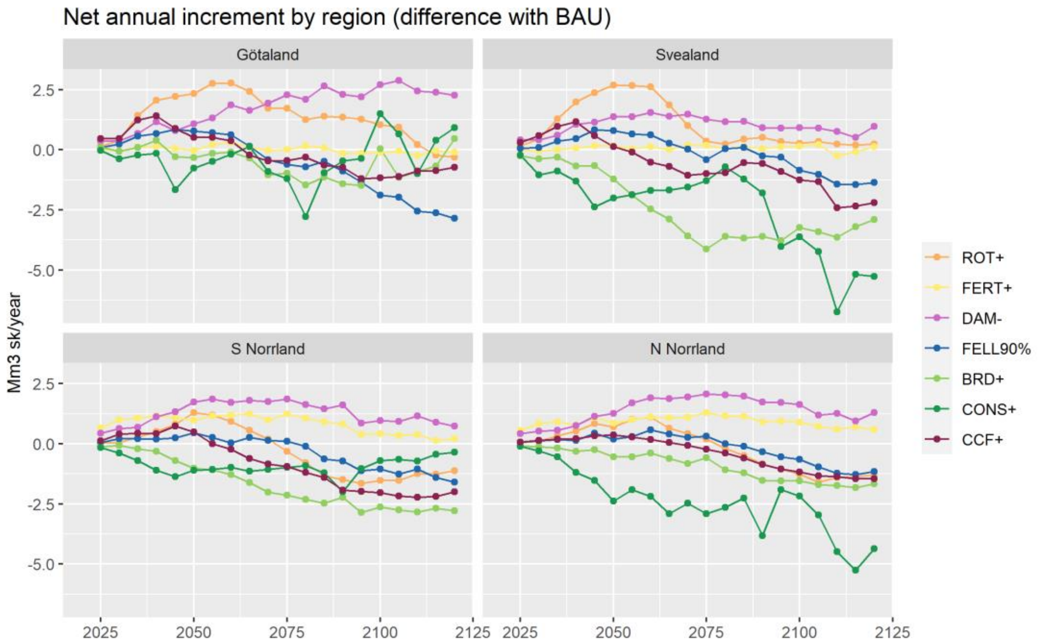

Figure 7 – Net annual increment on productive forest land (excluding montane forests) in different regions as a difference between the measure and BAU.

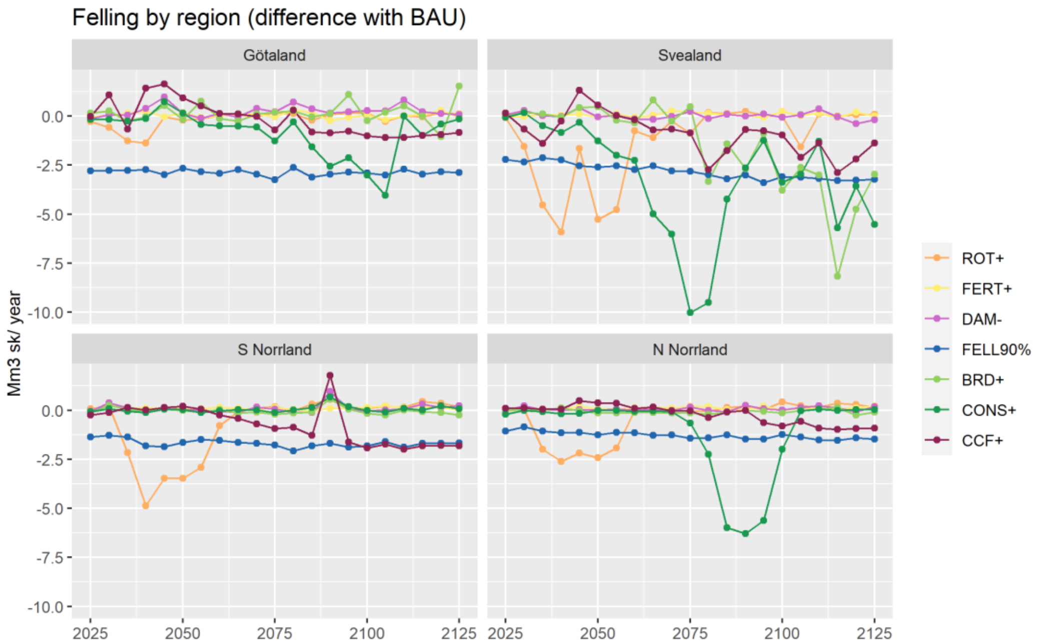

Figure 8 – Felling on productive forest land (excluding montane forests) in different regions as a difference between the measure and BAU.

3.2 Growing stock

The growing stock[7] in Swedish forests have greatly increased since the 1920s' and the forest in Sweden has therefore been a carbon sink over the past 100 years. Spruce forests contributed the most to the increase in productive forest land until the 1970s', but their volume has been more or less stable since the 1990s' except for the fluctuations after the storm Gudrun in 2005 (P. Nilsson et al., 2021). The

[77] Growing stock is defined as the volume of living trees

volume of Scots pine, lodgepole pine, birch and other broadleaves in productive forest land has steadily increased since the 1980's (P. Nilsson et al., 2022).

According to model results, the growing stock is going to increase in the future in Sweden regardless of the type of measure implemented (Figure 9). However, the increase will be significantly higher in the short and long term in FELL90% (+7% in 2050 and +13% in 2100) and in ROT+ (+8% in 2050 and +9% in 2100) compared to BAU. DAM- leads also to higher growing stock, but mainly in the long term (+8% in 2100) and a certain increase occur also in the long term in FERT+ (+3%). Small changes compared to BAU occur in the short term in FERT+ (+1%), CONS+ (-2%), CCF+ (+1%), or BRD+ (-1%). In the long term the growing stock is substantially lower only in BRD+ (-7%).

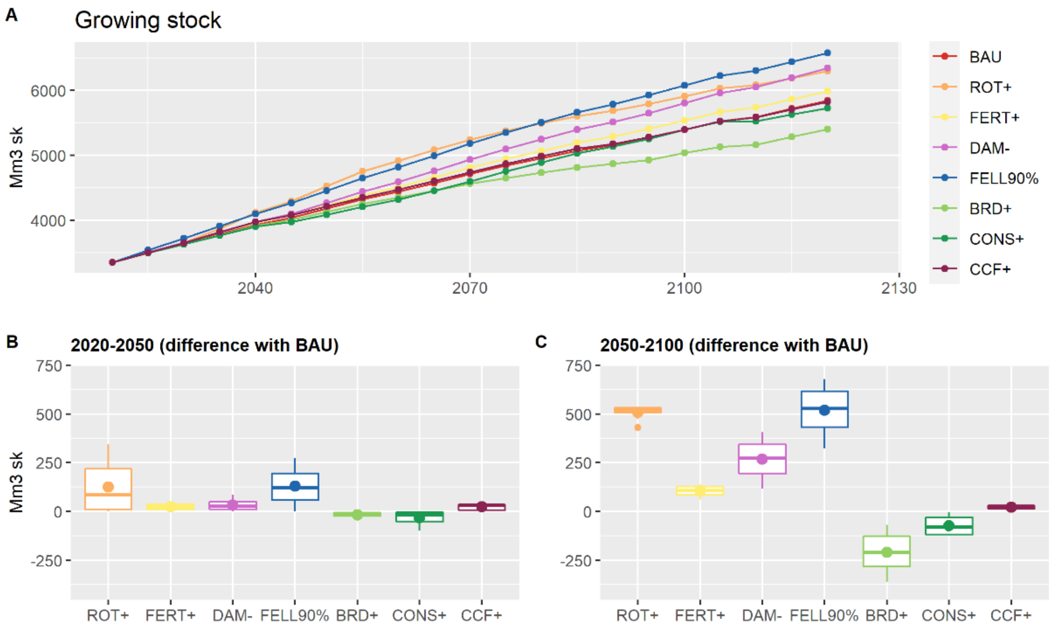

Figure 9 - Effect of different measures on the growing stock on productive forest land. A: development of growing stock over time; B: growing stock in the period 2020-2050 as a difference between the measure and BAU; C: growing stock in the period 2050-2100 as a difference between the measure and BAU.

The changes in growing stock can often be linked to a change of age-class distribution in the forest. The positive effect of FELL90% or ROT+ on the growing stock depends on the fact that the forest becomes older than in BAU (Figure 10). In ROT+, the area of forest that is 60 to 100 years old increases the most while FELL90% leads to a constant increase over time of forest in all age classes above 60-80 years.

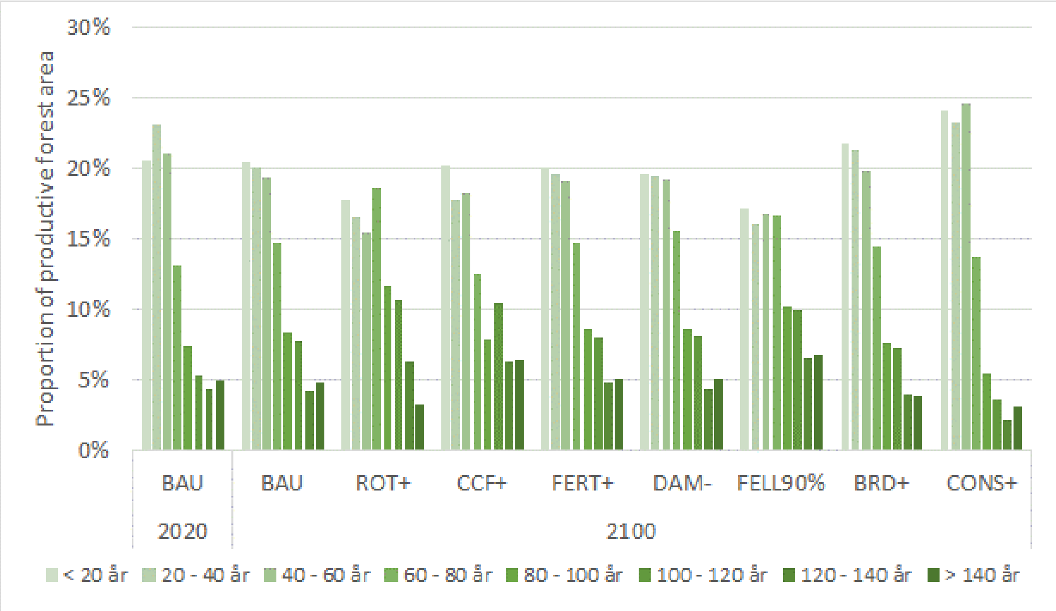

Figure 10 – Proportion of productive forest land in different age classes in 2100 compared to 2020 when different measures are implemented. In 2020 the proportion is the same in all the scenarios.

The effect of a measure on the forest growing stock differs in different parts of the country (Figure 11). According to the model FELL90% can have the greatest potential to increase the growing stock in Götaland, but in other regions ROT+ can increase the most the growing stock in the medium term. In Norrland, DAM- can play an important role both on the medium and long term but it has a lower effect in southern Sweden and only in the long term. The model results indicate that the growing stock in CCF+ is at the same level as in BAU, with a marginal positive effect in Svealand and negative in Norrland in the long term. FERT+ has the potential to increase the growing stock but not in Svealand or Götaland where the fertilized area is small.

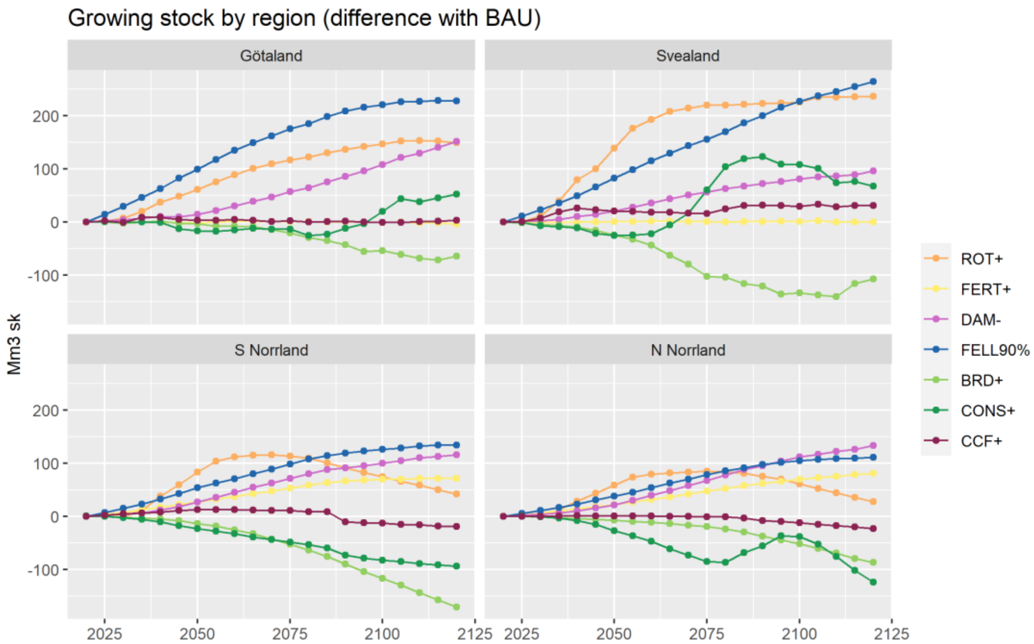

Figure 11 – Growing stock on productive forest land (excluding montane forests) in different regions as a difference between the measure and BAU.

3.3 Carbon fluxes and stocks

The effect of forest management on forest growth and mortality leads to changes in the forest carbon balance and therefore in the carbon that is stored in the ecosystem and wood products as well as in the carbon that is release back to the atmosphere. This section presents the effects of the selected measures on the carbon fluxes and carbon stocks in the forest (excluding soil) and HWPs.

3.3.1 Carbon fluxes

The carbon flux between the forest ecosystem and the atmosphere can be positive or negative and depends on the balance between forest growth and mortality (including natural mortality and felling). A part of the carbon that is taken out from the ecosystem with felling can be stored in HWPs and therefore is not released directly back to the atmosphere (Figure 12). Therefore, the changes of carbon stock in HWPs should be included in the assessment of carbon fluxes from the forest to the atmosphere.

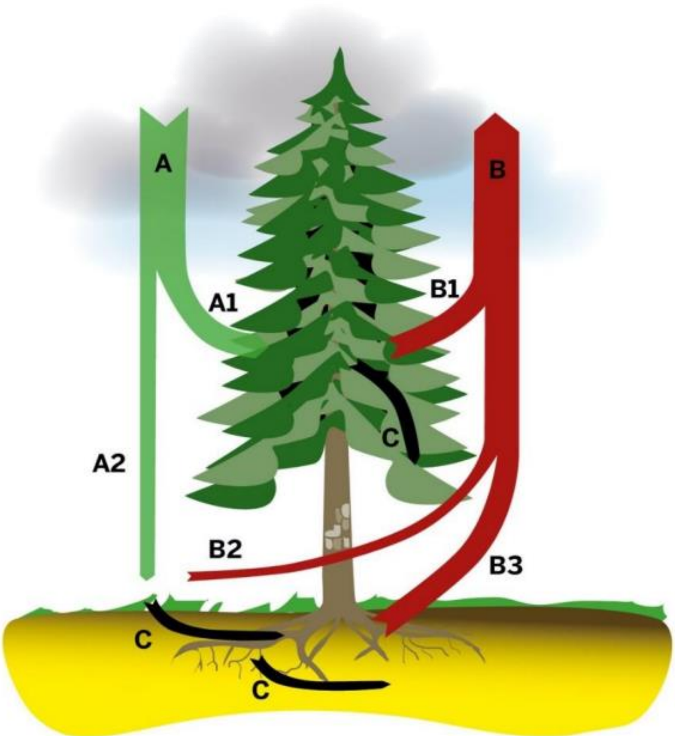

Figure 12 – Carbon fluxes in the forest. A: uptake of carbon dioxide through photosynthesis in tree biomass (A1) and ground vegetation (A2). B: release of carbon dioxide through respiration from trees (B1) and ground vegetation (B2) and decomposition of organic material in the forest (B3). Part of the carbon is transferred to the carbon pools in the litter and organic material in the soil (C). Carbon fluxes from and to HWPs are not included in the figure. Figure by Peter Roberntz (Bergh et al., 2020).

A positive carbon balance corresponds to a release of carbon dioxide to the atmosphere, and it occurs when the release of carbon from the forest ecosystem and HWPs is higher than the carbon sequestration in the forest and HWPs. A negative carbon flux means that the forest and HWPs are a carbon sink, that is, the total carbon stock in the forest and HWPs increases over time.

Because of an increasing forest growing stock, Swedish forests have been a carbon sink over the past 100 years. The ability of forests to keep functioning as a carbon sink depends on several factors such as age class distribution, tree species, climate and atmospheric deposition.

The model results indicates that the Swedish forests and HWPs will continue to be carbon sinks in the coming 100 years, but the sink will decrease over time (Figure 13). According to the model, the carbon sink in the trees, dead wood and HWPs in BAU will be -42.2 Mton CO2/y until 2050 and -37.5 Mton CO2/y until 2100. The carbon pool that plays the biggest role as a carbon sink is the tree biomass since soil carbon is excluded. The measures that have the greatest positive effect on carbon sequestration are FELL90% and ROT+ both in the short and long term (-9.6 and -7.5 Mton CO2/y until 2100). ROT+ leads to a temporary lower carbon sequestration in HWPs than in BAU in the short term (+2.1 Mton CO2/y until 2050), but the carbon sink will be at the same level as in BAU in the long term. DAM- have also positive effects on carbon sequestration compared to BAU, especially in the long term (-5.2 Mton CO2/y until 2100). The results are in line with the increasing positive effect that DAM- has on forest growth over time (Figure 3). However, DAM- leads to a lower carbon sink in dead wood because it reduces natural mortality compared to BAU. Negative effects on carbon sequestration occur in BRD+ and CONS+ (+6.2 and +1.3 Mton CO2/y until 2100). This negative effect on the carbon sink increases over time in BRD+ while it diminishes in CONS+. FERT+ have a limited positive effect on carbon sequestration and CCF+ leads to a carbon sink at about the same level as in BAU (Figure 13 och Table 3).

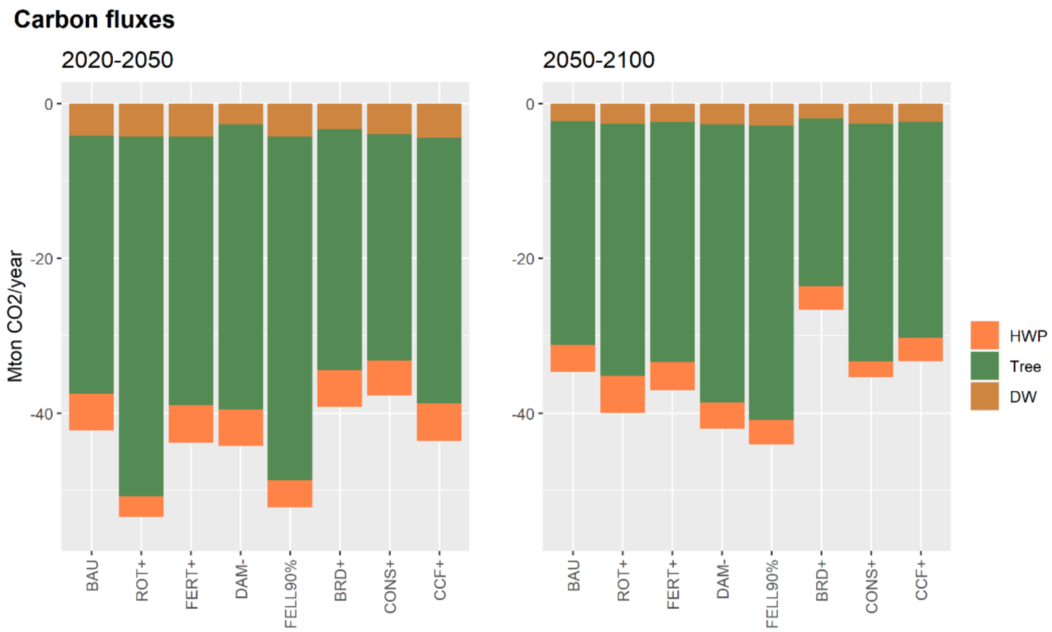

Figure 13 – Uptake of carbon dioxide in different pools in different periods (2020–2050; 2050–2100) when selected measures are implemented on productive forest land. The data in the figure is the average value over the entire period in million tons carbon dioxide per year. HWP: harvested wood products; Tree: living tree biomass; DW: dead wood in the forest. A description of the measures is given in Table 2.

The analysis at the regional level (Figure 14, Table 3) indicates that the forests in Norrland play a significantly bigger role as a carbon sink than the forests in the south of Sweden, mainly because of the lower felling intensity in Norrland and to a lesser extent because the area of productive forests is bigger in Norrland. FELL90% and ROT% increase the carbon sink in all the regions in the short and long term, while DAM- can have an effect in the long term. The measure that above all leads to a reduced carbon sink compared to BAU is BRD+, especially in Svealand (+2,1 Mton CO2/y until 2100). CONS+ leads also to a reduced carbon sink in the entire country in the short term, but the effect diminishes in the long term. FERT+ has positive effects only in Norrland where the measure is carried out to the greatest extent and CCF+ can lead to a limited positive effect in the short term in all regions which decreases over time.

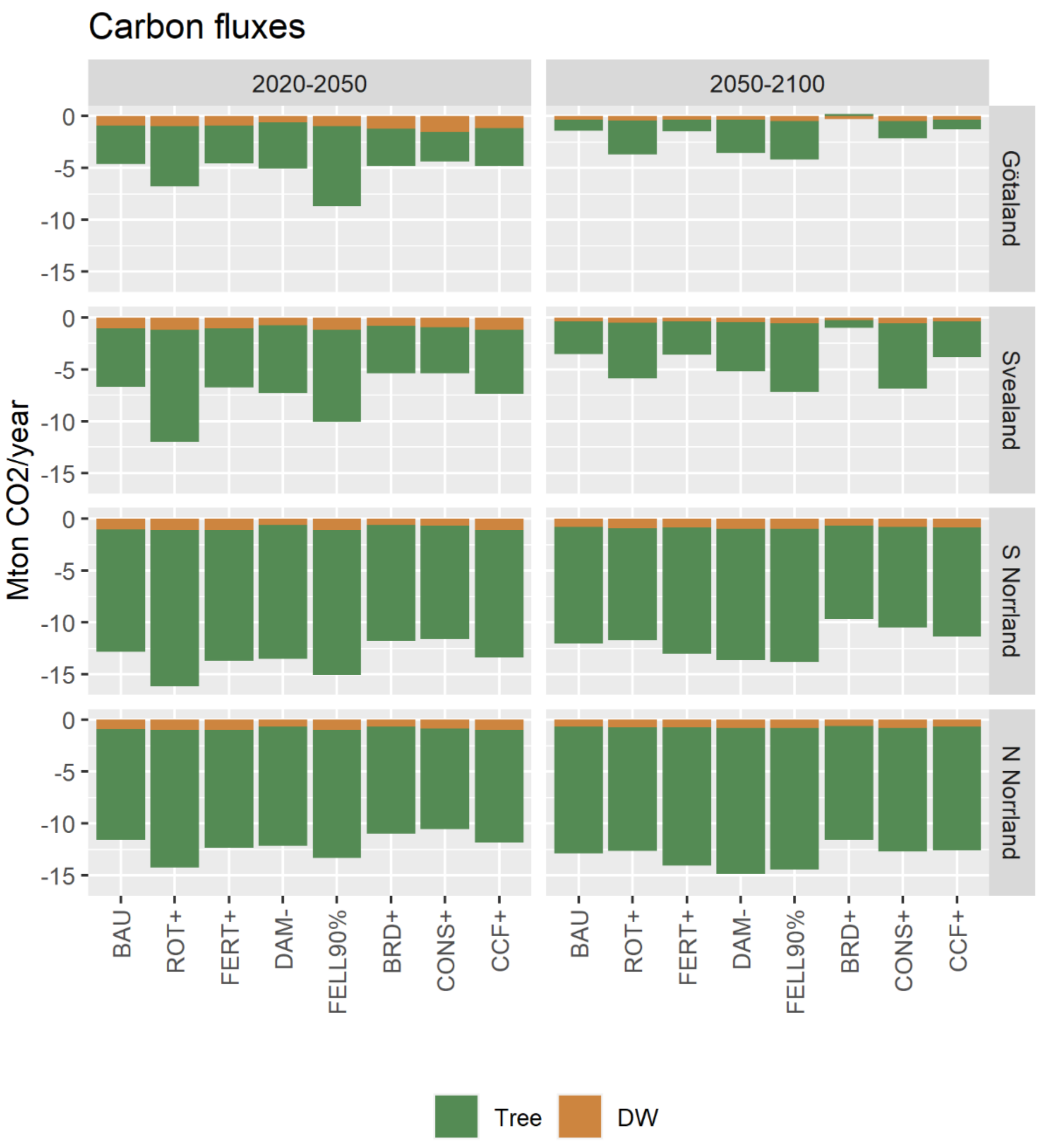

Figure 14 – Carbon fluxes in the forest (excluding the soil) in different parts of the country and over different periods (2020–2050; 2050–2100) on productive forest land (excluding montane forests).

Table 3 – Carbon fluxes (Mton CO2/y) per region and pool in the short term (2020–2050) or long term (2020–2100). The carbon fluxes for each measure are shown as a difference with the carbon flux in the same category in the BAU scenario. Note that the data in the long term are an average value over the entire period 2020-2100.

Period	Region	C pool	BAU	Difference with BAU						
				ROT+	FERT+	DAM-	FELL90%	BRD+	CONS+	CCF+
			Mton CO2/år							
2020–2050	Götaland	Trees	-3.7	-2.11	0.06	-0.72	-3.97	0.11	0.81	0.04
		Dead wood	-0.9	-0.02	0.00	0.30	-0.06	-0.28	-0.58	-0.20
		Total	*-2.3*	*-1.06*	*0.03*	*-0.21*	*-2.02*	*-0.08*	*0.12*	*-0.08*
	Svealand	Trees	-5.6	-5.20	-0.05	-0.89	-3.32	1.01	1.13	-0.62
		Dead wood	-1.1	-0.12	0.01	0.31	-0.09	0.31	0.16	-0.08
		Total	*-3.3*	*-2.66*	*-0.02*	*-0.29*	*-1.71*	*0.66*	*0.65*	*-0.35*
	S Norrland	Trees	-11.8	-3.24	-0.80	-1.12	-2.17	0.65	0.87	-0.49
		Dead wood	-1.0	-0.09	-0.06	0.43	-0.07	0.39	0.37	-0.09
		Total	*-6.4*	*-1.67*	*-0.43*	*-0.35*	*-1.12*	*0.52*	*0.62*	*-0.29*
	N Norrland	Trees	-10.7	-2.60	-0.68	-0.85	-1.63	0.40	0.95	-0.16
		Dead wood	-0.9	-0.05	-0.03	0.29	-0.05	0.25	0.11	-0.05
		Total	*-5.8*	*-1.33*	*-0.35*	*-0.28*	*-0.84*	*0.32*	*0.53*	*-0.11*
	Sweden	**Trees**	**-33.3**	**-13.17**	**-1.47**	**-3.58**	**-11.09**	**2.23**	**4.06**	**-0.97**
		Dead wood	**-4.2**	**-0.12**	**-0.07**	**1.50**	**-0.11**	**0.83**	**0.15**	**-0.28**
		HWP	**-4.7**	**2.11**	**-0.10**	**0.05**	**1.25**	**-0.08**	**0.28**	**-0.17**
		Total	**-42.2**	**-11.19**	**-1.64**	**-2.04**	**-9.95**	**2.97**	**4.49**	**-1.42**
2020–2100	Götaland	Trees	-2.1	-2.15	0.01	-1.59	-3.16	0.85	-0.07	0.12
		Dead wood	-0.6	-0.04	0.00	0.10	-0.09	-0.08	-0.30	-0.09
		Total	*-1.3*	*-1.10*	*0.01*	*-0.75*	*-1.62*	*0.38*	*-0.19*	0.02
	Svealand	Trees	-4.1	-3.31	-0.02	-1.28	-3.39	1.89	-1.52	-0.39
		Dead wood	-0.6	-0.13	0.00	0.05	-0.16	0.19	-0.06	-0.04
		Total	*-2.4*	*-1.72*	*-0.01*	*-0.61*	*-1.78*	*1.04*	*-0.79*	-0.21
	S Norrland	Trees	-11.4	-0.99	-0.91	-1.33	-1.84	1.62	1.26	0.25
		Dead wood	-0.9	-0.09	-0.06	0.07	-0.13	0.22	0.16	-0.07
		Total	*-6.2*	*-0.54*	*-0.49*	*-0.63*	*-0.98*	*0.92*	*0.71*	0.09
	N Norrland	Trees	-11.6	-0.78	-0.92	-1.45	-1.48	0.91	0.57	0.15
		Dead wood	-0.8	-0.07	-0.06	0.02	-0.10	0.13	-0.04	-0.03
		Total	*-6.2*	*-0.42*	*-0.49*	*-0.72*	*-0.79*	*0.52*	*0.27*	0.06
	Sweden	**Trees**	**-30.6**	**-7.21**	**-1.84**	**-5.73**	**-9.86**	**5.36**	**0.42**	**0.24**
		Dead wood	**-3.0**	**-0.26**	**-0.12**	**0.30**	**-0.41**	**0.53**	**-0.17**	**-0.15**
		HWP	**-4.0**	**-0.02**	**-0.09**	**0.12**	**0.70**	**0.26**	**1.03**	**0.29**
		Total	**-37.5**	**-7.49**	**-2.05**	**-5.31**	**-9.57**	**6.15**	**1.29**	**0.38**

3.3.2 Carbon stock

Carbon is stored in the forest as carbon stocks in living trees, dead wood, litter and soil. The soil carbon is the greatest part of the carbon stock in the forest ecosystem. It is estimated that the soil carbon in mineral soils is about 60% of the total carbon stock (Stendahl et al., 2017), but also that soil carbon is quite stable over time because changes occur over a long time (Bergh et al., 2020). Note that the soil carbon is not included in the analysis in this report. Therefore, the carbon stock in the living trees is the largest part of the stock.

Because of the positive carbon flow in the forest system and HWPs, the simulated carbon stock in living trees, dead wood and HWPs will increase over time (Figure 15, Table 4). The model assesses a total carbon stock of 1440 million tons carbon in 2020 in BAU which will increase by 24% in 2050 and 57% in 2100. The carbon pool that contributes the most to the effects on the simulated carbon stock is the living biomass.

The effect of the individual measures on the carbon stock is in line with their effect on the carbon sink. ROT+ and FELL90% leads to an increased carbon stock compared to BAU in the short term (+5% and +4%) and long term (+7% and +9%). Both measures reduce the carbon stock in HWPs, but the effect is significantly lower than in the forest. DAM- has mainly a positive effect on the carbon stock in the long term which corresponds to an increase by 6% compared to BAU. BRD+ and CONS+ have a limited negative effect on the carbon stock in the short term (-1% and -2%.) The negative effect increases in BRD+ in the long term (-6% in 2100) but is still marginal in CONS+ (-1%). FERT+ and CCF+ lead to a carbon stock that is at about the same level as in BAU. CCF+ leads to a positive effect in the carbon stock in dead wood.

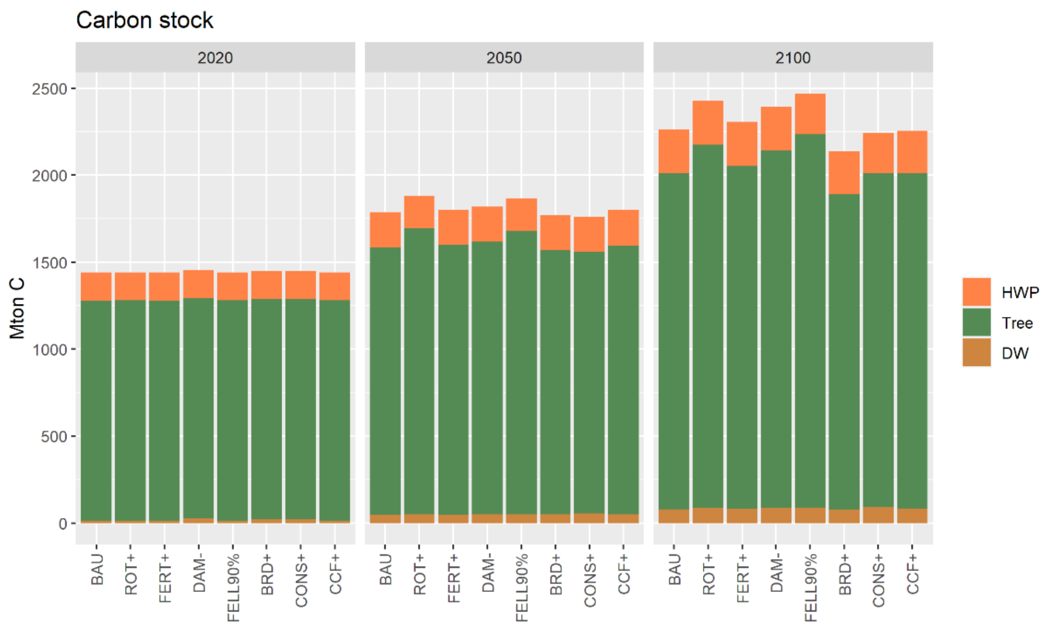

Figure 15 – Carbon stock in different carbon pools over time on productive forest land in Sweden. HWP: harvested wood products; Tree: tree biomass; DW: dead wood.

At the regional level (Figure 16,Table 4) FELL90% have the greatest potential in Götaland and Svealand and leads to 8-9% increase in the carbon stock in living trees and dead wood in 2050 and 18% increase in 2100 which correspond to 71–77.5 Mton carbon increase at the end of the century. FELL90% has also a positive effect in the short and long term in Norrland but the increase is less (+34.5–43 Mton carbon in 2100). ROT+ has also the biggest effect in southern Sweden, especially in Svealand where the effect is at about the same level as in FELL90%. However, in Norrland, ROT+ has only a temporary positive effect. FERT+ leads to increased carbon stock only on Norrland (+4% in 2100). BRD+ reduces the carbon stock especially in Svealand in the long term (-10%). CONS+ has a negative effect on the carbon stock in the entire simulation period in Norrland but has a positive effect in the long term in Svealand (+9% in 2100) och a marginal effect in Götaland. However, CONS+ has a positive effect on the carbon stock in dead wood in the whole country. DAM- has long-term positive effects in the whole country and CCF+ does not substantially affect the carbon stock compared to BAU.

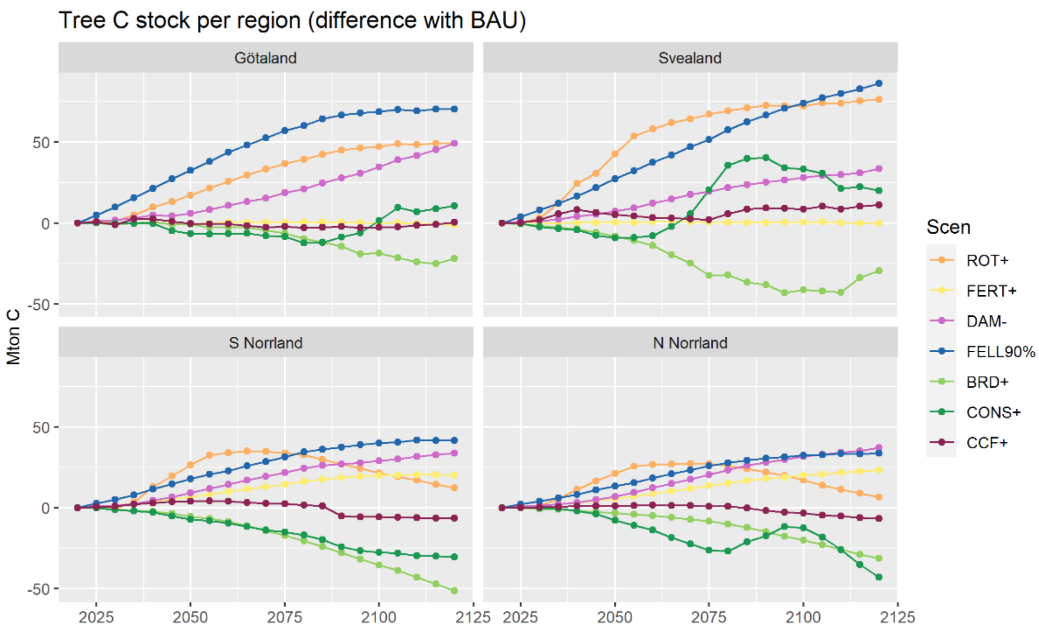

Figure 16 – Carbon stock in tree biomass in different regions on productive forest land (excluded montane forests). The data are shown as a difference with carbon stock in BAU.

Table 4 – Carbon stock per region and carbon pool in different periods. The carbon stock for each measure is shown as a difference with the carbon stock in the same category in the BAU scenario.

Period	**Region**	**C pool**	**BAU**	**Difference with BAU**						
				ROT+	**FERT+**	**DAM-**	**FELL90%**	**BRD+**	**CONS+**	**CCF+**
			Mtons carbon							
2050	Götaland	Trees	371.5	17.2	-0.5	5.9	32.5	-0.9	-6.6	-0.3
		Dead wood	10.5	0.2	0.0	0.5	0.5	-0.4	2.1	1.6
		Total	382.0	17.5	-0.5	6.4	33.0	-1.3	-4.6	1.3
	Svealand	Trees	359.9	42.6	0.4	7.3	27.2	-8.2	-9.2	5.1
		Dead wood	11.8	1.0	-0.1	0.5	0.7	0.6	1.8	0.6
		Total	371.7	43.6	0.3	7.9	27.9	-7.7	-7.5	5.7
	S Norrland	Trees	391.3	26.5	6.5	9.2	17.7	-5.3	-7.1	4.0
		Dead wood	12.1	0.8	0.5	0.6	0.6	0.9	1.0	0.7
		Total	403.5	27.3	7.0	9.7	18.3	-4.5	-6.0	4.7
	N Norrland	Trees	345.1	21.3	5.5	6.9	13.4	-3.3	-7.8	1.3
		Dead wood	10.3	0.4	0.3	0.6	0.4	0.9	2.1	0.4
		Total	355.4	21.8	5.8	7.5	13.8	-2.3	-5.7	1.6
	Sweden	**Trees**	**1537.3**	**107.8**	**12.0**	**29.4**	**90.7**	**-18.2**	**-33.1**	**7.9**
		Dead wood	**47.6**	**2.6**	**0.6**	**2.4**	**2.4**	**2.2**	**7.6**	**3.7**
		HWP	**201.8**	**-18.2**	**0.7**	**-0.1**	**-12.8**	**0.7**	**-1.4**	**1.7**
		Total	**1786.7**	**92.2**	**13.3**	**31.6**	**80.3**	**-15.4**	**-26.9**	**13.2**
2100	Götaland	Trees	386.3	47.0	-0.2	34.7	68.8	-18.5	1.6	-2.7
		Dead wood	15.2	1.0	0.0	0.9	1.9	-0.9	3.9	1.9
		Total	401.5	48.0	-0.2	35.6	70.8	-19.4	5.5	-0.9
	Svealand	Trees	403.3	72.2	0.5	28.0	74.0	-41.2	33.3	8.6
		Dead wood	17.0	2.8	-0.1	1.9	3.6	-1.0	4.4	0.8
		Total	420.3	75.0	0.4	29.9	77.5	-42.3	37.6	9.3
	S Norrland	Trees	544.0	21.6	19.8	29.0	40.1	-35.3	-27.5	-5.6
		Dead wood	23.2	1.9	1.4	2.6	2.7	-0.7	0.6	1.5
		Total	567.2	23.6	21.2	31.6	42.8	-36.1	-26.9	-4.1
	N Norrland	Trees	511.9	17.0	20.1	31.7	32.3	-20.0	-12.5	-3.4
		Dead wood	19.3	1.5	1.2	2.7	2.2	0.1	3.8	0.7
		Total	531.1	18.5	21.4	34.4	34.5	-19.8	-8.7	-2.6
	Sweden	**Trees**	**1931.6**	**157.4**	**40.2**	**125.0**	**215.1**	**-116.9**	**-9.1**	**-5.4**
		Dead wood	**78.6**	**7.1**	**2.5**	**8.2**	**10.4**	**-2.6**	**12.6**	**4.6**
		HWP	**251.5**	**-0.3**	**2.0**	**-2.5**	**-18.2**	**-5.6**	**-23.4**	**-5.4**
		Total	**2261.6**	**164.2**	**44.8**	**130.6**	**207.2**	**-125.0**	**-19.9**	**-6.2**

4 Discussion

The model results are limited to the effect of the selected measures on the carbon sink in Swedish forests and HWPs and do not include an analysis of the total climate benefit of the measures which would require an assessment of the effect of substitution of fossil-based products as well as of leakage. Moreover, the size of the effect on the carbon sink is influenced by the extent to which the measure is implemented which limits the possibility to draw conclusions on which measures have the greatest potential to increase the carbon sink in Swedish forests.

Reduced felling

FELL90% is according to model results a measure that leads to increased carbon sink both in the short (30 years) and long term (80-100) years. The carbon sink increases compared to BAU in the entire country, but the effect is greatest in southern Sweden where the forests are more productive and the current felling is almost at the same level as forest growth. Similar results were presented in Skytt et al. (2021), a study based on simulations with Heureka RegWise at the provincial level.

FELL90% increases the carbon sink by 9.57 Mton CO2/y on average in the period 2020-2100. In the short term, the increase is approximately the same, i.e., 9.95 Mton CO2/y until 2050. However, the increase of carbon sink in tree biomass and dead wood is higher than the total since the carbon sink in tree products deceases (0.7 Mton CO2/y less compared to BAU). Other factors can reduce the potential positive climate effect given by FELL90%, for instance leakage when felling is displaced to other countries, reduced substitution and increased risk for natural disturbances.

If the felling is reduced without reducing the demand for wood raw materials, there is a risk that these materials are imported from other countries or are substituted with fossil-based products. A newly published report estimated that only part of the reduced felling in Sweden could be compensated by increased felling in other countries (R. Lundmark, 2022). The leakage effect of reduced felling in Sweden was estimates to be around 25% for sawn timber and 50% for pulpwood. By assuming that 50% of the reduced logging would be compensated in other countries, it can be roughly estimated that FELL90% could lead to approximately 4.9 Mt CO2/y increased carbon sink on average in 2020–2100, i.e., half of the total potential according to model simulations. By choosing the highest proportion of leakage effect (50%), the estimate can be considered conservative. However, the estimate does not take into account higher emissions linked to reduced efficiency when importing raw materials (e.g., transport or other forestry practices).

If felling is reduced, there is also a risk that substitution of fossil-based products might also be reduced and thereby that fossil emissions increase compared to BAU, especially when the demand for wood products is expected to increase (Duvemo et al., 2015). Research results show that the substitution effect varies greatly depending on the type of product, material that is substituted, production technology and the life cycle of the wood product, as well as on the extent to which the felling volume leads to substitution and the time perspective assumed. Depending on which assumptions are made, a reduced substitution can to a lesser or greater degree affect the total climate benefit that reduced felling can lead to (Gustavsson et al., 2017; Leskinen et al., 2018; Schulte et al., 2022). The risk of reduced substitution can be diminished by increasing the efficiency or recycling of wood-based products, but further analysis is needed to deepen the knowledge of how and to what extent the wood supply chain can be made more efficient (Ahn et al., 2022; Husgafvel et al., 2018; Nunes et al., 2020). If there is a political will to achieve an increased carbon sink in the forest through reduced felling, policy instruments need to be introduced to incentivise it.

The model results indicate that FELL90% leads to a higher growing stock in the forest and that the forest becomes on average older, which are factors that can increase the risk of damage from natural disturbances. This risk becomes particularly high in even-aged forests dominated by one tree species. However, there are several forestry strategies that can be used to reduce felling, such as extending the rotation period, setting aside parts of production forest land and tree retention. The extent to which reduced felling affects the risk of damage from natural disturbances may depend on how and in which combination these strategies are implemented at the landscape level. Activities that are adapted to local conditions that increase the variability in the forest landscape can reduce the risk for damage (Messier et al., 2019, 2022), but further analysis is required to identify landscape-level strategies that can lead to synergies between reduced felling and climate adaptation.

Longer rotation periods

ROT+ has positive effects on the carbon sink, mainly because the measure leads to reduced felling at the beginning of the simulation period. ROT+ leads to an increased carbon sink of 11.2 Mton CO2/y in 2020-2050 compared to BAU. At the same time, ROT+ leads to a strong reduction of the carbon sink in HWPs (2.22 Mton CO2/y). However, this reduction decreases over time until the carbon sink in HWPs is approximately at the same level as in BAU. The effect of ROT+ on the forest carbon balance is higher than that of FELL90% in the short term (20 years) because felling is temporarily reduced by more than 10% compared to BAU. Felling decreases sharply at the beginning of the simulation period in Svealand and Norrland because the area that has reached the minimum felling age is not enough to maintain the level of felling. Unlike FELL90%, ROT+ seeks to fell a volume that corresponds to the felling in BAU. Therefore, after an initial period when felling is reduced, the felled volume returns to the same level as in BAU. Therefore, the positive effect of ROT+ on the carbon sink decreases over time. The carbon sink until 2100 increases by 7.5 Mt CO2/y compared to BAU while the carbon sink in HWPs is at the same level as in BAU.

ROT+ also leads to a change in the age class distribution in the forest. At the national level, the forest area in age classes 60–140 years is increasing compared to BAU, and the forest younger than 60 years or older than 140 years is decreasing. Due to the shift to the older age groups, the net annual increment is temporarily higher than in BAU, but this effect diminishes over time. However, the effect at the national level depends on different changes in age distribution in different parts of the country. In Götaland, the net annual increment and thus the carbon sink is higher than in the BAU until 2100. The difference is greatest in 2060 and then it decreases until the net annual increment is approximately at the same level as in BAU at the end of the century. In Götaland, the effect of ROT+ is mostly due to the change in age class distribution, as felling changes very little compared to BAU at the beginning of the simulation period. The forest in the age group 60–80 years increases, while the area of forest older than 100 years and younger than 20 years decreases. In Svealand and Norrland, the net annual increment and thereby the carbon sink increase mainly in the period when felling decreases compared to BAU. Therefore, the effect of the change in age class distribution seems to be less important in those parts of the country. In Norrland, the net annual increment is lower than in BAU after 2075 as well as the carbon sink in the tree biomass. The reason for a reduced net annual increment is a combination of increased area of mature forest (>100 years) and temporary higher felling after 2070 which may be caused by simulated disturbances.

When rotation periods are extended, and the forests become older, natural mortality increases. To some extent, a higher natural mortality can have a positive effect on the stock of dead wood and thereby on the forest carbon stock and on biodiversity (Roberge et al., 2016). However, the risk of damage from natural disturbances also increases with biomass stock and age (Forzieri et al., 2021). It is therefore important that the rotation periods are extended in forests where this risk of damage is limited. For example, the risk for spruce bark beetle attack increases with the volume of spruce and decreases with soil moisture (Müller et al., 2022) and therefore extended rotation periods in spruce forests on dry soils may be associated with increased damage risk.

Reduced browsing damage

Positive effects on the carbon sink in DAM- are mainly simulated in the long term. On average until 2100, the results indicate that the carbon sink can increase by 5.3 Mt CO2/y if browsing damage is halved compared to today. Until 2050, the carbon sink can increase by 2.0 Mt CO2/y. The measure has a similar effect in all parts of the country.

In Heureka RegWise, the measure was implemented without changing forest management. Alongside game management, measures to increase the proportion of broadleaves or pine and the density in young forests can be effective strategies to reduce browsing damage (Díaz-Yáñez et al., 2017; Pfeffer et al., 2021). Depending on the implemented forest management strategy, the potential carbon sink can change. For example, according to model results, an increased proportion of birch can reduce growth and thereby the carbon sink. On the other hand, the risk of damage is less in mixed forests, which can mean a lower but more stable carbon sink over time. An increased proportion of pine forests can also improve the resilience of the forest and thus increase the carbon sink when pine is planted on soils suitable for pine (e.g., dry soils).

The model simulations do not take into account for the different levels of browsing damage in different parts of Sweden but the same level of browsing damage is assumed in the entire country. However, inventory data show that the yearly damage by moose in young pine forests is much higher in Götaland (Bergquist et al., 2019). If this regional difference is considered, a greater positive effect of measures reducing browsing damage can be expected in Götaland.

Increased set-aside areas

The model results indicate that when more production forest land is set aside but felling is maintained at the same level as in BAU, the carbon sink in Swedish forests decreases, mainly in the short term. In CONS+, the carbon sink decreases on average by 4.5 Mton CO2/y until 2050 and by 1.3 Mton CO2/y until 2100. However, according to model simulations, the carbon stock in dead wood increases. As dead wood is considered an important indicator for biodiversity (MCPFE, 2003), the model results confirm that forest set-aside areas have an important role for biodiversity.

The results in this report are based on the assumption that a reduced wood production following increased set-aside can be replaced with increased felling in other forests within the same region. An earlier study by Kallio et al. (2006) based on a modelling analysis at the European level showed that a 5 percent increase in set-aside areas in Western Europe can lead to a 4 percent increase in the price of roundwood and a 3 percent reduction in felling in the same region, which in turn leads to leakage in Russia where felling of roundwood increases. The study suggests that several factors can affect timber prices and thereby the production of wood raw materials in the same and other regions as well as other countries, but also suggests that the impact of forest protection at the regional level should be analysed better. Given that it is unlikely that increased set-aside will lead to increased felling only at a local level, results from this report should be further analysed.

Increased proportion of birch

The model results for BRD+ indicate that an increased proportion of birch in Sweden's forests leads to a reduced carbon sink by 6.15 Mton CO2/y on average until 2100 and lower negative impact on the carbon sink in the short term (2.97 Mton CO2/y less until 2050). The measure does not include rejuvenation with other deciduous species than birch in southern Sweden. Moreover, the model simulations do not consider a reduced risk for damage from natural disturbances that this measure can lead to. When coniferous forests that are or will become vulnerable to storm, fire or pests are rejuvenated with an increased proportion of deciduous trees, the risk of damage from natural disturbances will probably decrease and thus the carbon sink will be more stable over time. This effect is not included in this study.

Increased nitrogen fertilization

According to the model, FERT+ can lead to an increased carbon sink by 2.05 Mton CO2/y until 2100. In the long term (until 2100), FERT+ increases the carbon stock in trees, dead wood and products by a total of 45 Mton carbon or 2 percent compared to BAU. In the short term (until 2050), the carbon stock will increase by 1 percent. Felling in this scenario was the same as in BAU and therefore the increase in growth from fertilization results in an increased carbon sink and not in an increased production of wood raw materials or substitution. The positive effect is limited to northern Sweden because 83 percent of the area that is fertilized per year in FERT+ is in that part of the country. The increase of fertilized forest land in

Götaland and Svealand was limited to 15,000 ha/y more than in BAU compared to an increase by 100,600 ha/y in Norrland. The assumption that fertilization is not increased much in Götaland and Svealand is based on restrictions given in southern Sweden in the General Guidance to the Foresty Act by the Swedish Forestry Agency (SKSFS 1991:2). Several scientific studies support the Guidance by showing limited effects of nitrogen fertilization in southern Sweden (Pettersson & Högbom, 2004) and increased risk for nitrogen leakage (Lucander et al., 2021). Increased risk for nitrogen leakage and negative effects on grazing for reindeer should also be taken into account to identify possible areas for nitrogen fertilization in northern Sweden, but no such restrictions were included in the impact analysis of FERT+. This means that the restrictions set in the Regulations and General Guidance to the Forestry Act to avoid fertilization near watercourses and lakes or in lichen-rich forests were not applied in the model simulations. Therefore, the potential annual fertilization area may be overestimated in the analysis. Results about the effect of FERT+ in this report should also be interpreted with caution because the nitrogen fertilization effect in Heureka RegWise is based on empirical functions that estimate volume increase after nitrogen fertilization (Pettersson, 1994a, 1994b), but do not consider local conditions and dynamic processes that affect nitrogen availability. Further analysis that integrates dynamic processes into modelling can contribute to a better understanding of the effect of nitrogen fertilization in different parts of the country in a changing climate.

Increased used of continuous cover forestry

The differences in carbon stocks and carbon flows in CCF+ compared to BAU are small, but there is some variation between different parts of the country and time periods. The model simulations indicate a limited positive effect of CCF+ on carbon fluxes and carbon stocks until 2070. The increased carbon sink is due to an increase in gross and net annual increment until 2060 which may be due to various factors, such as reduced felling or to how forest growth reacts to selective or patch cutting in the model. However, the net annual increment is projected to be slightly lower in CCF+ than in BAU from 2060 to 2100.

There are uncertainties about simulating forest growth after reiterated thinnings in the model as it is done in selective cutting. There is also uncertainty about whether all the stands where selective cutting and patch cutting are applied in the simulation are in reality suitable for these methods. In addition, there are uncertainties around the modelling of ingrowth during selective cutting. The model results in CCF+ should therefore be interpreted with caution.

Previous studies have shown that there is uncertainty about the effects of continuous cover forestry compared to rotation forestry, especially because continuous cover forestry involves several different management methods that affect the forest ecosystem in different ways. Comparisons between selective logging and rotation forestry suggest that it is unclear which of the two options leads to higher biomass production (Ekholm et al., 2023).

The effect of continuous cover forestry methods on the carbon balance, including HWPs, is also uncertain and different studies come to contradictory results depending on which assumptions are made (T. Lundmark et al., 2016; Pukkala, 2014). However, scientific studies show that an increased area that is managed with continuous cover forestry methods can be an effective strategy to better achieve multifunctionality in the forest (Díaz-Yáñez et al., 2020; Eyvindson et al., 2021; Peura et al., 2018) and can be positive for biodiversity (Seedre et al., 2018).

By increasing diversity at the landscape level with a combination of management methods, one can also increase resistance to natural disturbances (Messier et al., 2019) and thereby create a more stable carbon sink and carbon stock in the forest. At stand level, however, thinnings (and thus selective cutting) can lead to a temporarily increased risk for wind-throw over 3–5 years, depending on the type and intensity of thinning carried out (thinning from above and intensive thinning leads to higher increased risk) (Diaci et al., 2017). It is therefore important to carry out the transition from even-aged to uneven-aged forest through a low-intensity and frequent timber extraction, especially in areas where the risk of wind-throw is high (Andersson & Appelqvist, 2020; Diaci et al., 2017).

Soil carbon

The effect of the measures on soil carbon was excluded from the results due to the uncertainty of the simulated starting value of the soil carbon pool (see section 1.2). Previous studies that analysed the effect of forestry on soil carbon show that measures that have a positive effect on growth also have a positive effect on the supply of carbon to the soil, but also that a reduced risk of damage from natural disturbances can be important to preserve the soil carbon stock and thereby avoid large carbon losses (Jandl et al., 2007). In the future, climate change will likely affect the balance between decomposition and mineralization and thereby the carbon balance in the soil. Since soil processes are affected by temperature but also soil moisture, it is unclear how the carbon stock will be affected by climate change in Swedish forests (Belyazid & Zanchi, 2019). Given that the soil carbon is the largest part of the forest's carbon stock, small changes in the soil carbon can lead to large carbon losses or gains. Therefore, it becomes important to carry out further analyses that can estimate effects of forestry measures on soil carbon in a changing climate to avoid carbon loss from the soil pool.

Climate change and forest damage

The model simulations include effects of climate change on forest growth, which in turn affects the forest's carbon balance. The results indicate that in BAU the gross annual increment will steadily increase in the future in Norrland and Svealand, which should be analysed further, especially when taking into account seasonal variation in precipitation such as increased risk of summer drought. In addition, limiting factors such as nitrogen, water availability and sunlight may actually limit the potential growth driven by future temperature increases. Moreover, a single emission scenario and a single climate model were used for model simulations in the impact analyses, which limited the possibility of estimating the variability of the climate change effect.

The risk of damage from natural disturbances will probably increases in the future due to climate change, but in the analyses the frequency of damage was the same in all the measures. Some measures can lead to more varied forests (BRD+, CCF+, DAM-) or a more varied forest landscape (CONS+, CCF+) which can reduce the risk of damage from natural disturbances. On the other hand, some measures can lead to the forest becoming older (ROT+, CONS+, CCF+) or to increased biomass stock (FELL90%, FERT+, DAM-) and thereby to increased frequency of damage. These effects are not captured by the model. Strategies that can reduce forest vulnerability will most likely be very important in a changing climate. Resilient forests have the potential to preserve the carbon stock that already exists in Swedish forests and to contribute to a more stable carbon sink.

Regional differences

The results indicate that the effect of the selected measures differs at the regional level and that some measures are more effective in some parts of the country than in others. Taking regional conditions into account becomes important to identify which combination of measures can lead to the greatest positive effect on the carbon balance in the forest and at the same time avoid conflicts or promote synergies with other environmental goals.

FELL90% has positive effects on the carbon sink in the forest in the entire country but has the greatest effect in Götaland (more than doubled sink in 2020–2100) and Svealand (+75%) where the felling is highest today. ROT+ has a positive effect that diminishes over time and lasts the longest in Götaland, while it can be negative in Norrland in the long term.

FERT+ has positive effects on the carbon sink in Norrland, but lichen-rich forests should be avoided when considering reindeer husbandry. In southern Sweden, FERT+ has limited applicability due to current restrictions. In addition, increased fertilization on nitrogen-rich soils in southern Sweden may have limited effects on growth and negative effects on water quality.

The model results indicate that DAM- will have equal effects throughout the country, but further analysis assuming different degrees of browsing damage in different regions should be carried out to understand the regional effect of this measure. Given that browsing damage is highest in Götaland, greater positive effects can be expected in that region.

CONS+ has a positive effect on the carbon sink in Götaland because the measure does not affect the total net annual increment and leads to reduced felling. In other region CONS+ leads to a negative effect on the net annual increment which leads to a negative effect on the carbon sink in Norrland. In Svealand the negative effect on the net annual increment is compensated by a strongly reduced felling in production forest land that altogether leads to a positive effect on the carbon sink in the long term. Felling in Götaland and Svealand cannot be maintained at the same level as in BAU because of the current high felling intensity.

BRD+ leads to reduced carbon sinks throughout the country, but the effect is greatest in Svealand. However, further analysis is required to better understand synergies between increased proportion of deciduous trees and reduced browsing damage or increased resistance to natural disturbances, as well as in which regions these synergies may be greatest.

CCF+ has a limited impact on the carbon sink in all parts of the country. Further analysis and further model development is needed to better understand different effects of CCF+ in different parts of the country.

5 Conclusions

According to the model results, FELL90% has the potential to increase the carbon sink in Swedish forests by 9.6 Mton CO2/y until 2100. The measure has a positive effect on the carbon sink both in the short and long term and in all parts of the country, but the greatest potential is in southern Sweden, where the felling intensity is the highest today.

ROT+ can also increase the carbon sink in the forest (by 7.5 Mton CO2/y until 2100), but the effect is mainly linked to temporarily reduced felling. Only in Götaland ROT+ can lead to temporary positive effects on the carbon sink without significantly reducing felling. There, the higher carbon sink is due to a change in the age class distribution, which leads to a diminishing positive effect over time. In other parts of the country, ROT+ implies that the felling cannot be maintained for a certain period of time. The results in CONS+ also indicate that more set-aside areas will not contribute to an increased carbon sink if the remaining production forest land is used more intensively to maintain today's felling volume.

A reduced felling can lead to a reduced supply of wood raw materials which can lead to an increased demand for fossil materials or an increased import or reduced export of wood raw materials from or to other countries. That is, emissions of carbon dioxide can be moved to forests in other countries or to other sectors. To fully achieve the positive effect from reduced felling, the risk of indirect emissions from leakage or reduced substitution should be minimized. If there is a political will to achieve an increased carbon sink in the forest through reduced felling, new incentives that are lacking today need to be introduced to reduce felling and minimize the risks of leakage and reduced substitution (NV et al., 2022).

FELL90% also leads to Swedish forests becoming older on average. Depending on the structure and composition of the forests, this can have positive effects for several ecosystem services and biodiversity. It can also imply more unstable carbon stocks and a higher risk for damage from natural disturbances that can contribute to the release of greenhouse gases. Climate adaptation will be required both at the stand and landscape level regardless of whether felling is to be reduced or not and will play an important role in reducing the risk for damage from natural disturbances.

Other measures that can have a more long-term positive effect on the carbon sink are DAM- and to a lesser extent FERT+ (respectively 5.3 and 2.1 Mton CO2/y until 2100 more than in BAU). However, further analysis would be needed to investigate how browsing damage can be reduced in practice in different parts of the country and how the implemented measures would affect the forest's carbon sink. Nitrogen fertilization can lead to negative effects for other ecosystem services (for example water quality and grazing for reindeer), which limits the applicability of the measure also in the future and thereby its potential to increase the carbon sink.

The model simulations indicate that BRD+ can affect the carbon sink negatively, but further analyses should be carried out to confirm the results, especially for southern Sweden. The projections include neither the positive effect that an increased percentage of deciduous trees can have on reducing the risk of damage from natural disturbances nor the effect of the increased proportion of other deciduous trees than birch.

The results also indicate that CCF+ has no significant impact on the carbon sink. Further development of the model will be required to better describe the effects of different continuous cover forestry methods on forest ecosystems. Ongoing development of models and measurements will contribute to an increased knowledge of the effect of continuous cover forestry on the carbon sink.

The model results also indicate that different measures can be more or less effective depending on the part of the country in which they are implemented. Identifying different regional strategies is therefore crucial to effectively maintain and increase the carbon sink in Swedish forests.

Finally, it appears from the projections that the carbon sink in Swedish forests will decrease over time, regardless of the analysed measure. Data from the National Forestry Inventory indicate that growth has decreased in recent years, presumably because of increased summer drought. Previous analyses have shown the model needs to be developed to better describe the effect of drought on growth (Eriksson et al., 2015). That is, there is a risk that the carbon sink can decrease faster than in the results presented in this report. Therefore, it becomes even more important to identify measures that can preserve or increase the carbon sink in the forest and wood products to achieve the climate goals.

The analyses presented in this report are based on given assumptions which entail a number of limitations that are discussed in the report. Further analyses will be needed to increase understanding of and knowledge on the issue.

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